FLOOD, DROUGHT AND CLIMATE CHANGE ANALYSIS OF NEPAL

Water and Energy Commission Secretariat (WECS)

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ABBREVIATION

AO	Arctic Oscillation
AORI	Atmosphere and Ocean Research Institute
CBS	Central Bureau of Statistics
CDF	Cumulative distribution function
CMIP	Climate Model Intercomparison Project-6
CSDI	Cold Spell Duration Index
DDMA	District Disaster Management Authorities
DHM	Department of Hydrology and Meteorology
DMI	Dipole Mode Index
DRR	Disaster Risk Reduction
DRM	Disaster Risk Management
ENSO	El Niño–Southern Oscillation
ECMWF	European Centre for Medium-Range Weather Forecasts
FEWS	Flood Early Warning System
GCM	Global Climate Model
GCOS	Global Climate Observing System
GDI	Gender Development Index
GLOF	Glacial Lake Outburst Flood
HFA	Hyogo Framework for Action
HDI	Human Development Index
ICAR	Indian Council of Agricultural Research
IDW	Inverse Distance Weighing
IWRM	Integrated Water Resources Management
ILF	Instantaneous Low Flow
IMF	Instantaneous Maximum Flow/Flood
IOD	Indian Oscillation Dipole
IPCC	Intergovernmental Panel on Climate Change
IRBD	Integrated River Basin Development
ISO	International Organization for Standardization
ITSZ	Indus–Tsangpo Suture Zone
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
LAPA	Local Adaptation Plan for Action
LDOF	Landslide Dam Outbreak Flood
LULC	Land Use Land Cover
masl	meters above sea level
MBT	Main Boundary Thrust
MFT	Main Frontal Thrust
MCT	Main Central Thrust
MoHA	Ministry of Home Affairs
MPI	Multidimensional Poverty Index
MPIM	Max Planck Institute for Meteorology

NAPCC	National Action Plan on Climate Change
NAO	North Atlantic Oscillation
NDMA	National Disaster Management Authority
NDRF	National Disaster Response Framework
NDRRMA	National Disaster Risk Reduction and Management Authority
NIES	National Institute for Environmental Studies
NICRA	National Innovations in Climate Resilient Agriculture
NSDRM	National Strategy for Disaster Risk Management
NSE	Nash–Sutcliffe model efficiency coefficient
PBIAS	Percent Bias
PDO	Pacific Decadal Oscillation
PNR	Percentage Departure of Nepal Rainfall
RDI	Reconnaissance Drought Index
RSR	Ratio of the root mean square error to standard deviation
SDMA	State Disaster Management Authorities
SFDRR	Sendai Framework for Disaster Risk Reduction priorities for action
SNHT	Standard Normal Homogeneity Test
SDG	Sustainable Development Goals
SOI	Southern Oscillation Index
SOP	Standard Operation Procedures
SPI	Standardised Precipitation Index
SPEI	Standardised Precipitation-Evapotranspiration Index
SSI	Standardised Streamflow Index
SSP	Shared Socioeconomic Pathways
SST	Sea Surface Temperature
STDS	South Tibetan Detachment System
SWAT	Soil Water Assessment Tool
WCRP	World Climate Research Programme
WECS	Water and Energy Commission Secretariat
WSDI	Warm Spell Duration Index

EXECUTIVE SUMMARY

1. Background

Nepal is a mountainous country situated between the Tibetan Plateau and the Indo-Gangetic Plains. Its altitude ranges from 60 meters above sea level (masl) to 8,848.86 masl within a north-south stretch of less than 200 km. During the monsoon season, humid air traveling westward from the Bay of Bengal collides with Nepal's hills and mountains, resulting in heavy rainfall. However, the remaining eight months of the year experience minimal rainfall and are relatively dry. Due to its unique climatic conditions and geographical setting, Nepal is highly susceptible to both floods and droughts.

2. Literature Review

An extensive review of past literature related to floods, droughts, and climate was conducted. This review included relevant national and international legal frameworks, standards, policies, and practices on climate change impacts and mitigation measures. It also covered past flood and drought events in Nepal and their association with climate, as well as the institutional framework for flood and drought management in the country.

3. Assessment and Preparation of Data

Precipitation and temperature data from 1980 to 2022, along with flow data from 1980 to 2019, were collected from the Department of Hydrology and Meteorology (DHM), Government of Nepal. Based on the percentage of missing data and data homogeneity, rainfall records from 179 stations and temperature records from 67 stations were considered for various analyses in this study.

Digital Elevation Models (DEM), land use/cover data, and soil type information were obtained from freely available public sources. Projected climate data from climate models were retrieved from both national and global web platforms. Additionally, regional climate indices were extracted from public data sources. Data on past floods and their socio-economic impacts (spanning June 23, 1980 to September 30, 2023) were gathered from the websites of the Ministry of Home Affairs and DHM. Records of past Glacial Lake Outburst Floods (GLOFs) and Landslide Dam Outburst Floods, along with their impacts on various locations, were assessed using published literature.

Flow gauging stations with daily data spanning over 30 years were selected for further analysis. To ensure inclusion of critical downstream stations on Class A and Class B River, stations with at least 15 years of data were also considered. A total of 44 stations met these criteria and were selected for flood analysis, while 41 stations were used for low-flow analysis. Four key issues related to data availability and quality were identified: (i) Scarcity of climate data in northern Nepal: Higher-altitude regions, particularly the Karnali Basin, are significantly underrepresented; with no data available for the Tibetan region of China, (ii) Inadequate hydrological stations in the Terai region: Despite experiencing annual flood-related damages, this region has only three hydrological stations outside the nine major basins, (iii) Substandard data quality: The quality of data across most hydrological and climatological gauging stations is inadequate, and (iv) Low resolution of data and models: The DHM database primarily provides data series at a daily resolution. Similarly, the low resolution of DEM, soil, and land use/cover data fails to capture the physical variability of the terrain.

4. Climate Analysis

Rainfall Analysis

A very high spatial variation in rainfall was observed across Nepal. Annual rainfall magnitudes range from less than 300 mm to 5,500 mm, with the country's average annual rainfall of 1,563 mm. Approximately 80% of the annual rainfall occurs during the monsoon season (June to September). Within the monsoon period, nearly half of the rainfall is concentrated in July and August. The remaining three seasons receive minimal rainfall. Three main rainfall hotspots in Nepal are the Lumle, Num, and Gumthang regions.

The average one-day maximum rainfall in Nepal varies significantly by location, ranging from 59 mm to 516 mm. The average number of rainy days per year is 100, with a large variation from 50 to 200 days across locations. The average consecutive wet and dry days in Nepal are 66 days (range: 33–87 days) and 16 days (range: 5–71 days), respectively. These results show that there is a high probability of having some very dry years with some very wet years. The estimated probable maximum rainfall among the selected raingauge stations ranges from 190 mm to 1,873 mm. Over the past four decades, no specific temporal trend in annual rainfall in Nepal has been identified.

Temperature Analysis

Due to its varying topography, Nepal experiences a wide range of temperatures. Our analysis shows that temperatures in the country range from -14.0°C in the winter in the Himalayan region to 46.4°C in the Terai region during summer, with an overall average temperature of approximately 15°C. The minimum monthly temperatures typically occur in January across Nepal. In most parts of the country, there is a three-fourth probability that the maximum temperature occurs in May or June. However, the maximum temperature can occur in any month between April and August. Both maximum and minimum temperatures exhibit a significant increasing trend, with 56 out of 67 stations showing this pattern. This indicates that Nepal is consistently getting warmer over time.

Climate Extremes in Nepal

Data from 62 gauging stations with both precipitation and temperature records from 1980 to 2022 were used to assess extreme climate events (Hot-Dry, Cold-Dry, Hot-Wet, and Cold-Wet years) in Nepal. Over a span of 43 years, just over 5% of the total years were classified as extreme climate years. At least one station experienced some form of extreme climate in 36 of these years, while no station observed any type of extreme climate in seven years.

Comparison of Nepal's Climate with Regional Climate Indices

Five regional climate indices—Arctic Oscillation (AO) Index, North Atlantic Oscillation (NAO), Dipole Mode Index (DMI), Niño 3.4 Sea Surface Temperature (SST) Anomalies, and Southern Oscillation Index (SOI)—were compared with the overall climate of Nepal. Our results show that, for both monsoon and annual timescales, the SOI and SST Anomalies exhibit a stronger correlation (positive and negative respectively) with the Percentage Departure of Nepal Rainfall (PNR) compared to the other indices. These high correlations suggest that anomalies in SST and SOI can have a significant impact on the climate systems of Nepal.

Empirical Orthogonal Function Analysis

Rainfall anomalies from 179 stations were analyzed using Empirical Orthogonal Function (EOF) analysis to identify key patterns of variability across summer (JJAS) and winter (DJF) seasons in Nepal. In winter, 58% of the variance is explained by Mode 1, highlighting its dominance, whereas in summer, the variance is more distributed, with Mode 1 explaining only 21.7%. Spatial patterns were identified, showing central Nepal and the eastern/western belts as key regions for summer rainfall variability, while the central and western regions are dominant in winter. Correlations between EOF modes and climate indices were observed, indicating that El Niño-Southern Oscillation (ENSO), particularly Niño 3.4 and SOI, strongly influences summer rainfall, while the Dipole Mode Index (DMI) and SOI significantly affect winter variability. The study emphasizes that ENSO's role in shaping seasonal rainfall patterns is especially notable in summer.

5. Flood Analysis

The hydrology of Nepal is strongly influenced by its unique topographical and climatic features. There is significant variation in monthly river flows, with the maximum monthly flow occurring in July and August. Approximately 75% (Range: 68-83%) of the annual flow occurs during the monsoon season. Generally, the minimum monthly flow is observed either in February, March, or in April.

Flood Frequency Analysis

The Gumbel distribution was fitted to the flood flows of hydrological stations for frequency analysis in this study. Flood magnitudes were estimated for return periods of 2, 5, 25, 50, 100, 200, 500, 1,000, and 10,000 years at all 44 selected stations. Additionally, return periods for the top ten past Instantaneous Maximum Floods (IMF) at each station were also estimated. The analysis showed that thirteen past IMF events, out of a total of 1,573 flood events, exceeded the 100-year flood. Similarly, 25 and 49 events in Nepal were estimated to exceed the 50-year and 25-year flood levels, respectively.

Timing of Occurrence of IMF

Almost all the instantaneous flood events (i.e., > 98%) in Nepal occurred during the monsoon season (June-September). In the two months, July and August, 80% of such flood events occurred in the country. Fifteen gauging stations out of the 44 observed the highest floods in a single day, i.e., on the 26th of July 2016. In three other years (2000, 2013, and 2014), 12 stations recorded the highest floods on the same day.

Instantaneous Floods and Catchment Area Relationship

A power relationship was observed between instantaneous flood magnitude (Q_{IMF}: m^3/s) and catchment area (A: km^2) for Class A River of Nepal as:

$$Q_{IMF} = 6.0A^{0.65}$$

Flood Estimation of Ungauged Rivers

WECS/DHM 1990, DHM 2004, and Modified Dicken's methods were used to estimate floods of different return periods for Kamala River and 14 Class C Rivers due to the lack of gauging stations in these rivers.

Probable Maximum Flood and Trend in IMF

Probable floods of all 44 selected gauging sites were estimated in the study. No observable temporal trend on IMF was found in the river floods of Nepal over the last four decades.

Flood Disaster Events in Nepal

In the last 44 years (from June 23, 1980 to September 30, 2023), there were 5,070 flood incidents in Nepal that resulted in fatalities and/or property damage at various scales. This indicates an average of 115 flood disaster incidents occurring each year. The highest number of flood events (415) was recorded in 2002, while the lowest number (4) occurred in 1992. Four districts in the Terai region—Sarlahi, Morang, Rautahat, and Jhapa—each experienced more than 200 flood disasters during this period. In contrast, Terathum had only 8 such flood incidents, the fewest among all districts.

Relationship between IMF and One-Day Annual Maximum Flood

A linear relationship between instantaneous maximum floods and one-day annual maximum floods was found for all rivers except the Kankai. This indicates that the instantaneous maximum floods in Class A River are about 16% higher than the annual daily maximum floods. However, for Class B River, this value is approximately 60% for eastern rivers (Kankai and Bagmati) and 25% for western rivers (West Rapti and Babai).

GLOF and LDOF

Studies have shown that several glacial lakes in Nepal are growing significantly, increasing the threat of Glacial Lake Outburst Floods (GLOFs). Twenty-one glacial lakes in Nepal have been identified as potentially dangerous. The volume and peak flows for the major glacial lakes have been estimated.

Landslide dam outburst floods (LDOFs) are also common in Nepal's high, steep, and fragile mountains, particularly in deep and narrow gorges.

Flood Inventory

An inventory of Instantaneous Maximum Floods (IMF) and another inventory of one-day annual maximum floods in Nepal were prepared, following "Water Induced Disaster Management Policy 2072". Floods were categorized into four classes: (i) floods equal to or greater than a 100-year return period; (ii) floods equal to or greater than a 25-year but less than a 100-year return period; (iii) floods equal to or greater than a 5-year but less than a 25-year return period; and (iv) floods equal to or greater than a 2-year but less than a 5-year return period. Additionally, an inventory of flood disaster events with human losses exceeding 10 persons was also compiled.

Instantaneous Maximum Flood and Associated Climate

The top five instantaneous floods across the eight major river basins of Nepal were identified from the instantaneous data series. For each flood event, the average precipitation on the day of the IMF occurrence and the preceding four days was calculated using the arithmetic average of rainfall from selected rain-gauge stations within the basin. The precipitation on the day of the IMF occurrence was found to be lower for the highest flood compared to the precipitation on the day of occurrence of other lower-magnitude IMFs in almost all basins. Incessant precipitation is the major influencing factor for floods; however, blockage of river flow and breaching of the barrier upstream of the gauging station were also identified as contributing factors to IMFs.

Field Verification

The objective of the field visits was to observe flood-affected sites, verify the occurrence of past floods, and interact with local people/key informants to gather firsthand information about flood events. A total of 54 locations were visited during the field visits. Of these, only one reported no flood problems in recent years. The remaining 53 sites had encountered floods, whether large or small, in the past. A total of 105 flood events were reported by the respondents. These reported flood events were then compared with recorded flood events in the government's disaster portal (study duration: 1980-2023). Among the 105 reported events, 12 occurred before 1980. The occurrence of 72 reported flood events matched the MOHA database records.

All respondents stated that rainfall is the main cause of floods. They noted that floods are no longer limited to the monsoon season and can occur in any season or month of the year. Most respondents suspected that these changes in hydro-climatic conditions in recent years may be due to climate change.

6. Low Flow Analysis

The 2-, 5-, 10-, 25- 50- and 100-year low flow of 41 selected gauging stations were estimated by fitting the Log Person Type 3 (LP III) distribution to the observed instantaneous minimum flow. Almost all

ILFs of Class A River (i.e., > 99%) occurred in the non-monsoon season. However, the occurrences of ILFs in Class B River were distributed across the monsoon as well as dry seasons.

Concurrency between Instantaneous Maximum and Minimum Flows

The years of occurrence of the top 10 instantaneous maximum flows and the bottom 10 minimum flows were assessed at the selected flow gauging stations to determine if there is any likelihood of high- and low-flows (leading to floods and hydrological droughts) occurring in the same year. Our analysis reveals that there is about a one-third probability of a wet year also experiencing a dry period. In other words, there is more than a 30% chance that flood disasters and drought conditions could occur in the same year, particularly in Class A River Basins.

7. Drought

This study focused on three types of droughts: Meteorological (climate data-based), Hydrological (flow data-based), and Agricultural (soil moisture data-based), using various drought indices. The Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), Reconnaissance Drought Index (RDI), Soil Moisture Index (SMI), and Standardized Streamflow Index (SSI) were used to calculate drought parameters for 1-, 2-, 3-, 4-, and 12-month time scales. A drought event is categorized as "moderate" if the drought index value is ≤ -1.0 and > -1.5, "severe" if it is ≤ -1.5 and > -2.0, and "extreme" if it is ≤ -2.0. The drought parameters considered in this study include drought frequency, total drought duration (TDD), drought severity (DS), drought intensity (DI), and maximum consecutive drought duration (MaxCDD).

Drought Analysis

The drought parameters calculated from SPI and RDI are almost identical for all months. However, the parameters derived from SPEI show slight variations. The total drought duration (TDD) percentage is about 17% in all cases, except for the 1-month drought (15.5%). Based on these figures, we can tentatively estimate the occurrence probability of meteorological droughts in Nepal to be around 15-18%. Additionally, drought severity (DS) and drought intensity (DI) are higher for SPEI-1 compared to RDI-1 and SPI-1, while for the other months, these parameters are almost equal. The values of these parameters are slightly lower for 1-month droughts than for other months. Maximum consecutive drought durations (MaxCCDs) are nearly the same for all three indices.

The calculated values of DS based on the Soil Moisture Index (SMI) are the lowest (around -58) for all drought scales. However, the DS values based on the other indices are relatively high, i.e., less than -100. The drought intensity values are almost identical (around -1.41) in all cases. A DI_{TDD} value of -1.41 suggests that, on average, droughts in Nepal are of "moderate" intensity. MaxCCDs are almost the same for all SSI and meteorological droughts, except for SMI. In Nepal, the probability of a "moderate" drought (M = 12%) is nearly three times higher than that of a "severe drought" (S = 4%). Extreme droughts are rare, accounting for only 1% of total drought occurrences historically. The MaxCDD in the country is about 11.

Field Verification of Drought

During the field visits, a questionnaire survey was conducted with local representatives from 45 locations. Nearly all the respondents perceived that drought occurs when an area receives less rainfall than usual at the required time. The main reasons for drought, according to the locals, were decreased precipitation and increased temperatures. Almost two-thirds of the respondents reported experiencing drought every year, while one-fifth observed it once every two years. The most significant impacts were felt in agriculture and drinking water sectors, while other sectors were only mildly affected by droughts.

8. Hydrological Modeling

The Soil and Water Assessment Tool (SWAT) was employed to evaluate the hydrological processes of Nepal's nine major river basins. Separate models were developed for the Koshi, Gandaki, Karnali, Chamelia, Kankai, Kamala, Bagmati, West Rapti, and Babai River Basins. These models were calibrated and validated against observed flow data. The model performance was found to be excellent for the Class A River Basins, but less satisfactory for the Class B River Basins.

9. Impact of Climate Change on Climate and High & Low Flows

Three of the best climate models from the CMIP6 era were selected for each river basin from a pool of 20 models, based on their ability to generate historical climate data (precipitation and temperature). Bias correction of the outputs from these selected models was performed using the "quantile mapping" approach to minimize inaccuracies. The impact of climate change on precipitation, temperature, extreme flows (top and bottom five), and droughts was assessed by comparing future long-term averages (2025–2054) of these parameters with baseline values (1985–2014). Two scenarios, SSP245 and SSP585, were considered for the nine major river basins in the country.

The ensemble average change in precipitation for Nepal appears to be modest, with an increase of 3% (range: -1.5% to +10.7%) under SSP245 and 6% (range: -0.7% to +18.1%) under SSP585. The largest predicted increase in precipitation is in the Babai Basin by INM.INM-CM4-8 (+25.8%), while the largest decrease is in the Koshi Basin by MPI-ESM1-2-LR (-8.2%).

Both maximum and minimum temperatures across all basins are projected to increase in the future, albeit at varying rates. The overall average increase in maximum temperature is projected at 0.71°C under SSP245 and 0.84°C under SSP585. Similarly, the average increase in minimum temperature is projected at 0.96°C under SSP245 and 1.15°C under SSP585.

In Class A River Basins, the maximum increase in future flows (average of the top five high flows) under SSP245 is predicted in the Chamelia Basin (+12%), while the maximum decrease is predicted in the Karnali Basin (-23%). Under SSP585, these values are +16% for Chameliya and -19% for Karnali.

For Class B River Basins, the maximum increase in high flows under SSP245 is projected at +13% in the West Rapti Basin, while the maximum decrease is -5% in the Kankai Basin. Under SSP585, the highest increase is in the Kamala Basin (+61%), and the greatest decrease remains in the Kankai Basin (-14%).

The changes in low flows (average of the bottom five low flows) relative to baseline values in Class A River Basins range from -40% (Gandaki) to +90% (Karnali) under SSP245 and from -49% (Gandaki) to +48% (Karnali) under SSP585. In Class B River Basins, the changes range from -1% (Bagmati) to +109% (Kamala) under SSP245 and from -26% (Babai) to +128% (Kamala) under SSP585.

Drought parameters, including total drought duration, severity, and intensity, were calculated to assess changes in hydrological drought in the Koshi, Gandaki, and Karnali River Basins. The results showed mixed trends under both climate scenarios.

10. Flood and Drought Risk Management

Short-term measures focus on reducing the immediate risk of flooding, while medium-term measures aim to mitigate risks at the local level. Zoning floodplains to restrict development in flood-prone areas is also a crucial aspect of this approach. Drought risk management is divided into pre-drought and post-drought measures. Pre-drought measures include preparedness and mitigation strategies, whereas post-drought measures encompass reaction, response, and recovery efforts.

11. Conclusions and Recommendations

The report concludes with key findings and recommendations, based on the analysis of hydroclimatic data, focusing on floods, droughts, and climate. The technical recommendations highlight the need for data enhancement, address the probable causes of floods, discuss challenges in hydrological modeling for flood estimation, and suggest improvements in drought analysis methods and climate change impact assessments. Finally, policy recommendations are presented for flood, drought, and climate risk mitigation in Nepal. These recommendations are intended to guide policymakers in improving policies related to flood, drought, and climate risks in the country.

CHAPTER 1:INTRODUCTION

1.1 General Background of the Study

Nepal is a mountainous country situated between the Tibetan Plateau and the Indo-Gangetic Plains. The altitude ranges from 60 meters above sea level (masl) to as high as 8,848.86 masl along a north-south stretch of less than 200 km (Thapa and Pradhan, 1995). During the monsoon season (June to September), humid air from the Bay of Bengal encounters Nepal's hills and mountains, causing heavy rainfall—about 80% of the annual total—in the southern areas of these hills and mountains. Conversely, the remaining eight months (October to May) receive very little rainfall, accounting for around 20% of the annual total. Due to this unique physical setting and climatic characteristics, Nepal is highly prone to both floods and droughts. The country ranks 14th globally in flood risk by the percentage of population exposed to floods (29.4%; Conte, 2022) and 20th in the total number of people exposed to floods (WRI, 2015). It also ranks 10th worldwide in potential damages to physical assets from fluvial flooding (Dangal, 2011). In terms of climate change-related hazards, Nepal ranks 4th among 200 countries globally (MoHA, 2017). Additionally, its drought risk score position is 94th out of 154 countries (World Population Review, 2024).

Weather, Climate and Climate Change

Weather is the state of the atmosphere (precipitation, temperature, humidity, wind speed etc.) at a particular location over the short-term (minutes to hours, to days to weeks).

Climate is the average of the weather patterns in a location over a longer period of time, usually 30 years or more. Weather and climate describe the same thing—the state of the atmosphere—but at different time scales.

Climate change refers to any significant change in the measures of climate for extended periods of time, usually over decades or longer. This includes long-term changes in temperature, precipitation, humidity, wind patterns etc.

(NOAA, 2024; NASA, 2024)

Floods can have substantial impacts on local, regional, and national economies, depending on their scale and severity. The main sectors potentially affected include agriculture, infrastructure, manufacturing and industry, energy, tourism, healthcare, small businesses, real estate, government expenditure, and supply chains (Ashizawa et al., 2022; Pan and Qiu, 2022; Allaire, 2018; Svetlana et al., 2015). For instance, floods can damage irrigation systems and crops, erode topsoil, and disrupt farming operations, leading to reduced agricultural productivity and increased food prices. Similarly, they damage roads, bridges, and other critical infrastructure, resulting in costly repairs and disruptions to transportation networks. Floods can also disrupt manufacturing and industrial activities by damaging factories and equipment, causing production delays and financial losses. Likewise, they can harm power generation and distribution infrastructure, leading to power outages and increased energy costs. In tourism, floods may damage popular destinations, resulting in reduced visitor numbers and revenue loss. Damage to healthcare facilities lead to disruption of healthcare services. Governments often bear a significant financial burden for flood disaster response and recovery, diverting funds from other important development programs. Flood damage can also displace residents, and flood-prone areas may suffer devaluation. Additionally, floods harm ecosystems and wildlife, impacting the environment and potentially leading to long-term ecological consequences.

Flood and Drought

A flood is an overflow of water that submerges land that is usually dry. **Flood** occurs when water levels rise over the top of natural or artificial banks, such as a river inundating its floodplain.

(Britannica, 2024; National Geography, 2024; Earth Networks (2024)

Drought is generally defined as a deficiency of precipitation over an extended period of time, resulting in a water shortage. **Drought** is a slow-onset disaster generally characterized by a lack of precipitation.

(WMO, 2023; WHO, 2023; National Geography, 2023)

Likewise, droughts can have significant impacts on various sectors of the economy due to the shortage of water for multiple uses (WorldAtlas, 2023; WECS, 2011). Similar to floods, the sectors most affected by drought include agriculture, water supply, energy, healthcare, environment, and government expenditure. Droughts can lead to reduced crop yields, livestock losses, and increased production costs, causing food shortages and price hikes, which impact the entire food value chain (Mao et al., 2017; Hamal et al., 2020). Similarly, droughts can cause water scarcity, reduce hydropower generation, and increase costs for water supply and treatment. They can also raise the risk of heat-related illnesses and respiratory issues from dust. Droughts harm ecosystems, increase the likelihood of wildfires, and threaten biodiversity. Economies heavily reliant on rainfed agriculture, such as Nepal's, may suffer from reduced income, job losses, and economic recession during prolonged droughts.

Climate impacts river hydrology, groundwater availability, agriculture, fisheries, and forestry. It also influences the spread of diseases, heat-related illnesses, and food (in)security. Understanding local and national climate patterns, including long-term trends and short-term variations, is therefore critical for assessing and preparing for climate-related risks (Cho, 2019).

With ongoing climate change, the frequency and intensity of floods and droughts are likely to shift in Nepal (Adhikari, 2018; Tabari, 2020). Future winters are expected to be drier, while monsoon seasons may become even wetter compared to the present. Such changes could significantly increase both the intensity and frequency of current flood and drought events. These possibilities underscore the need for extensive studies on floods, droughts, and the interconnected climate crisis to ensure a safer, more resilient, and productive future. The goal remains to implement climate change mitigation measures alongside adaptation strategies (Karki et al., 2010). Additionally, climate studies are essential for aligning with international climate agreements and demonstrating a nation's commitment to reducing greenhouse gas emissions.

Effective preparedness for potential flood and drought events, sustainable water management, and adaptive agricultural practices are crucial for mitigating impacts and building resilience at local, regional, and national levels, especially in the face of flash floods and prolonged droughts. Therefore, accurate information on climate, flood, and drought patterns is vital for formulating policies on disaster management, natural resource management, renewable energy generation, and emissions reduction. To generate evidence-based insights on these issues, the Water and Energy Commission Secretariat (WECS) has entrusted Embark-E.I. Maven-Shrestha JV to study and analyze floods, droughts, and climate in Nepal.

1.2 Objectives of the Study

The overall objective of the study is to analyze flood, drought, and climate patterns across Nepal.

1.3 Scope of the Work

The scope of the work of this study includes the following:

- Review plans, policies, acts, regulations, and ordinances regarding flood, drought, and climate at the national as well as international levels.
- Review international standards, policies, and practices in incorporating the climate change effect and mitigation measures in national policy.
- Review past flood and drought events and associated climate in Nepal.
- Prepare an inventory of floods and drought in Nepal. Analysis of flood and drought inventory for recommendation in policy (Intervention in hydropower development planning, irrigation planning, agricultural development planning).
- Assess the cause of the past floods, droughts, and associated climate in Nepal and regional climate if necessary.

- Prepare an inventory of disasters caused by each flood and drought events. Also, carry out GIS mapping of these events.
- Carry out past and future climate change and variability analysis.
- Carry out changes in climatic extremes.
- Carry out physics-based distributed hydrologic modeling during flood and drought analysis.

1.4 Study Area

The study area covers all of Nepal, a mountainous country situated along the southern slope of the Himalayas. Nepal's terrain features remarkable altitudinal variation, ranging from lowland plains at less than 60 meters above sea level (masl) to perpetual snowy peaks above 8,000 meters (**Figure 1-1**). Due to its diverse geography, the country is broadly divided into three main regions: the southern plains, hills or middle mountains, and the high Himalayan region in the north (Duncan and Biggs, 2012).

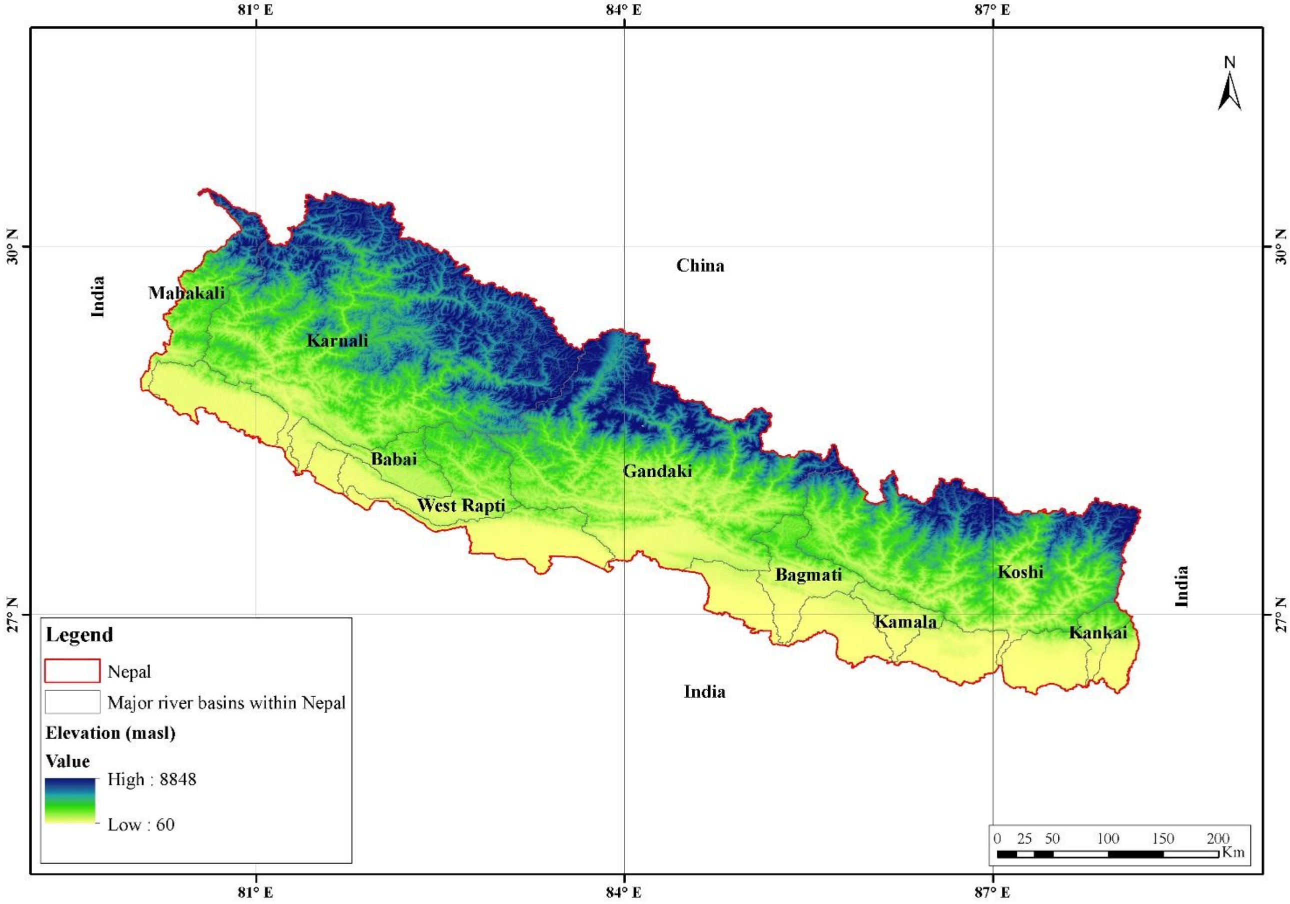


Figure 1-1 Study area

The southern plains, extending from east to west, cover about 17% of Nepal's area. This lowland region includes some hill ranges known as the Siwaliks, though the continuity of the Terai belt is interrupted in two areas: Dang and Chitwan. Nepal's hilly region lies between the Terai plains to the south and the Himalayan mountains to the north, covering 68% of the country's area. Although not as elevated as the Himalayas, the hills in this region still reach significant heights. The Himalayan region accounts for about 15% of Nepal's land area and is characterized by its towering mountain ranges. This region includes eight of the world's 14 highest peaks, including Mount Everest, the tallest mountain on Earth at 8,848.86 meters. In addition to these high mountains, a few valleys lie on the trans-Himalayan side to the north.

The country's physical, geological, hydro-climatic, environmental, administrative, and demographic features are briefly outlined in the following subsections.

1.4.1 Physical Setting

Nepal can be divided into five distinct physiographic zones, from south to north: (i) Terai plains, (ii) Churia Hills-Siwaliks, (iii) Hills, (iv) Middle Mountains, and (v) Himalayan Mountains, as shown in **Figure 1-2.**

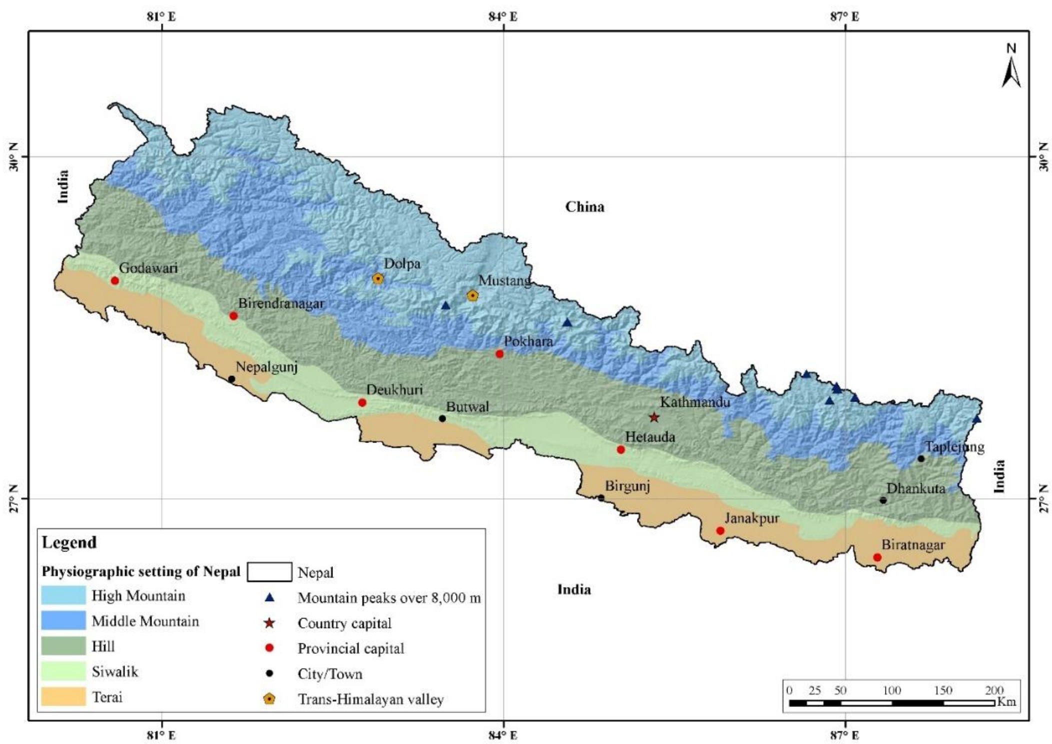


Figure 1-2 Physical setting of Nepal

The Terai plains lie at an elevation of less than 200 meters above sea level (masl), with an average width ranging from 10 to 50 km (Dhakal, 2014). The Terai is characterized by vast, flat plains that extend along the southern Nepal-India border. It is part of the larger Indo-Gangetic plains and has fertile soil, making it ideal for agriculture.

The Churia Hills (Siwaliks) are located immediately to the north of the Terai, rising to about 1,200 masl (Dhakal, 2014). The hilly region of Nepal is characterized by diverse topography, including hills, valleys, and small mountain ranges. These hills block moisture-laden air from the Bay of Bengal, causing heavy rainfall on their southern slopes. This region stretches from east to west, though in many places, it merges with the Siwalik Hills (Sharma, 1997).

The High Himalayas contain most of Nepal's important snow-covered peaks and feature diverse topographical elements such as glaciers, rivers, and glacial lakes. Snow and glacier melt significantly contribute to the river flows originating from this region. On the northern side of the High Himalayas, there are a few valleys situated above 4,000 masl, including the major valleys of Mustang and Dolpa.

1.4.2 Hydro-climatic Setting

Due to the unique physiographical and topographical features described above, Nepal experiences a variety of climates that range from tropical savannah in the southern plains to polar frost in the northern mountains, all within a horizontal distance of less than 200 km (Karki et al., 2017).

Nepal has four distinct seasons: pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November), and winter (December–February). The pre-monsoon season is characterized by hot, dry conditions with westerly winds and localized precipitation in narrow bands. The monsoon season brings moist southeasterly winds from the Bay of Bengal, and occasionally from the Arabian Sea, resulting in widespread precipitation throughout the country. Post-monsoon is a dry season with sunny days, and November is typically the driest month. Winter brings cold weather, with precipitation primarily in the form of snow in high-altitude mountainous regions.

Precipitation in Nepal is influenced by two major weather systems. The southwest monsoon significantly impacts the southeastern parts of the country during the monsoon season, while the western disturbances predominantly affect the northwestern high mountainous regions during the winter season. Precipitation during the pre- and post-monsoon seasons is generally higher in the eastern regions, similar to the monsoon season (Ichiyanagi, 2007). Nepal's precipitation patterns are mainly controlled by the orographic effect of the central Himalayan terrain and the east-west progression of the summer monsoon. As a result, precipitation distribution across the country is highly heterogeneous. For example, annual precipitation ranges from less than 200 mm in the driest regions (Mustang, Manang, and Dolpa), located on the leeward side north of the Annapurna Himalayan range, to over 5,000 mm in the Lumle region. Two additional wetter regions with annual precipitation greater than 3,500 mm are Num and Gumthang. Conversely, regions with low precipitation typically reside on the leeward side of the Khumbu, Everest, and other high mountainous areas along the central Himalayas (Karki et al., 2017). Additionally, Nepal's climate is closely linked to the Southern Oscillation Index (SOI) (Shrestha, 2000).

The hydrology of rivers of Nepal is mainly governed by their precipitation pattern and their origins. Rivers originating in the Himalayan region, also called Class A rivers, are perennial; having considerable flows even during the lean period. It is attributed to snowmelt and precipitation occurring in the respective basins. Rivers originating from the Mahabharat regions (Class B rivers) are rain-fed rivers. These rivers have reduced flows in the dry season. Class C rivers are the rivers originating from the Churia range and are usually referred to as southern rivers. Flows of these rivers occur with immediate response to monsoon precipitation. These rivers are, therefore, flashy in nature and are usually called ephemeral. Based on the origin of the rivers and their drainage pattern, Nepal can be classified into 10 major river basins viz., four Class A River Basins, five Class B River Basins, and one Class C River Basin as given in **Table 1-1** and shown in **Figure 1-3**. The total drainage area of all the rivers of Nepal is 194,471 km^2 and the total runoff is 7,125 m^3/s. However, 47,290 km^2 of the catchment area of these rivers lies in China and India. The flow generated from precipitation and snow/glacier melt within the Nepalese territory is estimated to be 5,480 m^3/s. The average specific discharge of these rivers is 0.037 $m^3/s/km^2$ (WECS, 2011; Tachamo-Shah et al., 2019).

Table 1-1 Drainage area and river flows of the major river basins of Nepal

SN	River Basin	Length (km)	Drainage Area (km^2)		Estimated Runoff (m^3/s)		Specific Runoff ($m^3/s/km^2$)	Types of River Basins
			Total	Nepal	From all Basins	From Nepal		
1	Mahakali	223			698	247	0.046	Class A
2	Karnali	507	44,000	41,555	1,441	1,371	0.033	
3	Gandaki	332	34,960	28,090	1,753	1,409	0.05	
4	Koshi	513	60,400	31,940	1,658	878	0.027	
5	Babai	190	3,400	3,400	103	103	0.03	Class B
6	West Rapti	257	6,500	6,500	224	224	0.034	
7	Bagmati	163	3,700	3,700	178	178	0.048	
8	Kamala	208	2,183	2,183	100	100	0.046	
9	Kankai	108	1,+ 330	1,330	68	68	0.051	
10	Southern		22,738	22,738	902	902	0.04	Class C
	Total				7,125	5,480	0.037	

Source: Modified from WECS (2011) and Tachamo-Shah et al. (2019)

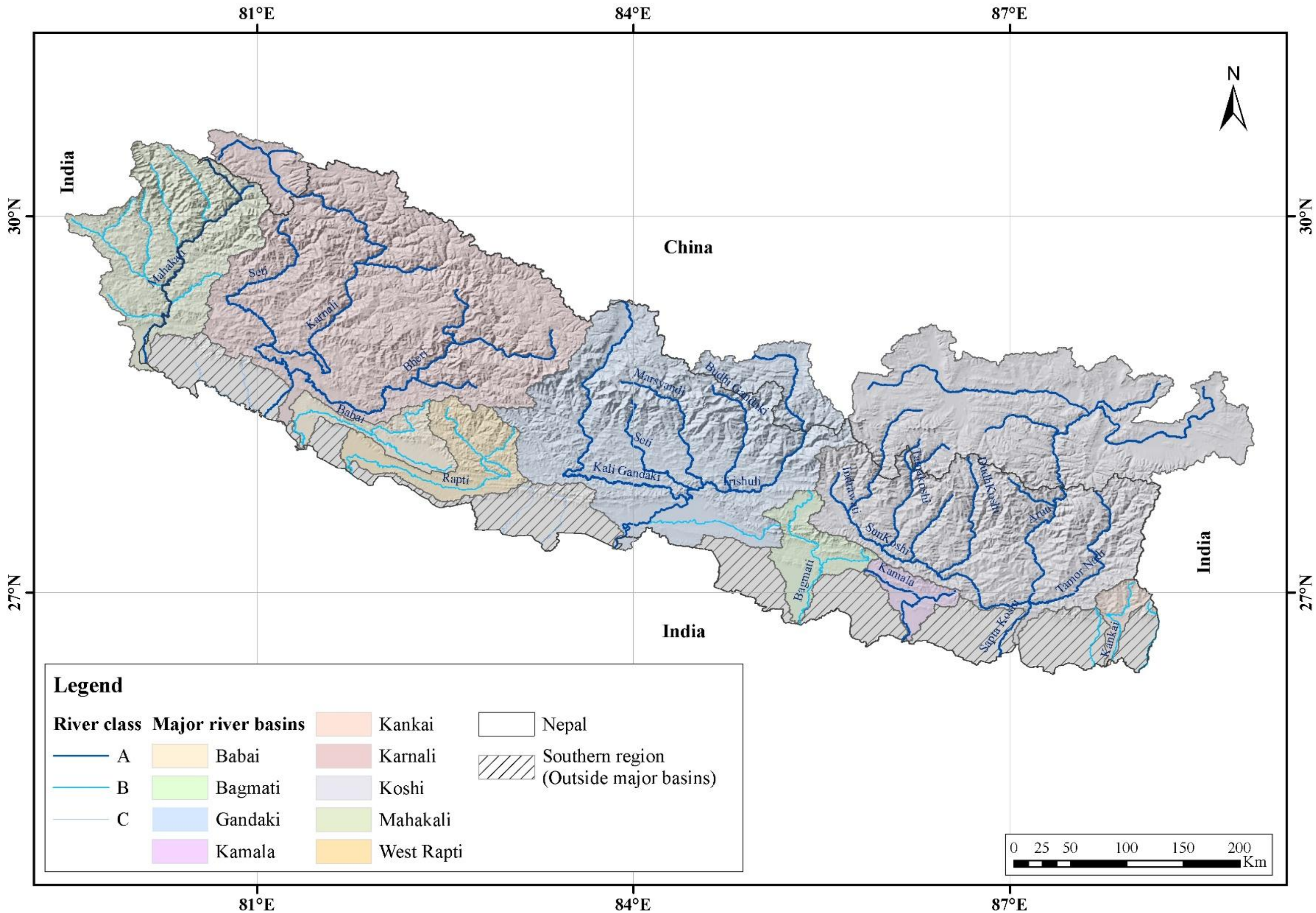
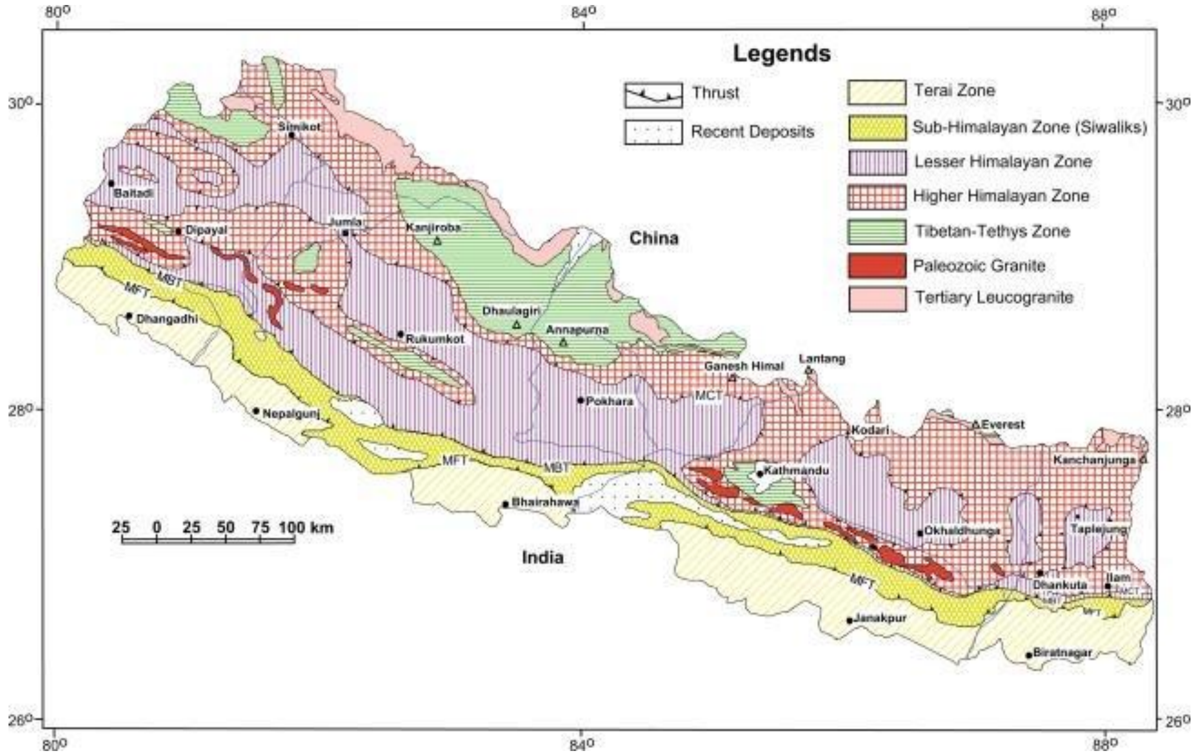


Figure 1-3 River Basins of Nepal

1.4.3 Geological Setting

Geologically, Nepal can be divided into five zones as shown in **Figure 1-4** (Dhakal, 2014). Each of the zones is characterized by its morphological, geological, and tectonic features. These zones, from South to North are (a) The Indo-Gangatic Plain (b) The Sub-Himalaya (c) The Lesser Himalaya (d) The Higher Himalaya, and (e) The Inner Himalaya.



Source: Dahal (2023)

Figure 1-4 Geological map of Nepal

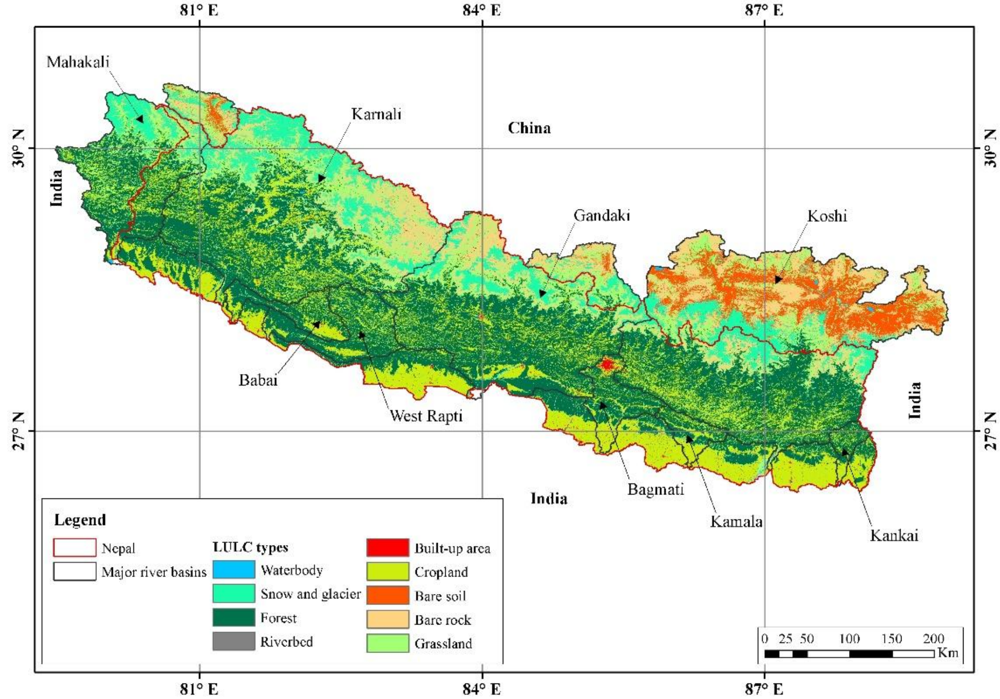
The Indo-Gangetic Plain (Terai) represents a vast alluvial tract formed by the Himalayan rivers and consists of recent Pleistocene deposits, including boulders, gravel, sand, clay, and remnants of animals and plants. The total thickness of this zone exceeds 1,000 meters. The Sub-Himalayan Zone (Siwaliks/Churia Range) is the southernmost mountain range of the Himalayas, bounded by the Main Frontal Thrust (MFT) to the south and the Main Boundary Thrust (MBT) to the north. It consists of fluvial sedimentary rocks from the Neogene to Quaternary period (14 million to 1 million years ago). These rocks are soft, loose, and easily erodible, including sandstone, siltstone, mudstone, and conglomerate (Dhakal, 2014). The Lesser Himalayan Zone (Mahabharat/Midland) is bounded by the MBT in the south and the Main Central Thrust (MCT) in the north. In many areas, high-grade metamorphic rocks from the northern Higher Himalayan zone have been displaced along the MCT, overlying low-grade metasedimentary rocks, resulting in reverse metamorphism. Typical rock types in this zone include schists, phyllites, quartzites, limestones, dolomites, and argillo-arenaceous and argillo-calcareous rocks, with marble beds. These rocks range in age from Precambrian to Proterozoic (Dhakal, 2014).

The Higher Himalayan Zone, sometimes known as the Greater Himalayan Zone, is bounded by the MCT in the south and the South Tibetan Detachment System (STDS) in the north. This zone is characterized by high-grade metamorphic rocks, primarily various types of gneisses (Dhakal, 2014). The Tibetan Tethys Zone is the northernmost zone of the Himalayas, bounded by the normal fault known as the STDS in the south and the Indus–Tsangpo Suture Zone (ITSZ) in the north, which extends beyond the Nepal border into the Tibetan Plateau. The ITSZ marks the boundary between the southern Indian Plate and the northern Eurasian Plate. This zone consists of the Tibetan-Tethys Sedimentary Series, which includes shale, sandstone, siltstone, and conglomerate, with competent limestone and quartzite beds (Dhakal, 2014).

1.4.4 Environmental Setting

1. Current Land Use Land Cover Pattern of Nepal

The land-use land cover (LULC) of Nepal for the year 2021 (ICIMOD, 2022) is shown in **Figure 1-5**. From this figure, it can be observed that the Terai region has most of its area covered by cropland and settlements, while snow, glaciers, and barren land are dominant land uses in the High Himalayan region. The remaining Middle Mountains, Hills, and Siwalik are mostly covered with forests and concentrated patches of settlements. The distributions of LULC of Nepal are presented in **Table 1-2**.



Source: ICIMOD (2022)

Figure 1-5 Current LULC status of Nepal

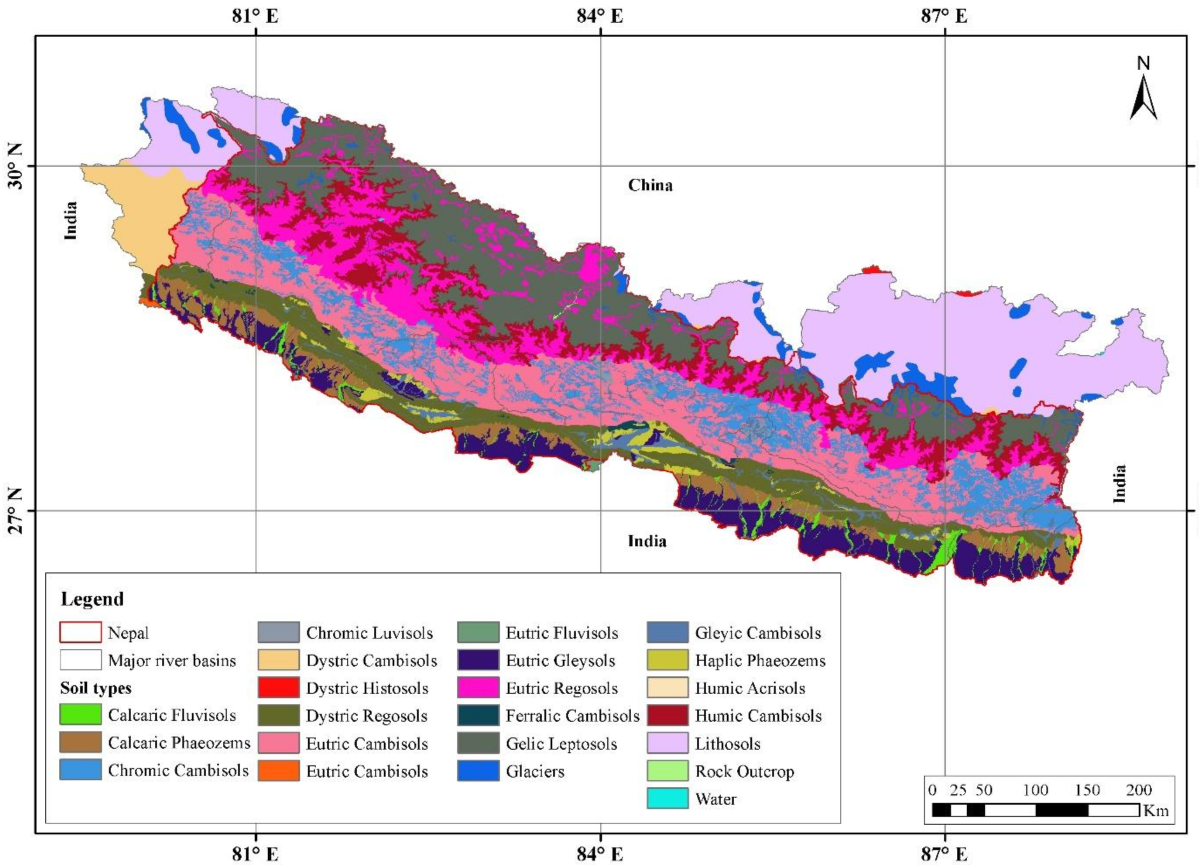
Table 1-2 Distribution of LULC in Nepal

SN	LULC Type	Waterbody	Snow and glacier	Forest	Riverbed	Built-up area	Cropland	Bare soil	Bare rock	Grassland
1	Nepal (km^2)	521.84	12,307.84	67,247.09	505.92	735.86	34,618.41	10.37	10,485.05	20,723.61
2	High Mountain (%)	0.29	34.27	4.75	-	0.33	0.21	0.01	27.60	32.53
3	Middle Mountain (%)	0.10	0.13	63.52	-	0.22	15.44	-	2.00	18.59
4	Hills (%)	0.28	-	66.49	0.11	0.61	28.40	-	0.01	4.11
5	Siwalik (%)	0.49	-	73.95	1.06	0.37	18.82	0.00	-	5.32
5	Terai (%)	0.90	-	20.87	1.32	1.14	72.06	0.02	-	3.70

Source: ICIMOD (2022)

2. Soil of the Study Area

The soil map of Nepal, shown in **Figure 1-6**, was extracted from the Soil and Terrain (SOTER) database (Dijkshoorn & Huting, 2009). The Gelic LEPTOSOLS (High Mountain), Eutric CAMBISOLS (Hill), and Eutric REGOSOLS (High Mountain) cover about 50% of the country while Humic CAMBISOLS (Middle Mountain), Chromic CAMBISOLS (Hill), Dystric REGOSOLS (Siwalik) and Eutric GLEYSOLS (Terai) and Calcaric PHAEOZEMS (Terai) are the other dominant soil types found in the country.



Source: SOTER (2009)

Figure 1-6 Soil map of Nepal

1.4.5 Administrative Setting

Nepal is officially called the Federal Republic of Nepal (GoN, 2015). The country is divided into seven provinces (**Figure 1-7)**. These provinces represent the first level of political subdivision, designed to provide efficient administrative services to the people and carry out developmental activities effectively. The provinces are further divided into 77 districts, which are then subdivided into municipalities and rural municipalities. In total, there are 753 local-level governments in Nepal. Of these, 276 are municipalities, including 6 metropolitan cities and 11 sub-metropolitan cities. The remaining 460 local levels are rural municipalities (MoFAGA, 2023). The distribution of metropolitan cities, sub-metropolitan cities, municipalities, and rural municipalities is provided in **Table 1-3**. The smallest political unit in the country is the ward, with a total of 6,743 wards in Nepal.

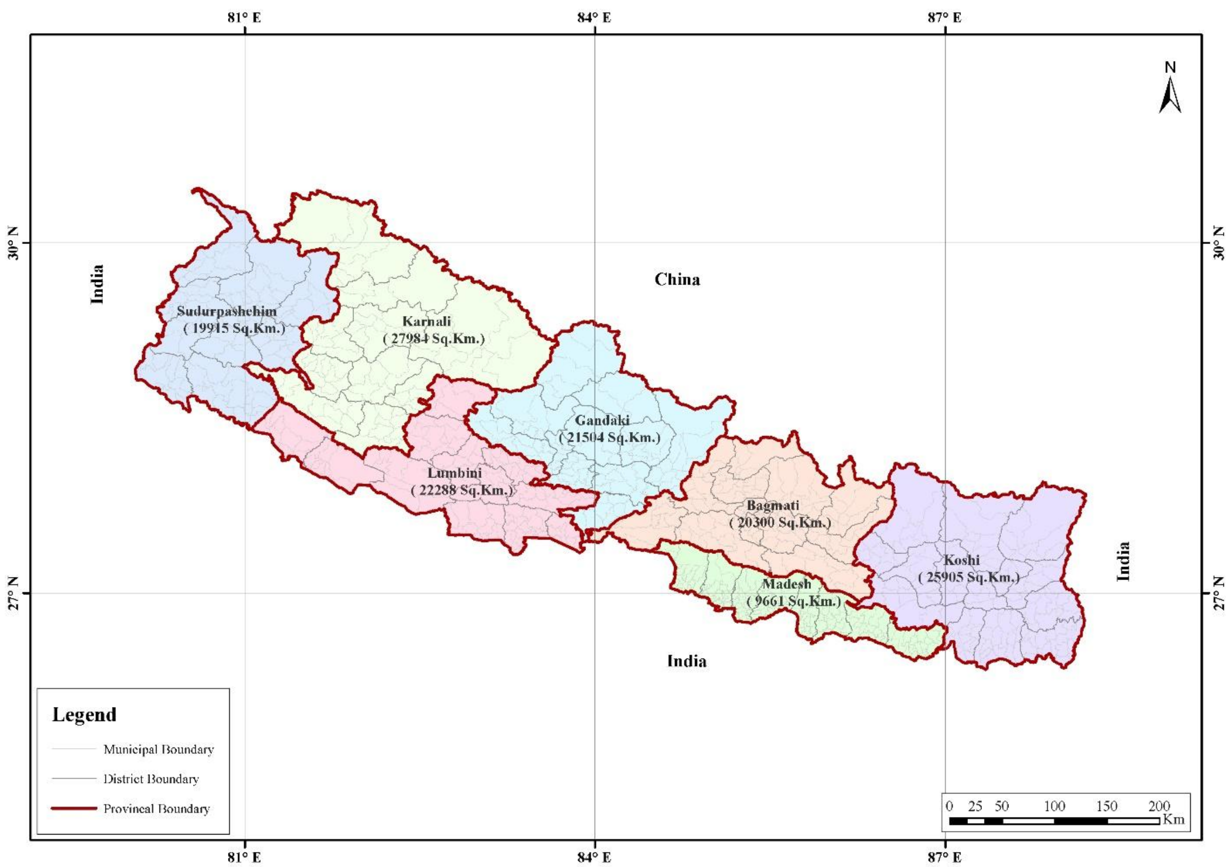


Figure 1-7 Administrative setting of Nepal

Table 1-3 Three tiers of the administrative setting of Nepal

S N	Province	No of District	Metropolitan City	Sub-Metropolitan City	Municipality	Rural Municipality	Total Local Bodies	No of Wards
1	Koshi	14	1	2	46	88	137	1,157
2	Madhesh	8	1	3	73	59	136	1,271
3	Bagmati	13	3	1	41	74	119	1,121
4	Gandaki	11	1		26	58	85	759
5	Lumbini	12		4	32	73	109	983
6	Karnali	10			25	54	79	718
7	Sudur-pashchim	9		1	33	54	88	734
	Nepal	**77**	**6**	**11**	**276**	**460**	**753**	**6,743**

Source: MoFAGA(2023)

1.4.6 Socio-economic Setting

According to the NSO (2021), the total population of Nepal is 29,164,578. The population distribution across the seven provinces of Nepal is presented in **Table 1-4**. Bagmati and Madhesh provinces have nearly equal populations, each accounting for about 21% of the country's total population. The province with the smallest population is Karnali, with around 6% of the total population. Karnali also has the lowest population density (54 persons/km²) among Nepal's seven provinces. With more than 5,000 people per km², Kathmandu has the largest population among the 77 districts. With a population density of less than three people per km², Manang, on the other hand, has the smallest population.

Table 1-4 Comparison of demographic and socio-economic status of the provinces

S. N.	Province	Population	HDI (2020)	GDI	MPI	Current GDP per Capita ($)
1	Koshi	4,961,412	0.580	0.901	0.066	1299
2	Madhesh	6,114,600	0.51	0.786	0.109	875
3	Bagmati	6,116,866	0.661	0.929	0.028	2455
4	Gandaki	2,466,427	0.618	0.896	0.035	1493
5	Lumbini	5,122,078	0.563	0.901	0.078	1126
6	Karnali	1,688,412	0.538	0.902	0.169	997
7	Sudurpashchim	2,694,783	0.547	0.903	0.105	1063
	Nepal	**29,164,578**	**0.587**	**0.886**	**0.074**	**1,399**

HDI: Human Development Index, GDI: Gender Development Index, MPI: Multidimensional Poverty Index

Source: UNDP and NPC (2020) for HDI and GDI; NPC (2021) for MPI

The population density of the local administrative units in Nepal is shown in **Figure 1-8**. Kathmandu Metropolitan City has the highest population density, exceeding 17,000 persons/km², followed by Bhaktapur and Madhyapur Thimi, both with population densities greater than 10,000 persons/km². A total of 77 local administrative units has a population density of more than 1,000 persons/km². The municipalities with the top ten highest populations, in decreasing order, are Kathmandu, Pokhara, Bharatpur, Lalitpur, Birgunj, Biratnagar, Ghorahi, Dhangadhi, Itahari, and Janakpur.

The Human Development Index (HDI) value also varies across provinces (**Table 1-4**). Bagmati province has the highest HDI (0.66), followed by Gandaki province (0.62). Madhesh scores the lowest (0.51) followed by Karnali (0.54). This indicates the uneven distribution of socio-economic development outcomes across different parts of the country. Similarly, the female HDI value for Nepal is 0.549, compared to 0.619 for males. This results in a Gender Development Index (GDI) value of 0.886. Across the provinces, the GDI value is the lowest in Madhesh (0.786), indicating the highest degree of gender disparity. The female HDI value for Madesh province (0.439) is roughly 21 percent lower than that of males (0.558). In contrast, Bagmati has the highest GDI value and hence the lowest gender disparity. Karnali Province has the highest levels of multidimensional poverty with an MPI (Multi-dimensional Poverty Index) of 0.169.

r4In Karnali Province, four out of ten individuals are multidimensionally poor. Thus, the incidence of poverty is nearly 40 percent in this province. Madesh province and Sudurpashchim province rank second and third in terms of multidimensional poverty, respectively. The lowest level (MPI: 0.028) of poverty is found in Bagmati Province.

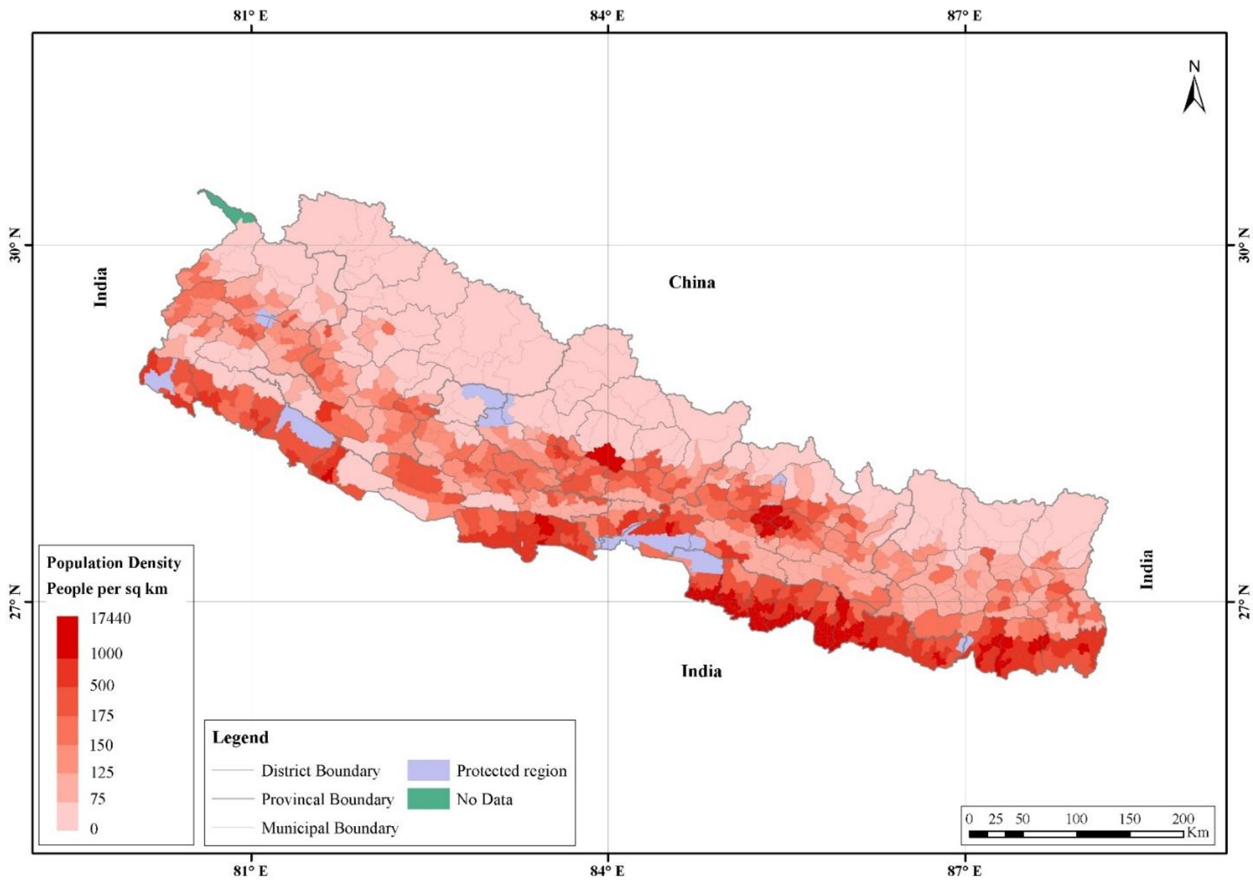


Figure 1-8 Demographic setting of Nepal

CHAPTER 2:LITERATURE REVIEW

An extensive review of past literature on flood and drought events, along with associated climate in Nepal, was conducted in this study. Major plans, policies, acts, regulations, and ordinances related to flood, drought, and climate were also reviewed at both national and international levels. International standards, policies, and practices—including examples from representative countries that address the effects of climate change and mitigation measures—were examined to assess best practices for mitigating the impact of climate change. The review and its findings are organized into five sections:

Section 2.1: National Legal Frameworks Relevant to Flood, Drought, and Climate

Section 2.2: International Legal Frameworks Relevant to Flood, Drought, and Climate

Section 2.3: Standards, Policies, and Practices on Climate Change Effects and Mitigation Measures

Section 2.4: Past Flood and Drought Events in Nepal and Associated Climate/Causes

Section 2.5: Relevant Institutions Responsible for Flood and Drought Management

2.1 National Legal Frameworks: Flood, Drought and Climate

2.1.1 National Acts

The major national legal frameworks related to flood, drought and climate, and associated disasters in Nepal are briefly presented below.

Constitution of Nepal, 2015

Article 51(g) of the constitution places specific emphasis on the development of sustainable and reliable irrigation and the management of water-induced disasters. It also highlights the need for early warning systems, preparedness, rescue, relief, and rehabilitation to mitigate risks from disasters, including those caused by floods, droughts, and climate-related events. Additionally, early preparedness, rescue, relief, and rehabilitation in response to natural and man-made calamities fall under the concurrent powers shared by the federation and the state governments.

Soil and Watershed Conservation Act, 1982

This act has, explicitly, mentioned the need to protect or save soil and catchment areas from natural disasters such as floods and landslides.

Water Resources Act, 1992

Clause 20 of the Water Resources Act states that floods should not have substantial adverse effects on the environment, implying that flood management is a crucial component of national development.

The Environment Protection Act, 2019

It includes a directive for the Government of Nepal to act prudently in mitigating the adverse impacts of climate change on local communities, ecosystems, and biodiversity. To address these impacts, the Federal Ministry, Provincial Ministry, and Local Level authorities may develop and implement adaptation plans at the national, provincial, and local levels, respectively.

The Local Government Operation Act, 2017

The Local Government Operation Act mandates local municipal governments to manage disasters, including preparedness, search and rescue, relief, and rehabilitation. This Act specifically directs the removal of obstructions to physical infrastructure caused by natural disasters like floods, landslides, and storms. Under these provisions, local governments are further empowered with additional functions, duties, and authority to formulate land use plans, policies, and action plans and to implement them in alignment with federal and provincial laws and regulations.

The Right to Food and Food Sovereignty Act, 2018

If a food crisis arises within the country due to an earthquake, excessive rainfall, drought, flood, landslide, or similar events, the Government of Nepal may declare the affected area a food crisis zone for a specified period. The federal, provincial, and local governments are then required to coordinate and adopt necessary measures to provide immediate food assistance in these zones. Additionally, the Government of Nepal should establish provisions for preventive measures to mitigate adverse impacts on food production due to climate change or related risks.

Disaster Risk Reduction and Management Act, 2019

The Disaster Risk Reduction and Management Act, 2019, addresses issues related to floods and other hydro-meteorological disasters, with a focus on risk reduction, preparedness, response, and recovery. This Act entrusts the National Disaster Risk Reduction and Management Authority (NDRRMA) with overseeing disaster management activities across the country, including those related to floods, droughts, and climate-related disasters. To support this mandate, programs are implemented for studies and research on river training, flood control, landslides, earthquakes, global warming, climate change, land use, and various other hazards and disaster mitigation measures. Additionally, Provincial Disaster Management Committees and Local Disaster Management Committees may be established at provincial and local levels for effective disaster management.

2.1.2 National Strategy and Policies

National Action Plan on Disaster Management, 1996

Nepal's National Action Plan on Disaster Management (1996) emphasizes four main areas of action: disaster preparedness, disaster response, disaster reconstruction and rehabilitation, and disaster mitigation.

Water Resources Strategy, 2002

The Water and Energy Commission Secretariat (WECS) prepared the Water Resources Strategy (WRS) in 2002, which prioritizes the prevention and mitigation of water-induced disasters such as floods and droughts. In this regard, several actions have been identified to mitigate the effects of these disasters, including: (i) preparing and implementing a water-induced disaster management policy and plan, (ii) conducting risk/vulnerability mapping and zoning, (iii) strengthening disaster networking and information systems, (iv) establishing disaster relief and rehabilitation systems, (v) carrying out community awareness and education on disaster management, (vi) activating Inundation Committees in collaboration with neighboring countries, (vii) preparing and implementing floodplain action plans, (viii) implementing disaster reduction and mitigation measures, and (ix) strengthening institutional setups and capacity.

National Agriculture Policy, 2004

The National Agriculture Policy, 2004 aims to protect, promote, and utilize natural resources, the environment, and biodiversity. It emphasizes the establishment and operationalization of monitoring and early warning systems for natural hazards, including extreme rainfall, droughts, and floods. The policy prioritizes activities related to the development of early warning systems for weather and climate, as well as research on droughts and floods.

National Water Plan, 2005

The WECS formulated the National Water Plan (NWP) to operationalize the Water Resources Strategy (WRS). The NWP identifies seven programs related to water-induced disasters (WID). It focuses on the formulation of WID mitigation policies, acts, regulations, and management guidelines. Other prioritized aspects include enhancing the capacity of all institutions related to water-induced disasters, preparing hazard maps, and zoning high-risk areas. Furthermore, the plan highlights the establishment and activation of disaster forecasting and early warning systems for floods, extreme precipitation, and drought. It also emphasizes strengthening community-based organizations, non-governmental organizations, local authorities, and professional societies for disaster management networking, as well as promoting regional and international cooperation in WID management.

National Strategy for Disaster Risk Management, 2009

The National Strategy for Disaster Risk Management (NSDRM) 2009 serves as a national framework reflecting the Government of Nepal's commitment to reducing disaster risks. It aims to develop a resilient community by identifying five priority areas for disaster risk reduction, in alignment with the Hyogo Framework (2005-2015). The strategy envisions a 'Disaster Resilient Nepal' and encourages the integration of Disaster Risk Reduction into the formulation and implementation of sectoral development plans. It also promotes the development and strengthening of institutional mechanisms, capacity building, and the effective implementation of emergency preparedness, response, and recovery programs. Additionally, it emphasizes the establishment of early warning systems for floods and landslides at the local level and discourages settlement in flood-prone areas.

National Disaster Response Framework, 2013

The National Disaster Response Framework (NDRF) 2013 focuses on developing an action plan for flood and inundation response. It provides guidance for an effective and coordinated response at the national level to disasters that impact various sectors of development. Under the directive of the Disaster Risk Reduction and Management Executive Committee, the National Disaster Risk Reduction and Management Authority (NDRRMA) and relevant agencies are primarily responsible for executing preparedness and response activities related to disasters. The NDRRMA collaborates with governmental agencies as well as organizations in the non-governmental and humanitarian sectors at the federal, provincial, and local levels.

Water Induced Disaster Management Policy, 2016

This policy emphasizes that water-induced disaster management programs should align with the principles of Integrated Water Resources Management (IWRM) and the concept of Integrated River Basin Development (IRBD). To align with IRBD and conservation efforts, a national master plan for water-induced disaster management should be formulated, recognizing the needs of the local level and ensuring full involvement of local governments. The policy prioritizes programs based on short-term, medium-term, and long-term perspectives, with a focus on active community participation in their implementation.

Disaster Risk Reduction National Strategic Plan of Action, 2018-2030

The National Disaster Risk Reduction and Management Strategic Plan of Action 2018-2030 is a legal framework that covers all stages of disaster risk management in the country. The goal of the strategic action plan is to prevent new risks and reduce existing natural and man-made disaster risks and losses. It focuses on preventing disaster risk, enhancing preparedness for response, rehabilitation, and reconstruction, and strengthening resilience. The plan outlines key priority actions aligned with the Sendai Framework for Disaster Risk Reduction (SFDRR) priorities for action.

National Water Resources Policy, 2018

The National Water Resources Policy 2018 has set a goal to mitigate the damaging impacts of floods, landslides, and droughts. To address flood risk, the policy emphasizes flood forecasting and early warning systems as key strategies. It clearly states the need for regular drills and training of local communities to enhance their capacity to manage flooding at the local level. The policy also aims to increase women's involvement to ensure gender equality in water resources management at all levels. Additionally, it stresses the clear roles and responsibilities of each institution involved in flood risk mitigation.

National Policy for Disaster Risk Reduction, 2018

The National Policy for Disaster Risk Reduction 2018 is Nepal’s first policy aimed at ensuring long-term provisions for disaster risk reduction and management. The policy is aligned with the Disaster Risk Reduction and Management Act 2074 BS (2017). Its main objective is to significantly reduce losses from both natural and man-made disasters, including those affecting lives, property, health, livelihoods, production, physical and social infrastructure, and cultural and environmental assets. The policy emphasizes regular monitoring and forecasting of natural disasters, including floods. It also calls for the development and implementation of forecast-based preparedness and response plans, supported by early warning systems. A key objective is to ensure the "Build Back Better" approach for post-disaster recovery, rehabilitation, and reconstruction, in line with the Sendai Framework for Disaster Risk Reduction (SFDRR)

National Climate Change Policy, 2019

The goal of the National Climate Change Policy 2019 is to contribute to the socio-economic prosperity of the nation by building a climate-resilient society. The policy focuses on reducing the loss or damage caused by climate-induced disasters to lives, property, health, livelihoods, physical infrastructure, and cultural and environmental resources. A Disaster Risk Reduction and Management System is to be developed at the federal, provincial, and local levels to prevent, reduce, and prepare for climate-induced disasters. Preparedness and response are to be strengthened by developing monitoring, forecasting, and early warning systems for disasters. The policy also aims to ensure energy security by promoting the multiple uses of water resources and the production of low-carbon energy.

2.1.3 National Plans and Programs

Periodic Plans

he Ninth Plan (1997/98-2001/02), Tenth Plan (2002/03-2006/07), Three-Year Interim Plan (2007/08-2009/10), Twelfth Three-Year Plan (2010/11-2012/13), Thirteenth Plan (2013/14-2015/16), Fourteenth Plan (2016/17-2018/19), Fifteenth Plan (2019/20-2023/24) and Sixteenth Plan (2023/24-2027/2028) have all prioritized the management of flood, drought, and climate change-induced disasters.

National Adaptation Program of Action, 2010

National Adaptation Program of Action (NAPA) of Nepal 2010 aims to enable to respond strategically to the challenges and opportunity posed by climate change. One of the main objectives of NAPA is to assess and prioritize climate change vulnerabilities and identify adaptation measures. Water resource sector is expected to suffer very much from climate change, i.e., too much water and/or to little water. It can affect almost all sectors of economy negatively (e.g., food to energy security, human settlements, and infrastructure.)

Local Adaptation Plans for Action, 2011

The water resources sector is expected to be severely impacted by climate change, facing issues such as water scarcity or excess. These changes could negatively affect nearly all sectors of the economy, including food security, energy security, human settlements, and infrastructure. Nepal's National Adaptation Program of Action (NAPA), 2010, aims to enable a strategic response to the challenges and opportunities posed by climate change. One of NAPA's primary objectives is to assess and prioritize climate change vulnerabilities and identify adaptation measures for each sector.

National Adaptation Plan, 2021

The National Adaptation Plan (NAP) (2021-2050) identifies floods, including glacial lake outburst floods (GLOFs), landslides, and drought as the primary climate hazards facing Nepal. The main aim of this plan is to reduce vulnerability to climate change impacts by building adaptive capacity and resilience.

2.1.4 National Manuals and Tools

Climate Resilient Planning Tool, 2011

Recognizing that climate change is likely to increase the frequency and magnitude of floods, flash floods, GLOFs, landslides, hailstorms, windstorms, forest fires, heat waves, cold waves, droughts, and epidemics, variables are assessed during the planning process of any development activity based on their risk ranking (high, medium, low, or not applicable), and appropriate interventions are identified.

Flood Control and Management Manual, 2019

Water and Energy Commission Secretariat (WECS) has endorsed the principle outlined in the Water-Induced Disaster Management Policy 2072 through its flood control and management manual, which includes land use zoning based on flood return periods for various purposes.

2.2 International Legal Frameworks: Flood, Drought and Climate

2.2.1 Global Frameworks

The main international legal frameworks related to flood, drought, and climate are the Hyogo Framework for Action: 2005-2015, the Sendai Framework for Disaster Risk Reduction 2015-2030 and the Sustainable Development Goals (SDGs), 2016 – 2030. Nepal is one of the signatories of these frameworks. The thrusts of these frameworks are briefly discussed below.

Hyogo Framework for Action, 2005-2015

The Hyogo Framework for Action (HFA), which aims for a substantial reduction in disaster losses—including lives, as well as social, economic, and environmental assets of communities and countries—identifies five priorities for action: (i) Ensure that disaster risk reduction (DRR) is a national and local priority with a strong institutional basis for implementation; (ii) Identify, assess, and monitor disaster risks and enhance early warning; (iii) Use knowledge, innovation, and education to build a culture of safety and resilience at all levels; (iv) Reduce risks in key sectors; and (v) Strengthen preparedness for response.

Sendai Framework for Disaster Risk Reduction, 2015-2030

The Sendai Framework for Disaster Risk Reduction 2015-2030 was adopted at the Third UN World Conference on Disaster Risk Reduction in Sendai, Japan, on March 18, 2015. It outlines seven clear targets and four priorities for action to prevent new and reduce existing disaster risks: (i) understanding disaster risk; (ii) strengthening disaster risk governance to manage disaster risk; (iii) investing in disaster reduction for resilience; and (iv) enhancing disaster preparedness for effective response and to 'Build Back Better' in recovery, rehabilitation, and reconstruction (UNDRR, 2015). The framework aims to achieve a substantial reduction in disaster risk and losses in lives, livelihoods, health, and the economic, physical, social, cultural, and environmental assets of individuals, businesses, communities, and countries.

Sustainable Development Goals, 2016 – 2030

Of the seventeen development goals, five explicitly focus on mitigating, adapting to, or restoring the effects of floods, drought, and climate change **( )**. However, all development goals are directly or indirectly affected by floods, drought, and climate change. For example, Goals 6 and 7, which aim to ensure the availability and sustainable management of water and sanitation for all and to provide access to affordable, reliable, sustainable, and modern energy for all, depend on reliable water resources. This sector is one of the most affected by drought and floods, with impacts exacerbated by climate change.

Table 2-1 SDG and its targets related to flood, drought and climate change

SDG No.	SDG	Target	Flood	Drought	Climate Change	Main Focus
1	End poverty in all its forms everywhere	1.5	⊗	⊗	⊗	Reducing the exposure of the poor and vulnerable people from climate-related extreme events
2	End hunger, achieve food security and improved nutrition, and	2.4	⊗	⊗	⊗	Adaptation to climate change, extreme weather, drought, flooding

SDG No.	SDG	Target	Flood	Drought	Climate Change	Main Focus
	promote sustainable agriculture					
11	Make cities and human settlements inclusive, safe, resilient, and sustainable				⊗	Adaptation to climate change, and resilience to disasters, in line with the Sendai Framework for Disaster Risk Reduction 2015–2030
13	Take urgent action to combat climate change and its impacts	13.1			⊗	Strengthening resilience and adaptive capacity to climate-related hazards and natural disasters
		13.2			⊗	Integrating climate change measures into national policies, strategies, and planning
		13.4			⊗	Improving education, awareness-raising, and human and institutional capacity on climate change mitigation, adaptation, impact reduction, and early warning
15	Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	15.3	⊗	⊗		Restoring degraded land and soil, including land affected by desertification, drought, and floods

2.2.2 International Acts, Policies, and Guidelines: Flood, Drought and Climate

Many countries in the South Asian region lack specific laws or acts for flood control and management. However, most have national disaster management acts, such as Nepal’s Disaster Risk Reduction and

Management Act of 2019, India's Disaster Management Act of 2005, Pakistan's National Disaster Management Act of 2010, and Bangladesh's Disaster Management Act of 2012. Bangladesh also has the Embankment and Drainage Act of 1952. In contrast, countries like China, the United States, and Japan have specific acts addressing flood control and management. A summary of the main contents of representative acts, policies, and guidelines is provided below.

1. South Asian Region

Bangladesh: The Disaster Management Act and Embankment and Drainage Act, 1952

Bangladesh's Disaster Management Act of 1952 is a legislative tool that establishes mandatory obligations and responsibilities for ministries, committees, and appointed officials. The objectives of the act are to reduce disaster risks to an acceptable level and to implement post-disaster emergency response, rehabilitation, and recovery measures. It also includes provisions for emergency humanitarian assistance to the most vulnerable communities and aims to strengthen institutional capacity for effective disaster management coordination.

The Embankment and Drainage Act of 1952 focuses on the construction, maintenance, removal, management, and control of embankments and watercourses to improve drainage and prevent potential flooding (UNEP-LEAP, 2023).

Bangladesh: National Plan for Disaster Risk Management, 2021-2025

The National Plan for Disaster Risk Management 2021-2025 establishes core goals to save lives and reduce economic losses at each stage of the disaster cycle, including disaster risk reduction (DRR), humanitarian response, and emergency recovery management. Recent disaster risk management plans (post-2015) reflect a paradigm shift from relief-based disaster response to proactive disaster risk reduction, with a strong emphasis on capacity building. This adaptive and flexible plan prioritizes disaster risk management (DRM) in the context of rapid urbanization and climate change, highlighting the necessity of DRM for sustainable development. The DRM plan identifies floods and drought as key hazards, among others, in Bangladesh (MoDMR, 2020).

India: Disaster Management Act, 2005

The Disaster Management Act of 2005 establishes a three-tier institutional framework for disaster management in India. It includes the National Disaster Management Authority (NDMA) at the national level, the State Disaster Management Authorities (SDMAs) at the state level, and the District Disaster Management Authorities (DDMAs) at the district level. These authorities are responsible for policy-making, planning, coordination, and the implementation of disaster management efforts within their respective jurisdictions.

The Act outlines the functions and responsibilities of the NDMA, SDMAs, and DDMAs, which include formulating disaster management plans, coordinating response and recovery efforts, promoting risk reduction measures, conducting research and development, and providing guidelines and standards for disaster management. Additionally, it emphasizes the importance of disaster risk reduction, mandates the preparation of disaster management plans, and includes provisions for disaster response, recovery, capacity building, and international cooperation.

The Act aims to promote a proactive approach to disaster management, enhance preparedness, and ensure effective response and recovery measures during disasters in India.

India: Disaster Management Policy, 2009

The disaster management policy has made a paradigm shift from the former relief-centric and post-event syndrome to pro-active prevention-, mitigation- and preparedness-driven disaster management in the country. The main focuses of the disaster management policy of India are: a) promoting prevention, preparedness, and resilience through knowledge, innovation, and education, b) carrying out mitigation measures based on technology, traditional wisdom, and environmental sustainability, c) mainstreaming disaster management into the developmental planning process, d) establishing institutional and techno-legal frameworks to create an enabling regulatory environment, e) ensuring efficient mechanism of identification, assessment, and monitoring of disaster risks, f) developing contemporary forecasting and early warning systems, g) Ensuring efficient response and relief, h) undertaking reconstruction an opportunity to build disaster resilient structures and habitat. It has provided a coordinated institutional set-up to disaster management at all levels, national to local. Capacity development in all spheres is another aspect that has been given high priority. The policy has recognized the need for the promotion of research in this sector (NDMA, 2009).

India: National Disaster Management Guidelines: Management of Floods, 2008

The national disaster management guidelines on the management of floods are used by various implementers and stakeholder agencies to address effectively the critical areas for minimizing flood damages. It has emphasized shifting the focus to preparedness by implementing, in a time-bound manner, an optimal combination of techno-economically viable, socially acceptable, and eco-friendly structural and nonstructural measures of flood management. It also focuses on ensuring regular monitoring of the effectiveness and sustainability of various structures and taking appropriate measures for their restoration and strengthening. Proper functioning of the flood forecasting, early warning, and decision support systems to minimize the flood disaster, improving the awareness and preparedness of all stakeholders in the flood-prone areas is highlighted by this guideline. It has spoken on the need for appropriate capacity development interventions for effective flood management that include education, training, capacity building, research and development, and documentation, and on the strengthening of the emergency response capabilities (NDMA, 2008).

India: National Disaster Management Guidelines: Management of Drought, 2010

The national disaster management guidelines for drought management are expected to be useful to authorities involved in drought management at both the central and state government levels. These guidelines aim to improve drought management by ensuring that all contemporary knowledge, experience, and information are incorporated. They also emphasize identifying clear objectives, drawing roadmaps with milestones, and conducting a wide consultative process involving all stakeholders. Furthermore, the guidelines focus on developing robust procedures for assessing drought intensity using multiple observations over time and establishing standard operating procedures for declaring drought, including the timing and criteria for declaration.

India: Ganga Flood Management Guidelines, 2004

The Ganga Flood Management Guidelines recommend that the design high flood level for embankments be based on a flood with a 25-year return frequency for predominantly agricultural areas. However, if the embankments are intended to protect townships, industrial areas, or other places of strategic or vital importance, the design high flood level should generally correspond to a 100-year return period (GFCC, 2004).

Pakistan: National Disaster Management Act, 2010

The National Disaster Management Act of Pakistan, 2010, provides for the establishment of the National Disaster Management Commission and the National Disaster Management Authority to carry out the following activities: set policies on disaster management; approve the National Plan prepared by the Ministries or Divisions of the Federal Government; establish guidelines to be followed by the Federal Government and Provincial Authorities; arrange for and oversee the provision of funds for mitigation measures, preparedness, and response; provide support to other countries affected by major disasters; and take additional measures for the prevention of disasters, mitigation, preparedness, and capacity building to deal with disaster situations (DMA, 2005).

2. Other Asian Countries

China: Law of Flood Control of the People's Republic of China

This law was promulgated by Order No. 88 of the President of the People's Republic of China, with the aim of preventing floods, minimizing damage, and ensuring the safety of human life and property (Informea, 1997). The prevention plans for major rivers and lakes, as determined by the state, are to be developed by the Water Administration Department of the State Council, in collaboration with the Water Administration

Departments of relevant provinces, autonomous areas, or municipalities. In other words, the law outlines the responsibilities of various government departments and authorities in flood management. As a result, China has established a comprehensive legal framework for flood management through the Flood Control Law.

Japan: The River Law, 1896 and Flood Fighting Law, 1949

The River Law of 1896 serves as the legal foundation for river management in Japan, including flood control and water resources development. Enacted and promulgated in 1896, it is commonly referred to as the Old River Law (IDI, 1999). The purpose of this law is to contribute to land conservation and national development, thereby ensuring public security and promoting public welfare. It does so by comprehensively managing rivers to prevent damage from floods, high tides, and other hazards, while also ensuring the proper use of rivers and the maintenance and conservation of the river environment.

Repeated occurrences of flood damage raised awareness about the importance of flood prevention and control in Japan. In response to this growing awareness, the Flood Defense Association Law was revised in 1949, and the Flood Fighting Law of 1949 was enacted in the same year. This law outlines flood-fighting activities to be carried out by flood defense associations. It emphasizes proactive measures such as flood control, evacuation planning, information sharing, hazard mapping, and the involvement of the private sector in flood management. Additionally, the law recognizes the centuries-old tradition of community-based flood-fighting activities to protect local communities.

Japan: Insurance for Water Disaster Risk

Compensation for damage to homes or household property caused by water-related disasters, such as typhoons, storms, floods from heavy rains, snowmelt floods, storm surges, landslides, falling rocks, and other events, is available (Plaza Homes, 2023).

3. Australia

Australia: Flood Insurance

Flood insurance covers damage caused by floodwater that has escaped or been released from the normal confines of any lake, river, creek, or other natural watercourse, whether or not altered or modified, as well as any reservoir, canal, or dam. However, in Australia, even if a policy excludes flood damage, other policies may still cover damage caused by storms or rainwater (ICA, 2023).

4. America

USA: The Flood Control Act, 1944 and 1946

The Flood Control Act of 1917 was the first legislation aimed exclusively at controlling floods. Subsequent acts, including the Flood Control Act of 1928, the Flood Control Act of 1944, and the Flood Control Act of

1946, further addressed flood management and control across the entire United States and its territories (FCA, 1944; FCA, 1946).

USA: The National Flood and Drought Insurance Program

The program is managed by the Federal Emergency Management Agency (FEMA) of the United States Department of Homeland Security and is delivered to the public through a network of more than 50 insurance companies and the National Flood Insurance Program (NFIP) Direct. The NFIP provides flood insurance to property owners, renters, and businesses, helping them recover more quickly when floodwaters recede. It also works with communities, requiring them to adopt and enforce floodplain management regulations that mitigate the effects of flooding (FEMA, 2023).

Similarly, drought insurance is available to compensate for the impact of drought on crops, livestock, pasture, rangeland, and forages (USDA, 2023; Douglas, 2022). However, compensation is based not on the area of crops lost, but on the amount of rainfall received. Several policy options are available, with variations depending on the state, county, and other factors.

5. Africa

Kenya: National Drought Management Authority Act, 2016

This act mandates the National Drought Management Authority (NDMA) to oversee all matters related to drought risk management and to establish mechanisms, either independently or with stakeholders, to end drought emergencies in Kenya (NDMA, 2016). The NDMA has implemented a robust early warning system that provides timely information on impending droughts. It has also developed and put into action drought contingency plans to guide the response to emergencies, while promoting and supporting risk reduction measures such as water harvesting, reforestation, and soil conservation. These efforts enhance the resilience of communities and ecosystems to drought. Additionally, the NDMA coordinates with various stakeholders, including government agencies, non-governmental organizations, and local communities, to implement drought management interventions.

2.2.3 Lesson Learned from the Review of Acts, Policies, Plans and Guidelines

Nepal has a range of legal instruments (acts, policies, strategies, etc.) to address flood, drought, and climate related disasters, aimed at reducing loss or damage to lives, property, health, livelihoods, infrastructure, and cultural and environmental resources. Most of these instruments emphasize coordination among the three levels of government, as well as with local communities, non-governmental organizations, and international organizations for effective disaster management. However, based on the literature review conducted in this study, the following issues are recommended for consideration when revisiting these legal instruments to better address the challenges posed by floods, droughts, and climate change.

1. Flood, drought, and climate-related disaster acts, policies, plans, and guidelines should focus more on a proactive approach.
2. Drought management should be given priority alongside flood and other disaster management efforts.
3. Guidelines for managing floods, including Glacial Lake Outburst Floods and Landslide Dam Outburst Floods, as well as drought and climate risk management, need to be developed.
4. Guidelines for the coordinated institutional set-up at among and within three tiers of government should be developed to deal with flood, drought and climate.
5. Research on disaster risk management (DRM), including flood, drought, and climate risk management, is minimal in Nepal, while other countries have prioritized it.
6. Insurance policies covering not only flood, drought, and climate-related disasters but also other disasters are either nonexistent or ineffective in countries of this region, including Nepal.

2.3 Standards, Policies and Practices on Climate Change

2.3.1 Climate Change: Causes and Impact

Human activities have been the main driver of climate change, primarily due to the burning of fossil fuels like coal, oil, and gas to generate power for the different economic sectors. Fossil fuels are by far the largest contributor to global climate change, accounting for over 75 percent of global greenhouse gas (GHG) emissions and nearly 90 percent of all carbon dioxide emissions (UN, 2024).

China, the United States, India, the EU27, Russia and Brazil were the world's six largest GHG emitters in 2022. Together they account for 50.1% of the global population, 63.4% of global fossil fuel consumption, and 61.6% of global GHG emissions. Global total GHG emissions and per capita emissions of 2022 are respectively 53,786 Megaton (=10^6 metric ton) CO_2eq and 6.76 tons CO_2eq/capita (EDGAR, 2023). These figures of Nepal are respectively 56.74 Megaton CO_2eq and 1.84-ton CO_2eq/capita (EDGAR, 2023). Agriculture, energy, transport, and buildings are the main sectors responsible for GHG emissions. Sectoral shares of GHG emissions of 2020 are given in **Table 2-2**. Energy (electricity and heat), industry (goods and foods, manufacturing and construction), transport, and buildings respectively produce 31%, 19%, 15%, and 6% of the total GHG emissions. Agriculture, land-use change and forestry emits 15% of the total emissions.

The effect of climate change goes beyond just temperature rise. It is bringing about multiple changes in different regions. Climate change is likely intensifying the global water cycle, leading to more erratic and intense rainfall and associated flooding, as well as more severe droughts in many regions (IPCC, 2021). In high latitudes, precipitation is expected to increase, while it is projected to decrease over large parts of the subtropics. Monsoon precipitation is anticipated to vary from region to region. Global warming will accelerate permafrost thawing, the loss of seasonal snow cover, and the melting of glaciers and ice sheets. Coastal areas will continue to experience rising sea levels, contributing to more frequent and severe coastal flooding in low-lying regions (IPCC, 2021).

Table 2-2 Sector-wise GHG emission- 2020

Sectors	Megaton	Percentage
Agriculture	5,865	12.1
Land use change and forestry	1,392	2.9
Waste	1,653	3.4
Buildings	2,981	6.2
Industry	3,127	6.5
Manufacturing and construction	6,223	12.8
Transport	7,288	15.0
Electricity and heat	15,181	31.3
Fugitive emissions of greenhouse gases from energy production	3,224	6.7
Other fuel combustion	579	1.2
Bunker fuels	938	1.9
Total	48,451	100

Source: Ritchie et al. (2020)

2.3.2 Global Policies and Practices on Climate Change Mitigation Measures

Realizing the realities of climate change, the first World Climate Conference was held in Geneva in 1979 to review the latest knowledge on climate change (CC), assess future impacts and risks, and formulate recommendations to mitigate the detrimental effects of CC. During the third United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP-3) in 1997, held in Kyoto, Japan, the Kyoto Protocol was adopted, focusing on the reduction of greenhouse gas (GHG) emissions by developed countries. At the COP-21 meeting in Paris in 2015, nations agreed to limit the global temperature increase to 2°C by 2100 and to pursue efforts to limit the increase to 1.5°C (Fawzy et al., 2020). Since then, several countries have begun formulating national policies to mitigate the impacts of climate change. A total of 140 countries pledged to achieve net-zero emissions, 100 countries committed to reversing deforestation, and 40 countries pledged to phase out coal at COP-26 in Glasgow (UK) (Fekete et al., 2021).

The main priorities of the recent COP 29, held in Baku, Azerbaijan, in November 2024, include establishing a new climate finance goal, empowering countries to take significantly stronger climate action, reducing greenhouse gas emissions, and fostering resilient communities. Another key focus is the upcoming round of national climate plans, which countries are preparing ahead of next year's deadline. These plans aim to be bolder, fully implementable, and investment-ready, encompassing economy-wide strategies that prioritize transitioning away from fossil fuels and limiting the global temperature increase to within 1.5 degrees Celsius (UNFCCC, 2024).

Emission reduction has mainly been achieved through the introduction of renewable energy, increased energy efficiency, and afforestation/reforestation-related measures. Sector-wise possible mitigation options are given in **Table 2-3**. Some global examples of good practice policy actions with corresponding country policy instruments and translation to policy impact are given **Table 2-4**. A brief description of some national and international standards, policies, and practices are also provided.

Table 2-3 Possible climate change mitigation options

SN	Sector	Possible CC Mitigation Options
1	Energy	• Increase in renewable energy: Promote renewable hydropower, wind and solar energy, and bioelectricity • Limits on coal-fired power plants • Reduction of venting and flaring in oil and gas production
2	Agriculture, forestry and other land use	• Carbon sequestration in agriculture • Reduce CH_4 and N_2O emission in agriculture • Afforestation, reforestation • Reduce food loss and food waste etc.
3	Buildings	• Efficient lighting, heating and cooling appliances • New buildings with high-energy performance • Enhanced use of wood products etc.
4	Transport	• Fuel-efficient light-duty vehicles • Electric light-duty vehicles • Shift to mass public transportation • Electric heavy-duty vehicles, incl. buses etc.
5	Industry	• Energy and material efficiency • Enhanced recycling • Fuel switching (electricity, natural gas, bio-energy, H_2) • Feedstock decarbonization, process change carbon capture with utilization etc.

Modified from IPCC (2022) and Fekete et al. (2021)

Table 2-4 Several international instances of effective policy actions, instruments and impact

Main sector	Policy action	Successful policy instrument	Policy impact
Energy supply	• Increase renewables in electricity production	• Renewable portfolio standard • Feed-in tariff (UK and Germany)	+1.35% growth in the share of renewable electricity generation per year
	• Reduce flaring and venting in oil and gas production	• Regulation and carbon tax (Norway)	4.4% annual reduction of oil/gas intensity (ktCO_2e/Mtoe) until 2030
Industry	• Enhance energy efficiency of industrial production	• Energy agreements (Ireland)	1% annual energy savings improvement above current efforts until 2030
	• Reduce fluorinated emissions	• North American Proposal to the Montreal Protocol	70% reduction of F-gas emissions below 2010 levels by 2030
Buildings	• Enhance the efficiency of the residential building envelope	• Regulation (EU)	Energy intensity of 0 kWh/m² by 2030 (space heating)
	• Set efficiency standards for appliances and lighting	• Appliance standards (EU)	Average efficiency improvement of 1.8% per year until 2030
Transport	• Improve fuel efficiency of cars	• Fuel economy standard (EU)	Fuel economy standard of 26 km/l in 2030
	• Increase the number of electric cars (charged with renewable electricity)	• Tax levies and investments in infrastructure (Norway)	25% share of new electric vehicles in 2020, 50% in 2030
LULUCF	• Reduce deforestation	• Regulations and enforcements (Brazil)	Decreasing deforestation rate relative to 2010 by 22% in 2020, 44% in 2030.

LULUCF: land use and land-use change and forestry

Source: Roelfsema et al. (2018)

2.3.3 National Policies, Framework for Action and Standards on Climate Change

National Climate Change Policy, 2020

The National Climate Change Policy 2020 replaces the previous 2011 policy, in part to empower constitutional provisions guaranteeing the right of every citizen to live in a clean and healthy environment. The stated goal of the policy is to "contribute to the socio-economic prosperity of the nation by building a climate-resilient society." The specific objectives of the policy include: a) to enhance climate change adaptation capacity; b) to build resilience in at-risk ecosystems; c) to promote a green economy through low carbon development; d) to mobilize national and international climate finance in a just manner; e) to conduct research and development and develop a climate information service; f) to mainstream climate change into policies, plans and programs at all levels and sectors; g) to mainstream gender equality and social inclusion into climate change mitigation and adaptation programs. The policy provides several sector-specific and inter-sectoral strategies, including those on the development of necessary laws, multi-level governance, and capacity building activities.

Priority Framework for Action: Climate Change Adaptation and Disaster Risk Management in Agriculture, 2011-2020

This policy outlines the Nepalese government's approach to adapting to climate change and disaster risk management in the agricultural sector. It has five priorities: (1) strengthening institutions, policy, and coordination; (2) assessing and monitoring climate risks and vulnerabilities; (3) improving knowledge management, database, and awareness raising; (4) implementing technical options by integrating community-based approaches and (5) strengthening capacities for effective risk preparedness, response and rehabilitation. This policy serves to integrate the priorities of Nepal's National Adaptation Program of Action and its National Strategy for Disaster Risk Management. In doing so, it creates space for government cooperation on the technical matters concerning both and enhances the government's ability to implement immediate actions concerning climate change adaptation and disaster risk management. This policy also outlines short-term priorities related to disaster response, medium-term priorities related to disaster risk reduction, and long-term priorities related to climate change adaptation, integrating them into a single policy.

Standard Operating Procedure for Flood Early Warning System, 2018

Nepal has developed the Standard Operating Procedure for Flood Early Warning System (FEWS) in 2018. It intends to provide consistent and standard procedures at the critical time of flooding events so that the communities can act effectively during the worst period of flood hazards. It is equally useful to reduce the loss of lives and properties due to (with or without climate change-induced) flood disasters.

2.3.4 International Policies and Practices on Climate Change Mitigation Measures

1. South Asian Countries

India: National Action Plan on Climate Change, 2008

The National Action Plan on Climate Change 2008 (NAPCC) outlines a national strategy that aims to enable the country to adapt to climate change and enhance the ecological sustainability of India's development path. There are eight National Missions which form the core of the National Action Plan. They are: i) National Solar Mission, ii) National Mission for Enhanced Energy Efficiency, iii) National Mission on Sustainable Habitat, iv) National Water Mission, v) National Mission for Sustaining the Himalayan Eco-system, vi) National Mission for a Green India, vii) National Mission for Sustainable Agriculture and viii) National Mission on Strategic Knowledge for Climate Change

India: National Innovation on Climate Resilient Agriculture, 2011

Indian Council of Agricultural Research (ICAR), Ministry of Agriculture and Farmers Welfare, Government of India launched a flagship network project 'National Innovations in Climate Resilient Agriculture' (NICRA) in 2011. The project aims at strategic research on adaptation and mitigation, demonstration of technologies on farmers' fields, and creating awareness among farmers and other stakeholders to minimize the climatic change impacts on agriculture. So far, 7 climate-resilient varieties and 650 district agricultural contingency plans have been developed besides assessing the risk and vulnerability of Indian agriculture to climate change. In the past nine years, 16,958 training programs have been conducted throughout the country under the NICRA project to educate stakeholders on various aspects of climate change and resilient technologies, covering 5,14,816 stakeholders to enable wider adoption of climate resilient technologies and increase in yields. In the strategic research, the main thrust areas covered are (i) identifying the most vulnerable districts/regions, (ii) evolving crop varieties and management practices for adaptation and mitigation and (iii) assessing climate change impacts on livestock, fisheries, and poultry and identifying adaptation strategies (NICRA, 2011).

India: Faster Adoption and Manufacturing of Hybrid and Electric Vehicles in India, 2015

This scheme aims to reduce pollution caused by diesel and petrol-operated vehicles and to promote the manufacturing of electric and hybrid vehicles. Its first phase ran for four years until 2019. The second phase is a 3-year subsidy program. It aims at supporting the electrification of public and shared transportation: around 7,000 electric and hybrid buses, 500,000 electric three-wheelers, 55,000 electric four-wheeler passenger cars, and one million electric two-wheelers (FAME, 2023).

India: Standard Operating Procedure for Hydromet Services, 2021

Standard Operation Procedures (SOP) for Hydromet Services 2021 documents the details of rule-based tools and standardization of techniques, procedures, and methodologies for preparing river basin precipitation forecasts, flash flood guidance, and preparation of rainfall statistics. This document aims to improve these services with regards to accuracy, precision, timely preparation, and effective dissemination of the information to the various users and stakeholders for making informed decisions and timely action. It includes both conditions i.e., with or without the climate change impact on hydro-meteorological phenomena.

Pakistan: National Climate Change Policy, 2012

The main objectives of Pakistan's National Climate Change Policy 2012 (NCCP) include: i) to pursue sustained economic growth by appropriately addressing the challenges of climate change; ii) to integrate climate change policy with other inter-related national policies; iii) to focus on pro-poor gender sensitive adaptation; iv) to build climate-resilient infrastructure; v) to track the impact of climate change on water, food and energy security of the country, and to implement remedial plans to support water, energy and food policies; vi) to minimize the risks arising from the potential increase in frequency and intensity of extreme weather events such as floods, droughts and tropical storms; vii) to develop climate- resilient agriculture and food systems for all agro-ecological zones in the country; viii) to promote the country's transition to cleaner, lower emission, and less carbon-intensive development; ix) to accelerate the policy coherence and integration to achieve the United Nations' Sustainable Development Goals (SDGs) in the light of its Sustainable Development Report 2020 (SDR2020) and the Nationally Determined Contributions; x) to strengthen inter-ministerial and inter- provincial decision making and coordination mechanisms on climate change; xi) to facilitate effective use of the opportunities, particularly financial, available both nationally and internationally; xii) to foster the development of appropriate economic incentives to encourage public and private sector investment in adaptation and mitigation measures; xiii) to enhance the awareness, skill, and institutional capacity of relevant stakeholders and xiv) to promote tree plantation, conservation of natural resources, nature-based solutions and long-term sustainability (MOCC, 2021).

The policy identifies vulnerabilities to climate change in the sectors of water resources, agriculture, forestry, coastal areas, biodiversity, and vulnerable ecosystems and spells out the appropriate adaptation measures to be adopted. It also puts forward appropriate measures concerning disaster preparedness, capacity building, institutional strengthening, and technology transfer.

2. Other Countries

Japan: National Plan for Adaptation to the Impacts of Climate Change, 2015

The plan details 'basic adaptation directions' and 'measures' regarding agriculture, water environments and fisheries, other ecosystems, and economic activity (ENV (2021). The plan presented seven strategies regarding climate change adaptation: i) Incorporate climate change adaptation into every relevant policy, ii) Promote climate change adaptation based on scientific findings, iii) Consolidate the knowledge of research institutions in Japan and develop information platform, iv) Promote climate change adaptation according to the local background, v) Deepen public understanding and promote climate change adaptation corresponding to business activities, vi) Contribute to enhancing the adaptive capacity of developing countries and vii) Ensure a system for close collaboration among relevant administrative agencies. Some of the adaptation measures recommended in the plan are given below.

- Agriculture: Development and diffusion of high-temperature-resistant varieties of rice
- Farmland: Preventing farmland flooding by developing drainage pump stations and drainage canals to prepare for increasing torrential rainfalls
- Flood: Constructing reservoir for flood control downstream
- Drought: Increase the capacity of existing facilities, including dam heightening and excavating or dredging deposited sediments in reservoirs constructed for flood control
- Reservoir Operation: While taking into account factors such as each dam's water reserves and precipitation conditions, consider the potential for efficient dam operations, including the integrated use of multiple dams located in the same river basin.
- Non-conventional Source of Water Use: Use of rainwater and reclaimed wastewater

USA: 2021 Climate Adaptation and Resilience Plan

The United States Department of Energy (DOE)'s Climate Adaptation and Resilience Plan is guided by the following principles: (i) Protecting DOE assets from climate change impacts by assessing its vulnerabilities, taking action to adapt to the changing environment, and making resilience a cornerstone of operations to ensure DOE has climate-ready sites. (ii) Using the scientific expertise and world-class research and development capabilities of DOE's National Laboratories to demonstrate promising adaptation technologies at DOE sites. (iii) Partnering with local communities and sharing the benefits of DOE's climate adaptation, resilience, and energy and environmental justice initiatives and (iv) Leveraging DOE's purchasing power in collaboration with other Federal agencies to spur innovation, identify and reduce climate-related financial risk, enhance resilience, expand the market for U.S.-manufactured sustainable products and services, and promote well-paying union jobs on the path to a clean energy economy. Its priority adaptation actions are: (i) assessing vulnerabilities and implementing resilience solutions at DOE sites; (ii) enhancing climate adaptation and mitigation co-benefits at DOE sites; (iii) institutionalizing climate adaptation and resilience across DOE policies, directives, and processes; (iv) providing climate adaptation tools, technical support, and climate science information; and (v) advancing deployment of emerging climate resilient technologies. Implementation methods, challenges and risks, performance tracking, and coordination of each of these adaptation actions are given in the plan.

International Organizations

World Bank, 2020

In countries around the world, climate change poses a significant risk threatening the lives and livelihoods of people. These risks cannot be reduced to zero, which means governments must take decisive action to help firms and people manage them. Proactive and robust actions ahead of time can go a long way in helping people and communities so that when a natural disaster strikes, not only are they better prepared to respond, but hard-won development gains are not lost (Hallegatte et al., 2020).

Asian Development Bank, 2021

Nepal is heavily affected by disaster displacement, with 3.4 million displacements recorded during 2012–2021(iDMC, 2022). Climate change and low levels of human development increase the risk of disaster displacement. Information on people's vulnerability and exposure to hazards—including economic, social, environmental, and governance factors— can strengthen displacement risk analyses and support better prevention and preparedness. ADB strongly supports Nepal to mitigate the effects of disasters and climate change (Nepal and ADB, 2024).

IPCC, 2021

AR6 WGI assessed with high confidence the increase in the extreme precipitation and associated increase in the frequency and magnitude of river floods in the future. A global flood database based on in situ measurement and satellite remote-sensing during 1985–2015 show that floods have increased 4-fold and 2.5-fold in the tropics and northern mid-latitudes, respectively (Najibi and Devineni (2018) in IPCC (2021). Expected drought risk is higher for populated areas and intensive crop and livestock farming regions, such as southern and central Asia (IPCC, 2021).

International Organization for Standardization (ISO), 2022

ISO has been developing international standards that provide a high-level framework for adaptation along with supporting guidelines that are suitable for public, private, and community-level organizations (ISO, 2022). They are designed to help organizations prioritize and develop effective, efficient, and deliverable measures tailored to the specific climate change challenges that they face. ISO 14090, adaptation to climate change provides principles, requirements, and guidelines, which is the world's first international standard on climate adaptation. It focuses on integrating adaptation within or across organizations by helping to understand the impacts and uncertainties of climate change and how these can be used to inform decisions.

2.3.5 Lesson Learned

From the review of relevant documents on climate change mitigation measures, the following lessons have been learnt:

1. **Implementation and monitoring**: Having only good policies is not enough for climate change adaptation and impact mitigation. Implementation methods, challenges and risks, performance tracking, and coordination of each of these adaptation actions are equally important.
2. **Information generation and dissemination**: Effective strategies must rest on the best available data on the nature and severity of likely impacts over different timeframes in given locales, and the cost and efficacy of possible response measures.
3. **Capacity building**: An overriding priority is strengthening capacities in the technical and planning disciplines most relevant to understanding potential climate impacts and devising response strategies.
4. **Integration with Development**: Integrating adaptation programs across the full range of development is necessary.
5. **Technology**: As in climate mitigation, adaptation success depends in part on access to and, in some areas, the development of technologies suited to the specific needs and circumstances of different countries.
6. **Institutions**—While adaptation must be integrated across existing institutions, focal points are needed at the national and international levels to garner expertise, develop and coordinate comprehensive strategies, and advocate for broad-based planning and action.
7. **Climate Insurance**: Committing stable funding for an international response fund or to support insurance-type approaches covering climate-related losses and promoting proactive adaptation in vulnerable countries is necessary.
8. **Enhanced research**: It is imperative to address uncertainties related to climate change, floods, and drought through enhanced research on climate scenarios and the impacts of climate change on future floods and droughts.
9. **Proactive investment**: Proactive investment in information and communication systems is worthwhile to mitigate climate impacts.

2.4 Past Floods, Droughts Events and Associated Climate

2.4.1 General

Climate is the mean and variability of meteorological variables (temperature, humidity, atmospheric pressure, wind, and precipitation) over the considered time period. Among the various climatic variables, the most significant variables of a given region's climate are probably average temperature and precipitation (NGS, 2022).

Nepal is susceptible to rainfall events and the subsequent flooding and droughts. For example, the cloudburst of 14–17 June 2013 in the northwestern mountainous region near the Nepalese border killed around 5,700 people and affected more than 100,000, extensively damaging property in both Nepal and India (Karki, 2017). Similarly, the heavy rainfall event of 14–16 August 2014 caused massive flooding and triggered a number of landslides, resulting in huge losses of life and property, affecting around 35,000 households (ReliefWeb, 2014). The recent flood in the Kagbeni region of Mustang, which resulted from a heavy rain-induced landslide upstream on 13 August 2023, caused the loss of property, damaged private houses, government and non-governmental buildings, business houses, and other structures (29 swept away and 13 damaged) and destroyed crops in the area (The Himalaya, 2023; The Kathmandu Post, 2023). Similarly, the heavy rainfall, exceeding 200 mm in just 24 hours in some areas, occurred from September 26th to 28th, 2024, triggering floods and landslides across most parts of the country. The event caused 249 deaths, 178 injuries, and left 18 people missing. According to the preliminary loss and damage assessment report released by the National Disaster Risk Reduction and Management Authority under the Ministry of Home Affairs, the economic loss resulting from the disaster is nearly Rs. 50 billion (TKP, 2024). The report also indicated that 41 roads and highways, 26 hydropower facilities, and 1,678 federal and provincial water supply and sanitation systems were damaged. As per initial reports, 5,996 houses were destroyed, while 13,049 others were damaged.

Besides rainfall-induced floods, glacial lake outburst floods (GLOFs) and landslide outburst floods (LDOFs), which evolve into debris flows through erosion and sediment entrainment while propagating down a valley, also cause destructive damage downstream. For instance, the Bhote Koshi-Sun Koshi GLOFs in 1981 damaged the only road link to China and disrupted transportation for several months (ICIMOD, 2011). The Thame incident which occurred on August 16th, 2024, is another example of a GLOF that destroyed one school, one health post, five hotels, and seven houses.

Similarly, the LDOFs in the Seti River (2012) and Melamchi (2021) are among the most recent episodes. The Seti River flood killed more than 70 people in 2012, while the Kali Gandaki River buried 27 buildings in the Baseri landslide in 2015 (UNDRR, 2021)

2.4.2 Climate Zones of Nepal

There are six major climatic zones in Nepal: tropical, sub-tropical, temperate, sub-alpine, alpine, and tundra, from the southern Terai plain to the northern high and trans-Himalaya regions (Nayava, 1975; Thapa and Pradhan, 1995; Sharma, 1997; Poudel, 2021). Based on these literatures, these climate zones are briefly discussed below.

1. Tropical Climate

The tropical climate in Nepal is observed in the areas below 1,000 masl, i.e., in the Terai plains, most of the Siwalik hills, and lower elevation river valleys of hills and mountain regions. In this climatic zone, summer is very hot and mild to cool dry winter.

2. Sub-tropical Climate

The sub-tropical climate is mainly found in the areas situated between 1,000 masl and 2,000 masl. This climatic zone mostly covers the middle mountain physiographic region of the country. This region experiences warm summer and mild to cool winter.

3. Temperate Climate

The temperate climatic zone lies in between the sub-tropical zone in the south and the sub-alpine zone in the north whose altitude ranges from 2,000 masl to 3,000 masl. The upper part of the middle mountain and the lower part of the high mountain physiographic regions observe temperate climates. The climate is mild in these regions.

4. Sub-alpine Climate

The sub-alpine climatic zone lies within the high mountain physiographic region of the country. The altitude range of this climatic zone is between 3,000 masl and 4,000 masl. The weather in this region is cold with low summer temperatures and frosty winter. Snow falls in the winter months in this region.

5. Alpine Climate

The elevation range in which this climate exists is between 4,000 masl and 5,000 masl. The climate of this region is very cold. Some of the area of this region is covered by snow.

6. Tundra Climate

The regions above 5,000 masl have a Tundra climate. It is very cold. Most of the area of this region has perpetual snow and cold desert-like conditions.

2.4.3 Floods in Nepal and Associated Climate and Causes

The recent major floods of Nepal which are mainly associated to intense rainfall events are given in **Table 2-5** and are described briefly hereunder.

Table 2-5 Major flood events of Nepal and associated causes

SN	Date	Location	Flood Type	Cause	Remarks	Loss	Source
1	26th-28th September 2024	• Almost all over Nepal	Cloud burst flood	Heavy rainfall (e.g. Kathmandu Airport: 239.7 mm)	All over Nepal	**Human loss:** 249 deaths, 178 injuries, and left 18 people missing **Damage**: 41 roads and highways, 26 hydropower facilities, and 1,678 federal and provincial water supply and sanitation systems, 7 irrigation projects, 446 telecommunication units. 5,996 houses were destroyed, while 13,049 others were damaged.	TKP (2024) NDRRMA (2024)
2	27th – 30th June 2022 (Ashad 13-16, 2079)	• Terai region of Koshi, Lumbini, and Sudur pashchim Provinces • Mid-Hills of Lumbini and Gandaki Provinces • Chitwan	Flood (Riverine flood in small and medium sized rivers	Intense rainfall	Kandra Khola at Pahalmanpur of Kailai district surpassed the Warning Level	**Damage**: Bridge at Ichhakamana Rural Municipality, Chitwan	DHM (2022) DRR Portal
3	1st -7th August 2022 (Shrawan 16-22, 2079)	Sunsari Udayapur Saptari Sindhupalchwok	Flood	Heavy rainfall Embankment broken at Belaka Municipality	Saptakoshi river was close to the Warning Level	**Affected locations**: Ward Numbers 6 and 9 of Baraha Chhetra Municipality of Sunsari, Ward Numbers 2, 3, 8, and 9 of Belaka Municipality of Udayapur, 6 and 7 Wards of Saptakoshi and 1, 2, 4, 5 and 10 Wards of Kanchanpur Municipalities of Saptari **Damage**: Bridge at Helambu Rural Municipality	DHM (2022) DRR Portal
4	14th – 18th September 2022 (Bhadra 29-	Terai region of the Lumbini and Sudure Pashchim Provinces, and in	Flood	Heavy rainfall	The water level at Kusum of West Rapti and at Chepang of Babai Rivers had		DHM (2022)

Table 2-5 Major flood events of Nepal and associated causes

SN	Date	Location	Flood Type	Cause	Remarks	Loss	Source
	Ashoj 2, 2079)	some parts of the hilly region			crossed the danger level in this duration while the water level of Karnali River at Chisapani was also just below the danger level		
5	5th – 10th October 2022 (Ashoj 19-24, 2079)	Terai region of Lumbini, Karnali, and Sudar Pashchim Provinces	Flood	Heavy rainfall	Bheri, West Rapti, Babai, and Karnili rivers, the Budhigandaki rivers crossed the Danger. Kaligandaki river at Kumalgaun, Marshyandi river at Bimalnagar and East Rapti at Rajaiya had crossed the Warning Level.	**Affected locations**: a number of places in Lumbini, Karnali, and Sudar Pashchim were affected by floods	DHM (2022)
6	14th – 16th June 2021	Lamjung Sindupalchowk	Flood	Heavy rainfall + debris flow	Rainfall induced landslides and consequent flood	**Deaths**: dozens of people **Damage**: Dordi hydropower intake site Melamchi flood (given separately below)	DHM (2021)
7	28th June – 4th Julu 2021 (Ashar 14-20, 2078)	Eastern region of Nepal	Flood	Heavy rainfall	The water level of the Bagmati, Kamala, and East Rapti rivers crossed the Danger Levels		DHM (2021)
8	26th -31st Augutst 2021 (Bhadra 10-15, 2078)	Southern part of the Gandaki province and the eastern part of the Lumbini province	Flood	Heavy rainfall			DHM (2021)
9	15th June and the following day in 2021	Melamchi, Sindupalchowlk	Flood (Local level-4Melamchi flood)	Incessant rainfall and massive debris flow		**Deaths**: 5 people **Missing: 20 people** **Displaced HH**: over 500	Sharma et al. (2023

Table 2-5 Major flood events of Nepal and associated causes

SN	Date	Location	Flood Type	Cause	Remarks	Loss	Source
						Loss: Infrastructure (building of Melamchi Bazaar)	
10	14 August 2020	Lidi, Jugal Municipality, Sindhupalchowk	Flood (Local level)	Rainfall-induced landslides and flood	Both floods and landslides	**Deaths**: 19 people **Missing**: 20 people **Injured**: 5 people **Affected HH**: 38 **Damaged/buried**: 13 hoses completely damaged and approximately 5 homes buried from the landslide	CFE-DM (2020)
11	11 July 2019	Main affected districts: Parsa, Bara, Rautahat, Sarlahi, Dhanusa, and Mohattari (Total 32 districts of the country)	Flood (National level)	Heavy rainfall	Rainfall induced landslides and flood	**Deaths**: 61 people **Missing**: 29 people **Injured**: 19 people **Affected HH**: 751 **Crop Damage**: 50% of planted rice	Neksap (2019) CFE-DM (2020) FRA (2019)
12	27 August 2018	Saptari	Flood (Local level-Saptakoshi flood)		Overflooding Saptakoshi River	**Waterlogged**: - Land: Six wards of Hanumannagar Kankalini Municipality (ward no. 5, 6, 7, 9, 11 and 12) and two wards of Tilathi Koiladi Rural Municipality (ward no. 4 and 5) - **Infrastructure**: ~ 540 Houses	RSS (2018)
13	11-14 August 2017	Flooding across 35 of Nepal's 77 districts (almost all Terai districts)	Flood (National level)	Incessant and heavy rainfall	Rainfall from 11 August across the south of the Churia hills	**Deaths**: 159 people **Missing**: 29 people **Injured**: 45 people **Displaced**: 460,000 people **Damaged HH**: 186,293 **People Affected**: 1.7 million **Inundated land**: > 80% of land in the Terai region **Damaged and destroyed:**	CFE-DM (2020) Sharma et al. (2023 Relief (2017) UNFRC (2017)

Table 2-5 Major flood events of Nepal and associated causes

SN	Date	Location	Flood Type	Cause	Remarks	Loss	Source
						- Infrastructures (80 schools destroyed, and another 710 schools damaged, 10 health posts destroyed and 64 damaged) - Crop (64,000 ha of standing crops were destroyed.	
14	13th-15th August 2014	Banke, Bardiya, Dang and Surkhet	Flood (Regional level)	Incessant rainfall		**Death**: 96 people **Missing**: 115 people **Injured**: 32 people Affected HH: 33079 **Damage**: Some sections of Babai and Sikta irrigation canals Economic loss: 300 million rupees (Banke alone)	Banke (2071) Bardiya (207) Sharma et al. (2023)
15	16th June, 2013	Darchula	Flood (Local level -Darchula flood)	Incessant and intense rainfall		**Death**: 12 people **Damage/swept way**: Infrastructure (79 houses and shops, and 17 huts destroyed, 13 government offices, 1 bridge over the Mahakali River was swept and more than 200 km of road was damaged) **Loss**: 20 Ropani of land **Economic loss**: Rs1.27 billion	Darchula, (2070) Relief (2020)
16	5 May 2012	Seti river, near Pokhara	Flash flood (Local level - Seti flood)	Landslide near Machhapuchhre mountain in Kaski district		**Damage**: Physical infrastructures (road: 3 km, 4 bridges, and 25 electric poles, 20 houses). **Deaths**: 40 **Missing**: 32 **Economic loss**: Rs. 80 million	Kaski (2069) CFE-DM (2020)
17	18th August 2008	Sunsari and Saptari districts	Flood (Local level - Koshi Flood)	Eastern embankment of the Sapta Koshi River breached and more than 90% of its	Cultivated land of Shreepur, Haripur, and western Kushaha villages in Sunsari	**Damage**: then 3 VDCs completely destroyed 2 VDCs partially affected.	MoHA 2009) Kafle et al., 2017) ADB (2009

Table 2-5 Major flood events of Nepal and associated causes

SN	Date	Location	Flood Type	Cause	Remarks	Loss	Source
				discharge began flowing along the river abandoned 100-year-old course.	district are still barren and remain filled with flood sediment of sizes from clay to sand.	**Affected HH**: About 7,563 in Sunsari and Saptari districts. **Economic loss**: US$ 18.7 million **Reduced GDP**: ~0.3% in 2009	
18	19th and 20th July 1993	Mountain Areas: Taplejung, Pantcher Hilly Areas: Dhading, Makwanpur, Sindhuli, Kavre, Ramechhap, Okhaldhunga, Palpa Kathmandu Valley: (Kathmandu, Lalitpur & Bhaktapur) Terai Lowlands: Rautahat, Sarlahi, Chitwan, Dhanusa districts	Flood (National level)	Unprecedented high-intensity rainfall (~ 540 mm in less than 24 hrs in some areas)		• **Dead**: 347 • **Missing**: 445 • **Injured**: 70 • **Affected**: 1,500,000 people • Affected HH: about 70 thousand • **Damage/washed away**: -Kulekhani hydroelectricity power plant, - Bagmati barrage, roads, - Irrigation canal -Dam under construction at Manohari (Makawanpur) washed away	Pokharel et al. (2023) Reliefweb (1993) Sharma et al. (2023)
19	14 October, 2014	Annapurna and Dhaulagiri areas in Manang and Mustang districts	Climate (Local level)	Snow storm and subsequent avalanche	Severe cold	**Deaths**: 43 people **Missing**: > 50 **Injured**: 175	UNDP (2018)

i. Country Level Flood of June 27-30, 2022

The Terai region of Koshi, Lumbini, and Sudur-pashchim Provinces received heavy rainfall and had consequent floods in small rivers of this region during June 27-30, 2022. The Mid-Hills of Lumbini and Gandaki Provinces also observed high rainfall and floods in small and medium-sized rivers lying in these provinces during these days. The water level of the Kandra Khola at Pahalmanpur of Kailai district surpassed the Warning Level in this period (DHM, 2022).

ii. East and Central Region Flood of August 1-7, 2022 Flood

Heavy rainfall occurred in some parts of the Koshi, Bagmati, and Gandaki provinces during August 1-7 of 2022. During the whole day of the 2^{nd} of August, the flood level of the Saptakoshi River was close to the warning level. On the 3^{rd} of August, the river washed a section of the embankment at Belaka Municipality (Western side of the river) and entered the residential area. It affected Ward Numbers 6 and 9 of Baraha Chhetra Municipality of Sunsari, Ward Numbers 2, 3, 8, and 9 of Belaka Municipality of Udayapur, 6 and 7 Wards of Saptakoshi and 1, 2, 4, 5 and 10 Wards of Kanchanpur Municipalities of Saptari (DHM, 2022).

iii. Western Region Flood of September 14-18, 2022

During this period, heavy rainfall occurred in almost all of the Terai region of the Lumbini and Sudure Pashchim Provinces, and in some parts of the hilly region. The water level at Kusum of West Rapti and at Chepang of Babai Rivers had crossed the danger level during this time while the water level of Karnali River at Chisapani was also just below the danger level (DHM, 2022).

iv. Central and Western Region Flood of October 5-10, 2022 Flood

From October 5-10 2022, a number of places in Lumbini, Karnali, and Sudar-pashchim were affected by floods because of the heavy rain. Rivers of these regions crossed their respective danger levels, i.e., by Bheri, West Rapti, Babai, and Karnili rivers. Similarly, heavy rainfall occurred in some parts of Bagmati and Gandaki provinces too. During this period, the Budhigandaki river at Arughat had crossed the danger level while the Kaligandaki river at Kumalgaun, Marshyandi river at Bimalnagar, and East Rapti at Rajaiya crossed the warning level. Seti at Dipayal and Mahakali at Parigaun also had high floods, almost close to the warning level. Due to these floods, many villages close to rivers were inundated and claimed more than 50 people’s lives (DHM, 2022).

v. Central and Western Region Flood of June 14-16, 2021

During June 14-16 of 2021, heavy rainfall occurred in almost all parts of the Gandaki Province and some parts of the Siwalik and Terai areas of Lumbini and Sudurpashchim provinces. Devghat of Gandaki River observed the highest water level of the year on June 15. Melamchi Bazar was devasted in this period because of the debris flow that entered the Bazar area. The Dordi incident in the Lamjung district also occurred during this period killing a dozen people working in the hydropower intake site (DHM, 2021).

vi. Eastern Region Flood of June 28 -July 4, 2021

Heavy rainfall and consequent floods occurred in the eastern region of Nepal during this period. However, heavy rainfall was observed not only in Koshi province but also in Gandaki, Bagmati, and Madhesh provinces. The water level of the Bagmati, Kamala, and East Rapti rivers crossed the danger levels at their respective gauging sites (DHM, 2021).

vii. National Level Flood of August 26-31, 2021

In this period, the southern part of the Gandaki province and the eastern part of the Lumbini province received very high rainfall. Almost all parts of Koshi, Madhesh, and Bagmati provinces and the remaining part of the Lumbini province experienced medium to high rainfall causing high floods in Koshi, Karnali, and Mahakali Rivers (DHM, 2021).

viii. Banke-Bardiya Flood of August 13-15, 2014 (Shrawan 28-30, 2071 BS)

On the 13th and 14th of August 2014, Banke was devasted by floods that occurred in the West Rapti River on the eastern side and Man Khola on the eastern side of the district, and in small streams within the district (Banke, 2071). It is mainly caused by the rainfall of very high intensity for these two days. All of the then 44 Village Development Committees and 2 Municipalities were under flood in these two days. In Bardiya districts the high rainfall, that occurred from the 13th to 15th of August 2014, caused floods in Karnali, Babai, Geruwa, Bhada, and Man Khola. The flood water entered the district and inundated it (Bardiya, 2071). Floods that occurred in these two districts took more than 65 human lives and affected more than 200 thousand people. The estimated infrastructure loss in Banke district alone is more than 300 million rupees (Bardiya, 2071).

ix. Darchula Flood, June 16, 2013 (Ashad 2, 2070)

Rainfall started from 15th June 2013 in the Mahakali River Basin. A big flood occurred due to this heavy rainfall on the 16th of June. It destroyed 79 houses and shops, and 17 huts located close to the river bank. Thirteen government offices were swept away by this flood. The flood did bank cutting and about 20 Ropani of land were lost because of this flood. One bridge over the Mahakali River was swept and more than 200 km of road was damaged. One person was missing in this flood (Darchula, 2070).

x. Bajura Flood, May 31, 2012 (Jestha 18, 2069)

Heavy rain on 31st May 2012 produced debris flow which destroyed and damaged 15 houses completely and 26 houses partially. Five people died and three were injured by this flood (Bajura, 2069).

xi. Seti Flood, May 5, 2012 (Baisakh 23, 2069)

On 5th May 2012, a flood occurred in the Seti River, near Pokhara, and caused a lot of damage to the physical infrastructure (road: 3 km, 4 bridges, and 25 electric poles). The total number of human deaths and missing are 40 and 32 respectively. An estimated economic loss incurred by this flood is more than NRs. 80 million (Kaski, 2069).

xii. Koshi Flood, August 18, 2008 (Bhadra 2, 2065)

On 18th August 2008, the Koshi River diverted to its 100-year-old course towards the eastern side by breaking its embankment with 90% flow of water to the settlements and agricultural land (MoHA 2009). The flood completely destroyed three Village Development Committees (VDC) whereas two VDCs were partially affected (Kafle et al., 2017). About 7,563 households in Sunsari and Saptari districts were affected by this flood event with one death. It was calculated that 25% of the affected cultivated land of Shreepur, Haripur, and western Kushaha villages in Sunsari district are still barren and remain filled with flood sediment of sizes from clay to sand. The economic loss incurred by the loss of the existing crops estimated at US$18.7 million reduced the National Gross Domestic Product (GDP) by 0.3% in 2009 (ADB, 2009).

xiii. Bagmati Flood 1993

In the Bagmati River Basin, the greatest single rainfall event was recorded at Tistung on 20 July 1993 where 540 mm of rain fell over a 24-hour period with an intensity as high as 65 mm/hr (Gautam and Pokhrel, 2004, Dhital and Kayastha, 2013). The corresponding peak discharge of the Bagmati River was 16,000 m^3/s on 21 July 1993 at the Pandheradobhan discharge station. This flood washed away/damaged the Kulekhani hydroelectricity power plant, Bagmati barrage and roads, and irrigation canals. A dam under construction at Manohari (Makawanpur) was also washed away. In this flood disaster, 347 people lost their lives while missing and injured number of people are 445 and 70 respectively. The total affected population from this event were around 1.5 million. Property loss was about 5 billion Nepalese rupees.

2.4.4 Glacial Lake Outburst Flood and Associated Causes

Glacial Lake Outburst Flood (GLOF) refers to the sudden release of stored glacial lake water. Due to the large volumes of water rapidly released, floods can breach existing river channels. It generally results in devastating socio-economic consequences downstream, including loss of life, buildings, bridges, transportation routes, arable land, and hydropower systems (Horstmann, 2004; Rounce, 2017; Bajracharya et al., 2020). GLOF can happen because of the entering of an avalanche into the lake, displacement waves from rockfalls, moraine failure due to dam settlement or piping, degradation of the ice-cored moraine, seismic activity, or rapid input of water from extreme events or from an outburst flood from glacial lakes located upstream. The unpredicted nature of the GLOF and their remote locations make it difficult to determine the exact trigger and the cause of its failure, quantification of the threat posed by such floods is necessary to minimize its potential damage downstream (Bajracharya et al., 2020). A list of the 10 largest GLOFs that occurred worldwide is given in **Table 2-6**. It can be seen from the table that 3 out of the 10 largest GLOF events occurred in Nepal, which shows Nepal as a potentially disaster-prone country in the world in terms of GLOF as well.

Table 2-6 Ten largest GLOF events of the world

SN	Location	Data	Country	Remarks
1	Dudh Koshi (Nare Lake)	September 3, 1977	**Nepal**	The cause behind this critical event was the collapse of a moraine dam 400 thousand cubic meters of water released from the Nare Lake Peak discharge of the water, roughly 800 m^3/s
2	Dudh Koshi (DigTsho)	August 4, 1985	**Nepal**	About 6-10 million m^3 of water drained from the lake within four hours. The water discharge had reached roughly 500 m^3/s
3	The Lugge Tsho GLOF	October 7, 1994	Bhutan	Upper part of the Pho Chuu, covering the eastern tributary
4	Glacial-dammed Lake 3 Outburst Flood	Around 1968	Switzerland	The glacial flood outburst massively eroded roughly 400,000 m^3 of debris.
5	Nanda Devi GLOF,	February 7, 2021	India	Catastrophic flash flood in Sumna village of Chamoli Garhwal district, near the India-China border of Uttarakhand, India
6	Lemthang Tsho GLOF	July 28, 2015	Bhutan	Gasa district of the north-western part of Bhutan
7	Ghulkin GLOF	2008	Pakistan	Cause of this event was the moraine collapse
8	Jinwuco GLOF	June 26, 2020	China	Eastern Nyainqentanglha, Jinwuco of Tibet
9	Upper Barun Valley	April 20, 2017	**Nepal**	Makalu-Barun National Park The debris accumulation dammed the floodwaters and reached the Barun Bazaar village
10	Gay	August 6, 2014	India	Cause of GLOF: ice cores thawing in the moraine

Source: Modified from Ghimire (2022)

About 450 years ago, the outburst of Machhapuchhre Lake resulted in a flood that covered Pokhara Valley with 50–60 m deep debris (ICIMOD, 2011). There have been at least 26 major glacial lake outburst floods (GLOF) events in Nepal that we know of, most having occurred since the 1960s (Nepal Times, 2020). However, a 2011 study by ICIMOD reported 24 GLOF events in the past, 14 of which had occurred in Nepal, while 10 were caused by overspills due to flood surges across the China (TAR)–Nepal border (Bajracharya et al., 2020). Some of the major GLOF events that happened due to the outburst of glacial lakes lying in Nepal with date of occurrences, associated main causes, and the losses imparted by them are given in **Table 2-7.**

Table 2-7 GLOF events and associated causes in Nepal

SN	Date	River basin	Location	Causes	Losses	Source
1	450 years ago	Seti Khola	Machhapuchchhre Lake	Moraine collapse	• Pokhara valley covered by 50-60m deep debris	ICIMOD (2011)
2	1921	Tamor River	Ghunsa, Lhonak Lake		• Destroyed all of farm lands • Loss of at least 1 life	Byers et al. (2020)
3	1956	Indrawati			• 40 thousand families of Indrawati Valley homeless	(Muller (1959) cited in Kattelmann, (2003)
4	1963	Tamor River	Olangchun Gola, Tiptola Lake	Moraine collapse (due to icefall from Chhochenphu Himal)	• Loss of nearly half of the houses of Olangchun Gola village	Byers et al. (2020)
5	1968	Tamor River	Olangchun Gola, Tiptola Lake	Moraine collapse (due to icefall from Chhochenphu Himal)	-	Byers et al. (2020)
6	3 Sep 1977	Dudh Koshi	Nare Lake	Moraine collapse	• Loss of 2 or 3 lives • Destruction of all the bridges up to 35 km downstream • Debris flows	ICIMOD (2011)
7	23 June 1980	Tamor	Nagma Pokhari	Moraine collapse	• Destruction: 4 bridges, • Loss of 10 human lives	ICIMOD (2011) Bajracharya et al. (2020) Byers et al. (2020)

Table 2-7 GLOF events and associated causes in Nepal

SN	Date	River basin	Location	Causes	Losses	Source
				• Destruction of villages as far as 71 km downstream of the source		
8	11 July 1981	Bhote Koshi	Cirenmacho Lake Zhangzangbo Valley	Ice Avalanche	• Damage to Sun Koshi hydropower project • Damage 2 bridges including Friendship bridge between Nepal and China • Extensive damages to various sections of the Arniko Highway • Economic loss: ~ US$ 3.0 million	ICIMOD (2011) Bajracharya et al. (2020) Mool (2001)
9	4 August 1985	Dudh Koshi	Dig Tsho	Ice avalanche	• Loss of 4 or 5 lives • Namche Small Hydel facility located 11 km from the breach • 14 bridges • Destruction of long sections of the main trekking route to the Mt Everest base camp	ICIMOD (2011) Bajracharya et al. (2020)

Table 2-7 GLOF events and associated causes in Nepal

SN	Date	River basin	Location	Causes	Losses	Source
				• Economic loss: US$ 1.5 million		
10	12 July 1991	Tama Koshi	Chubung	Moraine collapse	• Destruction of some houses • Damage to some farmland	ICIMOD (2011) Bajracharya et al. (2020)
11	3 September 1998	Dudh Koshi	Sabai Tsho (Tam Pokhari)	Ice avalanche	• Human lives • More than Rs 156 million	ICIMOD (2011) Bajracharya et al. (2020)
12	15 August 2003	Madi	Kabache Lake	Moraine collapse	Not known	ICIMOD (2011) Bajracharya et al. (2020)
13	8 August 2004	Madi	Kabache Lake	Moraine collapse	Not known	ICIMOD (2011) Bajracharya et al. (2020)
14	5 July 2016	Bhote Koshi	TAR-China (Gongbatongshacuo Lake in Tibet)	Moraine collapse	• Swept: 20 concrete houses, a boarding school and parts of a customs office • Damages: dozens more buildings, large stretches of roads, a hydropower plant Economic damages: about $70 million.	Bajracharya et al. (2020) Davis et al. (2021)

Table 2-7 GLOF events and associated causes in Nepal

SN	Date	River basin	Location	Causes	Losses	Source
15	20 April 2017	Barun Valley	Near Lower Barun	Rockfall to the unnamed glacier above Langmale glacial lake and	• Yangle Kharka (pasture land) was covered by debris	Bajracharya et al. (2020) Byers et al. (2018) Carpenter et al. (2017)
16	Uknown	Arun	Barun Khola Lake	Moraine		ICIMOD (2011)
17	Uknown	Arun	Barun Khola Lake	Moraine		ICIMOD (2011)
18	Uknown	Dudhkoshi	Chokarma Cho Lake	Moraine		ICIMOD (2011)
19	Uknown	Kaligandaki	Unnamed (Mustang)	Moraine		ICIMOD (2011)
20	Uknown	Kaligandaki	Unnamed (Mustang)	Moraine		ICIMOD (2011)
21	Uknown	Mugu Karnali	Unnamed (Mugu Karnali)	Moraine		ICIMOD (2011)
22	Aug 1935	Sun Koshi	Tara-Cho	Piping	66,700 sq.m of wheat fields livestock etc.	ICIMOD (2011)
23	25 Aug 1964	Trishuli	Longda	Not known	Not known	ICIMOD (2011)
24	21 Sep 1964	Arun	Gelhaipuco	Glacier surge	Highway and 12 trucks	ICIMOD (2011)
25	1964	Sun Koshi	Zhangzangbo	Piping	No remarkable damage	ICIMOD (2011)
26	1968	Arun	Ayaco	Not known	Road bridges etc.	ICIMOD (2011)
27	1969	Arun	Ayaco	Not known	Not known	ICIMOD (2011)
28	1970	Arun	Ayaco	Not known	Not known	ICIMOD (2011)
29	11 Jul 1981	Sun Koshi	Zhangzangbo	Ice Avalanche	Hydropower station	ICIMOD (2011)
30	27 Aug 1982	Arun	Jinco	Glacier surge	Livestock farmland	ICIMOD (2011)
31	6 Jun 1995	Trishuli	Zanaco	Not known	Not known	ICIMOD (2011)
32	16 Aug 2024	Thame	Thyanbo lake	Lake outburst	Destruction: One school, one health post, five hotels and seven houses	ICIMOD (2024)

2.4.5 Landslide Dam Outburst Flood and Associated Causes

Landslide dam outburst floods (LDOFs) are common in Nepal's high, steep, and fragile mountains with their deep and narrow gorges. For example, in September 1988, a big flood occurred in the Darban region of the Myagdi river killing 109 people. The LDOF in the Seti River (2012) and the LDOF in the Melamchi (June 15, 2021) are two most recent episodes. The Seti River flood killed more than 70 people in 2012 while the Kali Gandaki River buried 27 buildings in the Baseri landslide in 2015.

The risk of a landslide is high in the monsoon season due to the lubrication of soil in the slope by moisture. Another important factor triggering the landslide is earthquakes. When a landslide occurs near the river, it can block the river causing a damming effect. The water impounded by a landslide dam may create a reservoir (lake) that may last for a short time to several thousand years. Such dams are unstable and can cause flooding, if not breached in a controlled manner. Locations of major LDOF events are shown in **Figure 2-1**.

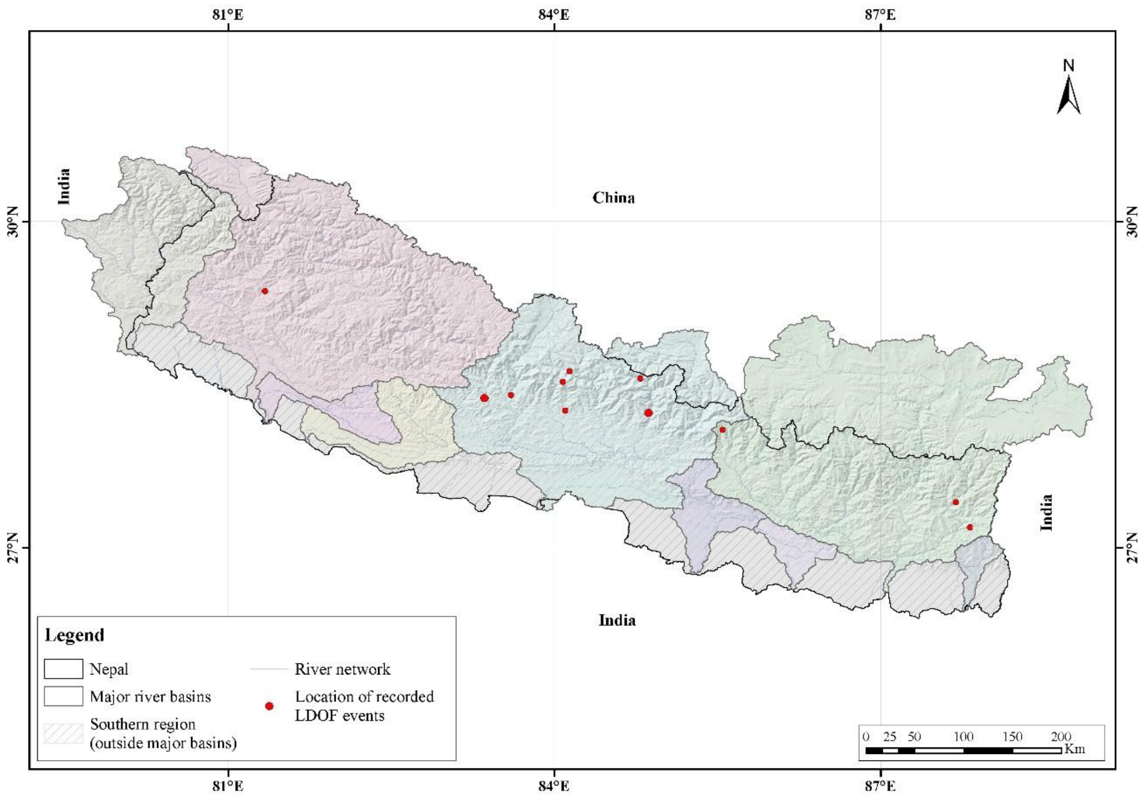


Figure 2-1 LDOF locations in Nepal

Some of the major LDOF events that occurred, their date of occurrence, locations, associated causes, and the losses imparted by them in Nepal are listed in **Table 2-8.**

Table 2-8 LDOF events and associated causes in Nepal

SN	Date	Location	Cause	Loss	River/District	Source
1	16th and 17th June 2023	Chainpur -4		**Hewa loss:** **Deaths**: 4 **Missing**: 15 **Loss**: Infrastructure (Rs. 800 million) Others **Damage**: - 30 hydropower projects of 463 MW in total capacity. - 13 operating projects with 132 MW **Economic loss**: ~ Rs 6 billion	Hewa Khola/Sankhuwasabha Also Taplejung, Panchthar, Sankhuwasabha and Bhojpur districts	Spotlight (2023 myRepublica (2023)
2	15th June and following day in 2021	Chokpu/Helambu Melamchi	Incessant rainfall caused landslides and massive debris flow	**Deaths**: 5 people **Missing: 20 people** **Displaced HH**: over 500 **Loss**: Infrastructure (building of Melamchi Bazaar) **Buried**: Headworks of Melamchi Drinking Water Project	Melamchi River Sindupalchowlk	Sharma et al. (2023) DHM (2021) Petley *(2021)*
3	20th April 2017	Syakshila Gola of Bhot Khola rural municipality	Flood in the Barun river has blocked the Arun River at their confluence	**Affected HH**: 54	Arun/Sankhuwasabha	ReportersNepal (2017)
4	10th July 2016	Sawadin/near Mitlung	Massive rockfall from the Nakla cliff, boulders blocked the river	**Buried**: 2 houses **Died**: some cattle	Tamor/Taplejung	The Kathmandu Post (2016)
5	13th March 2015	Langtang Valley/ Manaslu region			Tom Khola/Gorkha	NASA (2015)
6	23rd May 2015	Baseri/Ramche village	Heavy rainfall triggered landslides	**Affected**: 125 people **Damage:** -30 houses -2 km road from Beni to Jomsom **Operation Halted:** Kali Gandaki Hydro project	Kali Gandaki/Myagdi	Bhusal (2015) Davis (2015) Kathmandu Post (2015)

Table 2-8 LDOF events and associated causes in Nepal

SN	Date	Location	Cause	Loss	River/District	Source
7	25th April 2015	Gogane		**Observation**: Rockslides observed at the Marshyangdi Hydropower Project dam site	Marsyangdi River	Sunuwar (2018) Hashash et al. (2015)
8	2nd August 2014	Jure	Landslides induced dam	**Deaths**: 155 people **Complete damage**: ~120 houses **Partial damage**: 37 houses	Sunkoshi /Sindhupalchowk	Jaboyedoff (2015)
9	5th May 2012	About 25 km from Pokhara	Landslide near Machhapuchhre mountain in Kaski district	**Damage**: Physical infrastructures (road: 3 km, 4 bridges, and 25 electric poles, 20 houses). **Deaths**: 40 **Missing**: 32 **Economic loss**: Rs. 80 million	Seti /Kaski	Kaski (2069) CFE-DM (2020)
10	3rd October 2010	Sildjure/ Thumkodanda-9		**Deaths**: 4 **Inundation**: Irrigated paddy fields about 50 m east of the riverbank **Damage**: Suspension bridge	Madi River/Kaski	Khanal et al. (2013)
11	1988	Niskot Hill		**Deaths**: 109 people; **Injured**: 8 people **Damage**: 94 houses & 44 animals buried	Myagdi Khola/Myagdi	ICIMOD (2024) (Yagi et al. 1990)
	August 1985	About 5 km south of Duche	Heavy rainstorm triggered landslides		Trishuli River/	
12	2nd August 1968	Tarebhir/Labubensi		**Swept away**: One bridge and 24 houses at Arugahat	Budhi Gandaki/Gorkha	ICIMOD (2024)
13	1967	Tarebhir/Kashigaon		**Deaths**: No casualty by flood but the landslide killed 9 people	Budhi Gandaki/Gorkha	Villanueva et al. (2016) ICIMOD (2024)
14	21st April 2024	Birendra Lake Chun-Numbri	Spilling of lake water due to massive snowcapped landslide falling in the lake	A bridge swept away	Budhigandaki/ Gorkha	Online Khabar (2024)

2.4.6 Droughts and Associated Climate

1. General

Drought is a prolonged dry period within the natural climate cycle, characterized as a slow-onset disaster due to the lack of precipitation. Droughts occur in virtually all climatic zones, including areas with both high and low rainfall, and are primarily related to a sustained reduction in precipitation over an extended period. Such extreme dryness (drought) negatively impacts the yield of both cash and cereal crops (Revadekar and Preethi, 2012), thereby affecting the livelihood of approximately 60% of the Nepalese population who are directly dependent on agriculture (CBS, 2013). This impact is due to water shortages that prevent crops from meeting their water requirements for achieving full production potential. One of the worst winter droughts in the country, occurring in 2008/2009, reduced wheat and barley yields by 14% and 17%, respectively, leading to severe food shortages in 66% of rural households in the worst-hit far- and mid-western hill and mountain regions (MOACC, 2009). Drought also reduces water availability in reservoirs and rivers, which subsequently results in decreased hydropower generation.

2. Droughts Events and Associate Climate

A study by Sharma, et al. (2021) found that droughts have become more frequent in Nepal since 2000; escalating their severity and duration. The average length and severity of the short-term drought in Nepal were 2.8 months and 4.3, respectively while the long-term drought's length and severity were 8.6 months and 13.9, respectively.

The average frequency for the Standarized Precipitation Index (SPI) of 1-, 3-, 6- and 12-months of drought years for summer maize (winter wheat) in the western, central, and eastern regions increased by 13% (12.5%), 6% (7.5%) and 7% (8%) respectively from 1987–2000 period to 2001–2017 period (Hamal, et al., 2020).

The winter droughts of 2008–2009 had a significant negative impact on local agriculture and food security. Most monitoring stations recorded rainfall that was less than 50% of the normal values, 30% recorded no precipitation at all, and temperatures that were 1-2° C above average during that time, with a significant decrease in crop production (Dixit, 2010). The major drought events were observed during the periods 1982–1983, 1992–1993, 1994–1995, 2005–2006, 2008–2009, 2011–2012, 2013, and 2015, indicating increased drought events in recent decades (Bagale et al., 2021).

The Koshi basin of Nepal exhibited an increase in the frequency and severity of weather extremes (Shrestha et al., 2017; Khatiwada and Pandey, 2019). During the period from 1981 to 2012, the summers of 2004, 2005, 2006, 2009, and the winters of 2006, 2008, and 2009 were the worst seasons for widespread drought in the Gandaki basin (Dahal et al., 2016). Khatiwada and Pandey (2019), in their study, used the drought indices SPEI, Reconnaissance Drought Index (RDI), Self-calibrated Drought Index (Sc-PDSI), Standardrized Streamflow Index (SSI), and Palmer Hydrological Drought Index (PHDI) to assess the status of drought in the Karnali basin using the historical climate data of 1981-2014. Major drought events occurred in this basin in the recent years are: 1984–85, 1987–88, 1992–93, 1994–95, 2004–09, and 2012. They found that the winter droughts of 1999, 2006, and 2008–09 were widespread and the frequency of monsoon droughts was found increasing. Bista et al., (2020) used MODIS NDVI (MOD13) and MODIS ET-PET (MOD16) datasets to monitor and analyze the trend and pattern of agricultural drought scenarios based on the Drought Severity Index, in the Karnali and Sudurpaschim Provinces of Nepal. From an ecological perspective, hilly regions had the worst drought conditions compared to other regions of this study area.

Wang et al. (2013) used instrumental records, satellite measurements, and climate model simulations to examine the climatic circumstances and a historical perspective of the winter droughts in western Nepal. Their findings concluded that the Arctic Oscillation and its decadal variability are linked to the winter drought in western Nepal. Additionally, the persistent warming of the Indian Ocean is likely a factor in the suppression of rainfall through enhanced local Hadley circulation. In their study, the precipitation was also anticipated to decrease during the coming decades, according to simulations from the CMIP5 era and it is likely that both anthropogenic impacts and natural variability are contributing factors to the recent decadal droughts in Nepal (Wang et al., 2013).

Table 2-9 shows the drought years identified through various previous studies. Drought is one of the utmost imperative stress situation causing vast impression on growth and development of crop, thus affecting its productivity negatively (Iqbal et al (2020). In Nepal, the impact of drought on major crop production varies by year. The impact of drought on agricultural production is shown in **Table 2-10**.

Table 2-9 Identified drought years by past studies

Study	**Sigdel and Ikeda (2010)**			**Kafle (2015)**	**Dahal et al. (2016)**		**Adhikari (2018)**	**Khatiwada & Pandey (2019)**	**Bagale et al. (2021)**	
Duration	**(2071-2003)**			**(1982-2012)**	**(1981-2012)**		**(1972-2015)**	**(1981-2014)**	**(1977-2018)**	
Year	**Annual**	**Winter**	**Summer**		**Winter**	**Summer**	**Various Season**	**Annual**	**Annual**	**Summer**
1980										
1981	▨									
1982	▨		▨				▨			▨
1983										
1984								▨		
1985		▨						▨		
1986							▨			
1987								▨		
1988								▨		
1989										
1990										
1991			▨							
1992	▨		▨	▨			▨	▨	▨	▨
1993		▨						▨		
1994				▨			▨	▨	▨	
1995	▨							▨		
1996										
1997							▨			
1998										
1999		▨		▨						
2000										
2001	▨	▨								
2002							▨			

Study	**Sigdel and Ikeda (2010)**			**Kafle (2015)**	**Dahal et al. (2016)**		**Adhikari (2018)**	**Khatiwada & Pandey (2019)**	**Bagale et al. (2021)**	
Duration	**(2071-2003)**			**(1982-2012)**	**(1981-2012)**		**(1972-2015)**	**(1981-2014)**	**(1977-2018)**	
Year	**Annual**	**Winter**	**Summer**		**Winter**	**Summer**	**Various Season**	**Annual**	**Annual**	**Summer**
2003										
2004						▨		▨		
2005						▨		▨	▨	▨
2006				▨	▨	▨		▨	▨	▨
2007								▨		
2008					▨		▨	▨		
2009					▨	▨	▨	▨	▨	▨
2010				▨						
2011										
2012							▨	▨	▨	
2013							▨			
2014										
2015							▨		▨	▨
2016										
2017										
2018									▨	
Indices Used	SPI 12	SPI3	SPI3	RDI12	SPI3	SPI4		SPI3&SPI4	SPI12	SPI4
Areal Extent	Nepal			Far & Mid-Western Region	Central Nepal		Taken from Joshi (2018)	Karnali	Nepal	

Note: Hatched cells denote the drought years and non-hatched cells denote non-drought years

Table 2-10 Impact of drought on production of major crops in different years in Nepal

SN	Drought Year	Causes of Drought	Major Crop Loss (in Metric Ton)	Affected Regions
1	1982	**Late onset** of rainfall	727,460	Eastern
2	1986	Poor distribution of rainfall during August and September	377,410	Western
3	1992	**Late onset** of rainfall	917,260	Eastern
4	1994	Poor distribution of rainfall	595,976	**All regions**
5	1997	Poor distribution of rainfall	69,790	Eastern
6	2002	Poor distribution of rainfall	83,965	Eastern and Central
7	2008	Poor distribution of rainfall during November 2008 to February 2009	56,926	**All regions**
8	2009	**Late onset** of monsoon	499,870	Eastern and Central
9	2012	Long dry spell	797,629	Eastern and Central
10	2013	Inadequate rainfall that affected rice plantation	56,000	Eastern and Central Terai districts
11	2015	**Delayed monsoon** and weak at the onset, which delayed paddy transplantation	Not available	Eastern Terai
12	Mid-November 2015 to Mid-March 2016	Poor monsoon and drought	300,000 people highly insecure	Mid- and Far-Western hills and mountains

Source: Joshi (2018) cited in Adhikari (2018)

1. Late onset of monsoon (1982, 1992, 2009 and 2015)

The average onset of monsoon is 13th of June. The onset of monsoon of each year from 1980 to 2022 and the average day of its onset are shown in **Figure 2-2.** The onset is late by 14, 8 and 10 days in 1982, 1992 and 2009 as given in the above table. However, the delay of monsoon is not seen for the year 2015 as stated in previous literature and presented in the table.

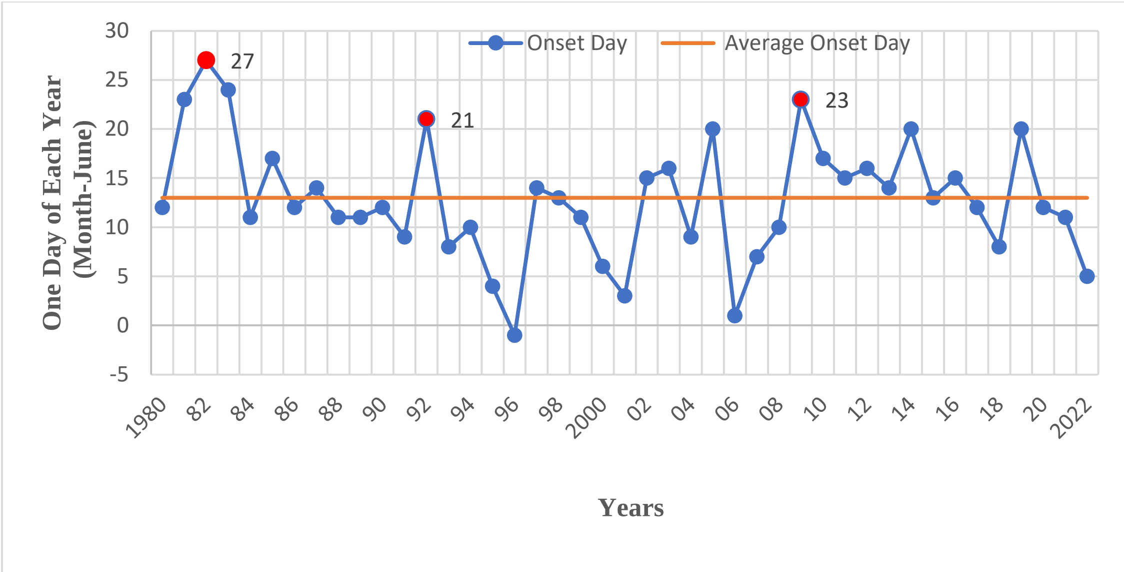


Figure 2-2 Onset of monsoon in Nepal

2. Poor rainfall:

The average rainfall for November, December, January, February, and March in Nepal from 1980 to 2022 (based on data from 179 stations used in this study—Chapter 3) was 7.8, 12.3, 20.7, 27.7, and 33.5 mm, respectively.

November 2008 – February 2009: Rainfall levels in November and December 2008 and January and February 2009 were significantly lower than the annual averages, measuring 2.5, 2.3, 1.3, and 6.1 mm, respectively.

November 2015 – March 2016: Rainfall in November and December 2015 and January, February, and March 2016 was 3.8, 0.3, 10.1, 9.4, and 32.8 mm, respectively. Except for March, rainfall during this period was also notably low compared to the annual averages.

2.4.7 Identified Major Causes of Past Floods and Droughts

Most of the hills and mountains within the river basins of Nepal are south facing forming barriers to the monsoon clouds traveling from the Bay of Bengal. Flash floods occur primarily in hilly or mountainous areas due to prevailing convective rainfall mechanisms, thin soils, and high river gradients. Due to this gradient change, the river flows at very high velocities in the uplands and possesses a high capacity to transport sediments downstream. When the river enters the Terai, velocity of flow slows down due to the gentle gradient, and the material being transported gets deposited. Because such deposition increases the level of the riverbed, consequently increasing the probability of flooding. Debris flows and landslides occasionally occur in the catchment area as well which also intensifies flooding. Due to temperature rises in recent years, the retreating of glacial lakes has also been increased. With this backdrop, the major conclusions that can be drawn from the literature review of the past events of floods and drought are:

1. Major floods in Nepal occur in the monsoon season, especially in July and August.
2. The major cause of flood and drought in Nepal is uneven temporal distribution of precipitation. In addition to intense rainfall, high gradient in the hilly and mountain regions, and low gradient in the Terai region, fragile geology are also cause of floods in Nepal.
3. GLOF is due to an increase in temperature in recent years and the breaching of glacial lakes.
4. LDOF is due to the combined effects of rainfall and the blocking of rivers by landslides.
5. Floods are causing a huge loss of properties and lives in the country
6. The major causes identified for the drought are late onsets of monsoon, poor distribution of rainfall, and reduced amount of rainfall.
7. Climate change is expected to enhance these extreme events.

2.5 Institutions Responsible for Flood and Drought Management

Drought is a disaster equally important as flood. However, drought has not got equal footing as other disasters like flood, landslide, earthquake, etc. There is no separate institutional mechanism for flood and drought management in the country. Their management, mainly flood management, also falls under the jurisdiction of disaster management institutions. Key national institutions responsible for flood and drought management are presented in **Table 2-11**.

Table 2-11 Key national institutions responsible for disaster management

Policy and Strategy	Planning	Implementation	
		Pre-disaster	**Post-disaster**
• Office of the Prime Minister and Council of Ministers • Ministry of Home Affairs (MoHA) • Water and Energy Commission Secretariat (WECS) • National Council for Disaster Risk Reduction and Management	• National Planning Commission (NPC) • Ministry of Home Affairs (MoHA) • National Disaster Risk Reduction and Management Authority (NDRRMA) • Ministry of Federal Affairs and General Administration (MoFAGA) • Department of Water Resources and Irrigation	• MoHA • National Emergency Operation Centre (NEOC) • Department of Hydrology and Meteorology (DHM)	• NEOC • Provincial Emergency Operation Centers (EOC) under Provincial Disaster Management Committee (PDMC) • District EOC under District Disaster Management Committee (DDMC) • Local Emergency Operation Centre (LEOC) • Local Governments • Security Forces (Nepal Army, Armed Police Force and Nepal Police)

Until now, the Ministry of Home Affairs (MoHA) has held the sole responsibility for implementing disaster management activities, while other ministries have had limited roles. This imbalance risks creating incoherence among ministries both horizontally and vertically. In this context, policy formulation and institutional set-up alone cannot achieve the desired outcomes unless they are complemented by the capability and competence to operationalize the intent of relevant acts and policies—namely, preparing for, responding to, rehabilitating, and mitigating the effects of disasters. Institutional mechanisms for managing flood disasters, particularly during the monsoon season, are relatively strong. However, the institutional framework for developing and implementing plans and policies for drought management remains insufficient.

CHAPTER 3: ASSESSMENT AND PREPARATION OF DATA

The main objective of the study is to assess the two-opposite hydro-climatic extremes: floods and droughts of the country and to see the level of association of these events to the climate. Preparation of flood and drought inventories is another major task of the study. Assessment of the impact of probable future climate on these extremes is the third important assignment of this study. The data required for these tasks can be broadly divided into two types: temporal and spatial. The temporal data include hydro-climatic data from observation stations and climate models while physical data such as DEM, soil type, and land use and land cover used in the analysis are spatial data. The fourth task of the study is to see if there exists any relationship between Nepalese climate and the regional climate indices.

3.1 Data Collection

The main data used for the analysis of climate in Nepal are precipitation and temperature, relative humidity and wind speed. The major data used for the analysis of floods in Nepal include historical daily flows, and instantaneous maximum and minimum flows measured at different gauging stations within the country. To calibrate and validate the hydrological model, historical precipitation, temperature and flow data are used. For drought assessment, precipitation, temperature, soil moisture and flow data are required. Additionally, to assess the impact of climate change, results of climate models, i.e., CMIP6 based simulated temperature and precipitation, are also required. All these tasks use secondary data that were collected either from various institutions and/or retrieved from national or global websites. Spatial data required for hydrological modeling were also obtained from different public data sources.

Precipitation and temperature data from 1980 to 2022 were collected from the Department of Hydrology and Meteorology (DHM). Relative humidity and wind speed were collected from open source (opendatanepal.com). Flow data, available until 2019, was also collected from DHM.

Data related to recorded past floods events and their socio-economic impacts from the 23rd of June 1980 to 30th of September 2023 were also collected from the website of the Ministry of Home Affairs and DHM. Records of Glacial Lake Outburst Floods (GLOFs) and Landslides Dam Outburst Floods occurred at various point of time and their impacts on different locations were assessed from various literature. Their sources are provided where the discussion of those events is done within the report.

Field verification of floods and drought were also made in this study. A total of 54 locations identified from literature review were visited if floods had occurred in the past and are troubling there even in these years. Similarly, 45 locations were visited for drought verification.

Regional Climate Indices namely Niño 3.4 SST Index, Arctic Oscillation (AO) Index, Pacific Decadal Oscillation (PDO), Southern Oscillation Index (SOI), North Atlantic Oscillation (NAO) and Dipole Mode Index (DMI) were extracted from public data source. Brief description of these indices is given in **Table 3-1**.

Table 3-1 Regional climate indices

SN	Indices	Description
1	Niño 3.4 SST Index	It is the area averaged Sea Surface Temperature (SST) from 5S-5N and 170-120W, calculated from the HadISST1
2	Arctic Oscillation (AO) Index	AO index is obtained by projecting the AO loading pattern to the daily anomaly 1000 millibar height field over 20°N-90°N latitude.
3	Pacific Decadal Oscillation (PDO)	SST anomalies poleward of 20N in the Pacific basin.
4	Southern Oscillation Index (SOI)	The SOI is defined as the normalized pressure difference between Tahiti and Darwin.
5	North Atlantic Oscillation (NAO)	The NAO is traditionally defined as the normalized pressure difference between a station on the Azores and one on Iceland. The NAO is calculated from Gibraltar and SW Iceland.
6	Indian Oscillation Dipole (IOD) and Dipole Mode Index, DMI)	Intensity of the Indian Oscillation Dipole (IOD) is represented by anomalous SST gradient between the western equatorial Indian Ocean (50E-70E and 10S-10N) and the south eastern equatorial Indian Ocean (90E-110E and 10S-0N). In other words, IOD can be defined as the difference in sea surface temperatures (SSTs) between the Eastern Indian Ocean (EIO-south of Indonesia) and the Western Indian Ocean (WIO-in the Arabian Sea). This gradient is named as Dipole Mode Index (DMI.

Source: https://psl.noaa.gov/gcos_wgsp/

The data used in this study, their sources, and main uses are given in **Table 3-2**.

Table 3-2 Secondary data collected from various sources and their uses

SN	Data Type	Main Uses	Source	Remarks
1	**Spatial data: Physical Data**			
1.1	Digital Elevation Model (DEM)	• Hydrological Model	➢ SRTM	Resolution 30m x 30 m
1.2	Land-Use Land Cover (LULC) Map	• Hydrological Model	➢ ICIMOD (2021)	Resolution 30m x 30m
1.3	Soil Type	• Hydrological Model	➢ SOTER	Resolution 1:1,000,000
2	**Temporal Data: Hydroclimatic Data**			
2.1	Temperature Data	• Trend analysis • Assessment of temperature indices • Extreme climate • Assessment of the association of climate to floods and droughts • Hydrological model • Drought indices and parameters	➢ DHM ➢ APHRODITE ➢ WCRP	DHM: Observed Series (1980-2022) APHRODITE: Gridded Dataset for the Country WCRP: Climate Model Outputs (1980-2055) **Note**: In this study rainfall and precipitation are interchangeably used.
2.2	Rainfall (Precipitation) Data	• Trend analysis • Assessment of rainfall indices and PMP • Extreme climate • Assessment of the association of climate to floods and droughts • Hydrological model • Drought indices and parameters		
2.3	Relative Humidity and Wind Speed	• Spatial analysis • Temporal trend analysis	➢ Opendatanepal	Historic data (1981-2019)
2.4	Daily Average Flow	• Hydrological model	➢ DHM	Historical data

SN	Data Type	Main Uses	Source	Remarks
		• Flood inventory • Drought index		(1980-2019)
2.5	Instantaneous Maximum and Minium Flow	• Flood magnitudes of different return periods • PMF estimation • Low flow of different return periods • Assessment of the association of climate to floods and droughts	➢ DHM	Historical Data (1980-2019)
3	**Other: Socio-economic and Human Casualty Data**			
3.1	Past Flood Events	Assessment of flood events based on human causalities	➢ MoHA ➢ DHM ➢ Various Literatures	Past data (1980-2023)
4	**Regional Climate Data**			
4.1	AO, PDO, SOI NAO and DMI	• Association of regional climate indices with the climate of Nepal.	➢ GCOS	

SRTM: Shuttle Radar Topography Mission; **ICIMOD**: International Centre for Integrated Mountain Development **SOTER**: Soil and Terrain, **PMP**: Probable Maximum Precipitation, **DHM**: Department of Hydrology and Meteorology, **WRCP**: World Climate Research Program, **PMF**: Probable Maximum Flood, **MoHA**: Ministry of Home Affairs. **AO**: Arctic Oscillation Index, **PDO**: Pacific Decadal Oscillation, **SOI**: Southern Oscillation Index, **NAO**: North Atlantic Oscillation and **DMI**: Dipole Mode Index and **GCOS**: Global Climate Observing System, Working Group on Surface Pressure

3.2 Climate Data Assessment

The main issues observed in the climate data collected from DHM are: (i) Missing data and (iii) Homogeneity of the data. These aspects have been briefly presented below.

The total number of precipitation and temperature stations in Nepal are respectively 271 and 129 (**Table 3-3**). Out of these stations, only 8 raingauge stations have complete data for the considered duration of 1980-2022, while no temperature gauging station has a complete data series. The locations of gauging stations and the availability of precipitation and temperature data in those locations are given in **Appendix A** (**Table A-1:** precipitation and **Table A-2:** temperature). Basinwise missing precipitation and temperature data status are given in **Appendix A (Table A-3:** precipitation**; Table A-4:** maximum temperature and **Table A-5:** minimum temperature).

From **Table A-1** (**Appendix**), we can see that out of the 271 raingauge stations, ten were found to have 100% missing rainfall data (Karnali:1, Gandaki:8, and Bagmati:1). Stations with complete missing data were excluded, resulting in 261 stations. Among them, only 185 stations (approximately 70%) met the criteria of having equal or less than 10% missing data (**Appendix A: Table A-1**). Maintaining this criterion led to several regions with no rainfall data. To enhance the spatial coverage as much as possible, the missing data criteria were extended to 20%. Thus, rainfall data of 207 stations out of the initial 271 stations (about 79%) were taken into account for further analysis (**Table 3-3**). Similarly, temperature gauging stations having equal or less than 10% missing data came to be only 10 out of 129 (**Appendix A: Table A-2**). The missing data criteria were, therefore, expanded to 20%. In this way, 68 temperature stations having equal to or less than 20% missing data were left for further analysis (**Table 3-3**). Basinwise brief description of the status of the missing data is presented in the **Sub-sections 3.2.1** and **3.2.2**.

Table 3-3 Summary information of climatological data

SN	Type of Data	Duration	Total Number of Stations	Number of Stations with No Missing Data	Stations with Missing Data Less than 20%	Number of Stations with Homogeneity Test (at 99% critical level)	Number of Selected Stations	Remarks
1	Precipitation	**1980-2022**	271	8	207	162	179	*162 homogeneous **useful** precipitation stations but 17 are **doubtful**. Suspect stations added for spatial coverage.
2	Maximum Temperature		129	0	68	20	67	67 stations which are common to T_{max} and T_{min}, satisfy less than 20% missing criteria.
3	Minimum Temperature		129	0	68	17	67	

3.2.1 Basinwise Status of Missing Rainfall Data

The rainfall missing data characteristics of major basins, considering 207 stations from 1980 to 2022 have been summarized below (see **Appendix A: Table A-3** and **Figure A-1**).

1. Mahakali River Basin

All 5 rain-gauge stations within this basin had missing data below ten percent. Station 108 (Satbanjh) has the lowest percentage of missing data (0.19%), while station 107 (Darchula-Khalanga)) has the highest missing data i.e., 7.37%. On average, the missing percentage of rainfall data within the Mahakali River Basin is 3.1%.

2. Karnali River Basin

Karnali River Basin has a lower density of rain-gauge stations compared to other basins. It has a total of 36 rain-gauge stations. Out of them, 27 and 29 stations have less than 10% and 20% missing data respectively. Stations 104 located at Dadeldhura and 406 located at Surkhet (Birendranagar) have no data gaps (0.0%) in their series, while Station 301 at Mugu Check post has the maximum data gaps (64.31%). The missing percentage for rainfall data within the Karnali River Basin was found 10.2%.

3. West Rapti River Basin

In the West Rapti River Basin, among the 7 stations, 5 stations have less than 10% missing data while the remaining 2 stations have more than 20% missing data. Station 419 (Sikta) has only 0.57% data missing, whereas station 730 (Sitapur-Nepaney) has the maximum number of missing data (52.15%). On average, the missing percentage of data within the basin was calculated to be 11.4%.

4. Babai River Basin

Within the Babai River Basin, out of 10 stations, 5 have less than 10% missing data, and 7 stations have less than 20% missing data. The extent of missing data ranged widely from 0.01% at station 511 (Salyan Bazar) to 95.35% at station 512 (Luwamjula Bazar). The percentage of missing data within the Babai River Basin came to 18.8%, on an average.

5. Gandaki River Basin

The Gandaki River Basin possesses the highest rain-gauge station count, i.e., 69, among all the river basins in Nepal. Among these stations, 40 have less than a 10% data gap in their time series, and 44 have less than 20% missing data. One-third of the total stations that did not meet the criterion of having less than 20% missing data were excluded. Station 804 situated at Pokhara Airport was found with no data gaps, while station 821 situated at Ghandruk has a 95.35% data deficiency in the time series between 1980 and 2022. The average percentage of missing data for stations within this river basin amounted to 18.3%.

6. Bagmati River Basin

The Bagmati River Basin has the highest number of precipitation stations (21) in terms of a number of rain-gauge stations per unit area. Only 12 stations have less than 10% missing data, and 14 stations have less than 20% missing data. Seven stations were, therefore, excluded due to not meeting the specified criteria.

Station 1030 at Kathmandu Airport has a complete rainfall data, while station 1082 of Nangkhel has the highest percentage of data gaps in its time series (51.64%). On an average, the basin has 17.4% missing data.

7. Koshi River Basin

The Koshi River Basin, recognized as one of the largest basins, encompasses 54 rain-gauge stations. Among them, 45 stations have less than 10% missing data, while 51 stations have less than 20% missing data. The range of missing data spanned from 0.01% at station 1023 (Dolalghat) to 67.35% at station 1124 (Kavre). The average percentage of missing data for all stations within the Koshi River Basin is 7.0%.

8. Kamala River Basin

The Kamala River Basin, considered one of the smallest basins, has only 3 rain-gauge stations, each having less than 20% missing data. Station 1112 (Chisapani Bazar) has the smallest percentage of missing data, i.e., 1.37%, while Station 1107 at Sindhuli Madhi has the highest percentage of data gaps (5.28%) in its time series. The overall average percentage of missing data of these 3 stations within the Kamala River Basin was found 5.3%.

9. Kankai River Basin

The Kankai River Basin is the smallest river basin among Class A and Class B River Basins. It has 3 rainfall stations. Similar to the Kamala River Basin, 2 stations met the criterion of having less than 10% missing data, and all 3 stations fulfilled the criterion of having less than 20% missing data. Station 1410 at Himali Gaun has the lowest percentage of missing data (0.59%), while station 1421 located at Gaida-Kankai has the highest percentage of data gaps in its time series (10.39%). On an average, the percentage of missing data for all stations within the Kankai River Basin was found 6.6%.

10. Southern River Basins

There is a total of 53 rain-gauge stations in the Southern River Basins (Class C River Basins) out of which 46 stations have missing values less than 20 %. The rain-gauge station located at Butwal has the maximum percentage of missing data (87.10%). There are a few stations (106 at Belauria/Santipur, 909 at Simara airport, 1111 at Janakpur airport, and 1319 at Biratnagar airport) that have no missing data. These basins account for 10.5% of missing data on an average.

3.2.2 Basinwise Status of Missing Temperature Data

The temperature data characteristics of major basins, considering the reduced number of 68 stations, are tabulated in **Table A-4** (maximum) and **Table A-5** (minimum) and also depicted in **Figure A-2** (maximum**) and Figure A-3** (minimum) in **Appendix A**, and has been discussed in brief in the following paragraphs.

None of the stations have a continuous temperature data series without any gaps. The maximum temperature stations and their data gap status are given in **Table A-4 (Appendix A)**. The average missing percentage in the maximum temperature data ranges from 12.8% (Kankai Basin) to 55.4% (Kamala Basin). In other basins too, this percentage is more than 25%. Station 1030 located at Kathmandu Airport lying in the Bagmati basin has the minimum missing percentage (0.1%), while some stations have gaps of more than 90% (Stations 404 at Jajarkot, 1321 at Tumlingtar, 921 at Kalayiya).

The minimum temperature stations and their data gap status are given in **Table A-5 (Appendix A)**. The average missing percentage in the minimum temperature series ranges from 13.3% (Kankai Basin) to 55.4% (Kamala Basin). Similar to maximum temperature, this percentage is more than 25% in other basins as well. However, Station 814 (Lumle) in the Gandaki basin has the minimum missing percentage, i.e., 0.1% while some stations have data gaps of more than 90% (Stations 404 at Jajarkot, 1321 at Tumlingtar, 921 at Kalayiya).

3.3 Filling of Missing Climate Data

The missing climate data: precipitation and temperature (max. and min.) have been filled in order to ensure the continuous time series prior to the analysis. The temperature series has been filled using the regression method with the neighboring stations.

For the temperature stations, the coefficient of determination (R^2) was calculated with its neighboring stations' data at the monthly scale, and the neighboring stations with a relatively better R^2 were used to form the regression equation.

In the case of precipitation, two-step approach was employed to fill the gaps in the precipitation series.

The observed series of a station of interest was compared with the series generated using the Inverse Distance Weighing (IDW) method, and the performance of this method was assessed using the evaluation metrics of Percent-bias (PBIAS), Nash–Sutcliffe efficiency (NSE) and Coefficient of Determination (R^2). Three nearby stations at a minimum and five at a maximum were used for the IDW. This method defines the relation of such stations with the rainfall data of the neighboring stations as the function of distance, which has been, popularly, used in Nepal (e.g., Nepal (2016) for the Gandaki basin, Eeckman et al., (2017) for the Everest regions). In this method, the modified IDW (Armanuos et al., 2020) is used, which uses the function of distance and elevation difference to estimate the precipitation. The equation used for the method is given in **Table 3-4**, along with the criteria to identify the applicability of the IDW method to fill the gaps.

i) For the stations with poor performance of the IDW method, the gridded precipitation of APHRODITE (Asian Precipitation: Highly-Resolved Observational Data Integration Towards Evaluation) was used in conjunction with ERA5 (Fifth Generation ECMWF re-analysis products) gridded precipitation datasets. As the APHRODITE datasets, which are the gridded datasets based on the DHM precipitation data, are only available up to 2015, the ERA5 precipitation datasets were reconstructed for the years after 2015, based on the APHRODITE series of the previous years, forming the APHRODITE-ERA5 gridded datasets for the period of 1980–2022. Based on the monthly regression between the observed series and the precipitation series of these gridded datasets at a pixel level, the gaps in the observed series were filled. The method used for filling in the missing data at the corresponding stations are depicted in **Table 3-4**.

3.4 Homogeneity Test

Homogeneity tests for temporal data are performed to assess whether the statistical properties of a data series remain constant over time. In other words, these tests are used to determine if the data is stationary or non-stationary. Understanding the stationarity of a time series is crucial for various data analysis and modeling tasks. The Standard Normal Homogeneity Test and Pettit's Test are the two approaches generally used for assessing temporal data in the study as these methods are simple and effective. These tests have, therefore, been used by many researchers for assessment of the homogeneity of the data (Alexandersson, 1986; Firat et al., 2011; Firat et al., 2012; Ullah et al., 2019b). It is noted here that the time series data is considered useful only if the series passes both the homogeneity tests. In any other cases, it would be labeled as suspect or doubtful for the intended uses.

1. Standard Normal Homogeneity Test

According to Alexandersson (1986), the Standard Normal Homogeneity Test (SNHT) can be used for a variety of hydro-meteorological variables, including river discharge, surface air temperature, precipitation, air pressure, etc. The time series (y-series) of the hydro-meteorological variables can be used to compute the standardized series of ratios $\{Z_i\}$ for the SNHT, which has a zero mean and unit standard deviation using **Equation (3-1)**.

$$Z_i = \frac{q_i - \bar{q}}{s_q} \qquad (3\text{-}1)$$

Where $q_i = y_i/\bar{y}$ or $q_i = y_i - \bar{y}$, and $\bar{q}$ and s_q are mean and standard deviation of the q-series respectively.

Table 3-4 Missing data filling methods

SN	Method	Formula	No. of Stations	Station Index	Remarks
1	IDW (with elevation correction)	$P_x = \frac{\sum_{i=1}^{p} \frac{p_i}{\Delta d * \Delta h}}{\sum_{i=1}^{p} \frac{1}{\Delta d * \Delta h}}$	122	101, 103, 104, 105, 106, 203, 206, 207, 208, 209, 212, 214, 217, 303, 304, 306, 310, 401, 402, 406, 408, 409, 410, 411, 412, 415, 416, 417, 419, 501, 507, 508, 510, 513, 604, 605, 606, 613, 614, 702, 707, 708, 715, 721, 723, 725, 726, 728, 729, 802, 804, 807, 810, 811, 813, 814, 815, 817, 818, 824, 902, 903, 905, 906, 907, 909, 911, 912, 915, 918, 921, 922, 1004, 1008, 1009, 1018, 1023, 1024, 1030, 1035, 1036, 1038, 1039, 1043, 1049, 1052, 1059, 1060, 1062, 1078, 1102, 1109, 1110, 1111, 1112, 1117, 1118, 1120, 1121, 1202, 1203, 1206, 1211, 1216, 1219, 1222, 1224, 1303, 1311, 1312, 1316, 1319, 1320, 1321, 1403, 1405, 1408, 1409, 1410, 1412, 1415, 1421	For stations with NSE≥60%, R^2≥60% and PBIAS≤25%
2	Aphrodite based-Filled Method	Monthly Regression Equations	57	102, 107, 201, 204, 210, 215, 302, 308, 309, 313, 405, 414, 418, 505, 511, 514, 601, 607, 608, 615, 616, 701, 705, 716, 805, 808, 809, 823, 904, 1007, 1016, 1020, 1029, 1055, 1057, 1058, 1101, 1103, 1108, 1115, 1207, 1210, 1215, 1223, 1226, 1301, 1304, 1305, 1306, 1307, 1308, 1309, 1314, 1317, 1322, 1325, 1420	For stations with NSE<60%, R^2<60% and PBIAS>25%

A statistic T(k), which compares the average of the first 'k' years of the record with the last '(n-k)' years of record (**Equation 3-2)**, is taken into account when performing the SNHT (Alexandersson, 1986).

$$T\ (k) = k\overline{z_1^2} + (n - k)\overline{z_2^2},\ \ k = 1,2, \dots \dots \dots \dots n \qquad (3\text{-}2)$$

Where,

$$\overline{z_1} = \left(\frac{1}{k}\right) \sum_{i=1}^{k} \frac{y_i - \bar{y}}{s}$$

$$\overline{z_2} = \left(\frac{1}{n-k}\right) \sum_{i=k+1}^{n} \frac{y_i - \bar{y}}{s}$$

$$s = \frac{1}{n} \sum_{i=1}^{n} (y_i - \bar{y})^2$$

From the (k-1) numbers of T(k) array, the maximum value gives the test statistic T_0 for the SNHT method, and the corresponding *k* indicates the break year. Break year is the timestep in the series in which the difference between the mean before and after this timestep is the maximum. The test indicates inhomogeneity if T_0 is greater than the critical value, which is a function of sample size and significance level. The table for the critical values is given in **Appendix A (Table A-6)**.

2. Pettit's Test

Pettit's test is a non-parametric rank test in which the ranks r_i if the y_i are used to calculate the statistic X_k as given in **Equation (3-3)** (Wijngaard et al., 2003; Ahmed et al., 2018).

$$X_k = 2 \textstyle\sum_{i=1}^{k} \big(r_i - k(n+1)\big),\ \ k = 1,2, \dots \dots \dots .. n \qquad (3\text{-}3)$$

Similar to SNHT, the maximum value of the X_k statistic array is the test statistic of the Pettit's test. This test indicates inhomogeneity if the test-statistic is greater than the critical value, which depends upon the sample size and the significance level.

The gap-filled climate data (rainfall and temperature) series was tested for homogeneity using both SNHT and Pettit's tests at an annual scale for the critical level of 99%. They are given in **Appendix A** (**Table A-7:** precipitation; **Table A-8**: maximum temperature and **Table A-9**: minimum temperature).

3.5 Selection of Stations for Climatic Data Analysis

Evaluation of precipitation and temperature data of stations which passed the missing data criteria across all 10 river basins in Nepal were carried out to classify them as useful, suspect, or doubtful based on their performance in statistical homogeneity tests, SNHT and Petit's test. The count of precipitation and temperature stations falling into each category is presented in **Table 3-5**. The meteorological stations passing both homogeneity tests are categorized as useful, and those passing only one of the tests are categorized as doubtful, indicating a moderate level of reliability. Moreover, precipitation stations failing both tests are designated as suspect, signifying lower data reliability.

Examining specific basins, the Koshi River Basin, which has the highest number of precipitation stations, also exhibits the highest numbers of suspect (7) and doubtful stations (7), with the count of 37 useful stations. In contrast, smaller river basins like West Rapti, Babai, Kamala, Kankai, and Chamelia (a sub-basin of the Mahakali basin), each have one suspect precipitation station but no doubtful stations. Gandaki basin shows 4 doubtful and 7 suspect stations while the Karnali basin shows 4 doubtful and 4 suspect stations.

The data of rain-gauge stations that showed homogeneity were considered in this study, along with doubtful stations for the sake of spatial coverage in the study. Through these screenings the total selected precipitation gauging sites considered were 179. The selected precipitation stations whose data were used for rainfall analysis in the study are shown in **Figure 3-1**.

Table 3-5 Homogeneity status of climate station

	Precipitation			Maximum Temperature			Minimum Temperature		
Inhomogeneity	**Useful**	**Doubtful**	**Suspect**	**Useful**	**Doubtful**	**Suspect**	**Useful**	**Doubtful**	**Suspect**
River Basin									
Mahakali	4		1		1				1
Karnali	21	4	4	3	8		5	4	2
Babai	4		1		1	2		2	1
West Rapti	6		1	1	1			2	
Gandaki	33	4	7	4	10	2	3	10	3
Bagmati	11	1	2		5		1	4	
Koshi	37	7	7		7	1	3	5	
Kamala	2		1						
Kankai	2		1		2		1	1	
Southern	42	1	3	12	7		4	13	2
Total	**162**	**17**	**28**	**20**	**42**	**5**	**17**	**41**	**9**

There are more doubtful stations in both cases of minimum and maximum temperatures. In the case of maximum temperature, out of 67 stations, there are 42 doubtful stations, 20 useful stations, and 5 suspect stations (**Table 3-5**). Similarly, for minimum temperature, there are 41 doubtful stations, 17 useful stations, and 9 suspect stations out of 67 stations (**Table 3-5**). A closer examination of specific basins reveals that the Gandaki River Basin, with the highest number of temperature stations (16), also has the highest number of doubtful stations. Interestingly, the Kamala River Basin has no stations meeting the criteria for all cases, as none pass the threshold of less than 20% missing data.

In the case of the temperature gauging stations, most of the stations showed inhomogeneity as presented in **Appendix A** (**Table A-8**: maximum temperature and **Table A-9**: minimum temperature). Upon discarding such stations, there would not be enough temperature stations to represent the study area. So, they have still been considered (n=67) for the study. The selected temperature stations whose data were used for temperature analysis in the study are shown in **Figure 3-2**.

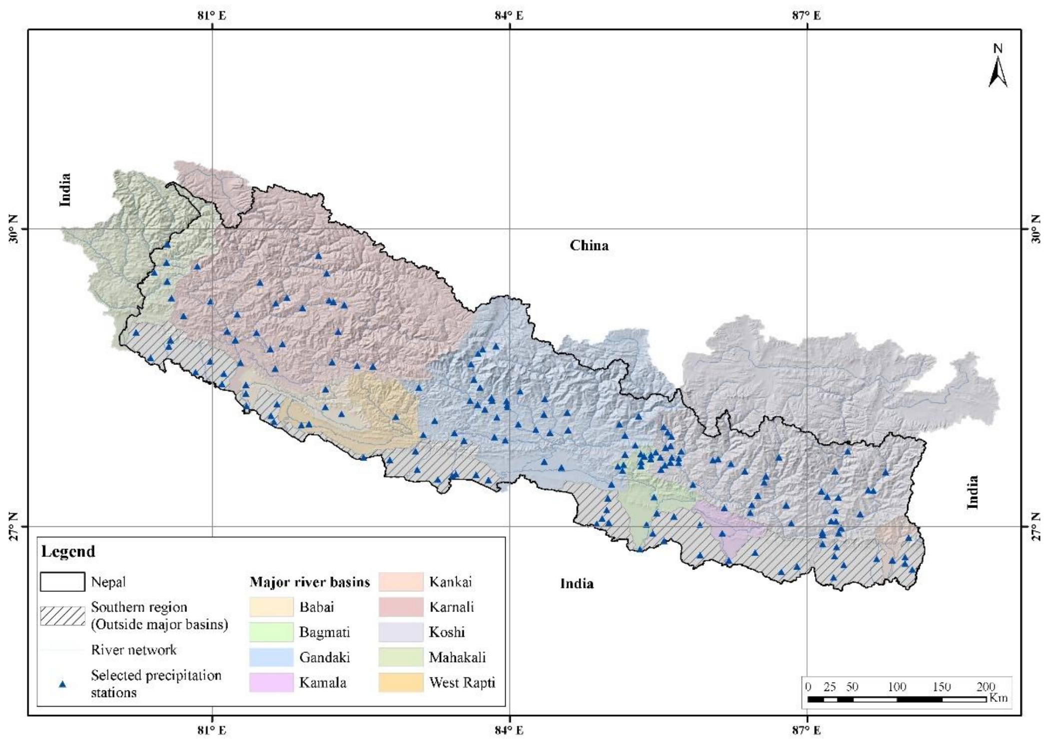


Figure 3-1 Selected precipitation stations

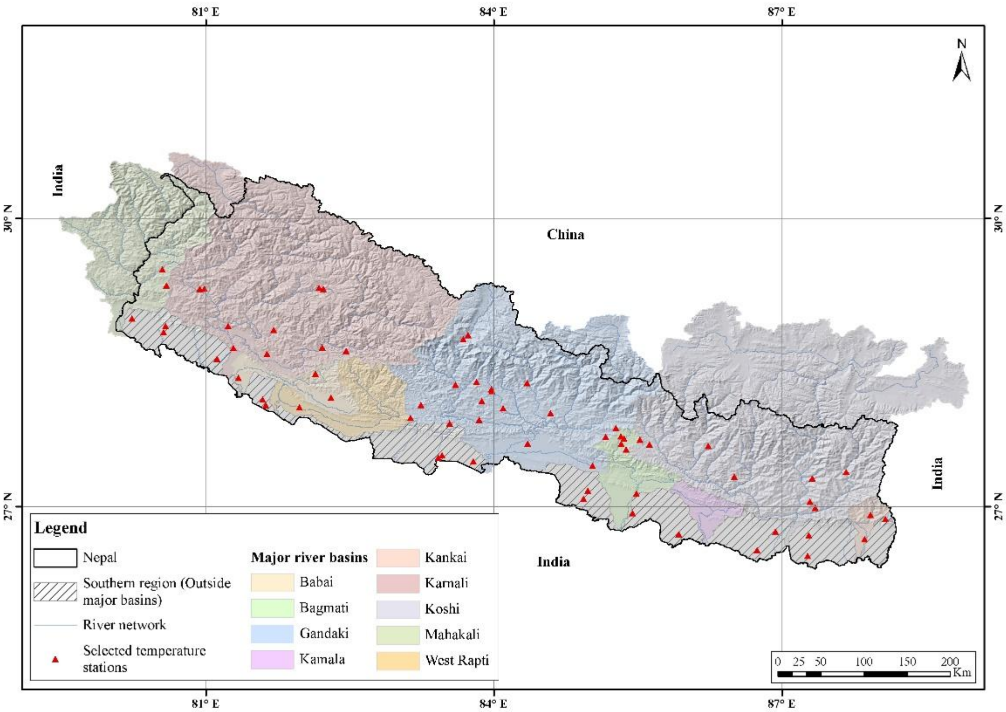


Figure 3-2 Selected temperature stations

3.6 Hydrological Data Assessment

Flow data from a total of 85 flow gauging stations (1980-2019) were obtained from DHM. Details of this data are given in **Appendix A** (**Table A-10**).

The river flow data is used for calibration and validation of the hydrological model to assess the impact of climate change on river hydrology. Additionally, flow data is also required to calculate the standardized streamflow index, one of the drought indices, and to prepare flood inventory. The long-term continuous flow data series is, therefore, a prerequisite for these purposes. One of the major issues of the hydrological data is gaps in the series. The second issue is the quality of the existing data (both instantaneous and mean daily flow data). These two aspects are briefly discussed below.

3.6.1 Missing Flow Data

Missing flow data of time span of 1980 to 2019 which were collected from DHM were checked first prior to further analysis. In **Table 3-6**, the percentage of missing data is given. It varies across stations, ranging from 0% to 87.7%. For example, at Stations 225 (Diware), 330 (Nayagaon), 360 (Jalkundi), and 447 (Betrawati) have complete data while Station 340 (Kalimatighat) in the West Rapti Basin has missing data around 90%. The Kankai River Basin, Bagmati River Basin, and Karnali River Basin have lower percentages of missing data i.e., 20.6%, 22.7%, and 20.1%, respectively. The temporal status of gaps in the flow series data of different hydrological stations has been shown in **Figure A-4 (Appendix A**).

Table 3-6 Status of collected flow data

River Basin	Min. Missing (%) Value	Min. Missing (%) Station	Max. Missing (%) Value	Max. Missing (%) Station	Avg. Missing (%) Value	Missing <= 10% Count	Missing <= 10% Avg. Value	Missing <= 20% Count	Missing <= 20% Avg. Value
Mahakali	2.29	120.0 [Nayalbadi]	53.73	115.0 [Harsingbagar]	36.34	1	2.29	1	2.29
Karnali	0.00	225.0 [Diware]	68.66	253.9 [Mattada]	22.05	8	1.08	10	3.57
Babai	3.88	286.0 [Daradhunga]	80.03	290.0 [Bargadha]	36.77	1	3.88	1	3.88
West Rapti	0.00	330.0 [Nayagaon], 360.0 [Jalkundi]	87.67	340.0 [Kalimatighat]	44.53	3	0.40	3	0.40
Gandaki	0.00	447.0 [Betrawati]	82.89	430.0 [Phoolbari]	28.67	11	3.76	12	4.40
Bagmati	5.04	589.0 [Padharadovan]	50.29	581.0 [Bhorleni]	22.70	2	6.17	3	10.70
Koshi	1.05	690.0 [Mulghat]	81.24	640.0 [Panauti]	24.11	9	3.77	13	7.30
Kankai	20.05	795.0 [Mainachuli]	21.11	728.0 [Rajdwali]	20.58	0		0	
Southern	33.77	387.4 [Kalimati]	65.12	390 [Butwal]	50.55	0		0	

3.6.2 Quality of Hydrological Data

In the context of hydrological data, there has been cases where the flow of the upstream gauging station is higher than downstream gauging station lying on the same river. An example of two gauging sites of the Karnali River viz. Asarghat (Station 240 and Catchment area: 19,260 km^2) which is located upstream of Benighat (Station: 250 and Catchment area: 21,240 km^2) showed that more than 20% of not only daily flow but also monthly average flow data of Asarghat is greater than those of Benighat during the span of 1980-2019.

Instantaneous maximum flow (IMF) of a given year of a flow gauging station must be equal or greater than the mean daily flow (d_{max}) of each and every day of that year. However, IMFs are lower than d_{max} in some instances in some years. For examples, the IMF of Chamelia at Nayalbadi (Station: 120) of 1995 was recorded as 194 m^3/s while d_{max} of that year in that location was recorded as 288 m^3/s. At Lalighat of Karnali River in 2006, the IMF and d_{max} are 988 and 1,539 m^3/s respectively, at Jalkundi of West Rapti River of

2014, the IMF and d_{max} are 4,680 and 5,822 m^3/s respectively. At Busti of TamaKoshi River, these figures of 1987 are 740 and 903 m^3/s respectively.

3.7 Selection of Stations for Instantaneous Maximum Flood and Minimum Flow Analysis

3.7.1 Selection of Stations for Instantaneous Maximum Flood Analysis

A total of 85 stations which has instantaneous maximum flow data from 1980 to 2019 were collected from DHM. Out of them, only eight stations have complete 40 years of data. Some of them have only four years' worth of such data. The larger the number of data points at a given gaging station, the higher the probability of capturing the hydrological variability of that location. Thus, stations having more than 30 data points were selected for further analyses. However, not to miss the important downstream stations of the Class A and Class B rivers, those stations were also included, even though the data points were less than 30 but not less than 15. With these criteria, a total of 44 stations were selected. The stations, number of data points, and basin wise their distribution are given **Table 3-7**. Only three gauging stations located in the most downstream points: Chepang of Babai River, Kusum of West Rapti River and Chatara of Koshi River have less than 30 data points. The Mahakali basin has only one gauging station. Other three Class A River Basins (Karnali, Gandaki and Koshi) have good and nearly equal numbers of stations. Class B River Basins i.e., Babai, West Rapti and Bagmati River Basins have 2, 4, and 2 stations respectively while Kankai has only one station which has more than 30 years of data. Kamala river, although a Class B river, does not have any hydrological station. Class C rivers also do not have a long-term recorded instantaneous data.

Table 3-7 Selected stations for instantaneous flood analysis

SN	Station	River Basin	Location	Catchment Area (km^2)	Number of Data Points	Basin Total
1	120	Mahakali	Nayalbadi	1150	39	1
2	215	Karnali	Tholtada	15200	39	9
3	220		Nagma	1870	39	
4	225		Diware	824	36	
5	240		Asaraghat	19260	37	
6	250		Benighat	21240	34	
7	260		Banga	7460	40	
8	265		Rimna	6720	39	
9	270		Jamu	12290	31	
10	280		Chisapani	42890	40	
11	286	Babai	Daradhunga	816	36	2
12	289.95		Chepang	2557	29	
13	330	West Rapti	Nayagaon	1938	40	4
14	350		Bagasotigaon	3380	39	

SN	Station	River Basin	Location	Catchment Area (km²)	Number of Data Points	Basin Total
15	360		Jalkundi	5150	40	
16	375		Kusum	5200	17	
17	404.7	Gandaki	Mangalghat	1112	38	12
18	420		Kotagaon Shringe	11400	39	
19	428		Lahachok	160	36	
20	438		Shisa Ghat	858	38	
21	440		Garam Besi	308	39	
22	445		Arughat	4270	40	
23	447		Betrawati	4110	35	
24	448		Belkot	653	39	
25	450		Devghat	31100	40	
26	460		Rajaiya	579	33	
27	465		Manahari	427	30	
28	470		Lothar	169	30	
29	505	Bagmati	Sundarijal	17	38	2
30	589		Pandhera Dobhan	2700	30	
31	602	Koshi	Tumlingtar	375	38	13
32	602.5		Pipletar	110	34	
33	604.5		Turkeghat	28200	40	
34	606		Simle	30380	34	
35	620		Jalbire	629	37	
36	630		Pachuwar Ghat	4920	39	
37	647		Busti	2753	33	
38	650		Rasnalu Village	313	35	
39	652		Khurkot	10000	33	
40	660		Sangutar	823	30	
41	670		Rabuwa Bazar	4100	39	
42	690		Mulghat	5640	40	
43	695		Chatara	54100	29	
44	795	Kankai	Mainachuli	1148	32	1
			Total		**1573**	**44**

3.7.2 Selection of Stations for Instantaneous Low Flow Analysis

Instantaneous minimum flow series of 88 stations from 1980 to 2019 was collected from DHM. Out of them only seven stations have all 40 years of data. However, some stations have only four years of data. The same criteria that we used for selecting the stations having instantaneous maximum flow data were used to select the stations in this case too: (i) stations having more than 30 years minimum flow data and (ii) if the station lies at the most downstream of the river, include them provided that the data points were more than 15. With these criteria, a total of 41 stations were selected. The stations, number of data points, and basin wise their distribution are given in **Table 3-8**.. Only three gauging stations located in the most downstream points: Chepang of Babai River, Kusum of West Rapti River, and Chatara of Koshi River have less than 30 data points. The Mahakali basin has only one gauging station. The other three Class A River Basins (Karnali, Gandaki, and Koshi) have good and nearly equal numbers of stations in this case too. Class B River Basins i.e., Babai, West Rapti, and Bagmati River Basins have 2, 4, and 2 stations respectively while Kankai has only one station which has more than 30 years of data. Kamala river, although it is also a Class B River, does not have any minimum instantaneous flow data. Class C rivers also do not have recorded instantaneous minimum flow data.

Table 3-8 Selected stations for instantaneous minimum flow analysis

SN	Station	River Basin	Location	Catchment Area (km^2)	Number of Data Points	Basin Total
1	120	Mahakali	Nayalbadi	1150	38	1
2	215	Karnali	Tholtada	15200	38	9
3	220		Nagma	1870	39	
4	225		Diware	824	34	
5	240		Asara Ghat	19260	39	
6	250		Benighat	21240	34	
7	260		Banga near Belgaon	7460	40	
8	265		Rimna	6720	38	
9	270		Jamu	12290	31	
10	280		Chisapani	42890	40	
11	286	Babai	Daradhunga	816	36	2
12	289.95		Chepang	2557	28	
13	330	West Rapti	Nayagaon	1938	40	4
14	350		Bagasoti Gaon	3380	39	
15	360		Jalkundi	5150	40	
16	375		Kusum	5200	17	
17	404.7	Gandaki	Mangla Ghat	1112	35	10
18	420		Kotagaon Shringe	11400	38	
19	428		Lahachok	160	35	
20	438		Shisa Ghat	858	36	
21	440		Garam Besi	308	39	
22	445		Arughat	4270	38	
23	447		Betrawati	4110	35	
24	448		Tadipul Belkot	653	40	

SN	Station	River Basin	Location	Catchment Area (km^2)	Number of Data Points	Basin Total
25	450		Devghat	31100	40	
26	460		Rajaiya	579	30	
27	505	Bagmati	Sundarijal	17	35	2
28	589		Pandhera Dobhan	2700	30	
29	602	Koshi	Tumlingtar	375	39	12
30	602.5		Pipletar	110	34	
31	604.5		Turkeghat	28200	40	
32	606		Simle	30380	32	
33	620		Jalbire	629	38	
34	630		Pachuwar Ghat	4920	38	
35	647		Busti	2753	31	
36	650		Rasnalu Village	313	36	
37	652		Khurkot	10000	32	
38	670		Rabuwa Bazar	4100	38	
39	690		Mulghat	5640	38	
40	695		Chatara-Kothu	54100	29	
41	795	Kankai	Mainachuli	1148	32	1
			Total		**1459**	**41**

3.8 Overall Impression of Hydroclimatic Data

Based on the observations of the available hydro-climatic data, following impression can be noted:

1. Lack of Climate Data in the Northern Part

The climate data of northern part of Nepal, especially in the higher altitude, is scarce. Karnali basin has the most severe in this regard, among the ten basins of Nepal (see **Figure 3-1** and **Figure 3-2**). Further, no data on the Tibetan region of China is available. Lack of climate data results in unrealistic basin and country average values (seasonal, monthly and extremes) for rainfall and temperature. Further, it posseses challenges in calibration and validation of hydrological model.

2. Lack of Flood Data in Terai

The Terai region experiences extensive flood damage every year. However, apart from the nine major basins, only three hydrological stations have been installed in the region. Even for these stations, the data from the period 1980–2019 is incomplete, with missing values ranging from 33.4% to 65.0%, and the data quality is poor. This makes flood analysis for the Class C River impossible. Estimating floods of different return periods using empirical equations does not yield accurate results, leading to either over-design or under-design of flood protection structures. In the case of over-design, scarce resources are wasted, whereas in the case of under-design, the intended protection of the area of interest may not be achieved.

3. Quality of Data

The data quality across hydrological and climatological gauging stations is inconsistent and often substandard. Consequently, analyses based on poor-quality data yield unreliable results. Policies formulated using such flawed analyses are likely to contain significant errors. Furthermore, there is a high risk of design flaws in hydraulic structures (e.g., dams, spillways, embankments, etc.) when relying on such data.

4. Temporal Resolution of Data

The DHM databases are oriented toward the data series of a daily resolution. However, the mean daily data deviates away from the actual magnitude of the flood. Thus, this situation poses challenges in hydrological modeling exercises to predict floods.

5. Spatial Resolution of Data

The poor spatial resolution of DEM, soil, land use, and land cover data fail to capture the physical variability of the basin. As a result, the application of physically based distributed models becomes less suitable for assessing the hydrological processes of the basin.

CHAPTER 4: ANALYSIS OF CLIMATE OF NEPAL

4.1 General Methodology of Climate Analysis

The methodology followed for the analysis of climate in Nepal is given in **Figure 4-1.** Secondary climate data from 1981 to 2022 were collected from DHM. Based on the missing percentage of the climate data and homogeneity test, the precipitation and temperature stations were selected as described in **Chapter 3**. Missing values of the data of these selected gauging stations were filled which was also discussed in **Chapter 3**.

Analysis of climate data is done (i) to see the seasonal and monthly variation, (ii) to calculate the major climate indices, (iii) to assess the temporal trend of the climate data (iv) to see if the climate of Nepal is influenced by regional climate through evaluating the relationship between annual and seasonal precipitation of Nepal and regional climate indices like SOI, DMI etc. and (v) to find out the climate extremes years. Details of the methods applied for each of these cases, wherever required, are given in respective sections.

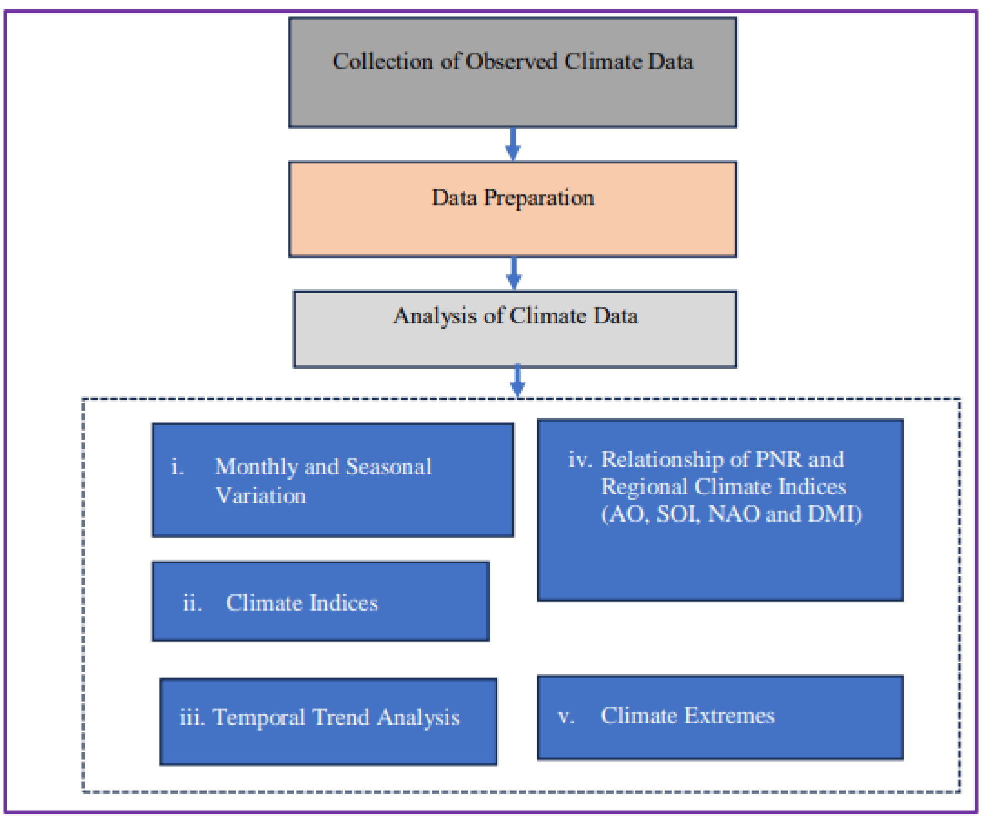


Figure 4-1 General methodology for climate analysis

4.2 Analysis of Rainfall

4.2.1 Rainfall Characteristics of Nepal

The rainfall data of the selected rain gauge stations showed a very high spatial variation within the country; ranging from less than 300 mm (St. 608-Ranipauwa: 277mm) to close to 5,500 mm (St. 814-Lumle: 5442 mm). Out of 179 selected rain gauge stations, 13 locations have an annual average rainfall of less than 1,000 mm while 12 locations have rainfall of more than 3,000 mm.

Based on the data of these selected rain-gauge stations from 1980 to 2022, the annual average rainfall results in 1,828 mm. This value is on the higher side if we think of the average rainfall of the country. Such a higher average value of the annual rainfall is attributed to the non-inclusion of stations' data present in high mountainous regions. It is because of the lack of (long-term) rainfall data in those stations (see **Chapter 3-** selection of stations), where the amount of annual rainfall is lower than in the other parts of the country. To rectify this issue, interpolation was carried out to cover the northern part, and the use of Aphrodite data on some regions where interpolation is not feasible was made. After creating data for the northern part, the annual average rainfall surface of the entire country was created. Based on this surface shown in **Figure 4-2**, the annual average rainfall of Nepal was calculated, which came to be 1,563 mm.

Annual variations of rainfall across the country can be clearly seen in this figure. Further, we can observe three main rainfall pockets namely Lumle, Num, and Gumthang regions.

The monsoon onset and withdrawal from 1981 to 2021 are shown in **Figure 4-3**. In Nepal, the monsoon onset typically occurs in June, with an average onset date of June 13, across these 41 years—except for 1996, when it deviated from this pattern.

On the other hand, monsoon withdrawal takes place either in September (21 out of 41 years) or October (20 out of 41 years). The figure clearly shows that during the 1980s and 1990s, withdrawal predominantly occurred in September. However, in recent years, it has shifted to October.

The shortest monsoon season was recorded in 1981, lasting 80 days, while the longest occurred in 2008, lasting 129 days.

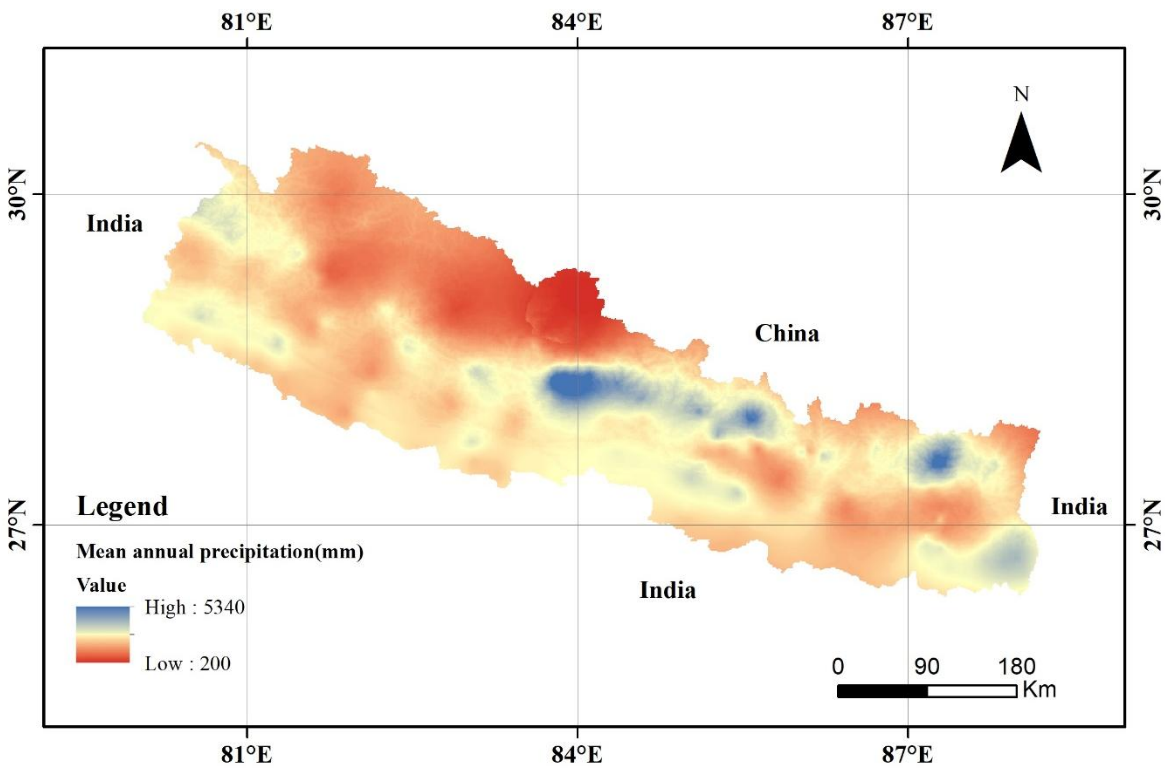
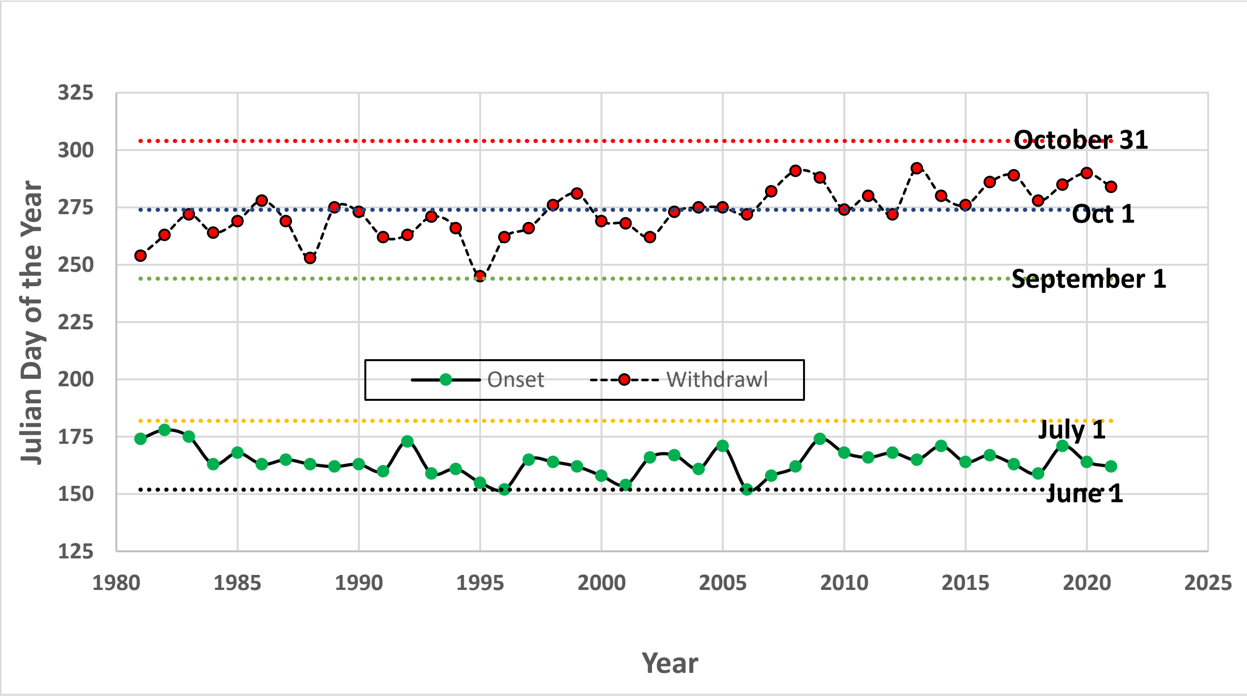


Figure 4-2 Annual precipitation surface map of Nepal



Source: DHM (2024)

Figure 4-3 Monsoon Onset and Withdrawal

4.2.2 Seasonal Variation of Rainfall

The seasonal variation of rainfall (basin level and country level) based on data of selected 179 raingauge stations are given in **Table 4-1**. Stationwise seasonal variation of rainfall is given in **Appendix B** (**Table B-1**). From these tables, it is evident that nearly 80% of the country's annual rainfall occurs during the monsoon season. Some areas receive as much as 89% of their total annual rainfall in the monsoon (e.g., Station 215 - Godavari), while others receive as little as 55% during the same period (e.g., Station 302 - Thirpu) (see **Appendix B: Table B-1**). Within the monsoon season itself, nearly half of the rainfall occurs in just two months—July and August. The remaining three seasons receive significantly less rainfall: Post-monsoon, Winter, and Pre-monsoon contribute approximately 4%, 3%, and 13% of the annual rainfall, respectively.

The basin-wise seasonal variation of rainfall, based on rain gauge data within each basin, is also presented in **Table 4-1**. Among the eight basins, the Gandaki Basin receives the highest amount of rainfall, while the West Rapti Basin records the lowest. In the winter season, however, the western basins of Nepal receive a higher percentage of their total annual rainfall compared to the eastern basins. For the other seasons, the rainfall characteristics align with the overall country-level seasonal variation.

Table 4-1 Basin wise seasonal variation of rainfall

River Basins	No. of Stations	Annual (mm)	Winter (%)	Pre-Monsoon (%)	Monsoon (%)	Post-Monsoon (%)	July and August (%)
Koshi	43	1,752	3	15	78	4	48
Gandaki	33	2,392	3	13	80	4	49
Karnali	25	1,474	7	12	77	4	51
Mahakali	3	2,149	5	11	80	3	54
Kankai	1	2,354	2	13	80	5	47
Bagmati	10	1,612	3	15	79	4	49
West Rapti	1	1,267	5	13	78	4	47
Babai	3	1,489	5	9	81	5	50
Country Level	179	1,828	3	13	80	4	50

The seasonal variation of rainfall of 12 stations is presented in **Table 4-2**. These stations were selected based on two criteria:

1. Statistics-based Selection:

   (i) Maximum annual rainfall: Station 814 – Lumle; (ii) Minimum annual rainfall: Station 608 – Ranipauwa; (iii) Median annual rainfall: Station 705 - Bhairahawa Airport and (iv) Average annual rainfall: Station 1121 – Karmiya

2. Proximity to National/Provincial Capitals:
(i) Nepal: Station 1030 - Kathmandu Airport; (ii) Koshi: Station 1319 - Biratnagar Airport; (iii) Madhesh: Station 1111 - Janakpur Airport; (iv) Bagmati: Station 906 – Hetauda; (v) Gandaki: Station 804 - Pokhara Airport; (vi) Lumbini: Station 419 – Sikta; (vii) Karnali: Station 406 - Surkhet Airport and (vii) Sudur Pashchim: Station 209 – Dhangadhi.

The seasonal variation in rainfall at these selected stations generally mirrors the country-level data (**Table 4-1**), with one notable exception: Station 608 - Ranipauwa (the station with the lowest annual rainfall). At this station, monsoon precipitation is lower, and winter precipitation is relatively higher. Similar characteristics are observed in other low-rainfall sites (**Appendix B: Table B-1**).

Table 4-2 Seasonal variation of rainfall in selected stations

SN	Station	Location	Annual Rainfall (mm)	Rainfall in % of Total Annual Value				
				Winter	Pre-Monsoon	Monsoon	Post-Monsoon	July and August
1	814	Lumle	5,442	2	9	85	4	53
2	608	Ranipauwa	277	13	14	69	4	51
3	705	Bhairahawa Airport	1,715	3	8	84	5	53
4	1121	Karmaiya	1,832	2	11	83	4	52
5	1030	Kathmandu Airport	1,491	3	15	78	4	47
6	1319	Biratnagar Airport	1,835	2	15	79	5	46
7	1111	Janakpur Airport	1,485	2	13	80	4	51
8	906	Hetauda	2,390	2	12	82	4	50
9	804	Pokhara Airport	3,878	2	14	79	5	46
10	419	Sikta	1,523	4	7	86	3	57
11	406	Surkhet Airport	1,614	6	9	82	3	55
12	209	Dhangadhi	1,857	4	6	87	3	57

4.2.3 Monthly Variation of Rainfall

The long-term monthly variation of the rainfall (1980-2022) in all the 179 stations is provided in **Appendix B** (**Table B-2**). Among these, the monthly rainfall variations for two stations—Lumle (the highest rainfall station in Nepal) and Ranipauwa (the lowest rainfall station in Nepal)—are illustrated in **Figure 4-4** and **Figure 4-5** respectively. Additionally, the monthly precipitation data for 12 selected stations are summarized in **Table 4-3**. It is evident that maximum rainfall occurs in July at the majority of rain gauge locations (170 stations), while 8 stations record their peak rainfall in August. Only one station, Station 1301 - Num, experiences its maximum rainfall in June (**Appendix B: Table B-2**). On average, nearly 50% of the annual rainfall (ranging from 30% to 58%) is concentrated in just two months—July and August.

Conversely, minimum monthly rainfall predominantly occurs in November, with 151 stations recording their lowest rainfall during this month. December and January follow, with 26 and 3 stations, respectively, reporting minimum rainfall. This data highlights that the post-monsoon and winter seasons in Nepal are generally dry.

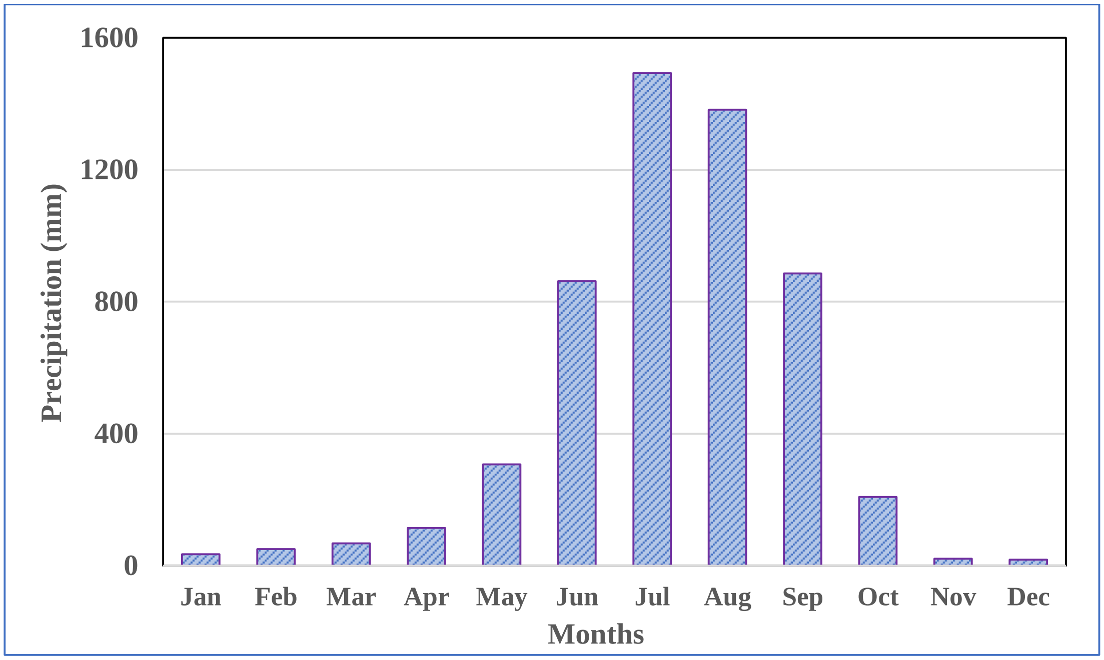


Figure 4-4 Monthly rainfall variation in Lumle

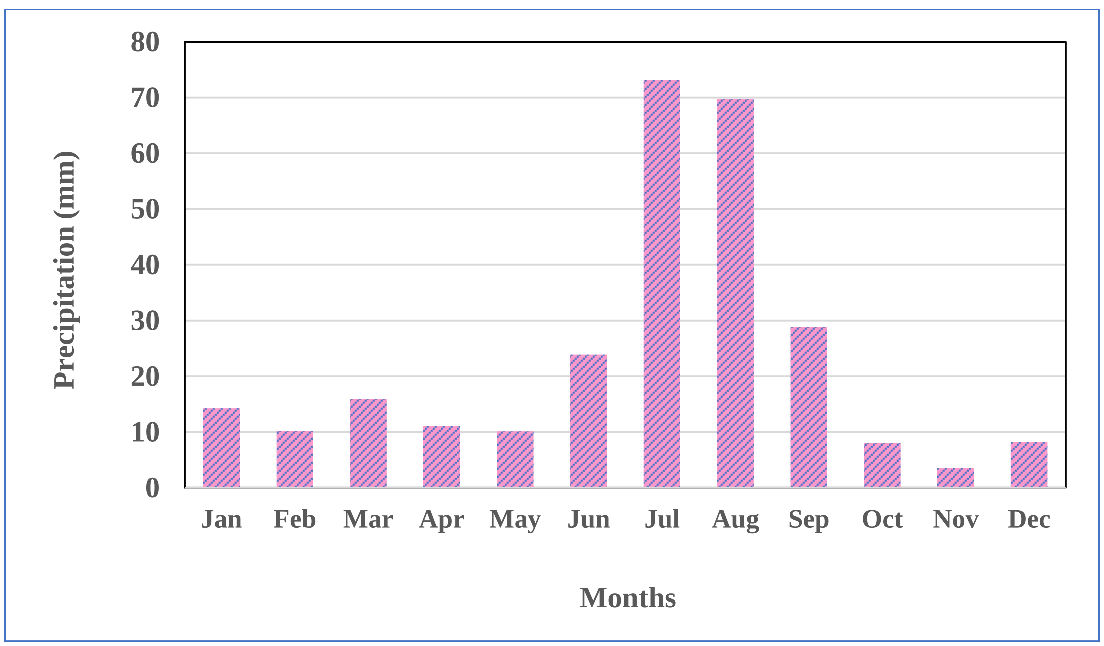


Figure 4-5 Monthly rainfall variation in Ranipauwa

Table 4-3 Monthly variation in the rainfall of some of the selected raingauge locations

Unit: mm

SN	Station	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	814	Lumle	34	50	68	114	307	863	1493	1382	885	208	21	18	5,442
2	608	Ranipauwa	14	10	16	11	10	24	73	70	29	8	4	8	277
3	705	Bhairahawa Airport	19	23	18	29	92	275	526	392	247	76	6	12	1,715
4	1121	Karmaiya	10	11	16	51	126	250	530	428	318	80	4	7	1,832
5	1030	Kathmandu Airport	14	22	36	60	130	238	382	325	213	53	6	12	1,491
6	1319	Biratnagar Airport	9	12	16	56	189	317	503	345	292	87	4	5	1,835
7	1111	Janakpur Airport	11	12	13	52	129	232	445	322	201	62	1	7	1,485
8	906	Hetauda	17	22	25	68	195	370	647	559	383	88	5	11	2,390
9	804	Pokhara Airport	22	36	64	132	341	658	941	830	663	158	16	18	3,878
10	419	Sikta	20	22	15	18	78	215	445	416	229	49	4	13	1,523
11	406	Surkhet Airport	37	43	28	28	94	244	470	416	186	46	7	16	1,614
12	209	Dhangadhi	30	29	20	20	75	254	551	502	296	61	3	15	1,857

4.2.4 Analysis of Rainfall Indices

The precipitation indices relevant to health, agriculture, water, and other socio-economic sectors are listed in **Table 4-4**. These indices were calculated based on the definitions provided in the table.

Table 4-4 Precipitation indices and their definitions

SN	Indices	Definition
1	One Day Maximum Precipitation	Maximum one-day value of the precipitation of the available data
2	Daily Average Precipitation	Long-term daily average value
3	P95	Precipitation at 95 percentiles
4	Highest No. of Very Wet Days	Highest number of days of a year with ($P > P_{95}$) during the data period
5	Lowest No. of Very Wet Days	Lowest number of days of a year with ($P > P_{95}$) during the data period
6	P99	Precipitation at 99 percentiles
7	Highest No. of Extreme Wet Days	Highest number of days of a year with ($P > P_{99}$) during the data period
8	Maximum Number of Rainy Days	Maximum number of annual total days when the precipitation is > 1 mm
9	Minimum Number of Rainy Days	Minimum number of annual total days when the precipitation is > 1 mm
10	Average Number of Rainy Days	Average number of annual total days when the precipitation is > 1 mm
11	Maximum No. of Consecutive Dry Days	Maximum length of consecutive days with daily precipitation < 1 mm
12	Minimum No. of Consecutive Dry Days	Minimum length of consecutive days with daily precipitation < 1 mm
13	Average No. of Consecutive Dry Days	Average length of consecutive days with daily precipitation < 1 mm
14	Maximum No. of Consecutive Wet Days	Maximum length of consecutive days with daily precipitation > 1 mm
15	Minimum No. of Consecutive Wet Days	Minimum length of consecutive days with daily precipitation > 1 mm
16	Average No. of Consecutive Wet Days	Average length of consecutive days with daily precipitation > 1 mm

Precipitation indices of all gauging stations are given in **Appendix B** (**Table B-3**). Maps of one-day maximum rainfall, P_{95}, P_{99}, the maximum number of very wet days, the maximum number of consecutive dry and wet days are shown in **Figure 4-6, Figure 4-7, Figure 4-8, Figure 4-9,** and **Figure 4-10** respectively. Also, precipitation indices of twelve selected gauging stations are presented in **Table 4-5**.

The one-day maximum rainfall varies significantly across locations. Among the 179 rain gauge stations, the observed maximum one-day precipitation during the data period (1980–2022) ranges from 59 mm at Station 608 - Ranipauwa to 516 mm at Station 906 - Hetauda, representing almost a tenfold difference.

During the same period (1980–2022), at least once, 22 rain gauge sites recorded rainfall exceeding 400 mm, 66 sites recorded rainfall exceeding 300 mm, 123 sites recorded more than 200 mm, and 171 sites recorded over 100 mm (**Appendix B-3**). These figures indicate that there is a likelihood of having a large precipitation event at any location in Nepal.

The P_{95} and P_{99} values of Nepal are 30 mm (range: 5-79 mm) and 67 mm (11-138 mm), respectively. The average number of rainy days is 100 per year; however, this varies significantly, with some locations experiencing nearly 200 rainy days and others as few as 50.

Based on these data, the average consecutive wet and dry days in Nepal are 66 days (range: 33–87 days) and 16 days (range: 5–71 days), respectively. These results suggest a high probability of significant year-to-year variability, with some years being very dry and others exceptionally wet. Additionally, some locations experience over 300 consecutive dry days, indicating a high susceptibility to drought. Conversely, other locations record up to 165 consecutive wet days, reflecting a high likelihood of flooding in those areas.

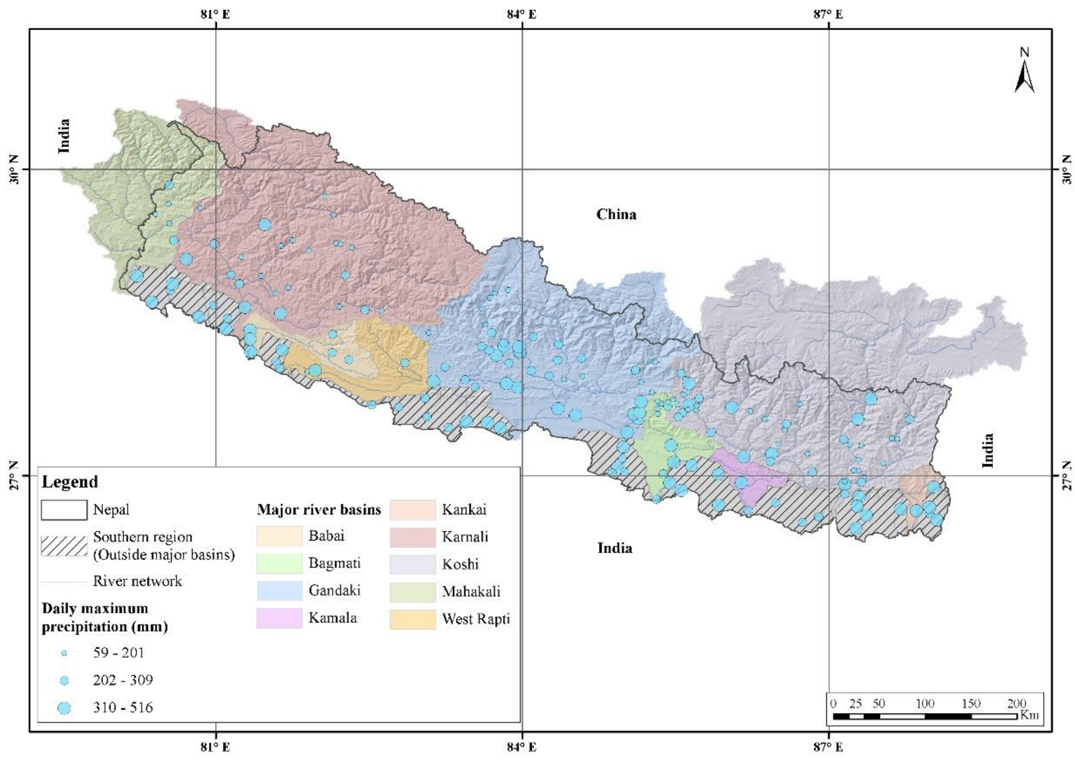


Figure 4-6 One day maximum precipitation

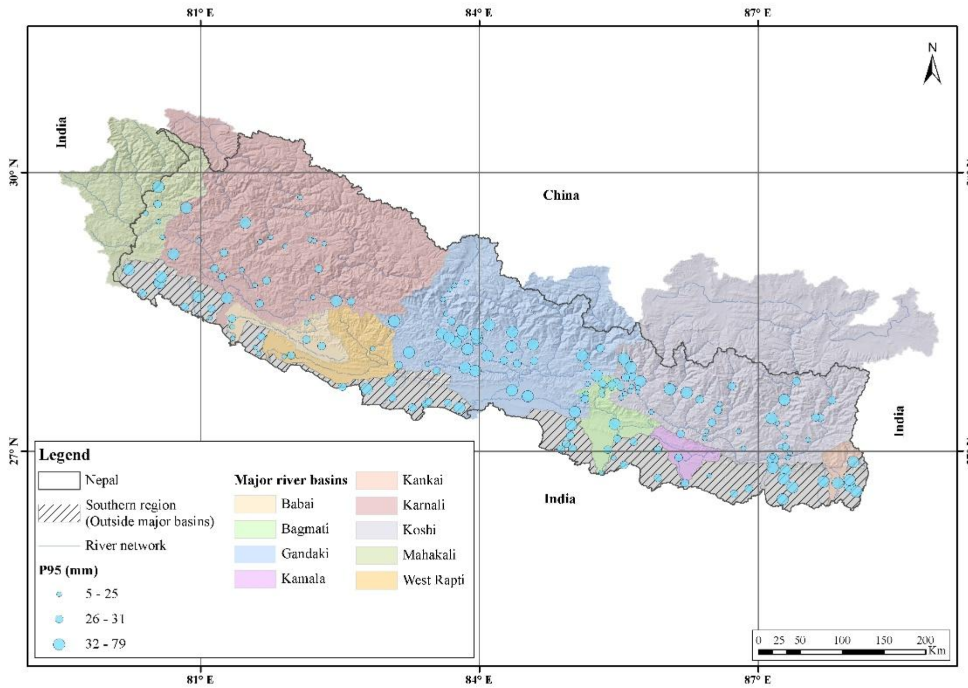


Figure 4-7 Precipitation at 95 percentile

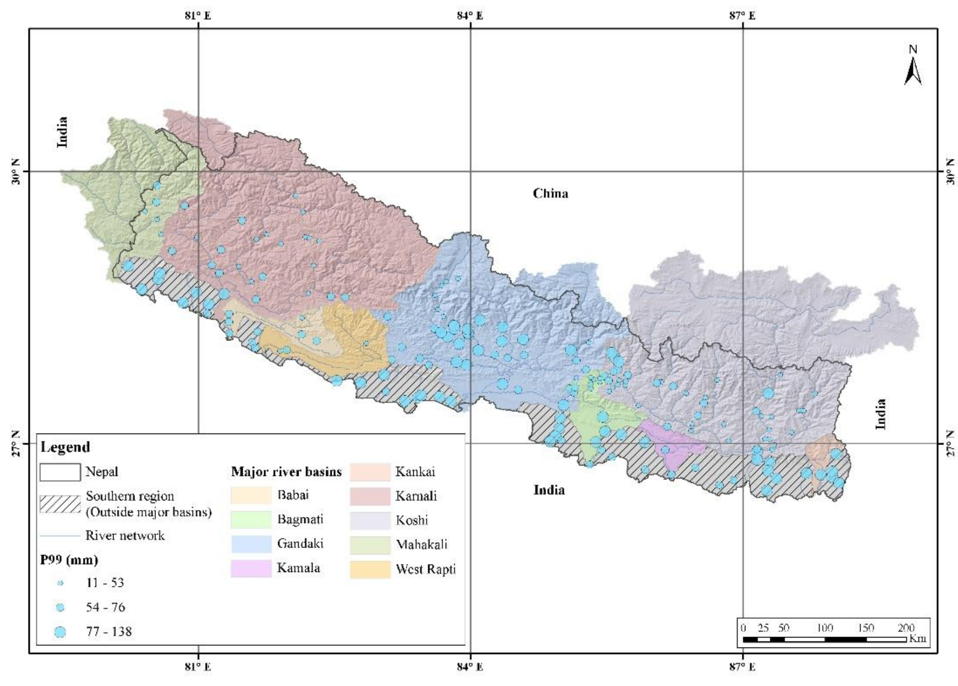


Figure 4-8 Precipitation at 99 percentile

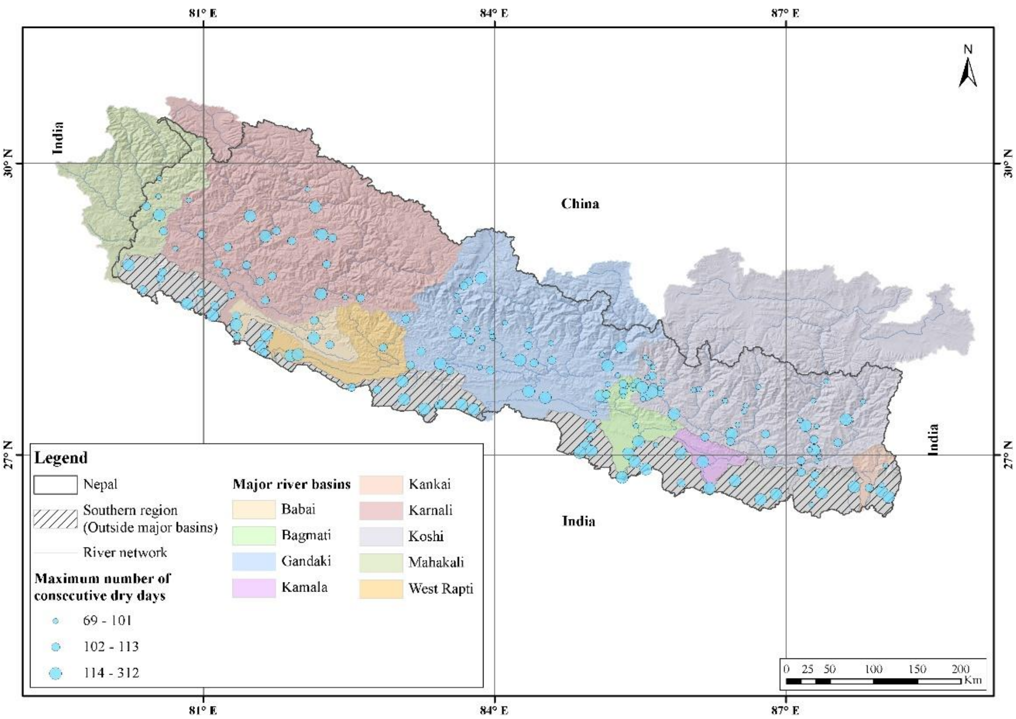


Figure 4-9 Maximum number of consecutive dry days

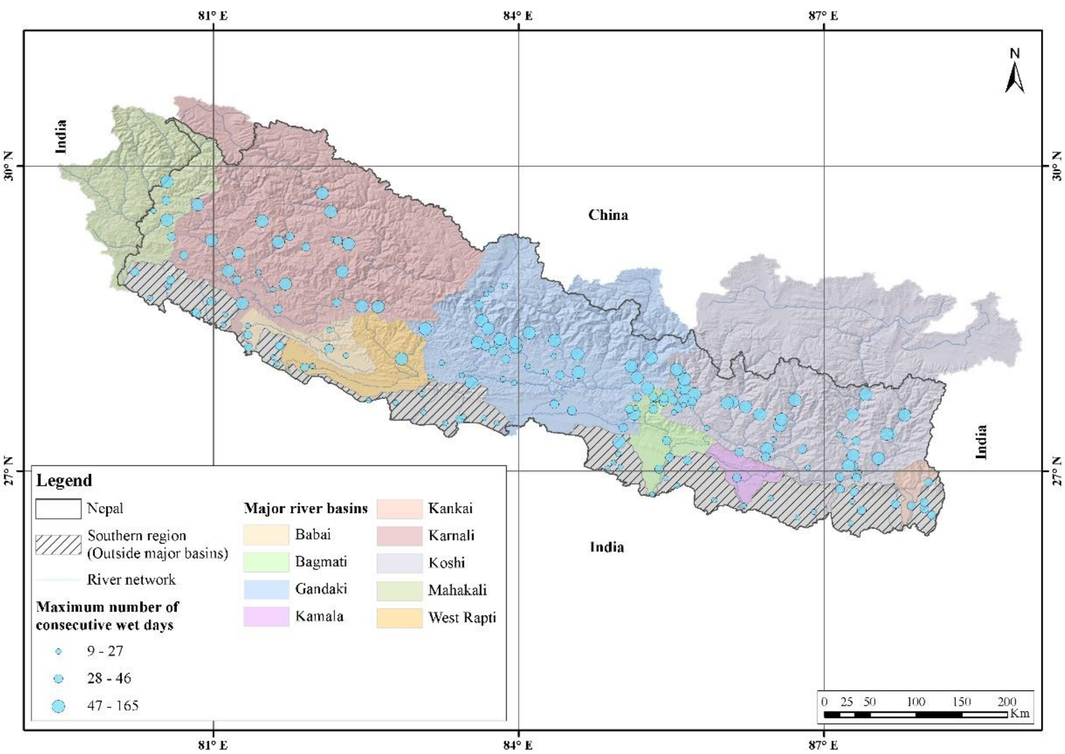


Figure 4-10 Maximum number of consecutive wet days

Table 4-5 Precipitation indices of selected stations

SN	Station		814	608	705	1121	1030	1319	1111	906	804	419	406	209
	Precipitation Indices	**Unit**	**Lumle**	**Ranipauwa**	**Bhairahawa Airport**	**Karmaiya**	**Kathmandu Airport**	**Biratnagar Airport**	**Janakpur Airport**	**Hetauda**	**Pokhara Airport**	**Sikta**	**Surkhet Airport**	**Dhangadhi**
1	Daily Maximum Precipitation	mm	308	59	267	432	177	323	340	516	357	420	423	291
2	Daily Average Precipitation	mm	14.9	0.76	4.69	5.02	4.08	5.02	4.07	6.54	10.62	4.17	4.42	5.08
3	P95	mm	79	5	29	31	25	32	27	36	58	29	28	33
4	Highest No. of Very Wet Days		29	43	37	31	30	29	35	25	31	28	30	29
5	Lowest No. of Very Wet Days		9	7	10	8	8	7	6	11	7	4	6	11
6	P99	mm	138	11	85	81	52	81	76	88	121	73	60	89
7	Highest No. of Extreme Wet Days		8	13	8	9	9	11	8	9	10	9	7	8
8	Maximum Number of Rainy Days		190	113	104	141	124	109	96	156	164	94	118	97
9	Minimum Number of Rainy Days		134	30	61	53	96	60	40	82	115	47	75	61
10	Average Number of Rainy Days		171	54	79	84	110	88	66	119	145	66	95	79
11	Maximum No. of Consecutive Dry Days		77	143	103	117	101	101	106	99	83	139	104	105
12	Minimum No. of Consecutive Dry Days		17	26	42	37	42	45	42	27	17	45	27	20
13	Average No. of Consecutive Dry Days		45	73	70	71	65	71	76	65	51	87	70	70
14	Maximum No. of Consecutive Wet Days		95	27	38	32	22	21	18	42	43	16	33	15
15	Minimum No. of Consecutive Wet Days		19	3	5	4	7	3	3	7	9	4	6	5
16	Average No. of Consecutive Wet Days		48	8	10	11	13	9	8	16	20	9	14	9

4.2.5 Probable Maximum Precipitation

Probable Maximum Precipitation (PMP) refers to the greatest depth of precipitation that is theoretically possible for a given location and time period under the most severe meteorological conditions. Hershfield (1960) formula to calculate probable maximum precipitation (PMP) is given in **Equation (4-1)**.

$$PMP = P_{mean} + K.P_{std} \tag{4-1}$$

Where P_{mean}= mean of annual maximum daily rainfall series

P_{std}= standard deviation of annual maximum daily rainfall series

K = a factor ranges from 5 to 30 (Reddi, 2001). However, TRACTEBEL (2016) used the following formula to calculate K (**Equation 4-2**).

$$K = \left[4.851 - 0.09995\sqrt{P_{mean}}\right]^2 \tag{4-2}$$

Using this formula, the *K*-value was calculated for all 179 selected precipitation stations. The values range from 11.7 to 19.4, with an average of approximately 15. However, the average *K*-value based on the prescribed range (5 to 30) in standard hydrology textbooks for the Horsfield method to calculate PMP is 17.5. In this study, a *K*-value of 17.5 was adopted to remain on the safe side. The PMP calculated for selected stations are provided in **Table 4-6** and of all the 179 stations are listed in **Appendix B** (**Table B-4).** The maximum PMP is estimated for St. 906/Hetuda i.e., 1,873 mm and minimum PMP came to be 190 mm at St. 306/Gamgadhi.

Table 4-6 Probable maximum precipitation of selected stations

SN	Station	Locations	P_{mean} (mm)	P_{std} (mm)	PMP (mm)
1	814	Lumle	206	41	928
2	608	Ranipauwa	20	11	219
3	705	Bhairahawa Airport	155	47	979
4	1121	Karmaiya	158	73	1443
5	1030	Kathmandu Airport	85	23	488
6	1319	Biratnagar Airport	139	51	1023
7	1111	Janakpur Airport	151	69	1358
8	906	Hetauda	190	96	1873
9	804	Pokhara Airport	196	48	1041
10	419	Sikta	136	62	1222
11	406	Surkhet Airport	125	62	1213
12	209	Dhangadhi	164	52	1079

4.2.6 Trend Analysis of Precipitation

To evaluate the trends in annual precipitation and annual temperature (maximum and minimum, discussed in the following chapter), the Mann-Kendall test was used in conjunction with the Sen's slope estimator method. The Mann-Kendall test is a statistical method primarily used to test the null hypothesis of no trend against the alternative hypothesis of a monotonic increasing or decreasing trend in hydro-climatic time series data. This non-parametric test is suitable for data series where the trend is assumed to be monotonic, meaning the trend consistently increases or consistently decreases without alternating, and where no seasonal or other cyclic patterns are present.

The statistic S is calculated as shown in **Equation (4-3)**.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \quad (4\text{-}3)$$

Where, x_j and x_i are annual values in years j and i, j > i respectively, n is the number of data points and $sgn(x_j\text{-}x_i)$ is calculated using **Equation (4-4)**.

$$sgn(x_j\text{-}x_i) = \begin{cases} 1 \; if \; x_j - x_i > 0 \\ 0 \; if \; x_j - x_i = 0 \\ -1 \; if \; x_j - x_i < 0 \end{cases} \quad (4\text{-}4)$$

A positive or negative value of S indicates an upward (increasing) or downward (decreasing) trend respectively. If the number of data values is 10 or more, the S – statistics approximately behave as normally distributed, and the test is performed with normal distribution with the mean and variation as given in **Equations (4-5a)** and **(4-5b)**.

$$E(S) = 0 \quad (4\text{-}5a)$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i(t_i-1)(2t_i+5)}{18} \quad (4\text{-}5b)$$

Where, n is the number of tied (zero difference between compared values) groups and t_i is the number of data points in the i^{th} tied group. The standard normal distribution (Z – statistics) is computed using **Equation (4-6)**.

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} \; if \; S > 0 \\ 0 \quad\quad\quad if \; S = 0 \\ \frac{S-1}{\sqrt{Var(S)}} \; if \; S < 0 \end{cases} \quad (4\text{-}6)$$

Statistically, the significance of the trend is assessed using Z-value. A positive value of Z shows an upward (increasing) trend while a negative value indicates a downward (decreasing) trend. To evaluate the significance of the data, the Z-score of Mann-Kendall's test is compared with the critical z-value for a given level of significance α, i.e., if $|Z| > Z_{1-\alpha/2}$ stays true, the null hypothesis is rejected and the significant trend is expected to exist.

Sen's non-parametric estimator method has been used for predicting the magnitude (true slope) of hydro-metrological time series data. Sen's slope estimator method uses a linear model for the trend analysis. The slope (T_i) of all data pairs is calculated using **Equation (4-7)**.

$$T_i=\frac{x_j-x_k}{j-k} \text{ for i =1,2,3……… N} \quad (4\text{-}7)$$

Where, x_j and x_k are data values at time j and k (j > k) separately.

The median of these n values of T_i is represented by Sen's slope of estimation (true slope) which is calculated using **Equation (4-8)**.

$$Q_i=\begin{cases} T_{\frac{n+1}{2}} & for\ n\ is\ odd \\ \frac{1}{2}\left(T_{\frac{n}{2}}+T_{\frac{n+2}{2}}\right) & for\ n\ is\ even \end{cases} \quad (4\text{-}8)$$

Sen's estimator (Q_{median}) is calculated using the above equation depending upon the value of n which is either odd or even and then (Q_{median}) is computed using 100 (1 – α) % confidence interval using a non-parametric test depending upon normal distribution. A positive value of Q_i indicates an increasing (upward) trend while a negative value of Q_i represents a downward or decreasing trend of time series data. Likewise, the Sen's slope gives the magnitude of the change, and using this value, the rate of change can be calculated for each test which is given as **Equation (4-9)**.

$$\text{Rate of Change} = \frac{\text{Sen's Slope} * \text{Length of Period}}{\text{Mean}} * 100 \quad (4\text{-}9)$$

The results of trend analysis of annual precipitation data showed no significant trend for most of the stations (149 out of 179) and even though the changes exist, it doesn't demonstrate any spatial pattern within the country. Almost the same results were found for seasonal rainfalls too. The results of the annual trend analysis test along with the rate of change are given in **Appendix B (Table B-5)**. The maps of trend analysis of annual and monsoon precipitation of selected 179 stations are given in **Figure 4-11** and **Figure 4-12,** respectively.

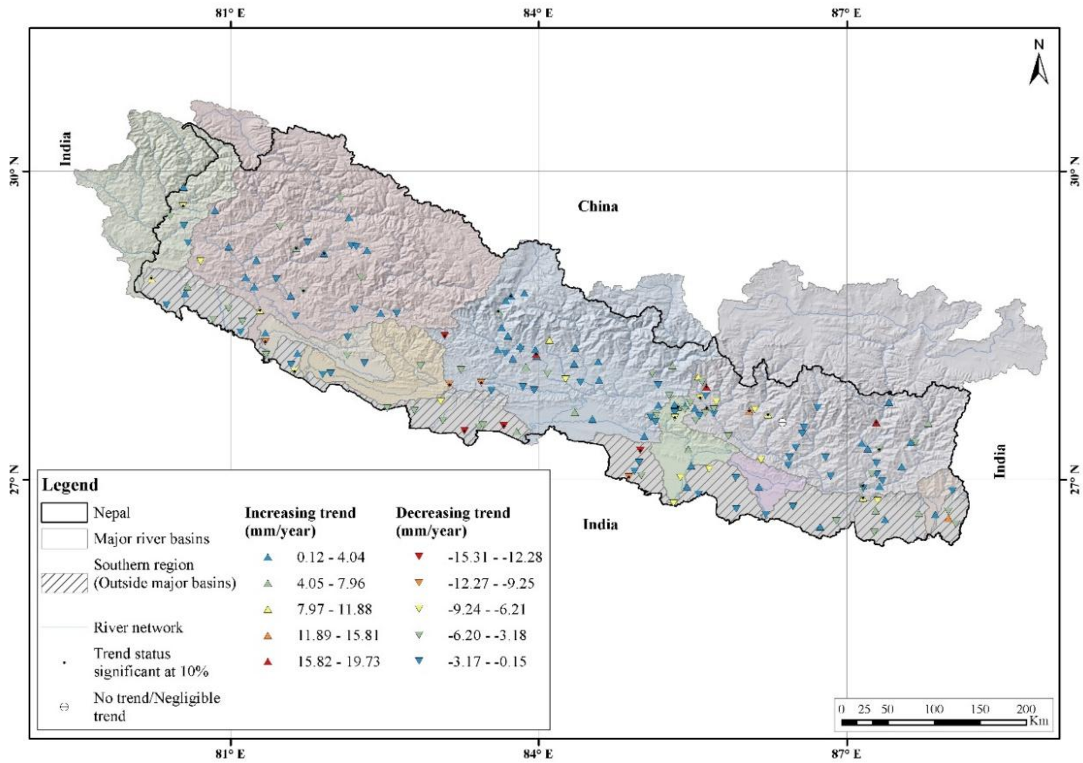


Figure 4-11 Trend of annual precipitation

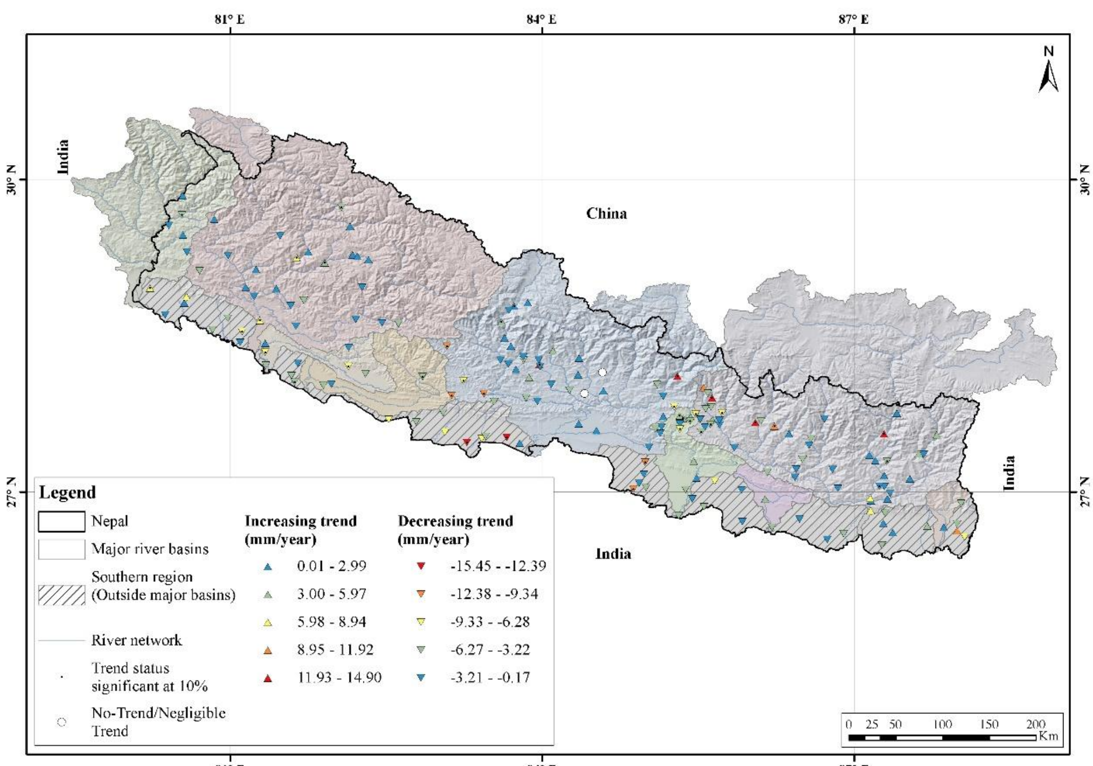


Figure 4-12 Trend of monsoon precipitation

The average of the annual total rainfall of selected 179 stations within Nepal is given in **Table 4-7**. It is plotted against the year in **Figure 4-13**. No observable trend is seen in this figure. Similarly, the average annual total rainfall of stations lying in Koshi, Gandaki, and Karnali basins are also given in **Table 4-7** and plotted against the year in **Figure 4-14**. Temporal trend is not seen even at basin level too. Also, the decadal average of rainfall at the country level, and Koshi, Gandaki, and Karnali basins are given in **Table 4-8**. From these tables and graphs, we cannot conclude the existence of a specific temporal trend of rainfall in Nepal.

Table 4-7 Annual rainfall of Nepal

Unit: mm

Year	Country Level	Koshi	Gandaki	Karnali
1980	1,721	1,697	2,340	1,396
1981	1,853	1,647	2,273	1,503
1982	1,661	1,498	2,196	1,507
1983	1,891	1,735	2,396	1,735
1984	2,033	1,849	2,561	1,501
1985	2,054	2,022	2,389	1,698
1986	1,794	1,655	2,437	1,499
1987	1,844	1,816	2,364	1,243
1988	1,949	1,763	2,646	1,567
1989	1,858	1,749	2,445	1,386
1990	1,951	1,781	2,443	1,658
1991	1,650	1,575	2,176	1,421
1992	1,450	1,453	1,847	1,242
1993	1,857	1,762	2,281	1,487
1994	1,629	1,714	2,269	1,304
1995	1,916	1,895	2,666	1,484
1996	1,872	1,896	2,395	1,501
1997	1,786	1,782	2,341	1,431
1998	2,100	1,898	2,670	1,585
1999	2,006	1,979	2,689	1,374
2000	2,008	1,812	2,734	1,691
2001	1,901	1,852	2,536	1,412
2002	1,884	1,919	2,478	1,471
2003	2,033	1,952	2,622	1,545
2004	1,777	1,754	2,271	1,285
2005	1,561	1,510	1,992	1,200
2006	1,561	1,576	2,000	1,217
2007	2,043	1,872	2,541	1,464
2008	1,773	1,689	2,284	1,483
2009	1,605	1,443	2,075	1,574
2010	1,795	1,724	2,487	1,399

Year	Country Level	Koshi	Gandaki	Karnali
2011	1,835	1,837	2,376	1,477
2012	1,595	1,585	2,237	1,424
2013	1,893	1,767	2,423	1,744
2014	1,689	1,605	2,297	1,464
2015	1,546	1,584	2,022	1,304
2016	1,788	1,817	2,332	1,355
2017	1,732	1,640	2,221	1,410
2018	1,652	1,659	2,191	1,359
2019	1,740	1,811	2,157	1,477
2020	2,163	1,966	3,109	1,630
2021	2,201	1,897	3,085	1,778
2022	1,954	1,890	2,582	1,713

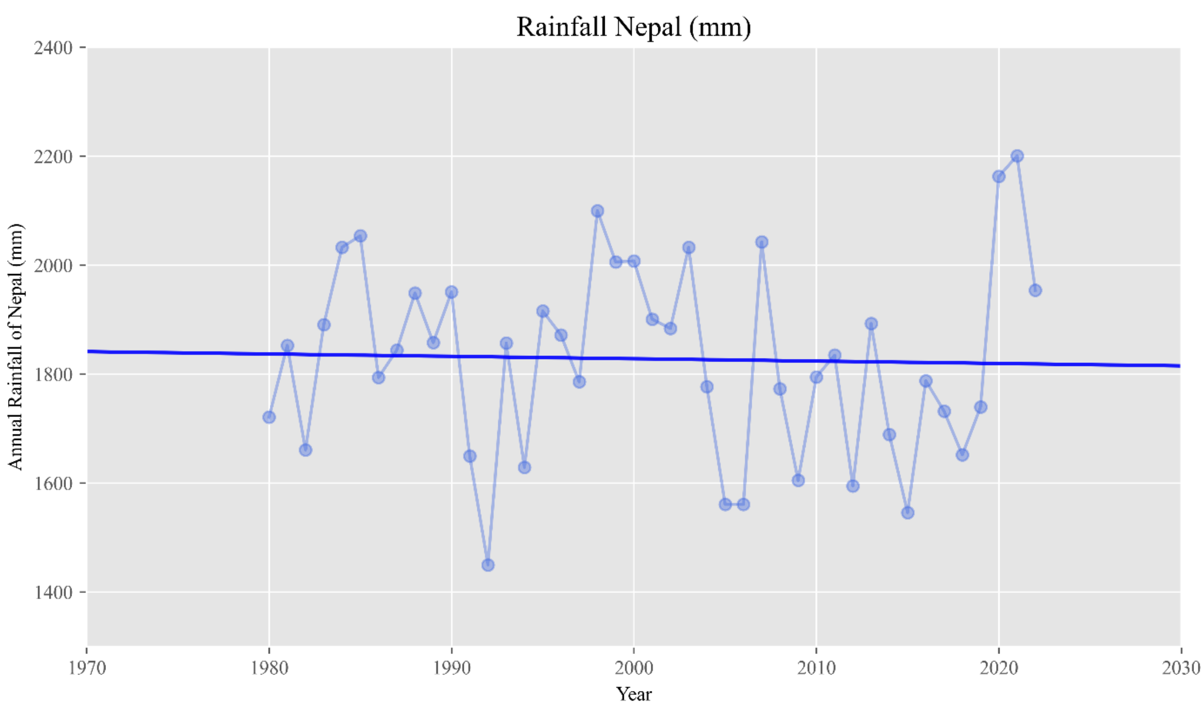


Figure 4-13 Temporal trend of rainfall in Nepal

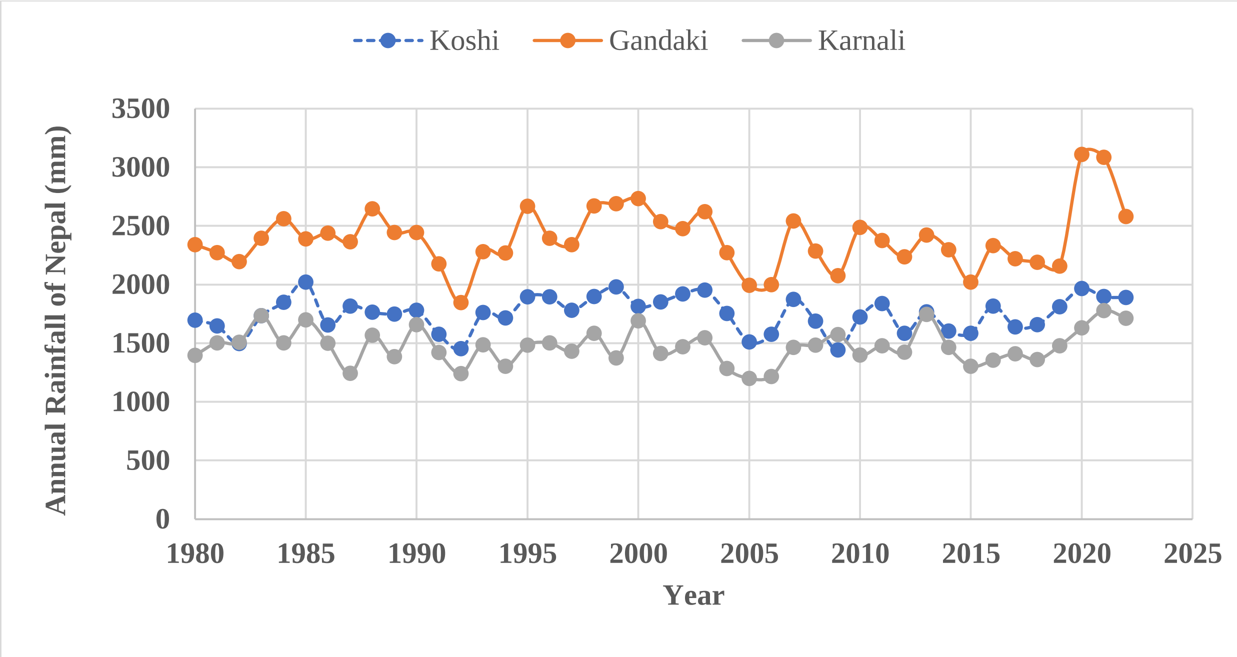


Figure 4-14 Temporal trend of rainfall in Koshi, Gandaki and Karnali Basins

Table 4-8 Average decadal rainfall of Nepal

Unit: mm

Year	Nepal	Koshi	Gandaki	Karnali
1980-1990	1,874	1,746	2,408	1,518
1991-2000	1,827	1,777	2,407	1,452
2001-2010	1,793	1,729	2,329	1,405
2011-2022	1,816	1,755	2,419	1,511

4.3 Temperature Analysis

4.3.1 Temperature Characteristics of Nepal

In a stretch of about 200 km from south to north, Nepal exhibits significant altitudinal variation, ranging from less than 100 masl to over 8,000 masl. Due to this diverse topography, the temperature variation across the country is also substantial.

Based on an analysis of data from 67 selected temperature recording stations in Nepal from 1980 to 2022, temperatures range from over 45°C (46.4°C at Station 209 - Dhangadhi) in the Terai region during summer to below -10°C (-14.0°C at Station 310 - Dipalgaun) in the Himalayas during winter. Of the selected stations, 33 recorded temperatures exceeding 40°C, and almost all (63 stations) experienced temperatures above 30°C at some point during the summer. Conversely, 28 stations recorded temperatures below 0°C, with 4 of these stations experiencing temperatures below -10°C during some winter periods within the study period. Additionally, the temporal variation, both seasonal and interannual, is notably high even at individual locations.

4.3.2 Seasonal Variation of Temperature

The seasonal and annual averages of maximum and minimum temperatures for 10 temperature gauging stations are presented in **Table 4-9**. These stations were selected based on two criteria:

1. **Temperature statistics**: Daily and monthly maximum and minimum temperatures recorded during the study period.
2. **Proximity to Federal or Provincial capital cities**: Selected from the 67 stations based on their closeness to or location within capital cities.

Stations such as St. 209 - Dhangadhi (daily maximum), St. 310 - Dipalgaun (daily minimum), St. 419 - Sikta (monthly maximum), and St. 303 - Jumla (monthly minimum) were chosen based on temperature statistics, while the remaining stations were selected based on their proximity to capital cities. Seasonal average temperature values for all 67 gauging locations in this study are provided in **Appendix B (Table B-6**).

The statistics given in **Table 4-9** and **Table B-6 (Appendix B)** indicate that both maximum and minimum temperatures are highest in the summer season and lowest in the winter season. However, the temperature difference between maximum and minimum values is smallest during the monsoon season among the four seasons. Furthermore, for the same season, the temperature differences are highest at St. 310 - Dipalgaun, which is located at a high altitude, compared to other stations.

Table 4-9 Seasonal maximum and minimum temperature of selected locations

Unit: °C

Station Index	Location	Type	Winter	Pre-Monsoon	Monsoon	Post-Monsoon	Annual
209	Dhangadhi	Tmax	23	35	34	30	31
		Tmin	8	18	25	16	18
310	Dipalgaun	Tmax	16	22	26	22	22
		Tmin	-4	4	14	1	5
419	Sikta	Tmax	23	35	34	30	31
		Tmin	8	17	25	15	17
303	Jumla	Tmax	15	22	25	21	21
		Tmin	-4	4	14	2	5
1319	Biratnagar Airport	Tmax	25	33	33	31	30
		Tmin	10	20	25	18	19
1111	Janakpur Airport	Tmax	24	34	33	31	31
		Tmin	10	20	26	19	20
906	Hetauda	Tmax	23	32	32	28	29
		Tmin	8	17	23	16	17
804	Pokhara Airport	Tmax	21	29	30	26	27
		Tmin	8	16	22	15	16
406	Surkhet Airport	Tmax	22	32	31	27	28
		Tmin	6	16	23	13	16

4.3.3 Monthly Variation of Temperature

Monthly averages of maximum and minimum temperatures data of a total of 10 temperature gauging stations are presented in **Table 4-10**. These values of all the selected 67 gauging locations in this study are listed in **Appendix B (Table B-7**). Further, monthly averages of maximum and minimum temperatures of two selected stations are depicted in **Figure 4-15** (Jumla) and **Figure 4-16** (Sikta).

From these tables, it can be inferred that the minimum monthly temperatures across all locations in Nepal occur in January. In most parts of Nepal, there is a 78% probability that the maximum temperature occurs in May or June. However, maximum temperatures can occur in any month between April and August.

Based on data from the 67 selected temperature measuring stations, the average maximum and minimum temperatures in Nepal are approximately 27°C and 15°C, respectively, giving an overall average temperature of 21°C. However, due to the lack of temperature measuring stations in the northern part of the country, these figures are likely skewed toward higher values. The monthly average maximum temperature reaches as high as 38°C at some locations (e.g., St. 419 - Sikta) but only up to 22 °C at others (e.g., St. 604 - Thakmarpha). Similarly, the monthly average minimum temperature can drop as low as -5°C (e.g., St. 303 - Jumla) and rises only to 11°C at some locations (e.g., St. 1121 - Karmaiya), resulting in an average minimum temperature of 16.5°C. From these figures, it can be surmised that the annual average temperature of Nepal is approximately 15°C.

Table 4-10 Monthly maximum and minimum temperature of selected four locations

Unit: °C

SN	Station	Location	Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	**209**	Dhangadhi	Tmax	20	25	31	36	37	36	33	33	33	32	28	23
			Tmin	7	10	13	18	22	25	26	26	24	19	13	8
2	**310**	Dipalaun	Tmax	14	16	19	23	25	27	26	26	25	23	20	17
			Tmin	-4	-3	0	4	8	13	15	15	12	4	-1	-4
3	**419**	Sikta	Tmax	21	25	31	37	38	37	34	34	33	32	28	23
			Tmin	7	9	12	18	22	25	25	25	24	19	12	8
4	**303**	Jumla	Tmax	14	15	19	22	24	26	25	25	25	22	19	16
			Tmin	**-5**	-3	1	4	8	13	16	15	13	5	-1	-4
5	**1030**	Kathmandu Airport	Tmax	19	22	25	28	29	29	29	29	28	27	23	20
			Tmin	3	5	9	12	16	19	20	20	19	14	8	4
6	**1319**	Biratnagar Airport	Tmax	23	26	31	34	33	33	32	33	32	32	29	25
			Tmin	9	11	16	21	23	25	26	26	25	21	15	11
7	**1111**	Janakpur Airport	Tmax	22	26	31	35	35	34	33	33	33	32	30	25
			Tmin	9	11	16	21	24	26	26	26	25	22	16	11
8	**906**	Hetauda	Tmax	22	25	30	34	34	33	32	32	31	30	27	24
			Tmin	7	9	13	18	21	23	24	24	23	18	13	9
9	**804**	Pokhara Airport	Tmax	20	22	27	30	30	31	30	30	30	28	24	21
			Tmin	7	9	13	16	19	21	22	22	21	17	12	8
10	**406**	Surkhet Airport	Tmax	20	23	28	33	34	33	31	31	31	29	25	22
			Tmin	5	8	12	17	20	23	24	23	22	16	10	6

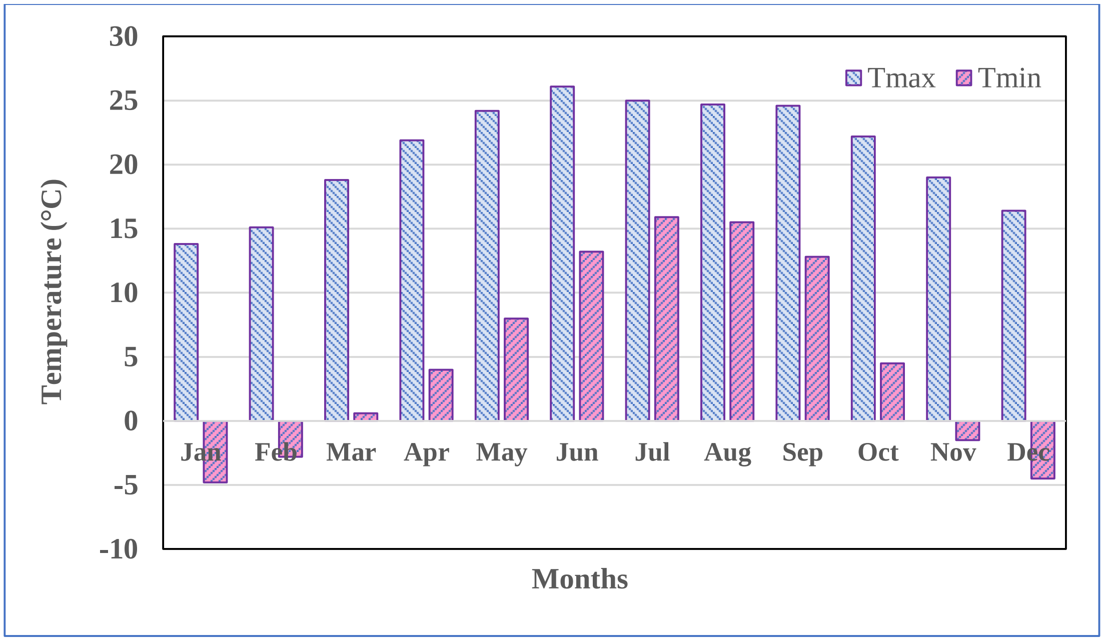


Figure 4-15 Monthly variation in   in Jumla

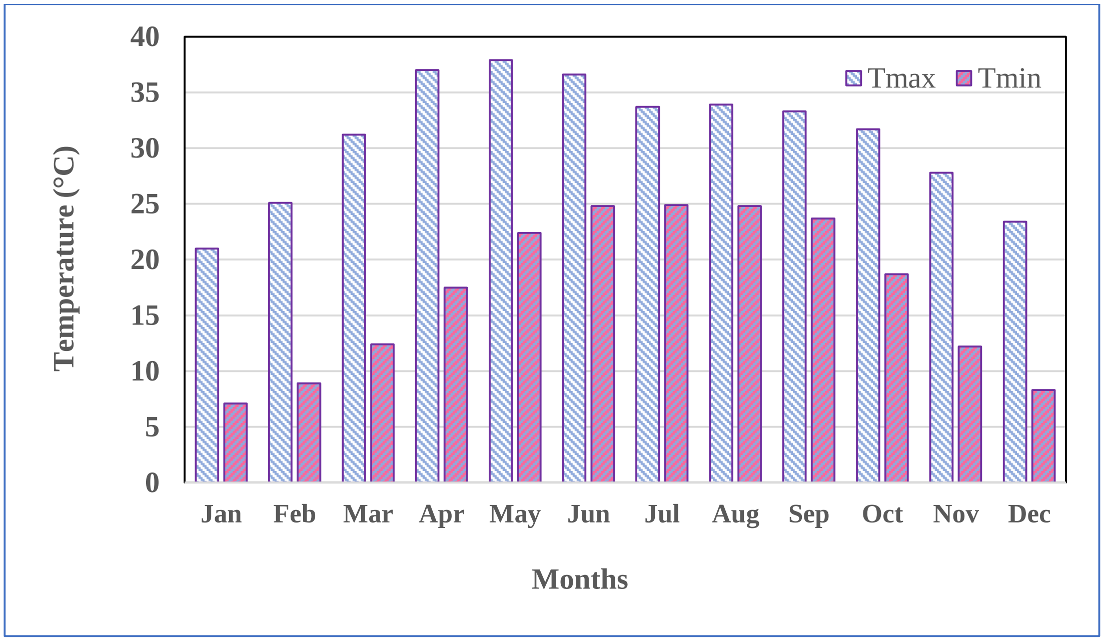


Figure 4-16 Monthly variation in maximum and minimum temperatures in Sikta

4.3.4 Temperature Indices

The major temperature indices along with their definition used in the analysis of temperature in this study are given in **Table 4-11**. Based on the values of T_{x90}, T_{n90}, T_{x10} and T_{n10} maximum, minimum and average percentage of warm days, warm nights, cold days, and cold nights of all the selected temperature gauging sites were calculated as per the definition given in this table along with the Warm and Cold Spell Duration Index.

Table 4-11 Temperature indices and their definition

SN	Indices	Definition
1	Tx90	Maximum temperature at 90th percentile
2	Tn90	Minimum temperature at 90th percentile
3	Tx10	Maximum temperature at 10th percentile
4	Tn10	Minimum temperature at 10th percentile
5	Warm days	Percentage of days when maximum temperature >90th percentile
6	Warm nights	Percentage of days when minimum temperature >90th percentile
7	Cold days	Percentage of days when maximum temperature <10th percentile
8	Cold nights	Percentage of days when minimum temperature <10th percentile
9	Warm Spell Duration Index	Annual count of days with at least 6 consecutive days when maximum temperature > 90th percentile
10	Cold Spell Duration Index	Annual count of days with at least 6 consecutive days when minimum temperature < 10th percentile

The temperature indices for 10 selected gauging stations are presented in **Table 4-12.** Temperature indices of all 67 sites are given in **Appendix B (Table B-8**). The T_{x90} value was found out to be in the range of 23°C (St. 604/Thakmarpha) to 39°C (St. 728/Semari) while the range of T_{n90} was between 13°C (St. 604/Thakmarpha) and 27°C (St. 416/Nepalgunj). The averages of T_{x90} and T_{n90} of Nepal are 32 and 22 °C respectively. Similarly, the range of T_{x10} and T_{n10} are 10°C (St. 601/Jomsom) to 25°C (St. 1212/Phattepur) and -5°C (St. 303/Jumla) to 12°C (St. 1121/Karmaiya) respectively. The averages of T_{x10} and T_{n10} are 20°C and 6°C respectively.

The proportion of warm days varies across locations. At some sites, warm days accounted for as much as 52% of the year (e.g., St. 1407 - Ilam), while others, such as St. 203 - Silgadi, did not observe any warm days during the study period. Warm nights also vary significantly, with the maximum percentage reaching 33% in a particular year at St. 1303 - Chainpur. In contrast, no warm nights were observed at certain locations, such as St. 1416 - Kanyam, during some years.

Cold days and nights were also observed in Nepal, with cold days reaching up to 32% of the year at St. 511 - Salyan Bazar and cold nights peaking at 36% at St. 902 - Rampur. However, some locations experienced neither cold days nor cold nights in specific years. The Warm Spell Duration Index (WSDI) in Nepal ranges from 7 to 27 counts, while the Cold Spell Duration Index (CSDI) ranges from 14 to 28 counts.

Table 4-12 Temperature indices of selected sites

SN	Temperature Indices	Stations	209	310	419	303	1030	1319	1111	906	804	406
		Unit	Dhangadhi	Dipalgaun	Sikta	Jumla	Kathmandu Airport	Biratnagar Airport	Janakpur Airport	Hetauda	Pokhara Airport	Surkhet Airport
1	Maximum of Maximum	°C	46	39	45	32	37	42	42	41	37	43
2	Average of Maximum	°C	31	22	31	21	26	30	31	29	27	28
3	Minimum of Maximum	°C	9	1	9	2	7	12	12	11	11	9
4	Maximum of Minimum	°C	31	24	35	19	23	30	30	29	25	28
5	Average of Minimum	°C	18	5	17	5	12	19	20	17	16	16
6	Minimum of Minimum	°C	0	-14	0	-13	-3	2	2	0	2	-1
7	Tx90	°C	38	28	38	27	31	35	36	35	32	35
8	Warm Days (Max)	%	18	23	20	19	24	20	17	22	21	23
9	Warm Days (Min)	%	3	0	3	1	1	2	3	1	2	2
10	Warm Days (Avg)	%	10	9	10	10	9	9	10	10	10	10
11	Tn90	°C	26	15	26	-16	20	26	27	24	22	24
12	Warm Nights (Max)	%	18	23	17	17	17	17	15	19	19	17
13	Warm Nights (Min)	%	3	0	1	2	1	2	0	0	2	4
14	Warm Nights (Avg)	%	9	10	8	10	9	10	8	9	10	10
15	Tx10	°C	23	14	23	14	19	24	24	23	20	21
16	Cold Days (Max)	%	16	18	17	18	18	17	15	27	19	20
17	Cold Days (Min)	%	3	2	4	4	2	3	2	3	2	2
18	Cold Days (Avg)	%	10	10	10	10	10	10	9	10	10	9
19	Tn10	°C	8	-5	7	-5	3	10	10	8	7	6
20	Cold Nights (Max)	%	25	19	16	21	20	18	16	19	19	15
21	Cold Nights (Min.	%	1	1	1	2	0	4	5	2	2	3
22	Cold Nights (Avg)	%	10	10	10	9	10	9	10	10	10	9
23	Average WSDI		24	10	27	13	13	11	18	17	11	25
24	Average CSDI		20	18	21	16	21	19	22	22	21	20

4.3.5 Trend Analysis of Temperature

Both maximum and minimum temperatures show a significant increasing trend, with 56 out of the 67 stations exhibiting this pattern. This trend clearly indicates that the country is experiencing continuous warming. The detailed results of these tests, along with the rate of change, are provided in **Appendix B (Table B-9:** maximum temperature, and **Table B-10:** minimum temperature**)**. Additionally, the maps illustrating the trend analysis for annual temperature are shown in **Figure 4-17** (maximum temperature) and **Figure 4-18** (minimum temperature), respectively.

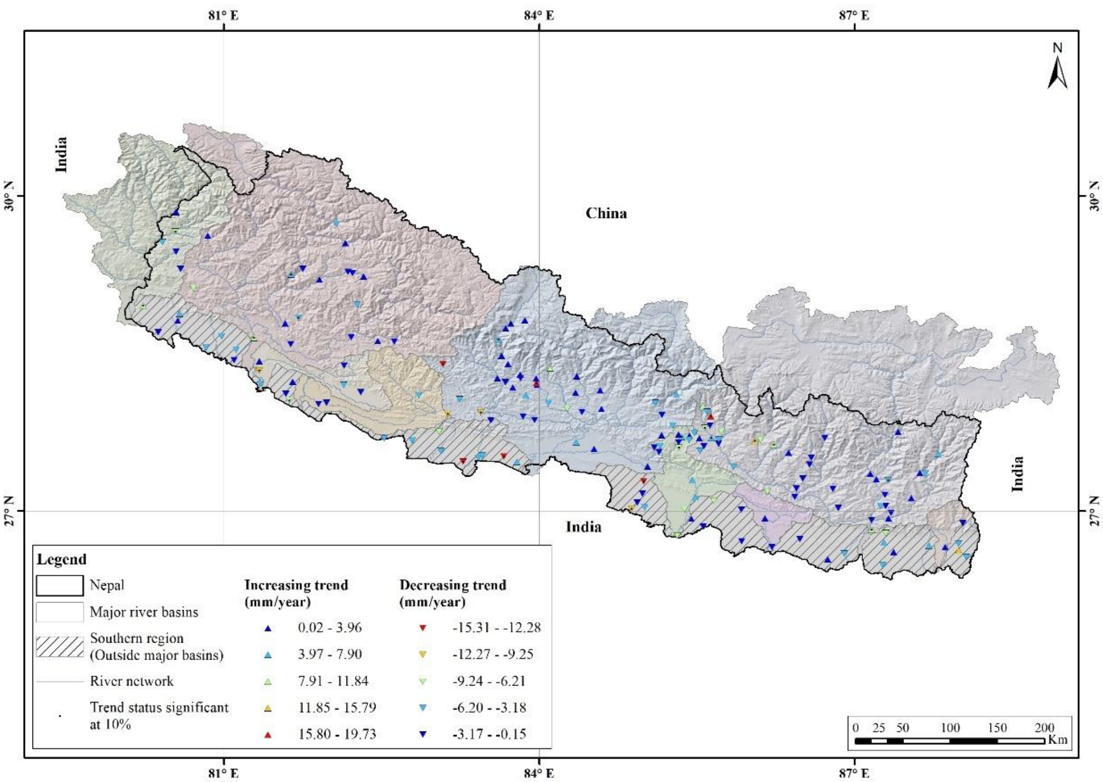


Figure 4-17 Trend of annual maximum temperature

The average temperature of all temperature stations of Nepal, Koshi, Gandaki and Karnali basins are plotted in **Figure 4-19** (maximum) and **Figure 4-20** (minimum). A clear temporal increasing trend is observed in maximum temperature across Nepal. The average increase in maximum temperature during the study period is 0.027°C/year (**Figure 4-13**). Among the three major basins, the Koshi Basin exhibits the highest increasing trend, while the Gandaki Basin shows the lowest, which is nearly comparable to the national average.

In contrast, the temporal trend of minimum temperature differs from that of maximum temperature. The Gandaki Basin exhibits the highest increase in minimum temperature among the three major basins. For Nepal as a whole, the average increase in minimum temperature is 0.015°C/year.

According to the IPCC's Sixth Assessment Report on the Physical Basis of Climate Change, the likely range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. The global warming rate over the past 50 years is 0.18 ± 0.01 °C/decade (Samset et al., 2023).

Based on the figures presented earlier, the average warming rate in Nepal—calculated as the mean increase in maximum and minimum temperature—is 0.21°C per decade. This rate is slightly higher than the global average.

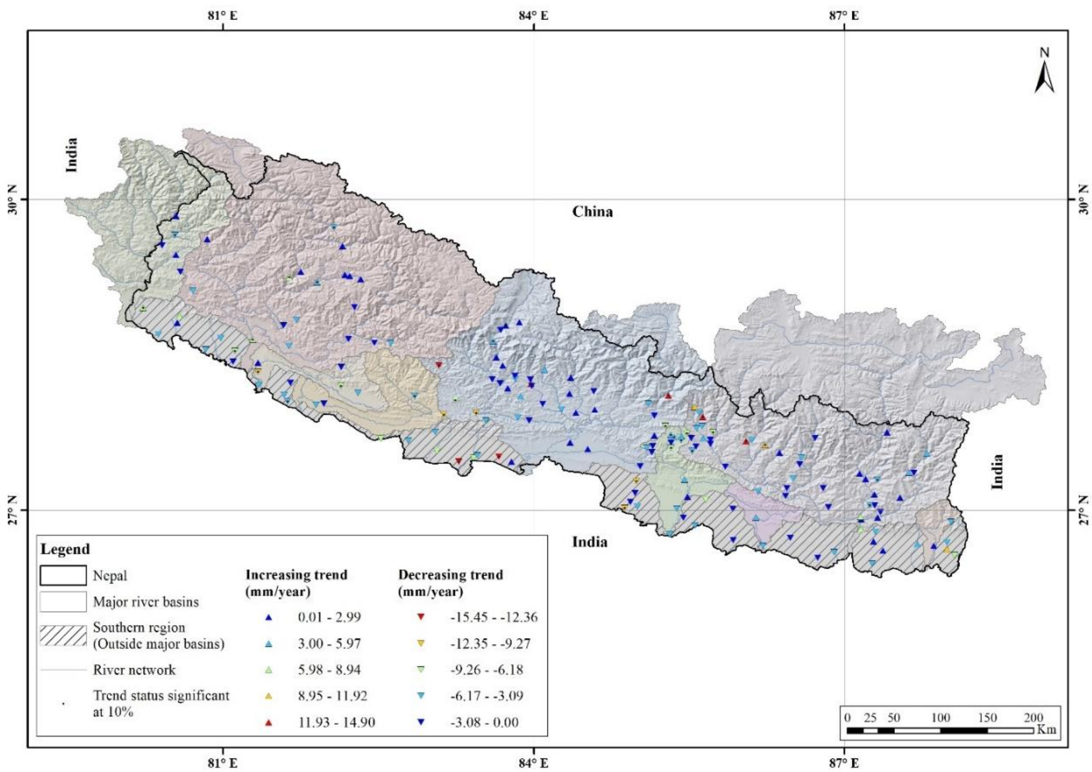


Figure 4-18 Trend of minimum temperature

Table 4-13 Temporal trend of maximum and minimum temperatures

Unit: °C/year

Temperature Type	Nepal	Koshi	Gandaki	Karnali	Remarks
Maximum	0.027	0.046	0.028	0.037	Higher than global warming rate (Nepal and all basins)
Minimum	0.015	0.009	0.020	0.002	Slightly lower than the global warming rate (Nepal). Koshi and Karnali less than global but not Gandaki basin

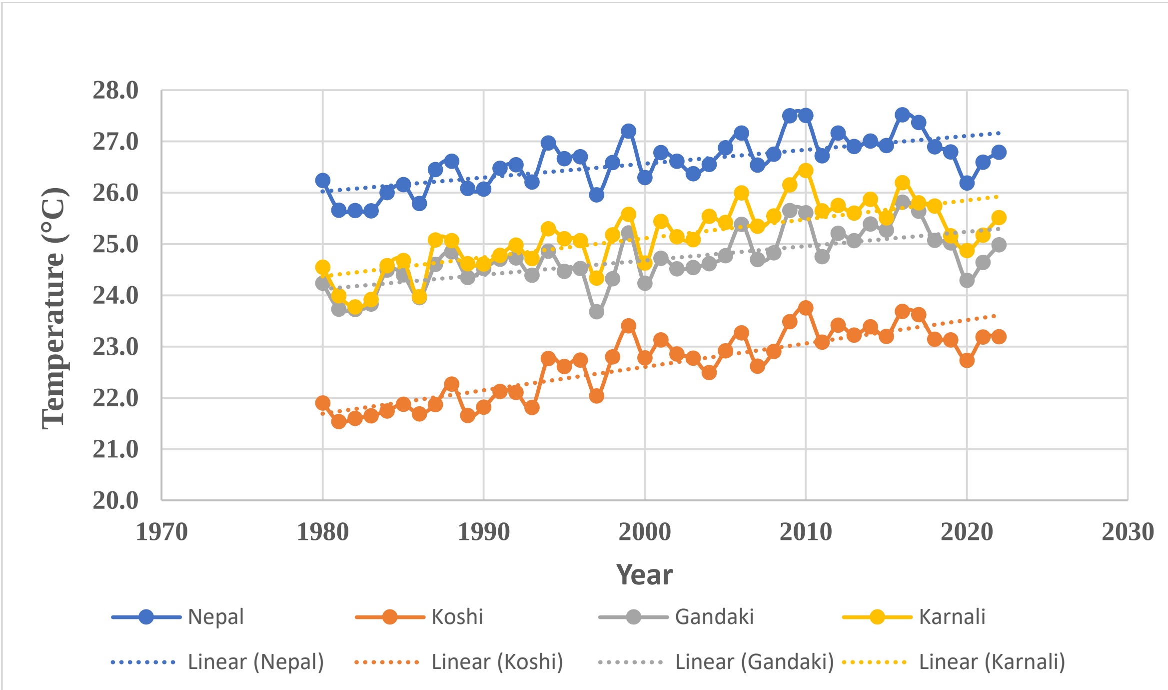


Figure 4-19 Temporal trend of maximum temperature

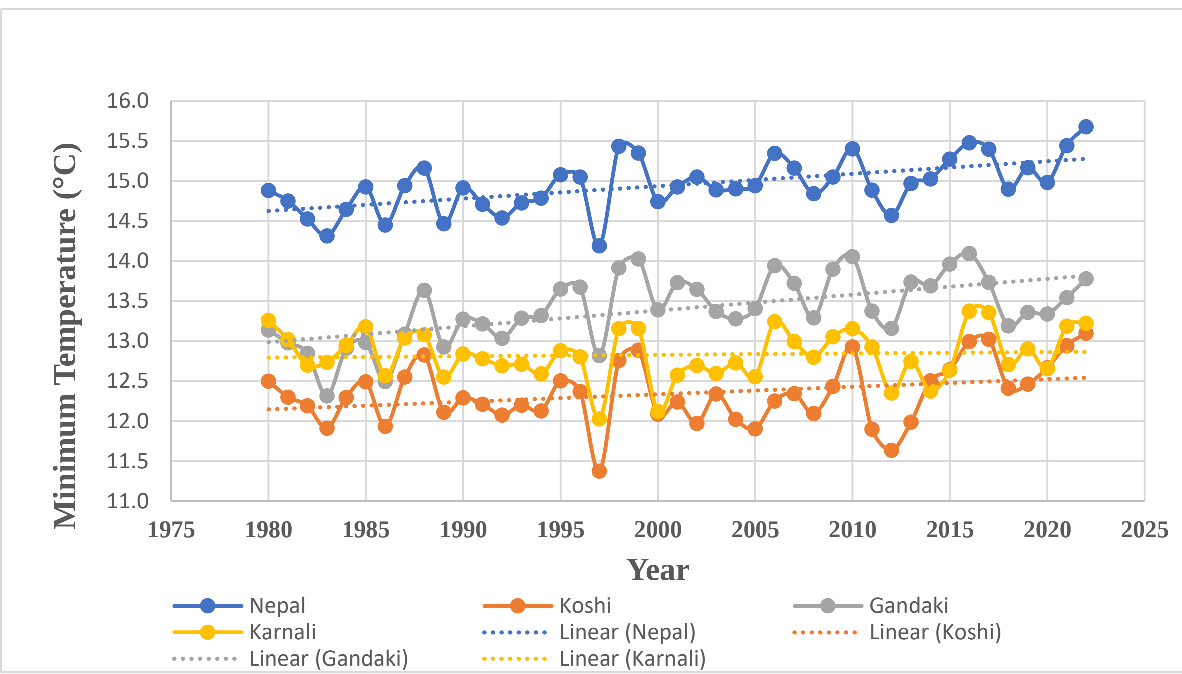


Figure 4-20 Temporal trend of minimum temperature

4.4 Analysis of Relative Humidity and Wind Speed

Relative humidity measures the amount of water vapor in the air relative to the maximum amount it can hold at a given temperature, expressed as a percentage. It plays a critical role in evaporation-transpiration rates: lower relative humidity accelerates these processes. Relative humidity also influences precipitation. When humidity nears 100%, the air becomes saturated, potentially resulting in rain or snow. Conversely, low relative humidity indicates dry conditions, which can lead to drought.

Wind speed significantly impacts the rate of evaporation-transpiration. Higher wind speeds enhance this process by dispersing the saturated layer of air above water surfaces or soil, enabling more water vapor to escape into the atmosphere.

Relative humidity and wind speed data from 62 locations were sourced from Open Data Nepal (2024). These datasets span the period from 1981 to 2019. In this study, relative humidity at 2 meters above the ground and wind speed at 10 meters above the ground were analyzed.

4.4.1 Temporal and Spatial Variation of Relative Humidity

The monthly variation of relative humidity (RH) based on data from these 62 locations is shown in **Figure 4-21**. It ranges from a minimum of 34% in March to a maximum of 84% in August, with an annual average of approximately 56%.

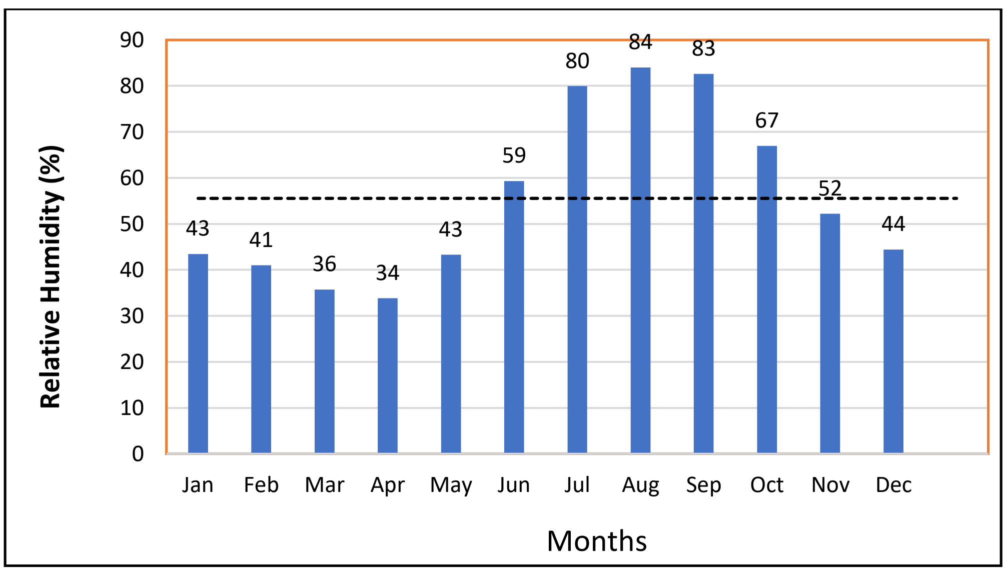


Figure 4-21 Monthly variation of relative humidity

From this figure, we observe that RH decreases in Nepal from September to April and begins to increase steadily until August. The long-term average RH values for the winter, pre-monsoon, monsoon, and post-monsoon seasons are 43%, 38%, 76%, and 60%, respectively. During the monsoon months (July–September), RH exceeds 80%.

The spatial variation in RH is also significant, with long-term average values ranging from 64% in Pachthar District to 47% in Bardiya District, as shown in **Figure 4-22**.

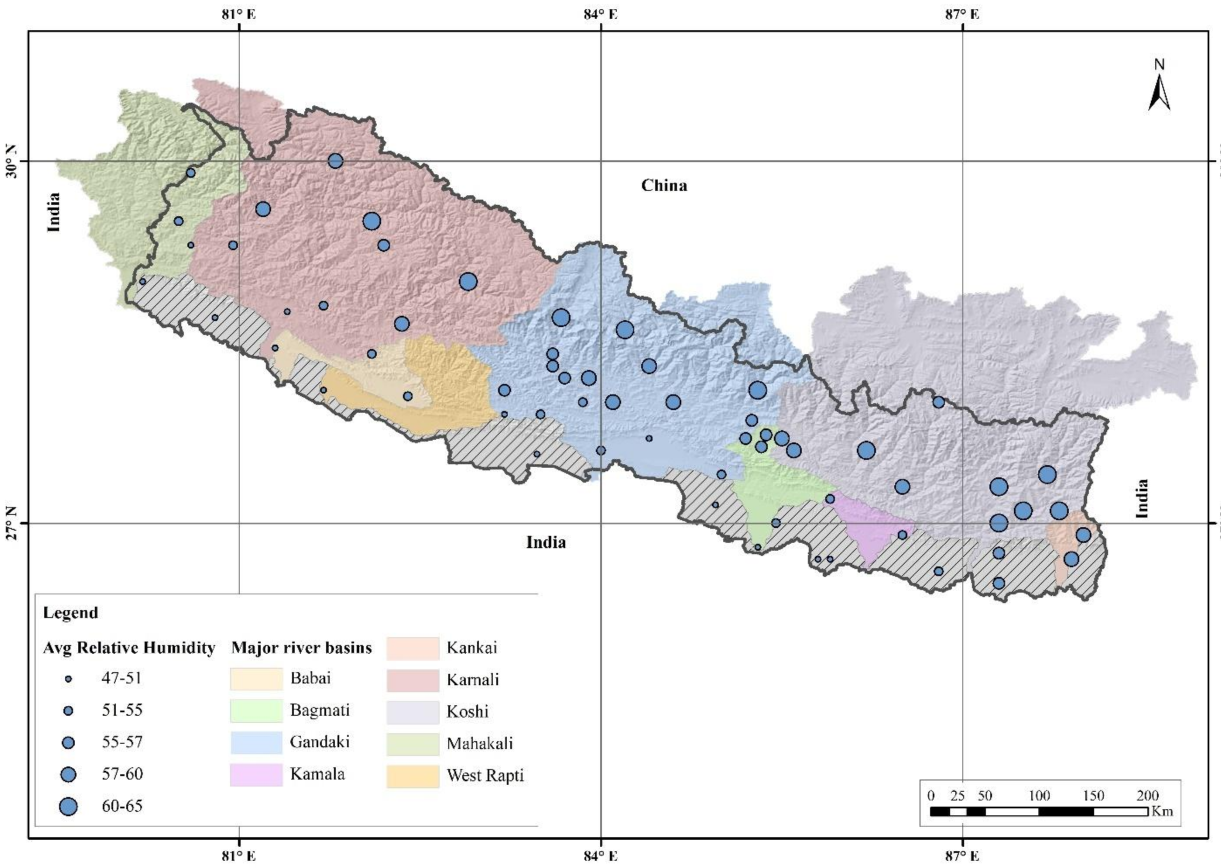


Figure 4-22 Spatial variation of relative humidity

4.4.2 Monthly and Seasonal Variation of Wind Speed

Long term monthly average wind speed calculated based on 62 locations of Nepal is plotted in **Figure 4-23**. The highest wind speed of 2.9 m/s occurred in April, while the lowest wind speeds (1.9 m/s) were recorded from October to December. It is interesting to note that wind speed increases from December to April and begins to decrease until October. The average wind speed across the 62 locations is 2.37 m/s. However, the values vary by location. For example, the long-term average in Solukhumbu is 3.4 m/s, while in Kathmandu, Lalitpur, Dhading, Dadeldhura, and Nuwakot, it is only 2.1 m/s. In Solukhumbu, the wind speed reached 5.8 m/s in February 1984. The spatial variation of the long-term average wind speed is shown in **Figure 4-24**.

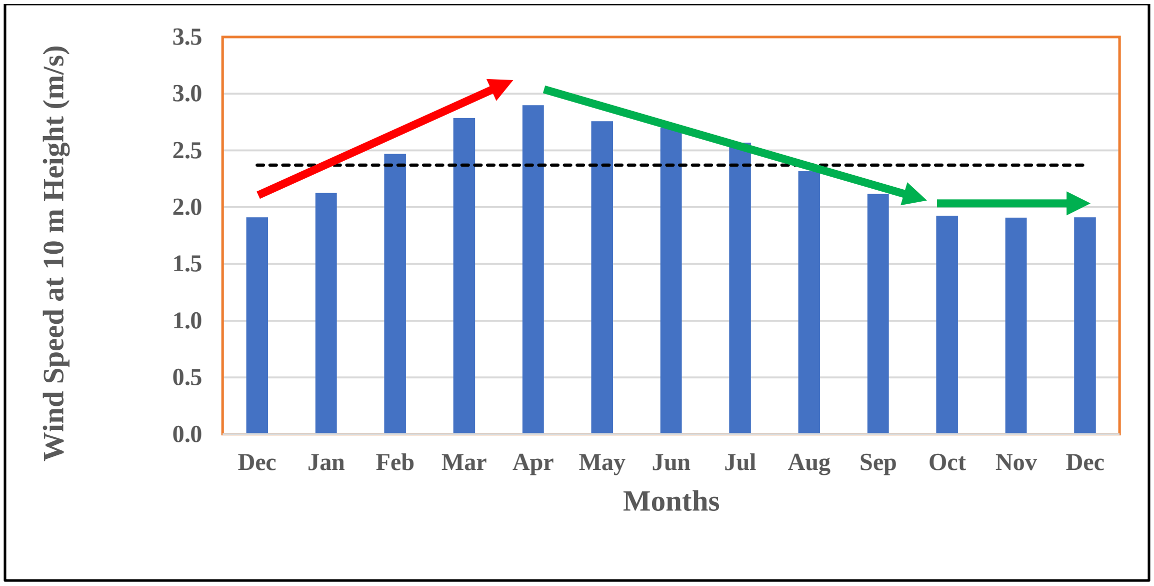


Figure 4-23 Monthly variation of wind speed

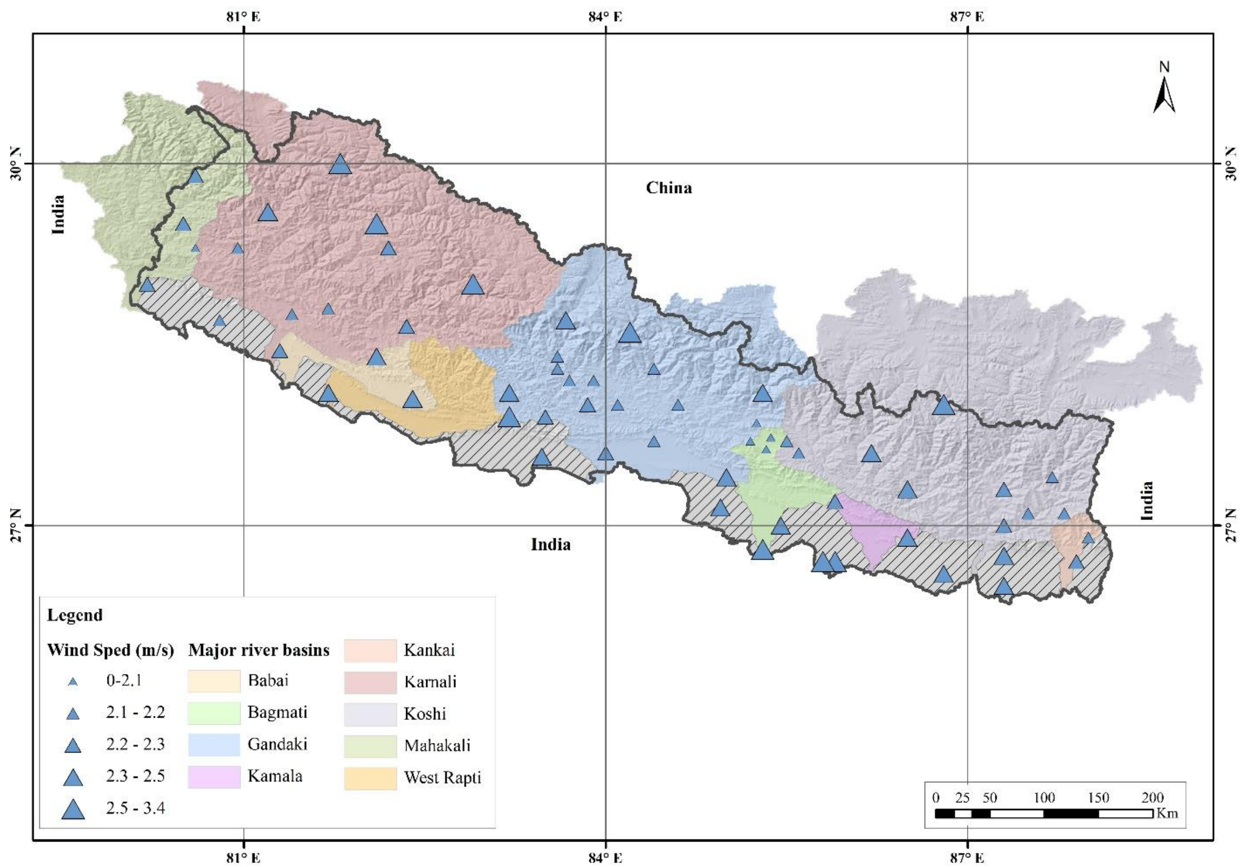


Figure 4-24 Spatial variation of wind speed

4.5 Analysis of Extreme Climates

4.5.1 Extreme Climate

Precipitation and temperature are the two primary parameters that govern the characteristics of a given location's climate. If the temperature is higher than the long-term average, the climate during that period is referred to as hot, while a lower temperature indicates a cold climate. Similarly, if precipitation is exceptionally high, it is described as a wet season or year, whereas low precipitation characterizes a dry period. The extreme climate of a given location for a specific year can be defined based on the annual values of these two parameters as shown in **Table 4-14** and illustrated schematically in **Figure 4-25**. This concept is adapted from Lutz et al. (2016).

Table 4-14 Possible extreme climate

SN	Climate Type	Temperature	Precipitation	Remarks
1	Hot-Dry	$T \geq T_{90}$	$P \leq P_{10}$	Temperature: High Precipitation: Low
2	Cold-Dry	$T \leq T_{10}$	$P \leq P_{10}$	Temperature: Low Precipitation: Low
3	Hot-Wet	$T \geq T_{90}$	$P \geq P_{90}$	Temperature: High Precipitation: High
4	Cold-Wet	$T \leq T_{10}$	$P \geq P_{90}$	Temperature: Low Precipitation: High

Here T: Annual average temperature value; P: Annual average precipitation value; P_x and T_x are x percentile of precipitation and temperature respectively.

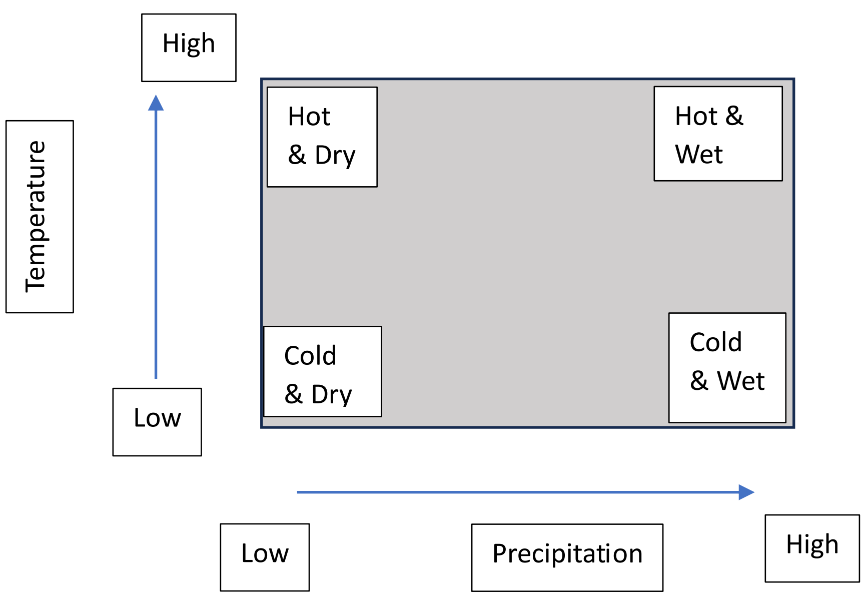


Figure 4-25 Schematic diagram of extreme climatic conditions

4.5.2 Assessment of Extreme Climate Years in Nepal

Data from 62 meteorological stations, each with precipitation and temperature records spanning from 1980 to 2022, were used to assess extreme climate years in Nepal. The 10th and 90th percentile values for both precipitation and temperature were calculated for each station, and the years during which extreme climates occurred at each station were identified. The year and the number of stations experiencing Hot-Dry, Cold-Dry, Hot-Wet, and/or Cold-Wet climates are listed in **Table 4-15**. Over the 43-year period, a total of 2,662 station-year data pairs were analyzed (43 years × 62 stations). Of these, 145 cases (just over 5%) were categorized as extreme climate events. These included 51 Hot-Dry cases, 31 Cold-Dry cases, 27 Hot-Wet cases, and 36 Cold-Wet cases. For example, in 1981, four stations experienced Cold-Dry climates, and two stations experienced Cold-Wet climates. The year 1983 recorded the highest number of stations with extreme climates, with 12 stations in total (5 Cold-Dry and 7 Cold-Wet). At least one station experienced some form of extreme climate in 36 of the 43 years. However, no station recorded extreme climate conditions in seven specific years: 1988, 1995, 1996, 2001, 2007, 2008, and 2018.

Table 4-15 Number of stations with extreme climate

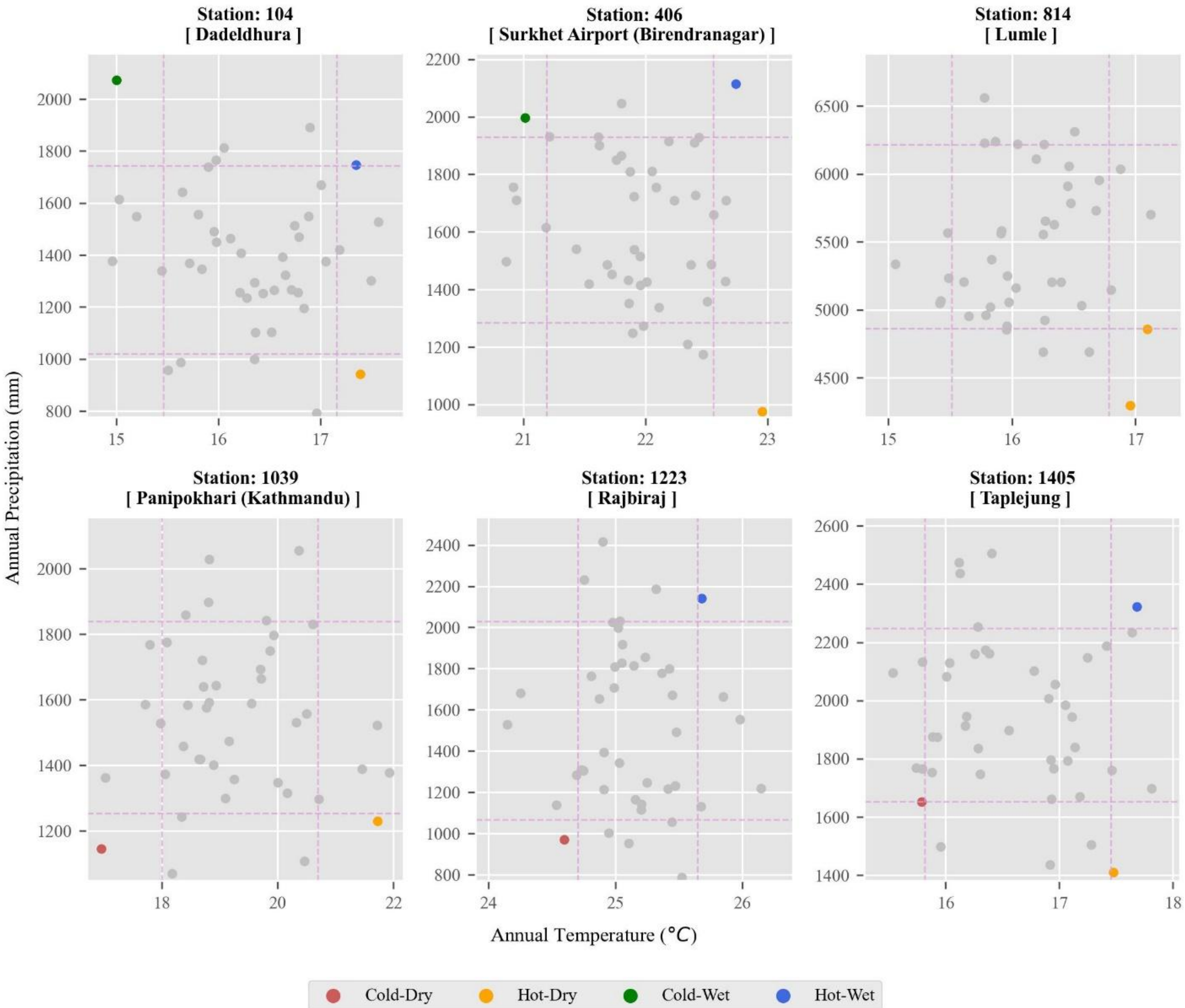
Year	Hot-Dry	Cold-Dry	Hot-Wet	Cold-Wet	Total
1980		3			3
1981		4		2	6
1982		6		2	8
1983		5		7	12
1984		1		2	3
1985		1		1	2
1986		3		1	4
1987	1			1	2
1988					0
1989		1		6	7
1990	1				1
1991	1				1
1992	1	1			2
1993	2			1	3
1994	2			1	3
1995					0
1996					0
1997		1		1	2
1998		1	4		5
1999			3		3
2000			1	2	3
2001					0
2002	2			1	3
2003			1		1

Year	Hot-Dry	Cold-Dry	Hot-Wet	Cold-Wet	Total
2004		1		1	2
2005	1				1
2006	9				9
2007					0
2008					0
2009	7		1		8
2010	4		1		5
2011	1	1			2
2012	3	2	1		6
2013			2		2
2014	1				1
2015	6				6
2016	4		2		6
2017	3		1		4
2018					0
2019	2				2
2020				4	4
2021			5	1	6
2022			5	2	7
Total	51	31	27	36	145

The basin-wise distribution of extreme climates is presented in **Table 4-16**. Hot-Dry extreme climates are more dominant than other extremes in the Gandaki and Karnali basins. However, this is not the case for the Koshi basin, where Cold-Dry and Hot-Wet extremes are more prevalent. The Gandaki basin shows a clear dominance of dry climates, with 13 Hot-Dry and 10 Cold-Dry cases recorded. Three basins have experienced no extreme climate events over the past 43 years. Number of extreme climates of some stations are shown in **Figure 4-26.** The spatial distribution of four climate extremes at selected meteorological stations in Nepal are depicted in **Figure 4-27, Figure 4-28, Figure 4-29, Figure 4-30** and **Figure 4-31**.

Table 4-16 Basin wise distribution of extreme climate

No. of Stations	Extremes Climate Events	Hot-Dry	Cold-Dry	Hot-Wet	Cold-Wet	Total
62	Nepal	51	31	27	36	145
8	Koshi	5	8	7	4	24
16	Gandaki	13	10	2	5	30
10	Karnali	9	2	6	7	24
1	Mahakali	0	0	0	0	0
1	Kankai	0	0	0	0	0
4	Bagmati	2	3	2	0	7
2	West Rapti	0	0	0	0	0
3	Babai	2	0	1	2	5


Station: 104
[Dadeldhura]
Station: 406
[Surkhet Airport (Birendranagar)]
Station: 814
[Lumle]
Station: 1039
[Panipokhari (Kathmandu)]
Station: 1223
[Rajbiraj]
Station: 1405
[Taplejung]
Annual Precipitation (mm)
Annual Temperature (°C)
Cold-Dry
Hot-Dry
Cold-Wet
Hot-Wet

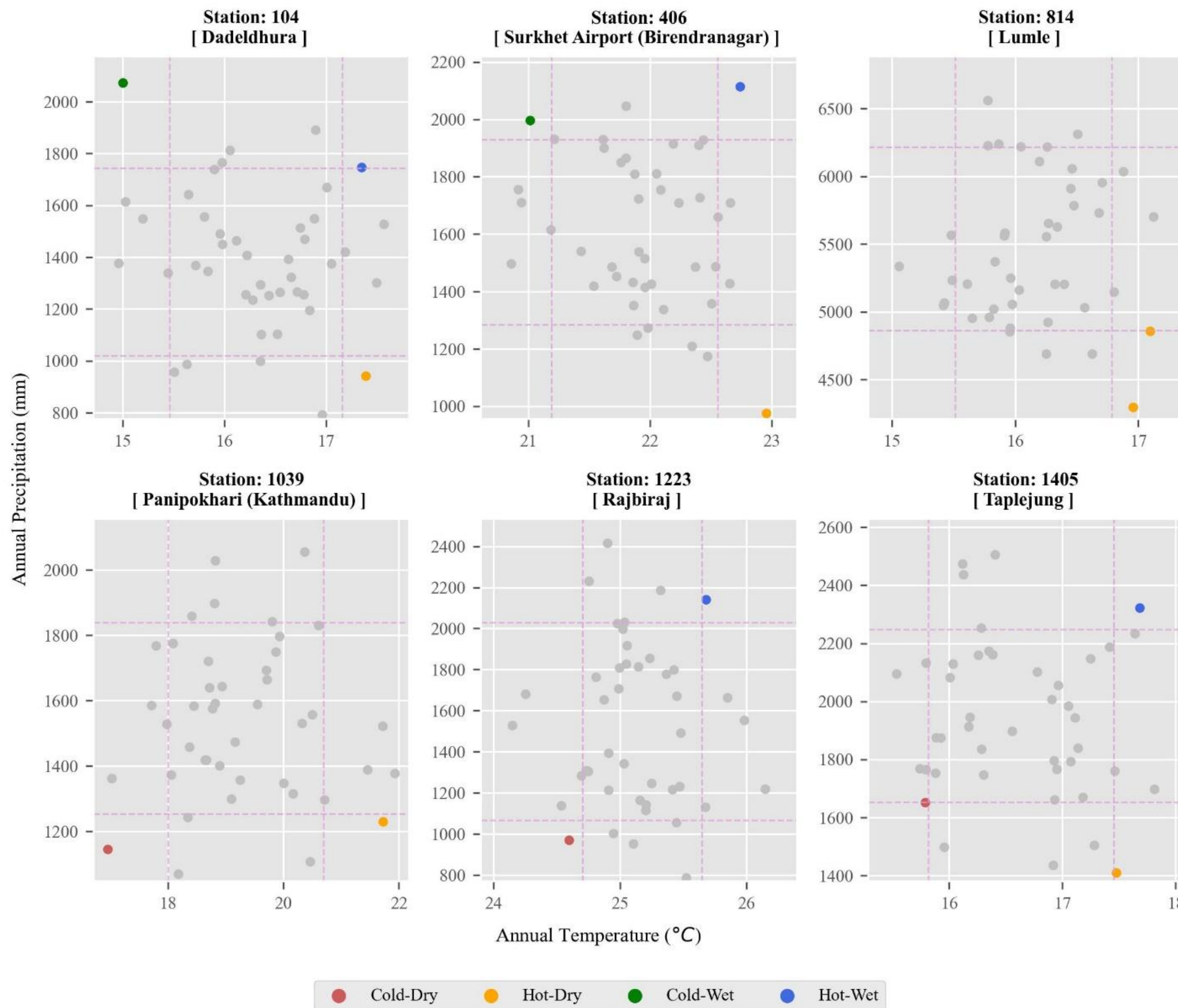


Figure 4-26 Examples of extreme climate years at different stations

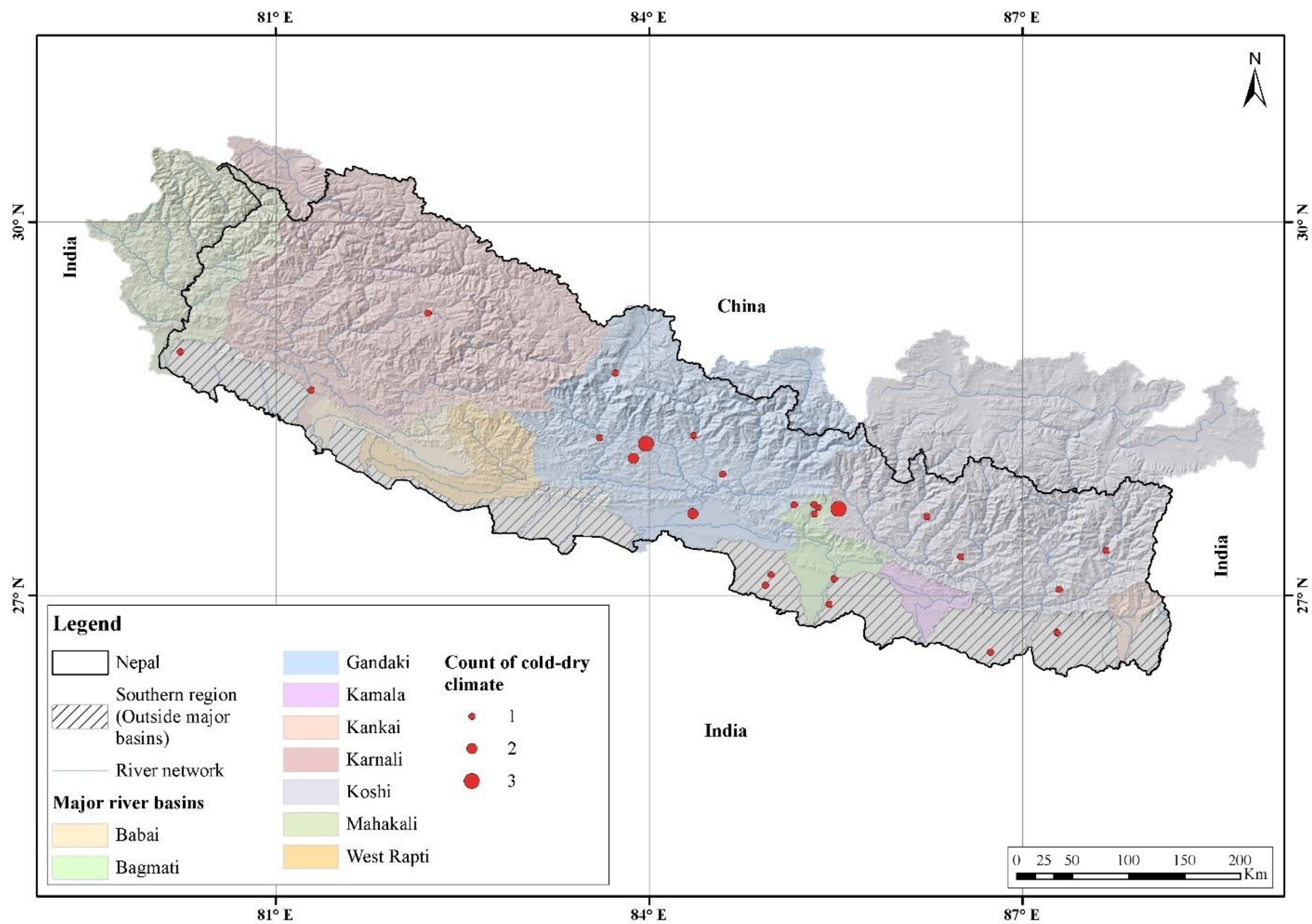


Figure 4-27 Spatial distribution of cold-dry climate of Nepal

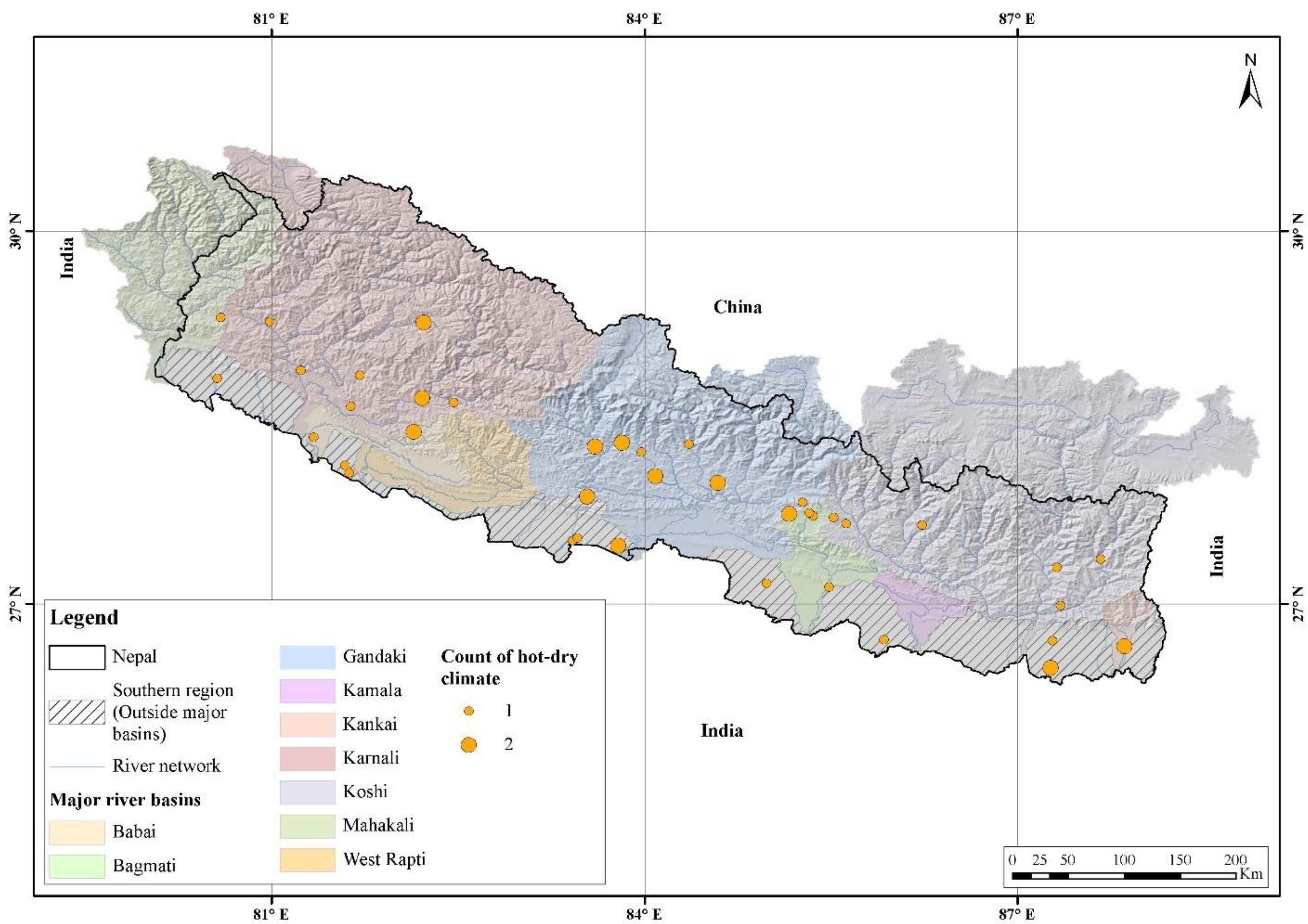


Figure 4-28 Spatial distribution of hot-dry climate of Nepal

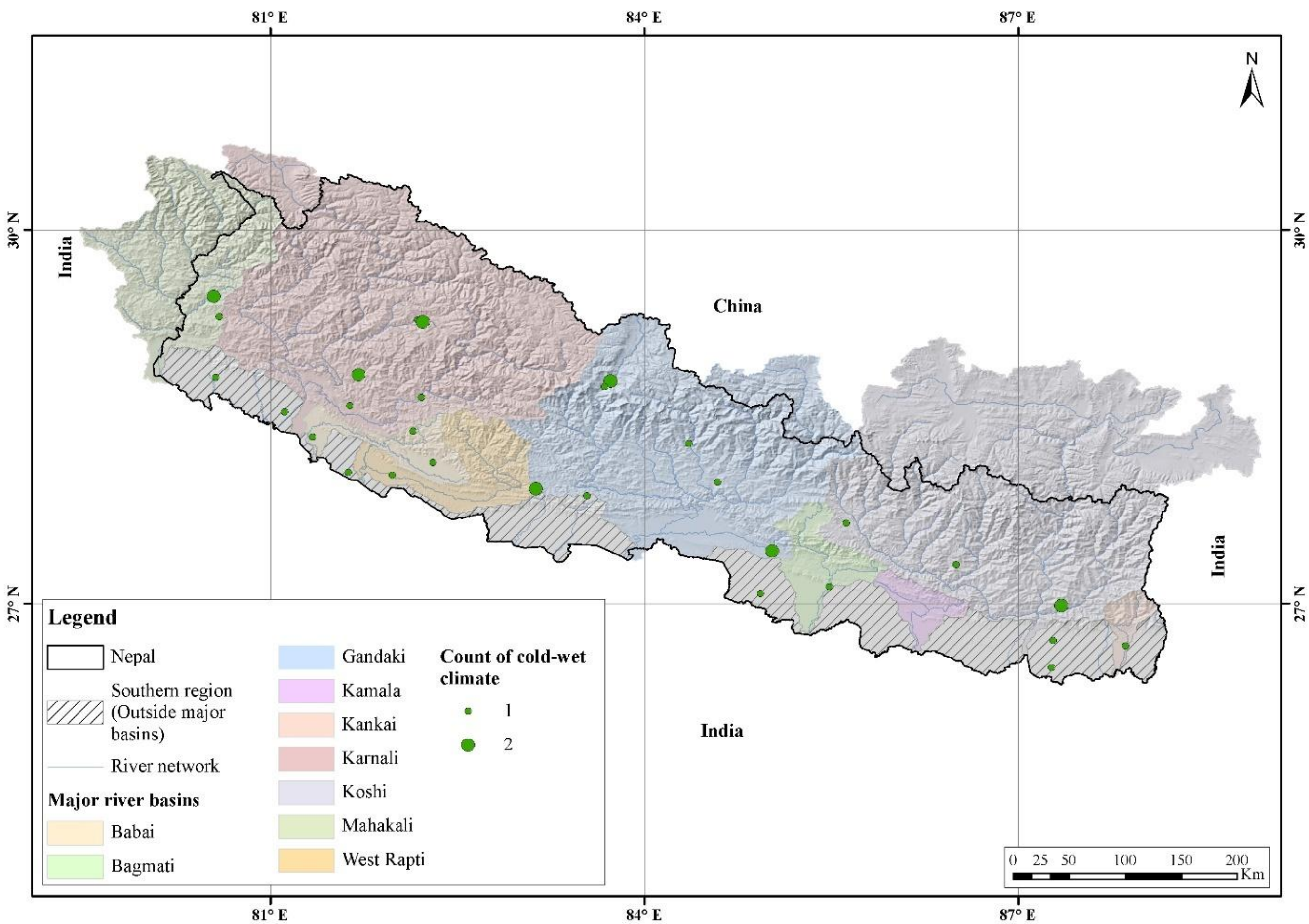


Figure 4-29 Spatial distribution of cold-wet climate of Nepal

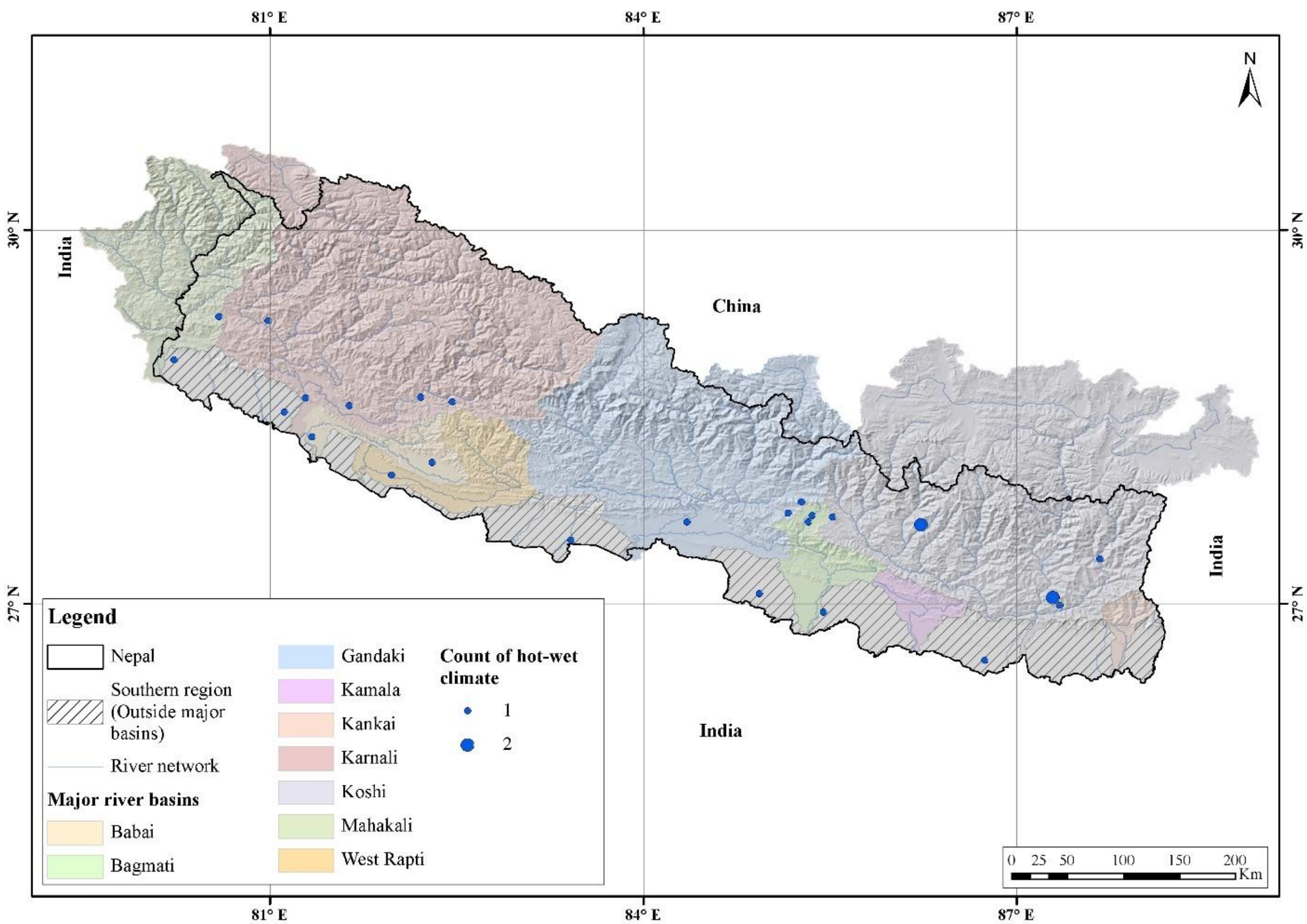


Figure 4-30 Spatial distribution of hot-wet climate of Nepal

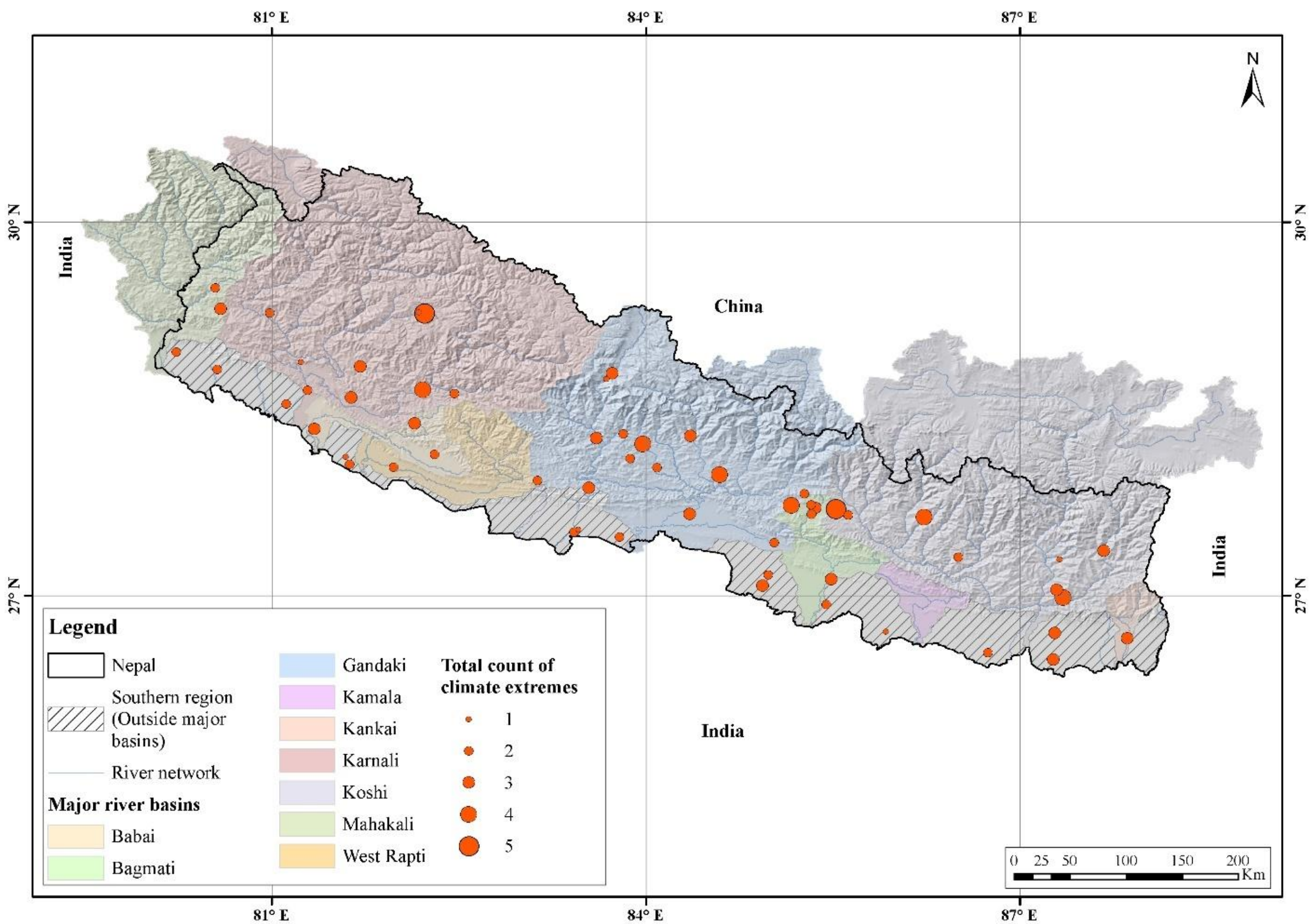


Figure 4-31 Spatial distribution of all four extreme climates in Nepal

4.6 Regional Climate Indices

The climate indices—namely the Arctic Oscillation (AO) Index, North Atlantic Oscillation (NAO), Dipole Mode Index (DMI), Niño 3.4 Sea Surface Temperature (SST) Anomalies, and Southern Oscillation Index (SOI)—were compared to the overall climate of Nepal. The comparison was based on the correlation results between the Percentage Departure of Nepal Rainfall (PNR) and these anomalies, following the approach of Shrestha (2000). Mathematically, for the seasonal precipitation P with a mean $\bar{P}$, PNR was calculated using **Equation (4-10)**.

$$PNR = \frac{P-\bar{P}}{\bar{P}} * 100\% \tag{4-10}$$

The graphical comparison of the PNR for monsoon and annual scale with the climate indices is shown in **Figure 4-32**, **Figure 4-33**, **Figure 4-34**, and **Figure 4-35** respectively. The comparison for monsoon and annual timescale shows that the Southern Oscillation Index (SOI) and Niño 3.4 Sea Surface Temperature (SST) Anomalies reflect a stronger correlation with PNR better in comparison with other indices. As the PNR swings towards a positive spell, the SOI has also been observed to swing towards the positive spell, but in the case of Niño 3.4 Sea Surface Temperature (SST) Anomalies, an opposite pattern exists. As the PNR shifts towards the positive region, the SST anomalies shift towards the negative zone. The results of such relations have also been presented in **Table 4-17**, which agrees with the aforementioned discussions. In addition to this, the table also shows the significance of the correlation. It has been observed that the Niño 3.4 Sea Surface Temperature (SST) Anomalies and Southern Oscillation Index (SOI) show significant results for monsoon and annual scale at the confidence of p=0.05. For the post-monsoon, the index Dipole Moment Index (DMI) shows a significant correlation of -0.2712 at p=0.1. Such results show that the anomalies in the sea surface temperature of the Nino 3.4 regions and sea pressure in the Pacific Ocean can have a significant impact on the climate systems of Nepal. Similar graphical comparisons for other seasons are provided in **Appendix B (Figure B-1, Figure B-2, Figure B-3, Figure B-4, Figure B-5, and Figure B-6**).

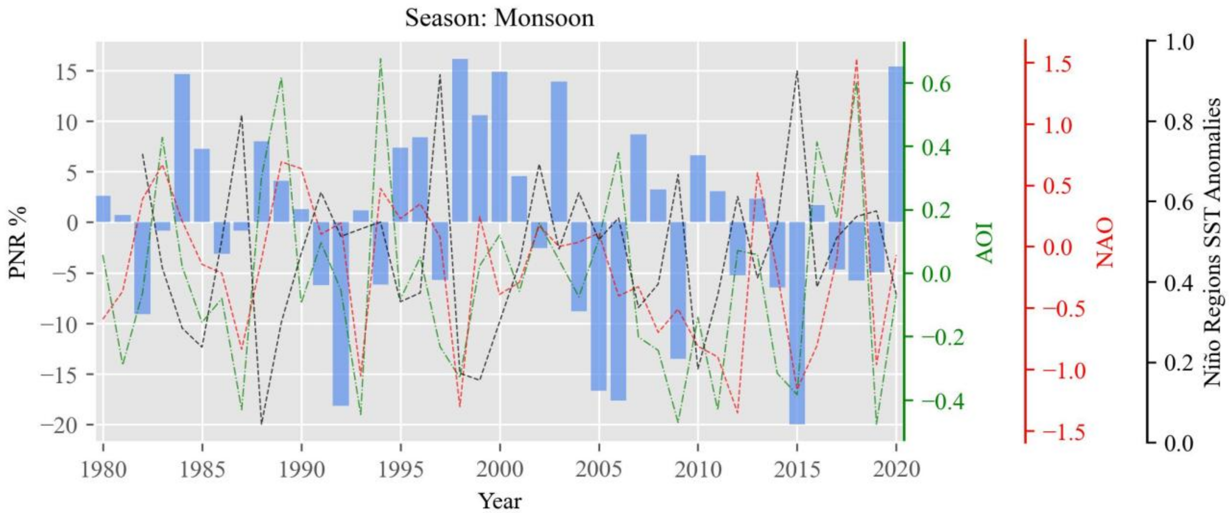


Figure 4-32 Comparison of PNR with AOI, NAO, and SST

Note: PNR: blue bars plotted on the primary y-axis;
AOI, NAO, and Nino Regions SST anomalies: plotted on the secondary y-axis

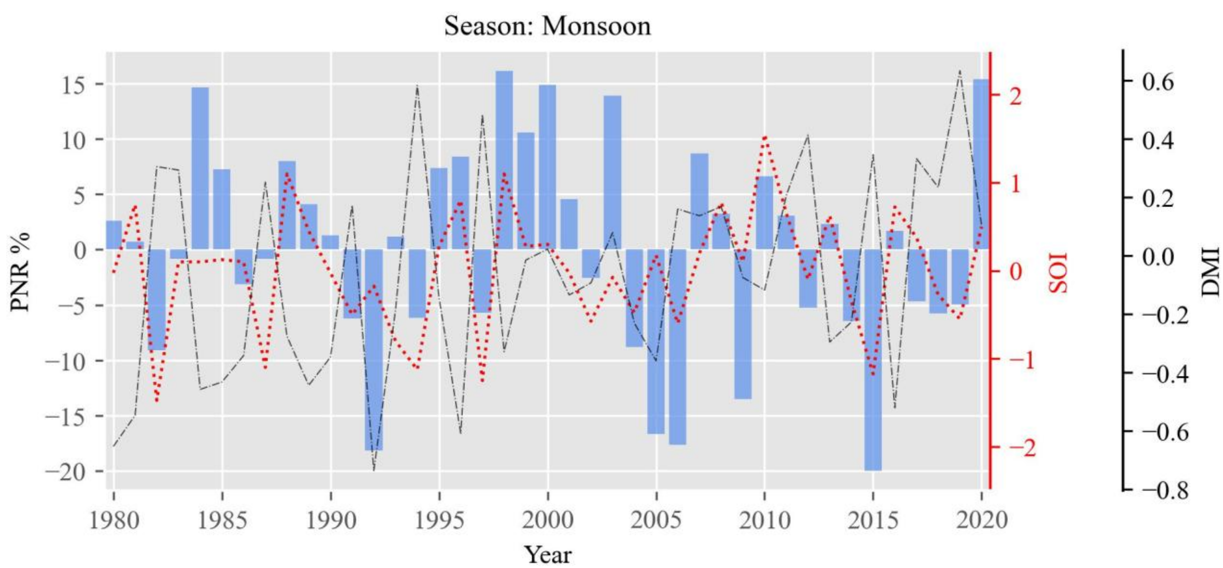


Figure 4-33 Comparison of PNR% with SOI and DMI at monsoon scale

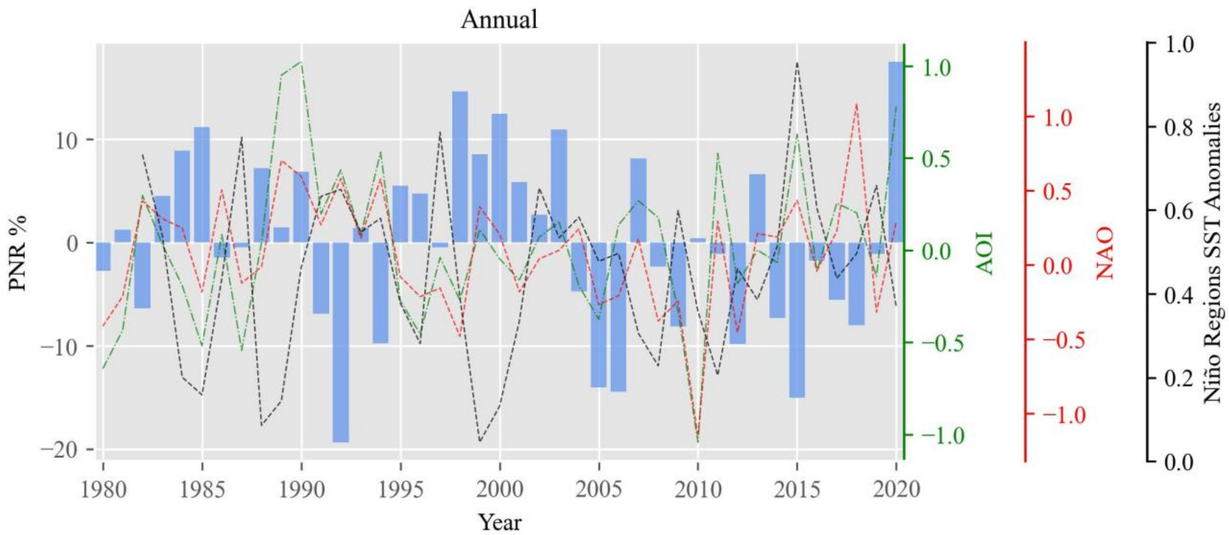


Figure 4-34 Comparison of PNR with AOI, NAO, and SST anomalies at annual scale

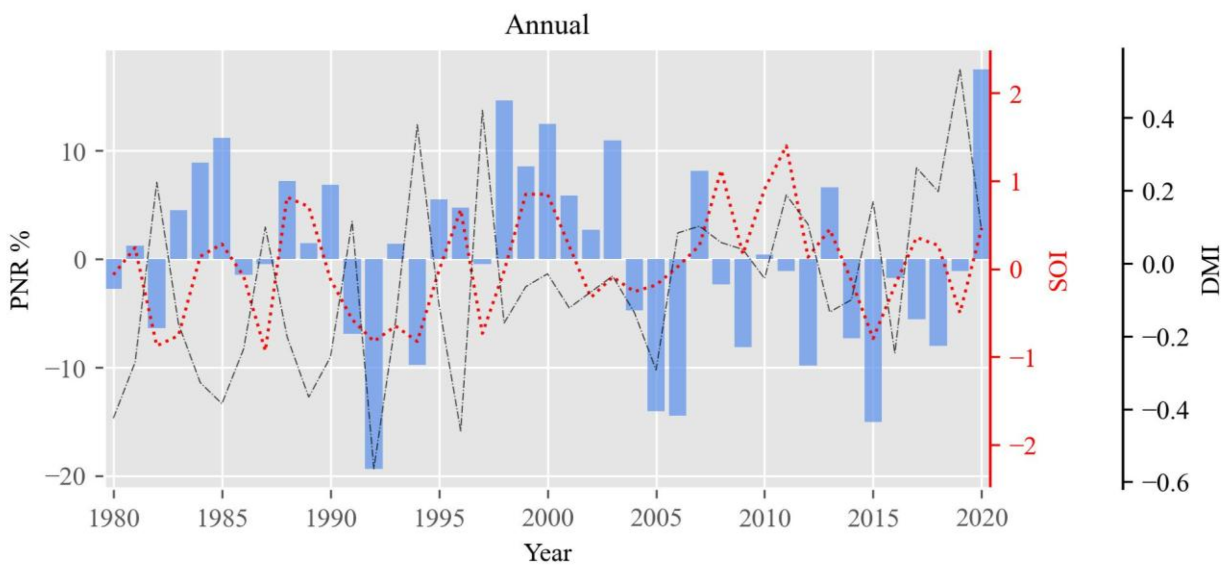


Figure 4-35 Comparison of PNR% with SOI and DMI at annual scale

Table 4-17 Correlation results of PNR at different seasonal timescale with the climate indices

Season	AOI	DMI	NAO	NR SST Anomalies	SOI
Winter	0.200	0.217	0.059	0.146	-0.140
Pre-Monsoon	0.231	0.174	0.093	-0.042	0.085
Monsoon	-0.008	-0.217	-0.018	-0.713*	0.564*
Post-Monsoon	0.030	-0.271**	0.035	-0.125	-0.080
Annual	-0.063	-0.180	-0.103	-0.561*	0.400*

The symbols * and ** represent significance at p=0.05 and p=0.01 confidence levels respectively.

4.7 Empirical Orthogonal Function Analysis

Empirical Orthogonal Function (EOF) analysis is utilized in climate science to study spatial patterns of climate variability and to understand how these patterns develop over time. (NCAR, 2013). In this method, the spatiotemporal climate variable can be eigenvectors, known as loading patterns, along with their associated principal component (PC) time series., as shown below (Sun et al., 2022):

Empirical Orthogonal Function (EOF) analysis is widely used in climate science to study spatial patterns of climate variability and to understand how these patterns evolve over time (NCAR, 2013). In this method, the spatiotemporal climate variable $Y_{s,t}$can be expressed through eigenvectors, known as loading patterns, along with their associated principal component (PC) time series, as described in **Equation (4-11)** (Sun et al., 2022):

$$Y_{s,t} = \sum_k PC_k(t) * \Lambda_{k_s} \tag{4-11}$$

Where,

Λ_{k_s} represents a distinct spatial pattern and

$PC_k(t)$ describes the temporal evolution of Λ_{k_s}.

This equation expresses a decomposition of the original dataset into several spatial (s) and temporal components (t). The spatial components Λ_{k_s} are mutually orthogonal and are ranked by $PC_k(t)$ describe oscillations in time. The eigenvectors (loading patterns) represent the independent modes of variability in the dataset and are often interpreted as physical features or phenomena within the system being analyzed.

In this study, rainfall anomalies from 179 stations are analyzed using EOF analysis to identify the main patterns of variability across different seasons. The analysis is performed separately for summer and winter to capture seasonal differences in rainfall behavior. The summer season is defined as the months of June through September (*JJAS*), while the winter season spans from December to February (*DJF*). By analyzing these two distinct periods, the study aims to better understand how rainfall variability changes between the wet and dry seasons and to isolate the dominant spatial and temporal patterns driving these anomalies.

The scree plot (**Figure 4-36**) illustrates the variance explained by each mode for both winter and summer. In the winter plot, Mode 1 accounts for 58.04% of the total variance, with a steep drop to Mode 2 at 7.21%, followed by smaller contributions from subsequent modes (Mode 3: 4.50%, Mode 4: 2.69%, etc.), indicating that most variance is explained by the first two modes. In contrast, the summer plot shows Mode 1 explaining 21.72% of the variance, followed by Mode 2 at 9.45%, with a more gradual decline in variance across the next modes (Mode 3: 6.37%, Mode 4: 5.94%, etc.). This indicates that the variance in winter is predominantly captured by the first mode, whereas in summer, the variance is relatively spread across several modes, highlighting the importance of considering additional modes in summer analysis. We focused on the first three modes for further analysis, as they account for 69.75% of the variance in winter and 37.54% of the variance in summer.

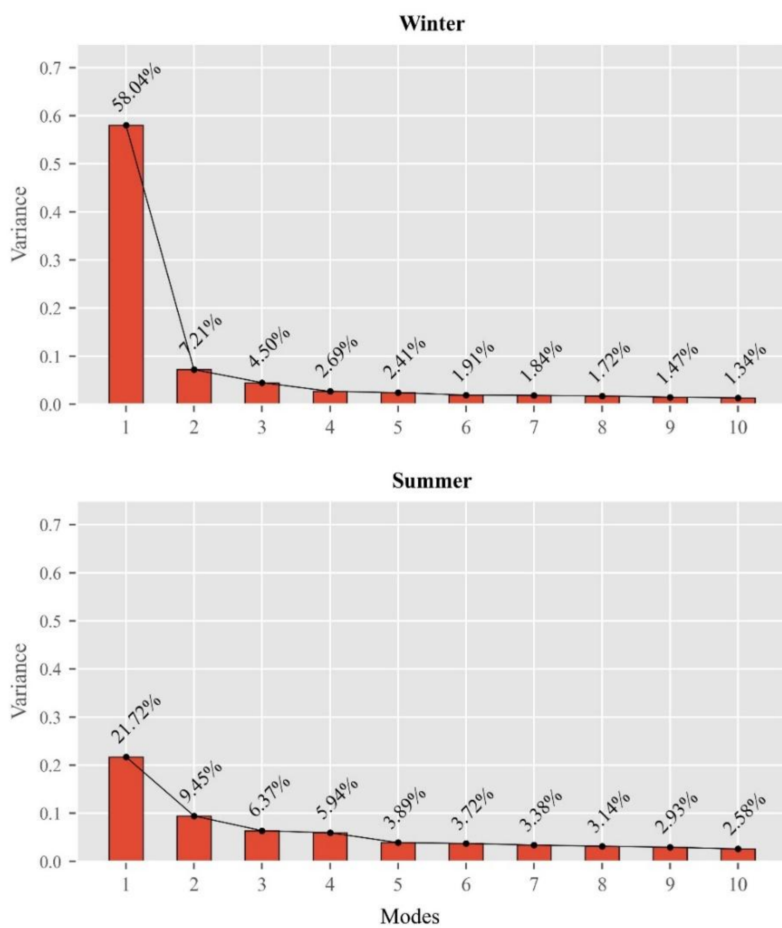


Figure 4-36 Scree plot of EOF for winter and summer seasons

Figure 4-37 illustrates the spatial patterns derived from an EOF analysis conducted on rainfall anomalies in Nepal during the summer season. The three panels represent the first, second, and third EOF modes for summer rainfall, with each mode capturing distinct aspects of rainfall variability. Analyzing these EOF modes is essential for identifying the primary spatial patterns of variability and their corresponding temporal changes. In the summer EOF1, the highest loadings are predominantly concentrated in central Nepal, as well as along the lower belt in the eastern and western parts of the country. For EOF2, a distinct dipole pattern is evident, with positive loadings in the western region and negative loadings in the east, highlighting contrasting rainfall variability between these areas. In EOF3, the strongest loadings are primarily located in the northern regions of Nepal, with a particularly large concentration between the eastern and the central portion of the country. The corresponding Principal Components (PCs) associated with the EOF modes, when compared to various climate indices, produced the results presented in **Table 4-18**. The PCs, along with the different climate indices, are illustrated in the **Figure 4-38**. The table presents the correlation coefficients between the Principal Components (PCs) derived from the EOF analysis and various climate indices, including the Arctic Oscillation Index (AOI), Dipole Mode Index (DMI), North Atlantic Oscillation (NAO), Niño 3.4 sea surface temperature anomalies (NINO, representing variations in sea surface temperatures in the Niño 3.4 region, a key indicator of El Niño and La Niña events), and the Southern Oscillation Index (SOI). Statistically significant correlations (with a p-value less than 0.1) are highlighted in bold and italics, signifying meaningful relationships.

For PC1, the Niño 3.4 sea surface temperature anomalies show a strong negative correlation (-0.635), indicating that warmer sea surface temperatures in the Niño 3.4 region significantly impact the dominant rainfall variability pattern in the region. Meanwhile, the SOI has a positive correlation (0.462), implying that La Niña-like conditions are associated with increased variability in PC1. PC2 also shows a positive correlation with the SOI (0.432), further suggesting that La Niña events influence this secondary mode of variability. For PC3, none of the climate indices exhibit statistically significant correlations, indicating that the third mode of variability may not be strongly influenced by these large-scale climate factors. The significant correlations with NINO and SOI emphasize the dominant role of ENSO (El Niño-Southern Oscillation) in shaping rainfall variability in the study area.

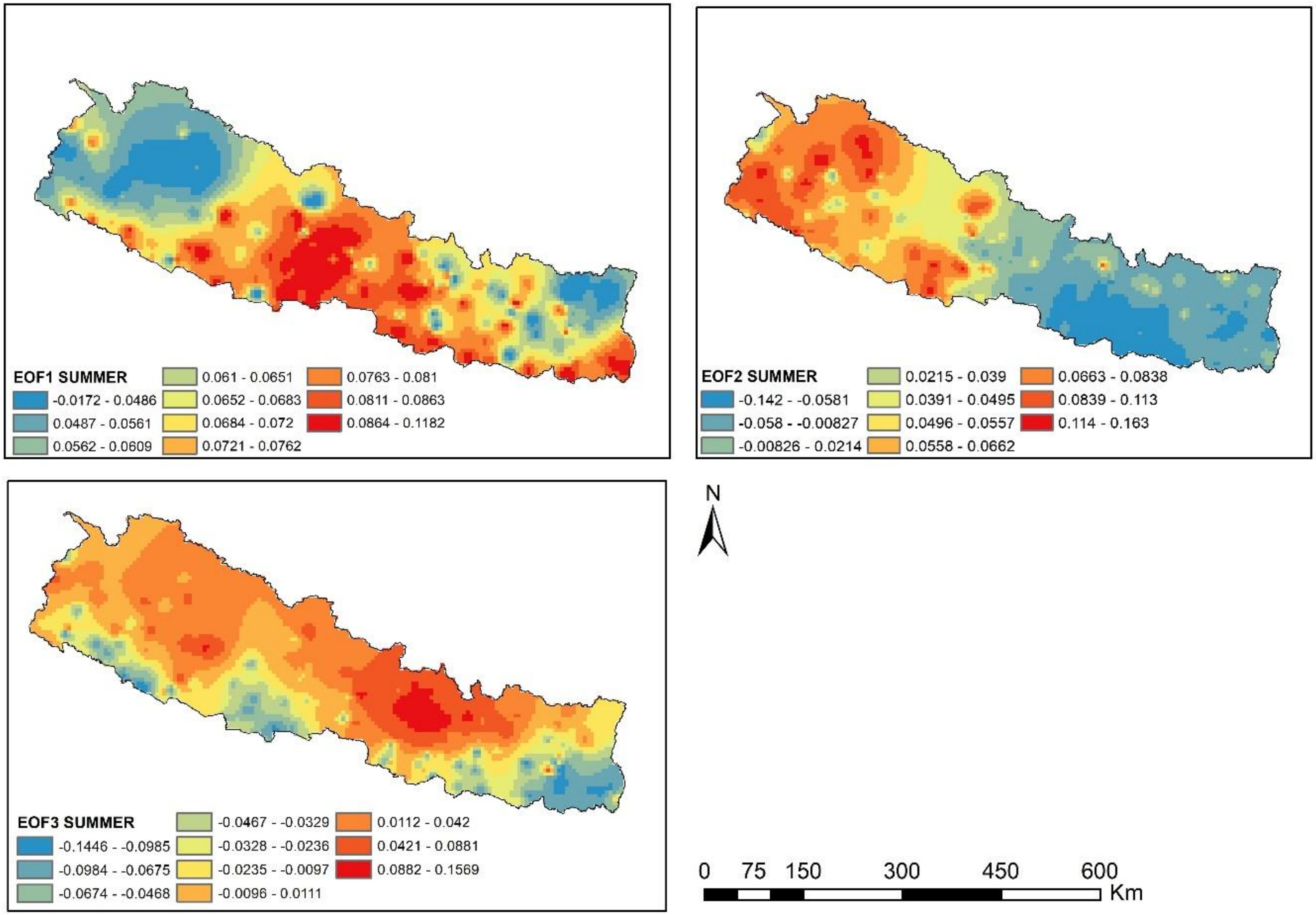


Figure 4-37 Spatial patterns of summer rainfall anomalies in Nepal: EOF Modes 1, 2, and 3

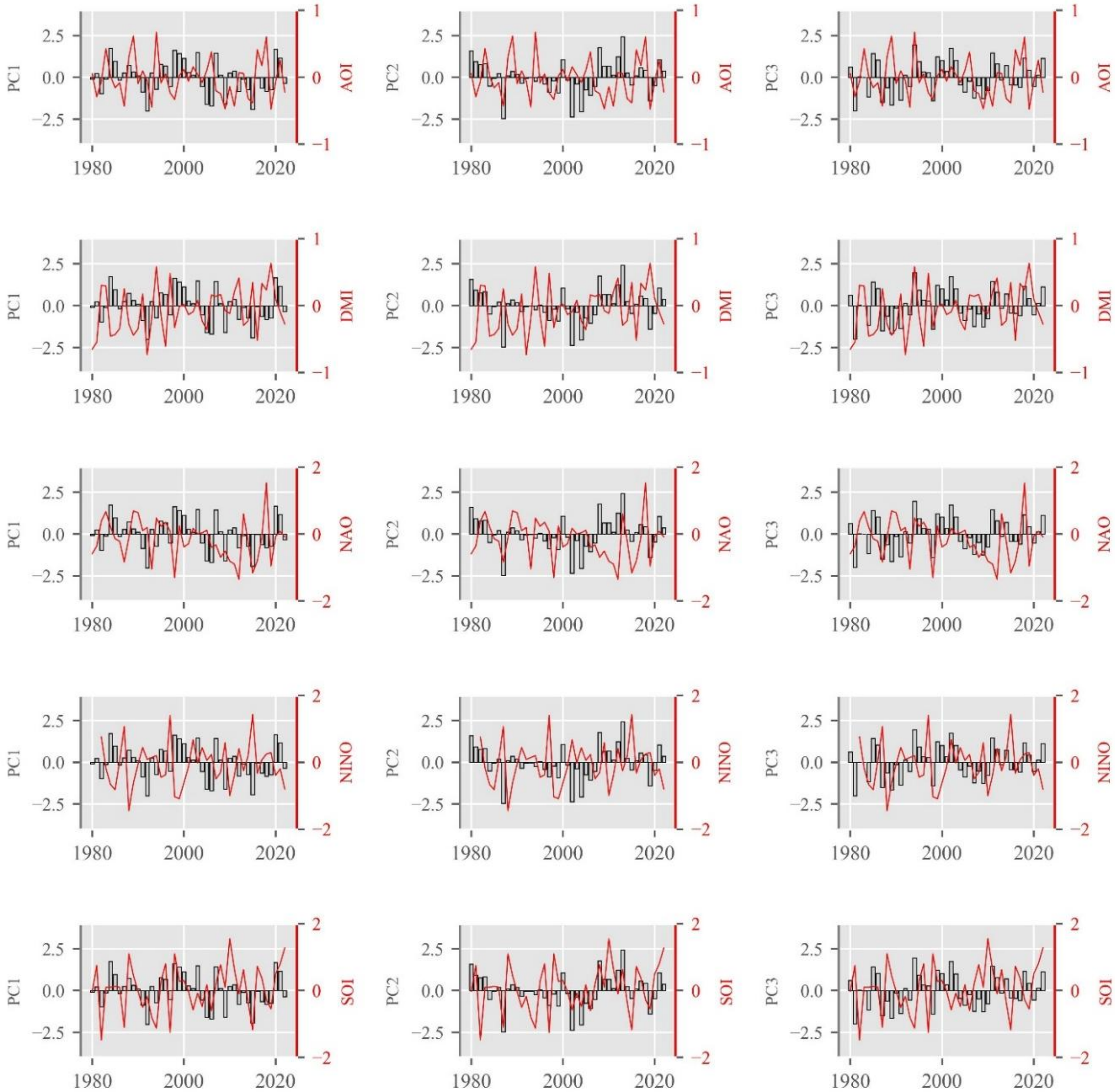


Figure 4-38 Summer principal components related to selected EOF modes and various climate

Table 4-18 Correlation Coefficient between Summer PCs and Climate Indices

	Correlation Coefficient		
Climate Indices	**PC1**	**PC2**	**PC3**
AOI	-0.025	0.137	0.181
DMI	-0.202	-0.165	0.190
NAO	-0.002	0.049	0.200
NINO	***-0.635***	***-0.311***	-0.006
SOI	***0.462***	***0.432***	-0.157

Note: Bold and Italic Numbers represent statistically significant with $p<0.1$.

Figure 4-39 illustrates the spatial patterns derived from an Empirical Orthogonal Function (EOF) analysis conducted on rainfall anomalies in Nepal during the winter season. In Winter, EOF1 exhibits higher loadings concentrated in the central and western regions of the country, with positive loadings observed throughout. Conversely, EOF2 reflects a dipole pattern similar to that seen in summer. For EOF3, weak loadings are mostly found in the central parts of the country compared to other regions. **Table 4-19** highlights the correlation coefficients between the winter Principal Components (PCs) and various climate indices. The PCs, along with the different climate indices, are illustrated in the **Figure 4-40**. The results show that for PC1, there is a statistically significant positive correlation of 0.321 with the Dipole Mode Index (DMI) and a significant negative correlation of -0.285 with the Southern Oscillation Index (SOI), indicating these two indices may influence the first mode of winter rainfall variability in Nepal. Other indices, such as the Arctic Oscillation Index (AOI), North Atlantic Oscillation (NAO), and Niño 3.4 (NINO), show weaker, non-significant correlations with PC1.

PC2 presents a slightly stronger correlation with the NAO at 0.238, though this remains statistically insignificant, suggesting that the influence of the NAO on winter rainfall variability, while present, may not be strong enough to be conclusive. Finally, PC3 has no significant correlations with any of the climate indices, with correlations ranging from -0.218 to 0.163. This implies that the third mode of variability in winter rainfall is not meaningfully connected to the climate indices considered in this analysis.

Overall, these findings indicate that among the climate indices examined, DMI and SOI have the most influence on winter rainfall patterns in Nepal, particularly through their connection to PC1. The other indices show weaker or insignificant relationships, suggesting that additional factors not analyzed in this study may play a more prominent role in shaping winter rainfall variability.

Table 4-19 Correlation Coefficient between Winter PCs and Climate Indices

	Correlation Coefficient		
Climate Indices	**PC1**	**PC2**	**PC3**
AOI	0.240	0.229	0.035
DMI	***0.321***	-0.025	-0.218
NAO	0.079	0.238	0.163
NINO	0.233	-0.008	0.032
SOI	***-0.285***	-0.014	-0.156

Note: Bold and Italic Numbers represent statistically significant with p<0.1.

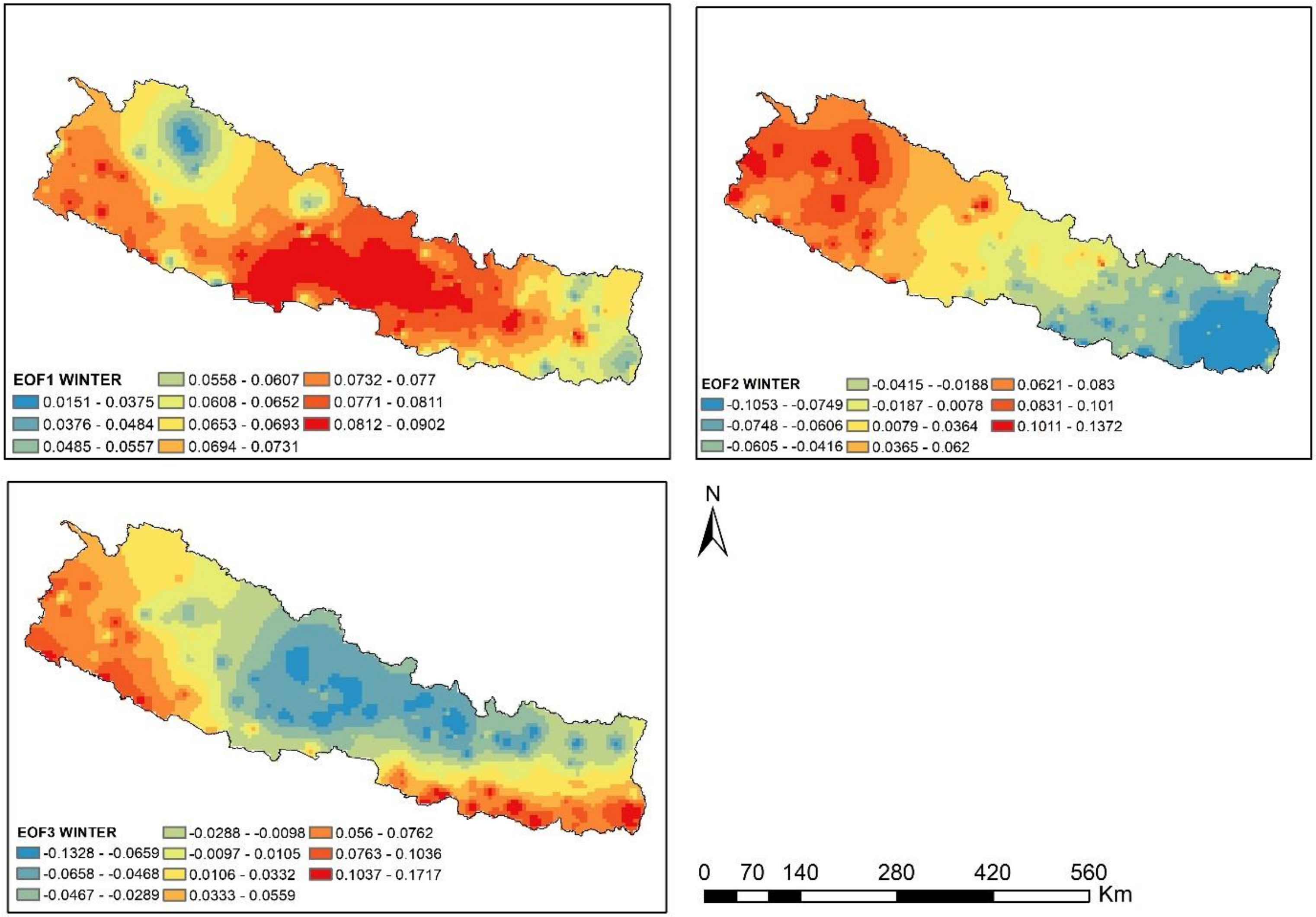


Figure 4-39 Spatial patterns of winter rainfall anomalies in Nepal: EOF Modes 1, 2, and 3

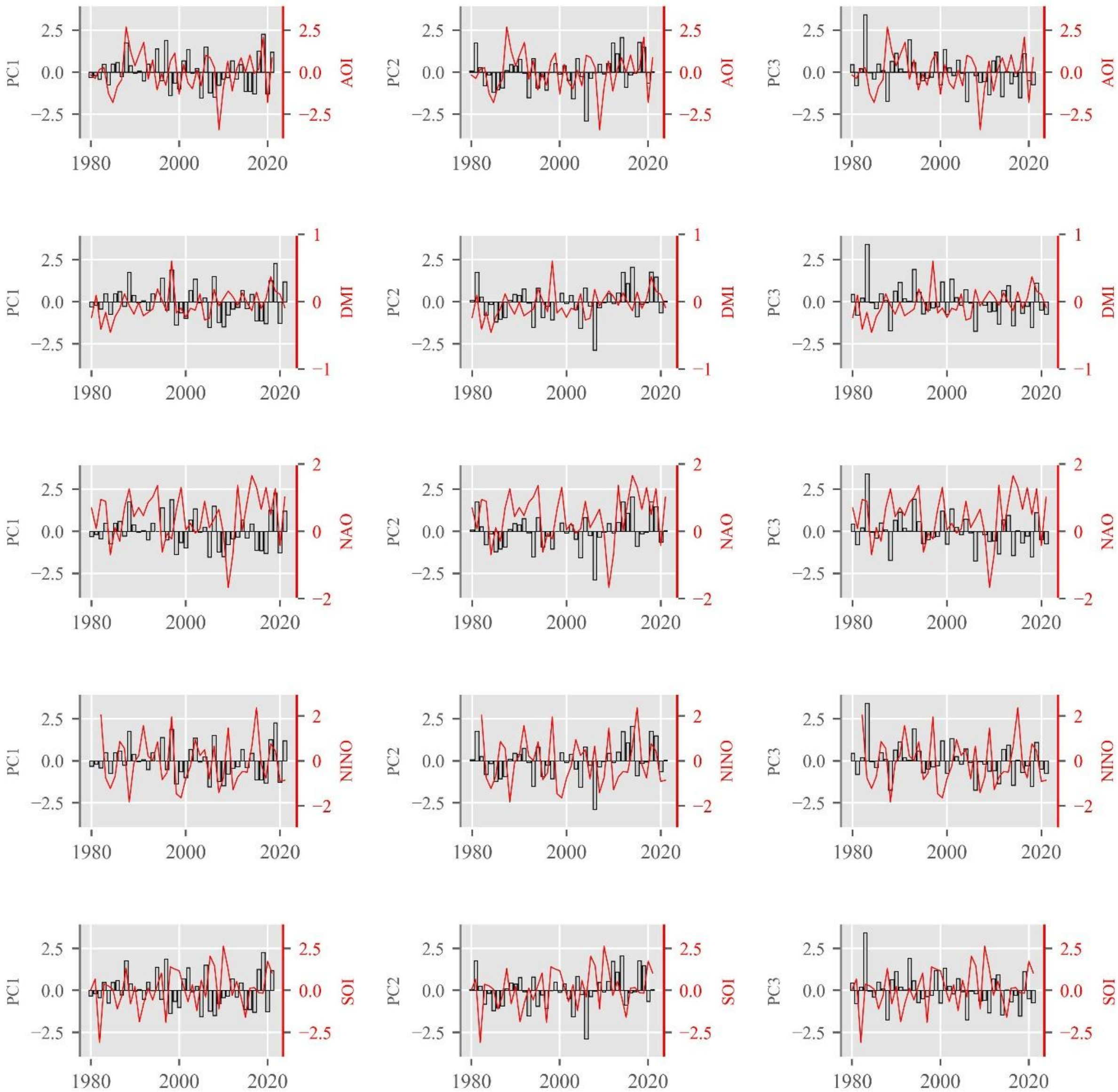


Figure 4-40 Winter principal components

CHAPTER 5: GENERAL HYDROLOGY AND FLOOD ANALYSIS

5.1 General Hydrology of Nepal

5.1.1 Flow Characteristics

The general hydrology of Nepal is significantly influenced by its unique topographical and climatic features. The country's topography is characterized by steep slopes and rugged terrain, with elevations ranging from the lowland Terai plains in the south to the towering peaks of the Himalayas in the north. This variation in topography greatly affects the distribution of rainfall and, consequently, the hydrology of its rivers.

The monsoon season, typically occurring from June to September, brings heavy rainfall to Nepal, resulting in high river flows and major flood events during this period. In contrast, river and stream flows are much lower in other seasons due to minimal rainfall.

Nepal's rivers are categorized based on their origin and flow characteristics:

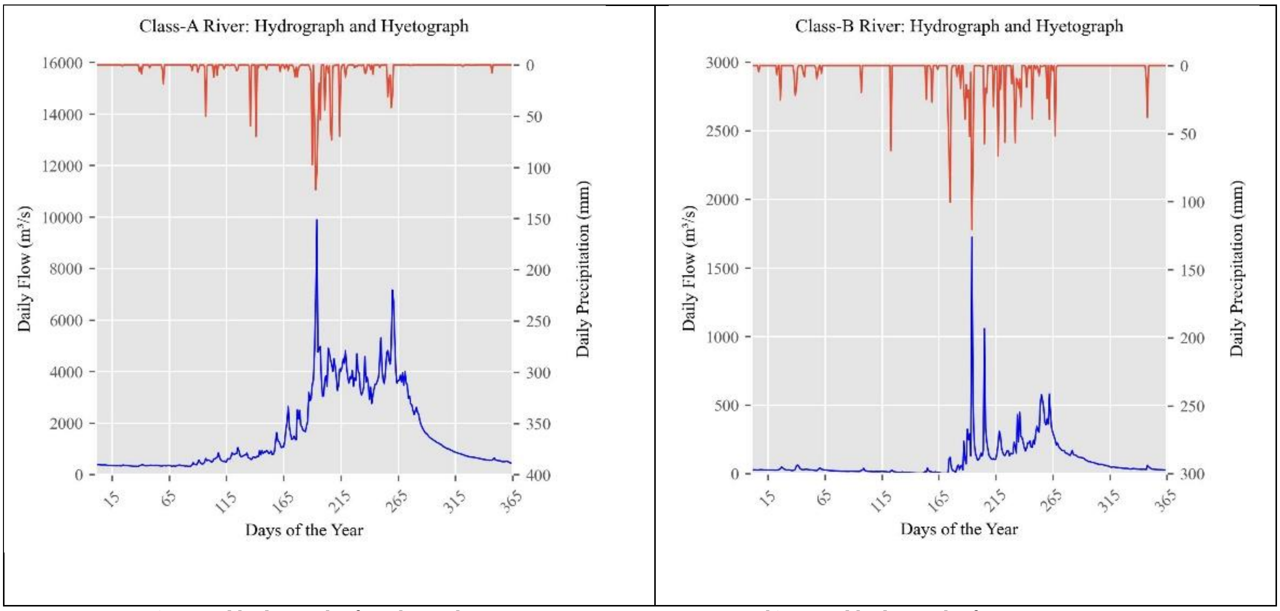
1. **Class A Rivers**: These include major rivers like the Koshi, Gandaki, Karnali, and Mahakali, which originate in the Himalayas. Their flows are primarily influenced by snowmelt and monsoon rainfall.
2. **Class B Rivers**: These include the Kankai, Kamala, Bagmati, West Rapti, and Babai Rivers, which originate in the Mid-hills. These are rainfed rivers, with flows driven mainly by rainfall during the monsoon season. In other seasons, groundwater and sporadic rains contribute to their flows.
3. **Class C Rivers**: These rivers originate either in the Churia Hills or the Terai plains. They are ephemeral in nature, characterized by flash floods during rainy periods and minimal or no flow during the rest of the year.

The flow characteristics of a river hydrology is generally depicted by annual hydrograph as shown in **Figure 5-1** for Class A and Class B rivers.

The daily flow statistics of the 44 selected flow gauging stations of Nepal viz. average, maximum, and minimum of the daily flows and their ratios, standard deviation, coefficient of variation, Q_5 (flow with 5% exceedance probability), Q_{10}, Q_{90}, Q_{95}, and the ratio of Q_{10} to Q_{90} are given in **Appendix C (Table C-1**).

The coefficient of variation of daily flow in Nepal's river systems ranges from 0.94 to 2.88, with an average of 1.42. This indicates significant variation in daily river flows. As shown in **Table C-1,** the ratio between maximum and minimum daily flows is notably high. Similarly, the ratio between the Q_{10} and Q_{90} values is also substantial, ranging from 8 to 29, with an average of 16.

These findings, along with the annual flow hydrographs, highlight the high variability of daily flows in Nepal's rivers. This variability is further illustrated by the flow duration curves of eight major rivers in Nepal, depicted in **Figure 5-2** (at Chatara of Koshi, Devghat of Gandaki, Chisapani of Karnali and Nayalbadi of Chamelia rivers) and **Figure 5-3** (Mainachuli in Kankai, Pandherodovan in the Bagmati, Kusum in the Rapti River and Chepang of the Babai Rivers). These characteristics of river flows suggest a higher probability of floods during the rainy season and significantly reduced flows during other seasons.



a) Annual hydrograph of Koshi at Chatara b) Annual hydrograph of West Rapti at Kusum

Figure 5-1 Annual hydrographs at Chatara and Kusum

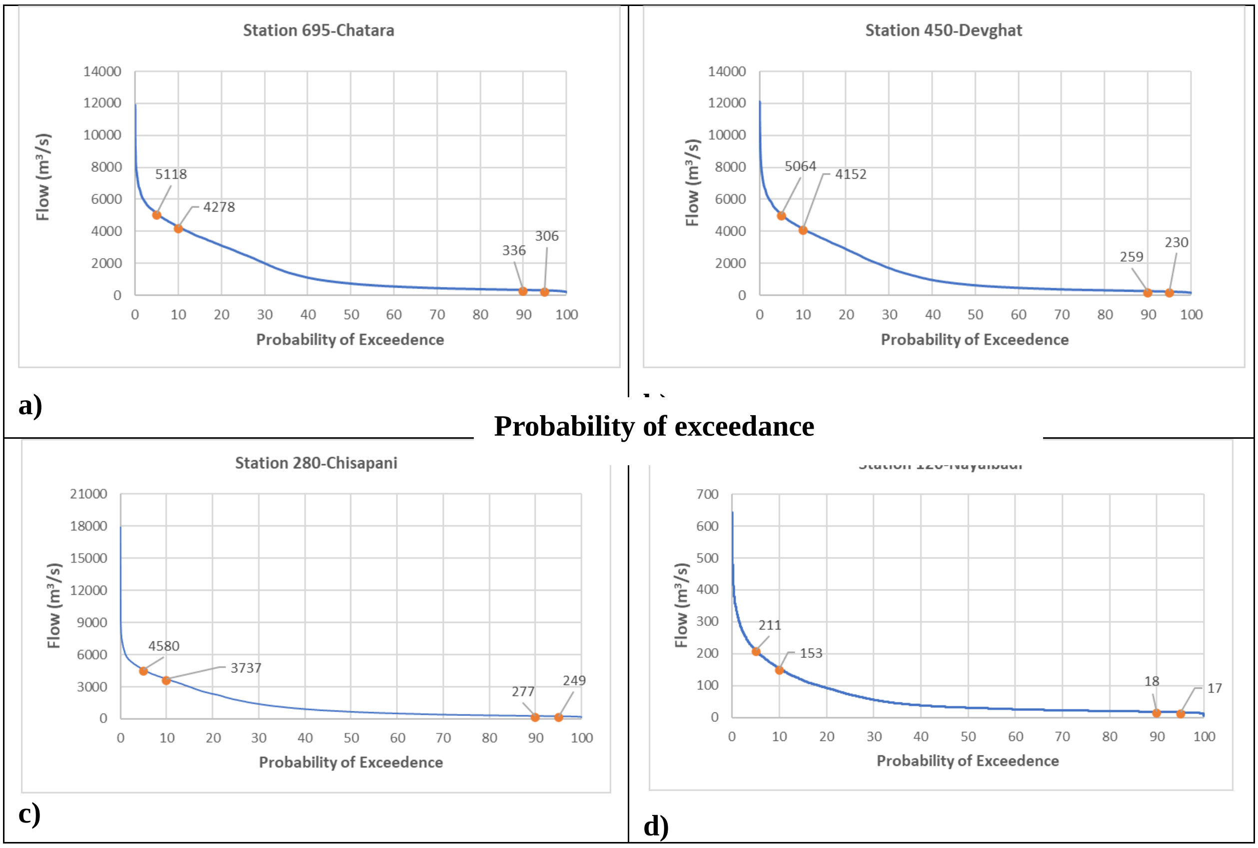


Figure 5-2 Flow duration curve of Class A Rivers

a) Koshi at Chatara b) Gandaki at Devghat c) Karnali at Chisapani and d) Chamelia at Nayalbadi

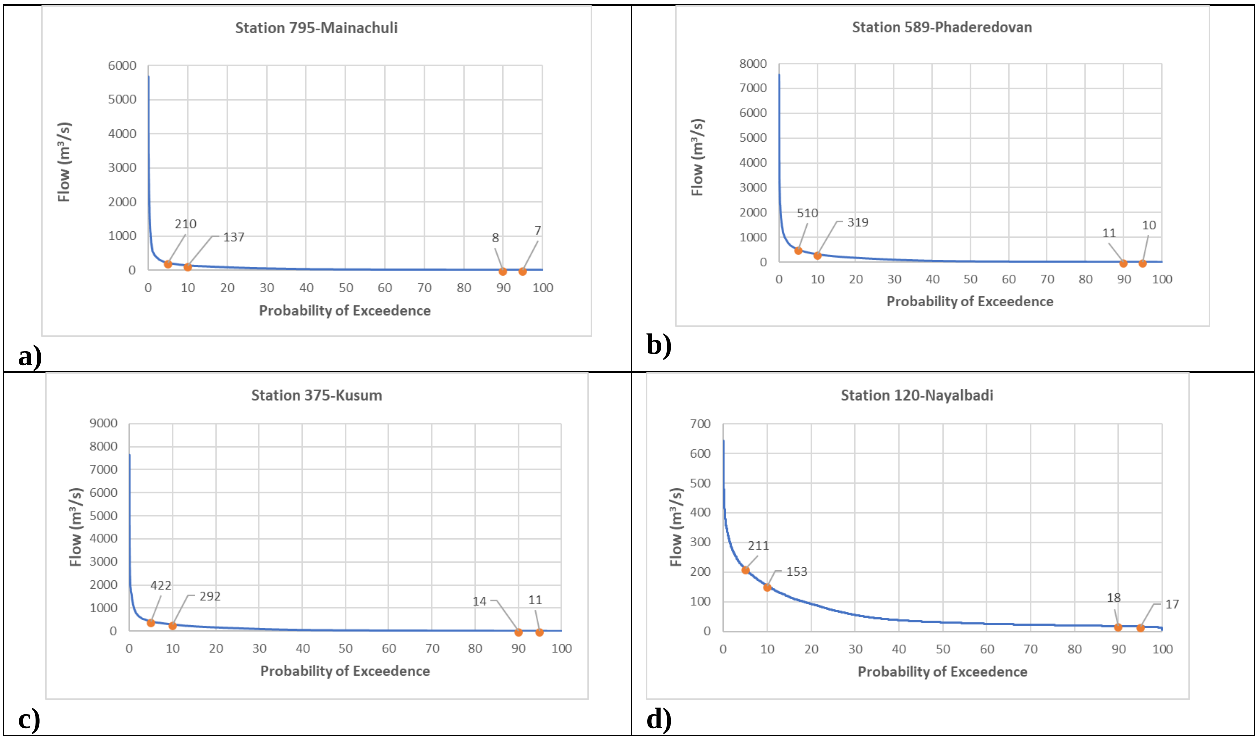


Figure 5-3 Flow duration curve of Class B Rivers

a) Kankai at Mainachuli b) Bagmati at Padheredovan c) West Rapti at Kusum and d) Babai at Chepang

5.1.2 Monthly and Seasonal Variations in River Flows

The mean monthly flows of the major eight rivers are given in **Table 5-1** and shown in **Figure 5-4** and **Figure 5-5**. The monthly flows of all the rivers are given in **Appendix C (Table C-2)**. From these tables, it is evident that at most gauging sites—41 out of 44 locations—the maximum monthly flow occurs in August. The remaining three locations (Mainachuli/St. 795, Padheredovan/St. 589, and Rasnalu/St. 650) record their maximum monthly flows in July.

March records the minimum monthly flow at half of the gauging stations (20 out of 44), followed by February (16 stations) and April (8 stations). The ratio of maximum to minimum monthly flows varies significantly, ranging from 8.5 (at Nagma of the Tila River) to 29.2 (at Padheredovan of the Bagmati River), indicating substantial monthly flow variation across Nepal's rivers. No gauging station has a ratio below 5. Approximately 9% of locations have a ratio below 10, 66% fall between 10 and 20, and 25% have a ratio exceeding 20.

Nepal has four distinct seasons viz. pre-monsoon (3 months: March to May), monsoon (4 months: June to September), post-monsoon (October and November), and winter (December to February). The percentage of annual flow occurring in these seasons is summarized in **Table 5-2**. Around 75% (range: 68–83%) of the annual flow occurs during the monsoon season, consistent with the fact that about 80% of the annual precipitation falls during this period. This underscores that the hydrology of Nepal's rivers is largely monsoon-driven and exhibits flashy characteristics. River flows are significantly lower during the other seasons.

Table 5-1 Monthly flows of the major rivers of Nepal

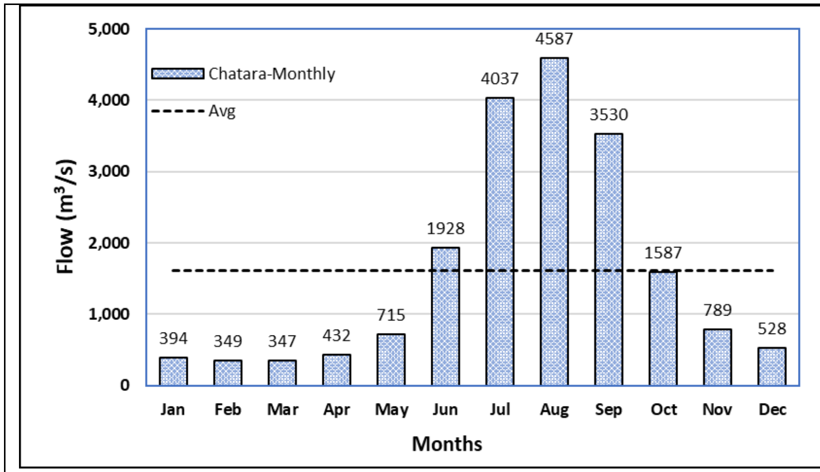
Unit: m^3/s

SN	Station No.	Location	River Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	695	Chatara	Saptakosi	394	349	347	432	715	1928	4037	**4587**	3530	1587	789	528	1,611
2	450	Devghat	Gandaki	337	280	262	328	594	1526	4016	**4514**	3273	1406	724	453	1,486
3	280	Chisapani	Karnali	345	301	303	431	757	1284	3214	**4246**	2735	1164	637	444	1,331
4	120	Nayalbadi	Chamelia	21	19	19	23	28	46	130	**175**	122	57	33	25	58
5	795	Mainachuli	Kankai	12	10	10	10	19	62	**203**	158	128	56	23	15	59
6	589	Padharadovan	Bagmati	18	15	13	13	28	106	**386**	385	275	96	35	22	117
7	375	Kusum	Rapti	31	27	21	19	20	46	263	**406**	245	125	54	37	109
8	289.95	Chepang	Babai	14	12	9	8	9	24	123	**172**	112	48	21	15	48

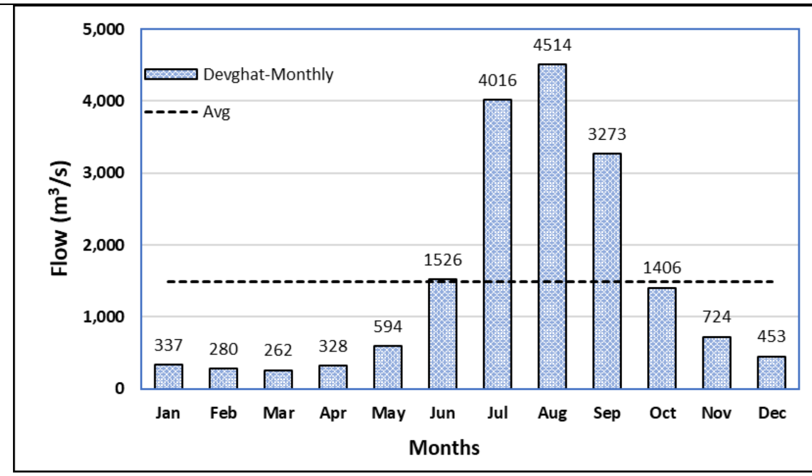
Table 5-2 Seasonal flow variation of the major rivers of Nepal

Unit: %

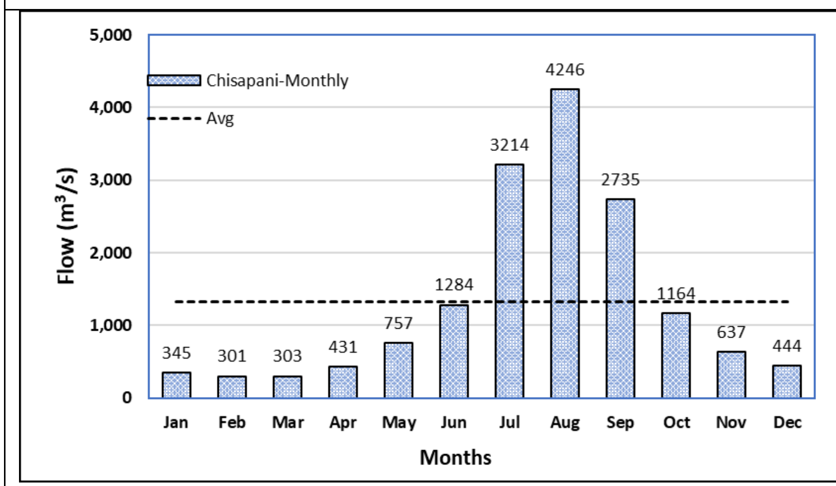
SN	Station No.	Location	River name	Pre-monsoon	Monsoon	Post-monsoon	Winter
1	695	Chatara	Saptakosi	8	73	12	7
2	450	Devghat	Gandaki	7	75	12	6
3	280	Chisapani	Karnali	9	72	11	7
4	120	Nayalbadi	Chamelia	10	68	13	9
5	795	Mainachuli	Kankai	5	78	11	5
6	589	Padharadovan	Bagmati	4	83	9	4
7	375	Kusum	Rapti	5	74	14	7
8	289.95	Chepang	Babai	5	76	12	7



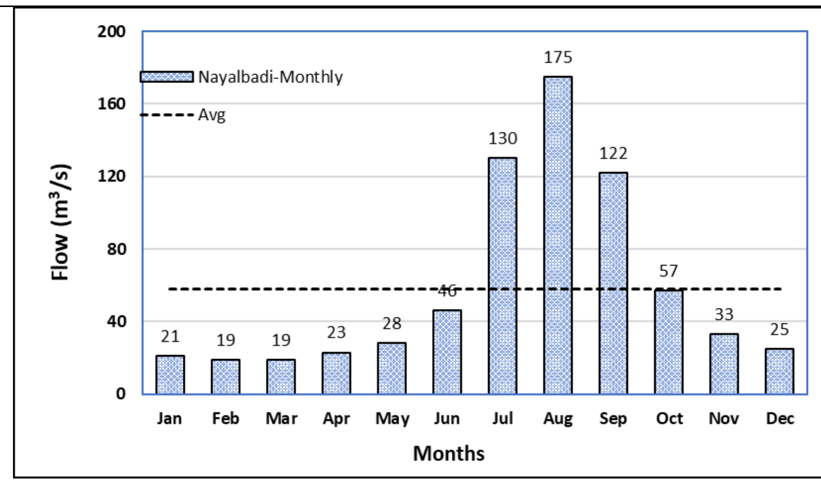
a) **Koshi**



b) **Gandaki**



c) **Karnali**



d) **Chamelia**

Figure 5-4 Monthly variation in flows of Class A River Basins

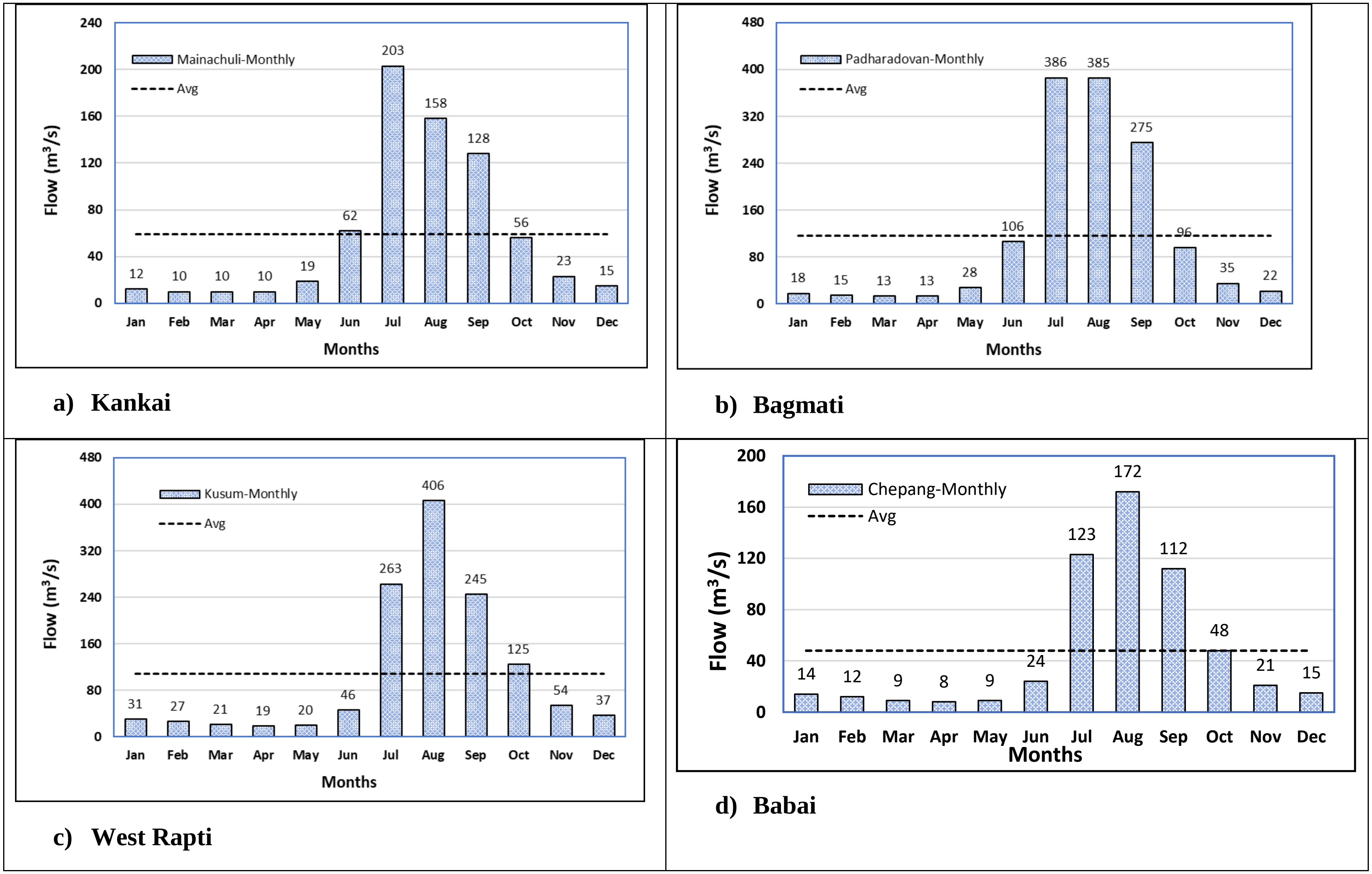


Figure 5-5 Monthly variation in flows of the Class B River Basins

5.2 Flood Analysis

Floods are a common phenomenon in Nepal during the monsoon season, causing significant loss of lives and property (as discussed extensively in **Chapter 2**). In Nepal, landslides and floods claim the lives of over 300 people annually and result in an average economic loss of 626 million rupees in property damage (Shrestha et al., 2020).

Floods are generally classified into four types, which are briefly described below.

1. Flash floods

A sudden rush of water resulting from intense rainfall, usually occurring within a very short period—often within minutes to a few hours—is known as a flash flood. However, it can also be caused by dam bursts, glacial lake outbursts, or landslide dam outbursts. Flash floods typically cover a relatively small area and occur with little to no lead time for preparation.

Flash floods are characterized by their rapid onset and high velocity. They are more common in areas with steep terrain or downstream plains. The steep slopes accelerate the flow of water, making these floods particularly dangerous due to their high velocity and unpredictability. As a result, flash floods are considered among the most destructive natural disasters, posing significant risks to human life and causing substantial property damage.

For example, floods occurring in small rivers in the Terai region often take the form of flash floods when short but intense rainfall occurs in the Chure region. Notable instances include the 2016 flood in the Bhote Koshi River, triggered by a Glacial Lake Outburst Flood (GLOF) near the lower Barun area, and the landslide-induced flood of 2021 in the Melamchi River.

2. Riverine flood

A riverine flood is characterized by the gradual overflow of riverbanks, typically caused by heavy rainfall over an extended period. However, it can also result from snowmelt or the release of water from upstream reservoirs. The extent of a riverine flood depends on the size of the river, its water-carrying capacity, and the amount of rainfall.

After reaching peak water levels, riverine floods gradually recede as excess water flows downstream, infiltrates the ground, or evaporates. Unlike flash floods, riverine floods usually have a slower onset and are more predictable. While they rarely result in loss of life, they can cause immense economic damage. In Nepal, floods in major rivers such as the Koshi, Gandaki, Karnali, and Mahakali are typically of this type.

3. Urban floods

An urban flood is a type of flooding that occurs in urban areas (cities and towns) as a result of heavy rainfall. Urban floods happen when the volume of runoff from heavy rainfall exceeds the drainage capacity of the city or town. A lack of natural drainage, poor drainage infrastructure (such as storm drains, culverts, and sewers), and constriction of river channels, combined with an increase in impervious surfaces due to excessive urbanization, can also contribute to such floods.

Urban floods pose unique challenges due to the characteristics of urban landscapes and the high population density in these areas. Although water levels may only reach a few centimeters, urban floods can cause significant structural damage and property loss. A notable example of an urban flood is the 2023 flood in Ranibari, Kathmandu, which tragically swept away a 12-year-old schoolboy.

4. Pluvial floods

Pluvial floods occur in flat areas where limited infiltration of rainwater leads to the formation of puddles and ponds. Pluvial flooding is similar to urban flooding but occurs in rural areas. Unlike riverine floods, which result from overflowing rivers or other water bodies, pluvial floods are primarily caused by heavy rainfall. These floods can significantly impact agricultural activities and damage properties in affected areas. Floods in some parts of the Terai region are typically pluvial in nature.

Nepal's hydrology is largely driven by the monsoon. Among the different types of floods, riverine floods are particularly significant in the Nepalese context. Therefore, this study primarily focuses on various aspects of riverine floods.

Information on high flows and floods in rivers is crucial for designing water control structures, such as dams and embankments, to minimize potential damage to human lives and property. Several succeeding sections are, thus, devoted to exploring various aspects of flood.

In addition, information on low flows is essential for proper water allocation among competing uses, such as hydropower generation, irrigation, and water supply, particularly during the lean season. To address this need, minimum flow analysis has also been conducted to assess certain aspects of low flows in this study (Please refer **Chapter 6**).

5.2.1 General Methodology of Flood Analysis

The theoretical background on flood analysis, where necessary, is provided in the respective sections. In this study, alongside the analysis of various aspects of instantaneous maximum floods and annual maximum daily flows, flood estimation for ungauged basins and probable peak flows of glacial lakes is also conducted. Additionally, the study includes an examination of floods and associated climatic factors, as well as the preparation of a flood inventory.

General methodology of flood analysis is given in **Figure 5-6**.

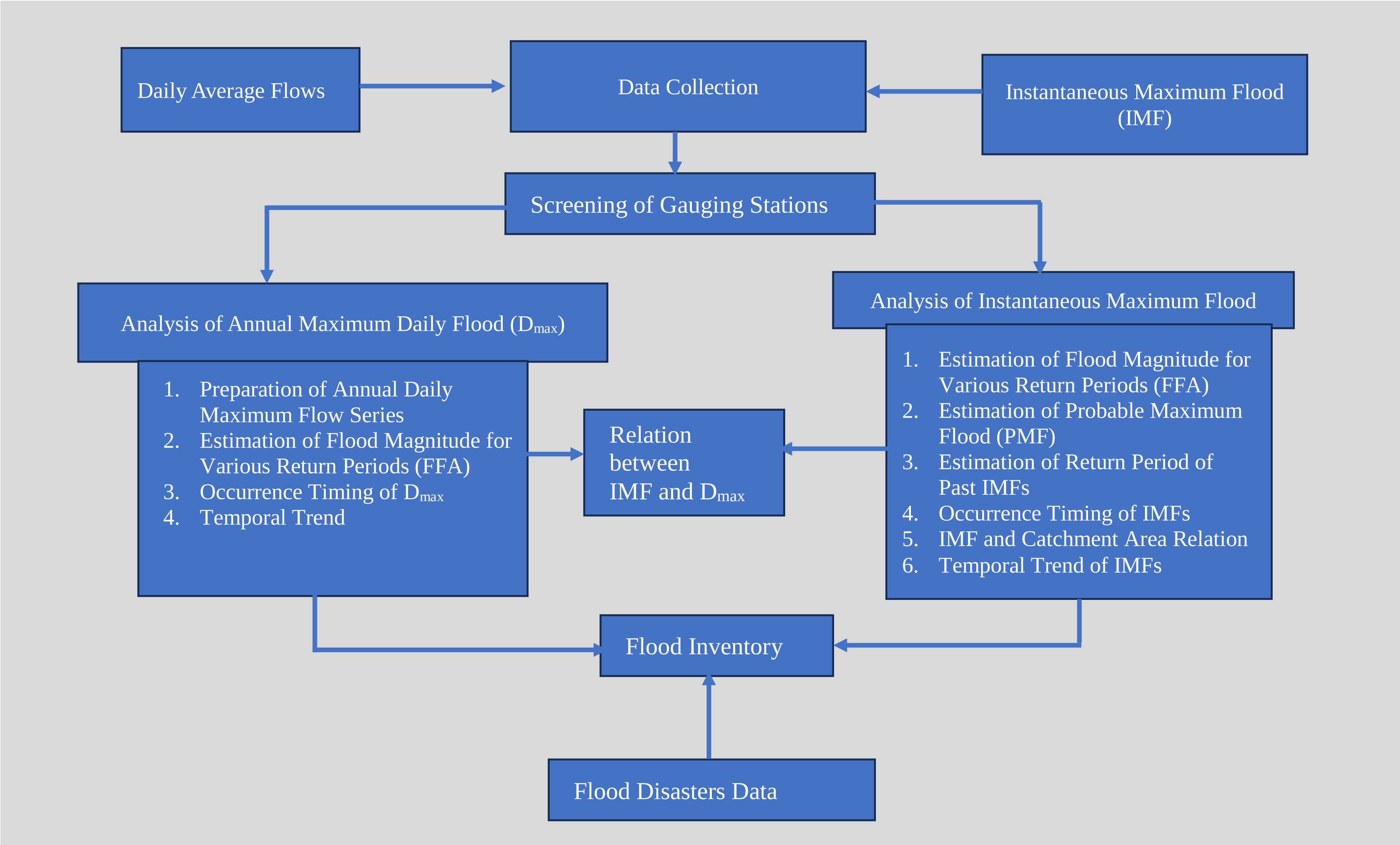


Figure 5-6 General methodology of flood analysis

1. Data Collection and Selection of Gauging Stations

Secondary flow data (1980-2019), both instantaneous and daily average flows of different stations were collected from DHM. Screening of the stations for further analysis was based on the availability of long-term and reliable continuous data. The details of the selection criteria were given in **Chapter 3**.

2. Analysis of Data

The following analysis were carried out in this study. Details of the analysis methods are given in the respective sections/sub-sections.

(i) Flood frequency analysis was carried out to estimate the flood, both one-day maximum and instantaneous maximum flow (IMF) of different return periods.

(ii) Estimation of probable maximum floods (PMFs).

(iii) Estimation of the return period of past IMFs.

(iv) Timing of occurrence of floods.

(v) Relationship between IMF and one day annual maximum flow.

(vi) Temporal trend of IMF.

(vii) Flood inventory based on one day annual maximum flow, IMF and flood disaster events.

(viii) Volume and peak flow estimation of major glacial lakes of Nepal.

(ix) Floods and associated climate.

5.3 Instantaneous Maximum Flow Analysis

5.3.1 Flood Magnitude Estimation of Gauged Basins

The design of water resource development projects requires accurate estimation of flood magnitudes for specific return periods. Therefore, one key task in flood analysis is to estimate the magnitude of floods corresponding to different return periods at a given location.

The Gumbel distribution is commonly used in hydrology for flood frequency analysis, particularly for estimating extreme flood events (Zhang et al., 2020; Salas et al., 2019; Devkota and Gyawali, 2015; Marahatta et al., 2021). In this study, the Gumbel distribution was applied to flood flow data to perform the frequency analysis.

The flood magnitude corresponding to a given return period is generally calculated using **Equation (5-1)** (Chow et al., 1988).

$$Q_T = \bar{Q} + K_T . s \tag{5-1}$$

where,

Q_T=Flood of a T year return period

$\bar{Q}$ = Mean of the instantaneous flood data series

s = Standard deviation of the instantaneous flood data series

K_T = Frequency factor, defined as in **Equation (5-2)**

$$K_T = \frac{y_T - \mu_n}{\sigma_n} \tag{5-2}$$

Here, y_T is a Gumbel reduced variate, a function of return period, as given by **Equation (5-3)**

$$y_T = -\ln\left[\ln\left(\frac{T}{T-1}\right)\right] \tag{5-3}$$

μ_n and σ_n are corrections factors which depends on the sample size, n. Values of these factors are given in standard text books on hydrology.

The flood parameters (mean and standard deviation) are derived from instantaneous flood data series of the gauging station. A sample calculation of floods of different return periods made for Karnali River at Chisapani gauging station is presented in **Table 5-3.**

Table 5-3 Sample flood estimation for different return periods

Return Period (T-years)	Reduced Variate (y_T)	Frequency Factor (K_T)	Flood (Q_T) (m^3/s)
2	0.3665	-0.155	8,603
5	1.4999	0.838	12,557
25	3.1985	2.326	18,483
50	3.9019	2.943	20,937
100	4.6001	3.554	23,372
200	5.2958	4.164	25,799
500	6.2136	4.968	29,001
1,000	6.9073	5.576	31,421
10,000	9.2103	7.594	39,455

$\bar{Q}$= 9,221 m^3/s and s= 3,981 m^3/s; n= 40, μ_n= 0.54362 and σ_n= 1.14132

The flood statistics (mean and standard deviation) of Class A and Class B rivers were calculated for IMFs of selected 44 stations. It is mentioned here that all the floods listed by DHM as instantaneous maximum flows are considered while calculating flood statistics. Flood magnitudes were estimated applying the **Equations (5-1:5-3)** for the return periods of 2, 5, 25, 50, 100, 200, 500, 1,000 and 10,000 years at these stations. The estimated flood magnitudes of all 44 selected locations are given in **Table 5-4**. Due to its small catchment area (17 km^2), Sundarijal naturally experiences the smallest floods among the analyzed stations. Interestingly, while the catchment area of the Karnali River at Chisapani is about 25% smaller than that of the Koshi River at Chatara, the flood magnitudes at Chisapani are approximately 10% higher than those at Chatara. This discrepancy is attributed to the higher average and standard deviation of flood flows observed at Chisapani. The higher average flood values at Chisapani are influenced by greater rainfall and the simultaneous response of rainfall over the catchment. The higher standard deviation reflects a greater scattering of data, indicating higher temporal variation in flows within the Karnali Basin compared to the Koshi Basin. This analysis demonstrates that while flood magnitudes are influenced by catchment size, they are also heavily dependent on the combined interaction of rainfall patterns and catchment characteristics.

Table 5-4 Floods of different return periods at selected gauging sites

Unit: m^3/s

SN	Station	Location	n	Average	Std.Dev.	Q_2	Q_5	Q_{25}	Q_{50}	Q_{100}	Q_{200}	Q_{500}	Q_{1000}	Q_{10000}
1	120	Nayalbadi	39	375	182	346	528	800	912	1,024	1,135	1,282	1,393	1,761
2	215	Tholtada	39	1,684	490	1,608	2,096	2,828	3,130	3,431	3,731	4,126	4,424	5,416
3	220	Nagma	39	228	80	216	295	415	464	513	562	626	675	836
4	225	Diware	36	116	17	114	131	156	166	177	187	201	211	245
5	240	Asaraghat	37	2,256	587	2,165	2,751	3,630	3,994	4,355	4,715	5,190	5,549	6,740
6	250	Benighat	34	2,776	740	2,662	3,407	4,525	4,987	5,446	5,904	6,508	6,964	8,479
7	260	Banga	40	3,229	1,858	2,940	4,785	7,551	8,696	9,832	10,965	12,459	13,588	17,337
8	265	Rimna	39	1,126	341	1,073	1,412	1,920	2,131	2,339	2,547	2,822	3,029	3,718
9	270	Jamu	31	2,311	821	2,186	3,019	4,269	4,786	5,300	5,811	6,486	6,997	8,691
10	280	Chisapani	40	9,221	3,981	8,603	12,557	18,483	20,937	23,372	25,799	29,001	31,421	39,455
11	286	Daradhunga	36	238	192	208	401	690	809	928	1,046	1,202	1,320	1,711
12	289.95	Chepang	29	1,625	1,241	1,436	2,704	4,605	5,392	6,173	6,952	7,979	8,755	11,332
13	330	Nayagaon	40	606	270	564	832	1,234	1,401	1,566	1,730	1,948	2,112	2,657
14	350	Bagasotigaon	39	1,932	1,152	1,753	2,900	4,619	5,331	6,038	6,742	7,671	8,373	10,703
15	360	Jalkundi	40	3,170	1,616	2,919	4,523	6,928	7,924	8,913	9,898	11,197	12,179	15,440
16	375	Kusum	17	3,389	2,055	3,107	5,217	8,378	9,688	10,987	12,282	13,990	15,281	19,568
17	404.7	Mangalghat	38	535	187	506	693	973	1,089	1,205	1,319	1,471	1,585	1,965
18	420	Kotagaon	39	4,584	1,710	4,319	6,021	8,572	9,628	10,676	11,721	13,099	14,140	17,599
19	428	Lahachok	36	149	88	136	224	357	412	466	521	592	646	826
20	438	Shisa Ghat	38	666	343	613	954	1,467	1,679	1,890	2,100	2,376	2,586	3,281
21	440	Garam Besi	39	337	221	303	523	852	989	1,124	1,259	1,437	1,572	2,019
22	445	Arughat	40	841	253	802	1,053	1,429	1,585	1,740	1,894	2,097	2,251	2,761
23	447	Betrawati	35	1,174	395	1,113	1,510	2,105	2,352	2,596	2,840	3,161	3,404	4,211
24	448	Belkot	39	562	275	519	793	1,204	1,374	1,543	1,711	1,933	2,101	2,658
25	450	Devghat	40	9,728	2,469	9,345	11,797	15,472	16,994	18,505	20,010	21,996	23,497	28,480
26	460	Rajaiya	33	745	604	652	1,262	2,176	2,555	2,931	3,305	3,799	4,173	5,412
27	465	Manahari	30	518	388	459	854	1,447	1,693	1,936	2,179	2,499	2,742	3,545

SN	Station	Location	n	Average	Std.Dev.	Q_2	Q_5	Q_{25}	Q_{50}	Q_{100}	Q_{200}	Q_{500}	Q_{1000}	Q_{10000}
28	470	Lothar	30	286	254	247	506	895	1,056	1,216	1,375	1,585	1,743	2,270
29	505	Sundarijal	38	9	6	8	15	24	28	32	36	42	45	58
30	589	Pandhera Dobhan	30	4,506	2,666	4,099	6,816	10,887	12,573	14,247	15,914	18,114	19,777	25,297
31	602	Tumlingtar	38	230	129	210	338	531	611	690	769	874	952	1,214
32	602.5	Pipletar	34	44	17	42	59	84	95	106	116	130	141	175
33	604.5	Turkeghat	40	3,001	930	2,856	3,780	5,165	5,738	6,307	6,874	7,622	8,188	10,065
34	606	Simle	34	3,579	1,058	3,416	4,482	6,078	6,739	7,395	8,049	8,911	9,563	11,728
35	620	Jalbire	37	584	382	525	907	1,479	1,715	1,950	2,185	2,494	2,727	3,502
36	630	Pachuwar Ghat	39	1,654	597	1,562	2,156	3,046	3,414	3,780	4,145	4,626	4,989	6,196
37	647	Busti	33	1,204	340	1,152	1,496	2,011	2,224	2,436	2,647	2,925	3,136	3,834
38	650	Rasnalu Village	35	627	768	509	1,280	2,436	2,914	3,389	3,862	4,487	4,958	6,525
39	652	Khurkot	33	3,968	1,585	3,725	5,326	7,724	8,717	9,703	10,686	11,982	12,961	16,213
40	660	Sangutar	30	325	97	310	409	557	618	679	739	819	880	1,080
41	670	Rabuwa Bazar	39	2,271	1,513	2,036	3,542	5,798	6,733	7,660	8,584	9,803	10,725	13,784
42	690	Mulghat	40	3,449	1,391	3,233	4,614	6,684	7,541	8,391	9,239	10,357	11,203	14,009
43	695	Chatara	29	8,152	3,576	7,608	11,264	16,743	19,012	21,264	23,509	26,469	28,707	36,136
44	795	Mainachuli	32	3,739	1,720	3,476	5,218	7,828	8,909	9,982	11,051	12,462	13,528	17,068

Note: n= Number of data points (years), Q_x = Flood of return period of x year

5.3.2 Probable Maximum Flood Estimation

The Probable Maximum Flood (PMF) is the largest flood that could theoretically occur at a specific location, resulting from the most extreme hydrological and meteorological conditions. The PMF is commonly used in the design and safety evaluation of dams, spillways, and other critical infrastructure to ensure they can withstand such extreme events (LaRocque, 2013).

Applying similar approach to PMP estimation, Probable Maximum Flood (PMF) was estimated using **Equation (5-4)**.

$$PMF = Q_{mean} + K.Q_{std} \quad (5\text{-}4)$$

Where, Q_{mean}= mean of the instantaneous maximum flow series

Q_{std}= standard deviation of the instantaneous maximum flow series

K = a factor

It is noted that the ratio of the Probable Maximum Flood (PMF) to the 10,000-year return period flood for the Budhigandaki Hydroelectric Project was 1.57, for Upper Marshyandi II was 1.4, and for Upper Trishuli I was 2.0 (TRACTEBEL, 2016). The calculated PMF, using a K value of 17.5 (the average of 5 and 30), is very close to twice the magnitude of the 10,000-year return period floods. To err on the side of caution, a K factor of 17.5 is recommended for estimating PMF in rivers of Nepal. The calculated PMFs for the selected 44 stations are provided in **Table 5-4**.

5.3.3 Return Period Estimation

To assess the socio-economic or even environmental impact of floods, knowledge on the return periods of the past flood events at a particular location can be very useful. Return periods of the top ten past flood events are, thus, estimated in this study. Using **Equations (5-1)** and **(5-2)**, the Gumbel reduced variate (y_Q) can be calculated for a given flood magnitude (Q) as given by **Equation (5-5).**

$$y_Q = \mu_n + \sigma_n\left(\frac{Q-\bar{Q}}{s}\right) \quad (5\text{-}5)$$

With this calculated y_Q value, the corresponding return period (T_Q) is calculated using **Equation (5-6)** which is an inverse form of **Equation (5-3)**.

$$T_Q = \frac{e^{e^{-y}}}{e^{e^{-y}}-1} \quad (5\text{-}6)$$

Table 5-5 Probable maximum flood of selected gauging stations

SN	Station	Location	PMF (m^3/s)		SN	Station	Location	PMF (m^3/s)
1	120	Nayalbadi	3,563		22	445	Arughat	5,266
2	215	Tholtada	10,265		23	447	Betrawati	8,091
3	220	Nagma	1,626		24	448	Belkot	5,382
4	225	Diware	411		25	450	Devghat	52,943
5	240	Asaraghat	12,522		26	460	Rajaiya	11,319
6	250	Benighat	15,730		27	465	Manahari	7,312
7	260	Banga	35,742		28	470	Lothar	4,739
8	265	Rimna	7,086		29	505	Sundarijal	122
9	270	Jamu	16,675		30	589	Pandhera Dobhan	51,167
10	280	Chisapani	78,896		31	602	Tumlingtar	2,487
11	286	Daradhunga	3,601		32	602.5	Pipletar	342
12	289.95	Chepang	23,335		33	604.5	Turkeghat	19,281
13	330	Nayagaon	5,332		34	606	Simle	22,089
14	350	Bagasotigaon	22,101		35	620	Jalbire	7,264
15	360	Jalkundi	31,447		36	630	Pachuwar Ghat	12,098
16	375	Kusum	39,352		37	647	Busti	7,162
17	404.7	Mangalghat	3,815		38	650	Rasnalu Village	14,061
18	420	Kotagaon Shringe	34,509		39	652	Khurkot	31,709
19	428	Lahachok	1,695		40	660	Sangutar	2,020
20	438	Shisa Ghat	6,665		41	670	Rabuwa Bazar	28,743
21	440	Garam Besi	4,203		42	690	Mulghat	27,785
22	445	Arughat	5,266		43	695	Chatara	70,734
23	447	Betrawati	8,091		44	795	Mainachuli	33,844

The total number of instantaneous flood records for the selected 44 stations is 1,573. The estimated return periods of the top ten past instantaneous maximum floods (IMFs) for each of the eight major rivers are provided in **Table 5-6**. From the table, it can be seen that two flood events—one on June 25, 1980, at Chatara of the Koshi River, and another on July 21, 1993, at Pandherodovan of the Bagmati River—had return periods greater than 100 years (Chatara: 233 years, Pandherodovan: 207 years).

Two floods that occurred at Chisapani of the Karnali River on September 11, 1983, and August 15, 2014, exceeded the 50-year return period (both with a return period of 62 years). The largest flood event at Nayalbadi of the Chamelia River was close to the 50-year return period value. Other floods at these selected locations were well below the 50-year return period value.

Estimated return periods of top ten past IMF of all the selected stations are listed in **Appendix C** (**Table C-3**). The analysis showed that thirteen past IMF events exceeded the 100-year return period. These events occurred at the following locations: Asarghat of the Karnali (210 years), Daradunga of the Sarada (101 years), Shisaghat of the Madi (130 years), Arughat of the Budhigandaki (422 years), Rajaiya of the Rapti

(184 years), Sundarijal of the Bagmati (143 years), Pandherodovan of the Bagmati (207 years), Tumlingtar of the Shabha Khola (103 years), Pipaltar of the Hinwa Khola (117 years), Jalbire of the Balephi (156 years), Pachuwarghat of the Sunkoshi (135 years), Rabuwa Bazaar of the Dudhkoshi (530 years), and Chatara of the Koshi (233 years).

Similarly, 25 and 49 events out of the 1,573 flood events in Nepal were estimated to have return periods greater than 50 and 25 years, respectively.

5.3.4 Basinwise Distribution of Major Past IMF Events

Basin wise distribution of major past IMF events is tabulated in **Table 5-7**. Due to the varying number of basins and sub-basins considered in this study, as well as the available data on instantaneous maximum floods (IMFs) for each basin/sub-basin, the number of IMF events differs across the eight major basins. The Koshi, Gandaki, Karnali, and Mahakali basins (Class A River Basins) have 461, 437, 335, and 39 IMF events, respectively. The number of floods with return periods greater than or equal to 100 years, 50 years and 25 years in these basins are:

- Koshi: 6 (100 years), 6 (50 years), 14 (25 years)
- Gandaki: 3 (100 years), 8 (50 years), 14 (25 years)
- Karnali: 1 (100 years), 7 (50 years), 11 (25 years)
- Mahakali: 0 (100 years), 0 (50 years), 1 (25 years)

Table 5-6 Return period estimation of top ten past floods

Major Class A River Basins												
River	Saptakoshi			Gandaki			Karnali River			Chamelia		
Location	Chatara			Devghat			Chisapani			Nayal Badi		
Flood Order	Date	Q-695 (m^3/s)	T-695 (year)	Date	Q-450 (m^3/s)	T-450	Date	Q-280	T-280	Date	Q-120 (m^3/s)	T-120
1	1980-06-25	24,000	233	1999-08-27	14900	19	1983-09-11	21700	62	2018-07-11	898	46
2	2019-07-13	11,000	5	2018-08-17	14000	13	2014-08-15	21700	62	2016-08-01	734	17
3	2018-08-15	10,400	4	1986-09-14	13400	10	2013-06-18	17900	21	2000-06-08	643	10
4	2000-08-02	10,000	4	2013-07-22	13200	9	2009-10-07	17000	17	2017-08-14	641	10
5	1999-07-03	9,930	3	2001-08-23	13000	8	1988-07-16	12500	5	2010-08-22	627	9
6	2003-07-09	9,760	3	1988-08-23	12700	7	2000-08-01	12500	5	2009-10-06	598	7
7	2017-08-11	9,640	3	2007-09-06	12300	6	2008-09-20	12500	5	2014-07-28	591	7
8	2014-08-14	9,610	3	2011-07-01	12000	5	2007-08-13	9900	3	2011-08-01	504	4
9	2002-08-21	9,550	3	2003-07-31	11900	5	1995-08-13	9550	2	1997-08-03	501	4
10	2001-08-20	9,520	3	2016-07-26	11800	5	1998-08-04	9400	2	2019-08-06	495	4
Major Class B River Basins												
River	Kankaimai			Bagmati River			West Rapti			Babai		
Location	Mainachuli			Pandherodovan			Kusum			Chepang		
Flood Order	Date	Q-795 (m^3/s)	T-795	Date	Q-589 (m^3/s)	T-589	Date	Q-375 (m^3/s)	T-375	Date	Q-289.95 (m^3/s)	T-289.95
1	1990-08-12	7,500	20	1993-07-21	16,000	207	2014-08-15	9,100	37	2017-08-13	5,060	37
2	1981-08-12	6,430	10	2002-07-23	8,000	8	2016-07-26	6,160	8	2014-08-15	3,990	15
3	2002-07-28	6,050	8	1984-09-17	7,630	7	2013-07-22	5,720	6	1995-08-09	3,870	13
4	2003-07-09	5,920	8	2004-07-09	6,850	5	2009-10-07	4,860	4	2007-07-26	3,640	11
5	1999-08-26	5,680	7	2000-08-02	6,200	4	2017-08-13	3,950	3	1994-09-11	3,520	10
6	2009-08-16	5,680	7	1990-08-27	5,620	3	2003-07-31	3,380	2	2006-08-27	2,550	4
7	2001-10-05	5,600	6	2005-08-07	5,580	3	2005-10-20	3,380	2	2009-07-28	2,320	4
8	1983-07-15	5,500	6	1982-07-19	5,080	3	2006-07-08	2,940	2	1996-07-11	1,870	3
9	1996-08-19	5,350	5	1999-07-03	5,080	3	2019-07-13	2,610	2	1992-07-08	1,750	2
10	2005-08-26	4,420	3	2010-08-24	4,780	2	2012-08-03	2,500	2	2003-07-10	1,490	2

The Kankai, Bagmati, West Rapti and Babai basins (Class B River Basins) respectively have 32, 68, 136 and 65 IMF events. Out of them, the number of flood events greater than or equal to 100-year return periods occurred in these basins were 0, 2, 0 and 1 respectively. The occurrences of these figures greater than or equal to 50 years return periods are 0, 2, 1 and 1 in Kankai, Bagmati, West Rapti and Babai basins respectively.

Table 5-7 Basin wise distribution of top ten past IMF events

Basins	Nepal	Koshi	Gandaki	Karnali	Mahakali	Kankai	Bagmati	West Rapti	Babai
Category\No. of Basins	44	13	12	9	1	1	2	4	2
No. of IMF Events	1573	461	437	335	39	32	68	136	65
No. of IMF ≥ 100 years	13	6	3	1	0	0	2	0	1
No. of IMF ≥ 50 years	25	6	8	7	0	0	2	1	1
No. of IMF ≥ 25 years	49	14	14	11	1	0	2	5	2
No. of IMF ≥ 5 years	298	88	79	67	7	9	10	26	12
No. of IMF ≥ 2 years	440	130	120	90	10	10	20	40	20

Note: IMF = Instantaneous Maximum Flood

5.3.5 Timing of Occurrence of Instantaneous Floods

The month-wise distribution of instantaneous floods (n=1,573) of the selected 44 stations is shown in **Figure 5-7**. From this figure, it can be observed that nearly all instantaneous flood events (i.e., >98%) in Nepal occurred during the monsoon season (June-September), which is expected. In the months of July and August alone, 80% of these flood events occurred. A few events occurred in October (1.3%).

Interestingly, one flood event at Sundarijal in the Bagmati River occurred in January, while another event took place at Pipaltar of the Hinwa Khola (Koshi Basin) in March. Additionally, two flood events occurred in April (at Pipaltar of Hinwa Khola and Tumlingtar of the Shabha Khola, both in the Koshi Basin) and May (at Khimti Khola in the Koshi Basin and Sharada River in the Babai Basin).

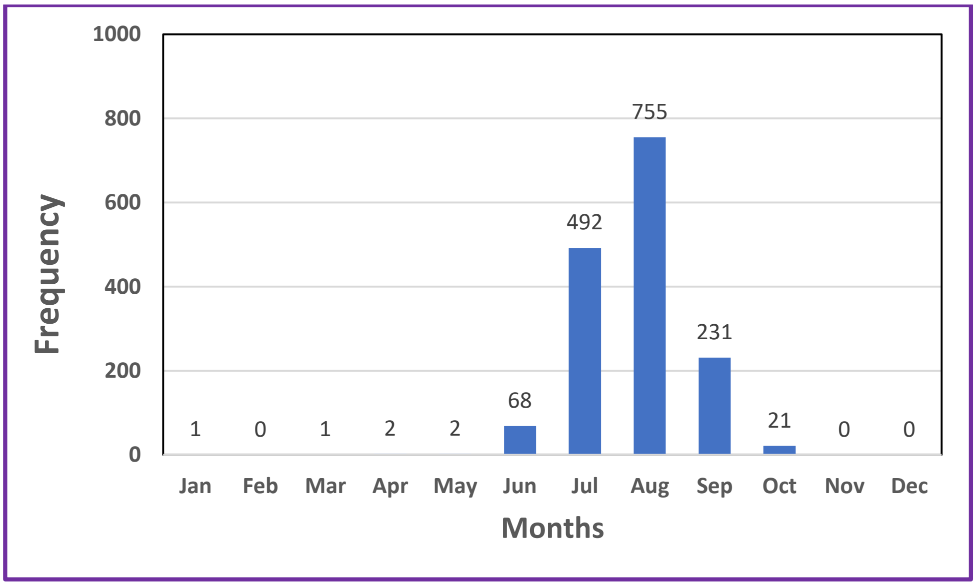


Figure 5-7 Timing of occurrence of instantaneous floods

Basin-wise distribution of timing of occurrence of IMF events is given in **Table 5-8**. The occurrence of IMFs is nearly consistent across all basins. In July and August, the occurrence ranges from 73% (West Rapti) to 87% (Bagmati). In the monsoon season, the occurrence percentage of IMF are 94, 97, 96, 97, 100, 97, 93 and 95 in Koshi, Gandaki, Karnali, Mahakali, Kankai, Bagmati, West Rapti and Babai basins respectively.

To assess how the highest floods in a particular year occur across the country, floods occurring in more than seven gauging stations on the same day were extracted. The spatial distribution of these occurrences of past IMF events on a single day is presented in **Figure 5-8**, with basin-wise distribution provided in **Table 5-9**. From the figure and table, it can be observed that nearly one-third of the gauging stations (15 out of 44) recorded the highest floods on the same day, i.e., on July 26, 2016. In three other years—2000, 2013, and 2014—twelve stations recorded the highest floods on the same day. On August 3, 2012, 11 gauging stations experienced the highest floods. Similarly, in 1988, 1996, and 2000, 10 stations each recorded the highest floods of the year on a single day. These records show that the highest flood events have a high probability of occurring on the same day in much of the country.

Additionally, there is a possibility of a one- or two-day shift in these events. For example, in 2000, the highest flows occurred in most of the Karnali sub-basins on August 1, while the highest flows in most of the Gandaki sub-basins occurred on August 2. Similarly, in 2014, most of the Koshi sub-basins recorded the highest flows on August 14, while most of the Gandaki and Karnali sub-basins had their highest flows on August 15.

From **Table 5-9**, it is evident that the probability of high flows occurring in all locations, even within a given basin, on the same day is relatively low.

Table 5-8 Distribution of occurrence of flood events in different river basins

Month	Total Frequency	Koshi	Gandaki	Karnali	Mahakali	Kankai	Bagmati	West Rapti	Babai
Jan	1						1		
Feb	0								
Mar	1	1							
Apr	2	2							
May	2	1							1
Jun	68	24	15	15	1		1	10	2
Jul	492	148	158	71	13	14	20	45	23
Aug	755	212	191	200	19	13	39	54	27
Sep	231	69	72	37	5	4	7	25	12
Oct	21	4	1	12	1	1		2	
Nov	0								
Dec	0								
Total	1573	461	437	335	39	32	68	136	65

Basins	M	Karnali Basin									Babai		West Rapti				Gandaki Basin												Bgmti		Koshi Basin													KK	
Date\St.No.	120	215	220	225	240	250	260	265	270	280	286	289.95	330	350	360	375	404.7	420	428	438	440	445	447	448	450	460	465	470	505	589	602	602.5	604.5	606	620	630	647	650	652	660	670	690	695	795	Total
2016-07-26										*	*	*	*	*	*	*			*	*					*									*	*	*			*				*		15
2000-08-01		*	*	*	*	*		*		*	*																	*					*		*							*			12
2013-07-22											*			*	*	*		*		*	*		*	*	*	*															*				12
2014-08-15				*		*		*		*	*	*	*		*	*		*			*				*																				12
2012-08-03		*											*	*	*	*	*						*			*											*				*		*		11
1988-08-01																				*	*	*	*											*	*	*		*	*		*				10
1996-08-13		*			*	*									*							*	*	*	*											*			*						10
2000-08-02									*												*	*	*	*	*				*	*				*									*		10
1982-08-28		*		*	*	*	*			*												*	*						*																9
1999-07-03											*									*		*		*			*			*				*								*	*		9
1981-09-29			*	*	*	*	*											*							*			*																	8
1982-07-19																														*	*		*			*			*	*	*	*			8
2007-09-05																						*		*									*	*		*	*				*	*			8
2014-08-14																										*							*	*		*	*		*		*		*		8
1983-09-11		*	*	*	*					*				*	*																														7
1984-09-17																										*	*	*		*	*								*		*				7
1987-07-25	*																			*					*				*							*	*				*				7
1990-08-27									*			*										*				*	*	*		*															7
1992-08-24																			*			*	*	*	*											*		*							7
1993-08-06			*	*	*	*		*	*																												*								7
1993-08-10							*														*	*	*		*											*			*						7
2003-07-09																			*	*	*													*								*	*	*	7
2003-07-31															*	*						*			*			*		*								*							7
2004-08-20																		*		*		*			*											*	*		*						7
2008-09-20	*				*					*		*	*	*				*																											7
2009-10-07			*			*	*		*	*						*						*																							7
2013-06-18		*	*	*	*	*	*			*																																			7

Figure 5-8 Spatial distribution of occurrences of past IMF events in a single day

Table 5-9 Basin wise distribution of past IMF events occurred on a single day

Basins	Mahkali	Karnali	Babai	West Rapti	Gandaki	Bagmati	Koshi	Kankai	Nepal
Date\Total Basins No.	1	9	2	4	12	2	13	1	44
2016-07-26		1	2	4	3		5		15
2000-08-01		7	1		1		3		12
2013-07-22			1	3	7		1		12
2014-08-15		4	2	3	3				12
2012-08-03		1		4	3		3		11
1988-08-01					4		6		10
1996-08-13		3		1	4		2		10
2000-08-02		1			5	2	2		10
1982-08-28		6			2	1			9
1999-07-03			1		4	1	3		9
1981-09-29		5			3				8
1982-07-19						1	7		8
2007-09-05					2		6		8
2014-08-14					1		7		8
1983-09-11		5		2					7
1984-09-17					3	1	3		7
1987-07-25	1				2	1	3		7
1990-08-27		1	1		4	1			7
1992-08-24					5		2		7
1993-08-06		6					1		7
1993-08-10		1			4		2		7
2003-07-09					3		3	1	7
2003-07-31				2	3	1	1		7
2004-08-20					4		3		7
2008-09-20	1	2	1	2	1				7
2009-10-07		5		1	1				7
2013-06-18		7							7

5.3.6 Instantaneous Floods and Catchment Area Relationship

The catchment area of selected 44 river basins/sub-basins, their average of instantaneous floods, their ranges (maximum and minimum values), and specific flood discharges of the past IMF are given in **Table 5-10**. The average specific instantaneous flood discharge of river basins in Nepal is found to be 0.62 $m^3/s/km^2$. The average specific discharge of Class A River Basins is 0.53 $m^3/s/km^2$, while that of Class B River Basins is 0.95 $m^3/s/km^2$. Among Class A River Basins, the Karnali basin has the minimum specific flood discharge value of 0.18 $m^3/s/km^2$, while the maximum value is found in the Gandaki basin (0.79 $m^3/s/km^2$). The specific flood discharges of the Koshi and Mahakali basins are 0.54 and 0.33 $m^3/s/km^2$ respectively. The range of such discharges is also quite high (maximum: 3.26 $m^3/s/km^2$, minimum: 0.11 $m^3/s/km^2$) when considering both types of river basins. However, if we consider only Class A River Basins, the range is significantly reduced, lying between 0.11 and 2.00 $m^3/s/km^2$.

Table 5-10 Instantaneous flood, specific flood and catchment area

SN	Station	Catchment Area (km^2)	IMF_Qavg (m^3/s)	IMF_Qmax (m^3/s)	IMF_Qmin (m^3/s)	Sp. Flood Discharge ($m^3/s/km^2$)
1	120	1150	375	898	122	0.33
2	215	15200	1684	2680	867	0.11
3	220	1870	228	470	107	0.12
4	225	824	116	162	84	0.14
5	240	19260	2256	4740	1390	0.12
6	250	21240	2776	4800	1680	0.13
7	260	7460	3229	9540	1320	0.43
8	265	6720	1126	2140	721	0.17
9	270	12290	2311	5150	1320	0.19
10	280	42890	9221	21700	4560	0.21
11	286	816	238	930	26	0.29
12	289.95	2557	1625	5060	303	0.64
13	330	1938	606	1240	165	0.31
14	350	3380	1932	6030	625	0.57
15	360	5150	3170	7390	1300	0.62
16	375	5200	3389	9100	1090	0.65
17	404.7	1112	535	927	176	0.48
18	420	11400	4584	8430	1800	0.40
19	428	160	149	437	30	0.93
20	438	858	666	1970	274	0.78
21	440	308	337	1040	140	1.09
22	445	4270	841	2060	542	0.20
23	447	4110	1174	2100	495	0.29
24	448	653	562	1380	216	0.86
25	450	31100	9728	14900	4900	0.31
26	460	579	745	3260	170	1.29
27	465	427	518	1730	83	1.21

SN	Station	Catchment Area (km²)	IMF_Qavg (m^3/s)	IMF_Qmax (m^3/s)	IMF_Qmin (m^3/s)	Sp. Flood Discharge ($m^3/s/km^2$)
28	470	169	286	1170	58	1.69
29	505	17	9	34	4	0.55
30	589	2700	4506	16000	2100	1.67
31	602	375	230	694	98	0.61
32	602.5	110	44	108	18	0.40
33	604.5	28200	3001	5720	1400	0.11
34	606	30380	3579	5550	1620	0.12
35	620	629	584	2100	192	0.93
36	630	4920	1654	3940	820	0.34
37	647	2753	1204	2130	736	0.44
38	650	313	627	2620	73	2.00
39	652	10000	3968	7880	1860	0.40
40	660	823	325	587	175	0.40
41	670	4100	2271	9880	870	0.55
42	690	5640	3449	6760	1330	0.61
43	695	54100	8152	24000	2940	0.15
44	795	1148	3739	7500	992	3.26

In **Figure 5-9**, the average instantaneous floods are plotted against the catchment areas of the Class A River Basins. A power relationship between them is clearly seen in this figure. The relation takes the form as given in **Equation (5-7)**.

$$Q_{IMF} = 6.0A^{0.65} \tag{5-7}$$

Where,

Q_{IMF} =Instantaneous flood (m^3/s)

A = Catchment area (km^2)

The above equation is applicable to only Class A River Basins of Nepal. It is because the inclusion of Class B River Basins greatly reduces the value of performance parameter i.e., coefficient of determination.

Specific flood discharges of Class A River Basins are plotted against their catchment areas in **Figure 5-10.** Although weak, inverse relationship between these two variables is seen from the graph. It takes the form given by **Equation (5-8)**.

$$q_{IMF} = 6.0A^{-0.35} \tag{5-8}$$

Where,

q_{IMF} = Specific instantaneous flood discharge ($m^3/s/km^2$)
A = Catchment area (km^2)

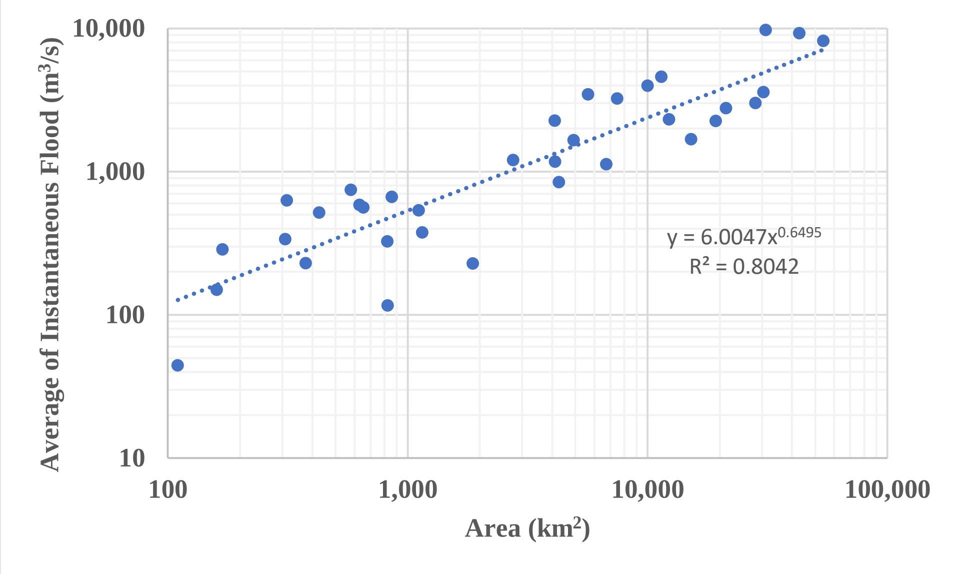


Figure 5-9 Relationship between average instantaneous floods and catchment area

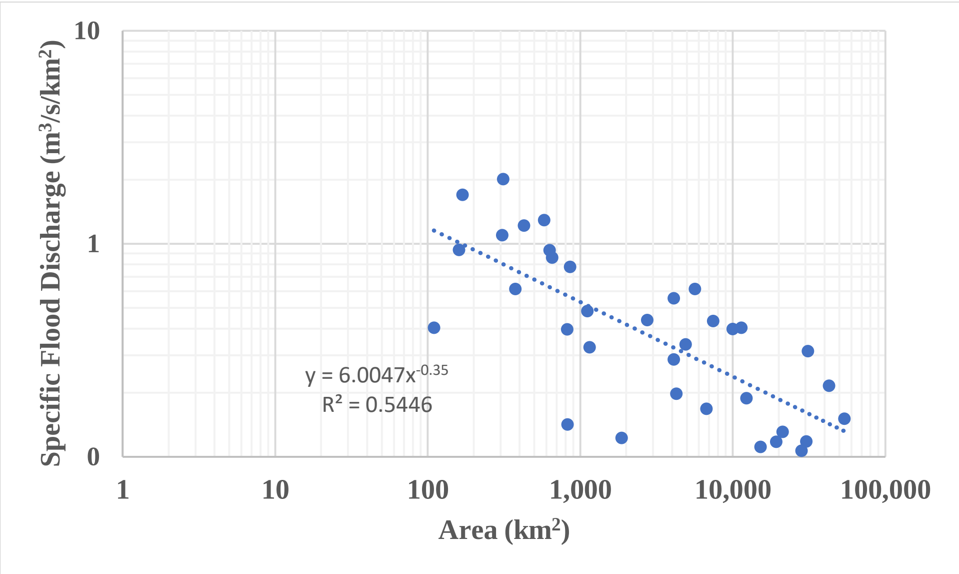


Figure 5-10 Relationship between specific flood discharge and catchment area

5.3.7 Temporal Trend of Instantaneous Floods

Temporal trend on the instantaneous maximum floods was assessed by calculating the deviation of the IMFs (ΔQ in percentage) from the average of the IMF series for each basin. It was calculated using **Equation (5-9).**

$$\Delta Q = \frac{Q-\bar{Q}}{\bar{Q}}\% \tag{5-9}$$

Where,

Q = IMF of a particular year of a given basin

$\bar{Q}$= Average of IMFs of the given basin

Equation (5-9) normalizes the floods of any magnitude which makes it possible to plot data of number of basin/sub-basins in a single graph. The deviation percentage of IMFs of Koshi, Gandaki and Karnali basin/sub-basins are plotted against the years and is shown in **Figure 5-11**, **Figure 5-12** and **Figure 5-13** respectively. Upon reviewing these figures, it is difficult to deterministically conclude whether the floods in Nepal's rivers are increasing or decreasing. However, flood records from some stations in the Karnali basin show a somewhat continuous increase in flood values after 2005. On the other hand, floods in the Koshi and Gandaki basins exhibit decreasing trends in recent years, as seen in the decadal average deviation percentages of the IMFs for these two basins, presented in **Table 5-11**. Similar decreasing trends are observed in the West Rapti and Babai basins. In contrast, the Chamelia basin shows a clear decadal increasing trend in its IMF. The occurrences of the top ten floods across the country, as well as in the Koshi, Gandaki, and Karnali basins, are shown in **Figure 5-14** and **Figure 5-15**, respectively. These figures show no clustering of floods during any particular period, implying that there is no clear observable temporal trend in the flows of Nepal's rivers.

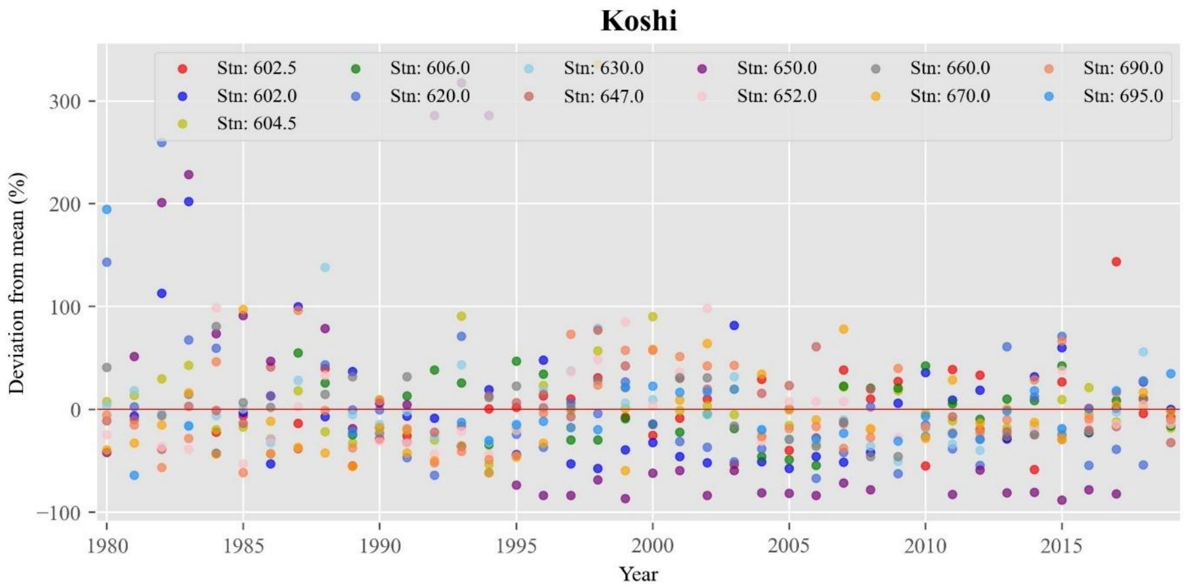


Figure 5-11 Deviation of instantaneous floods from the average-Koshi Basin

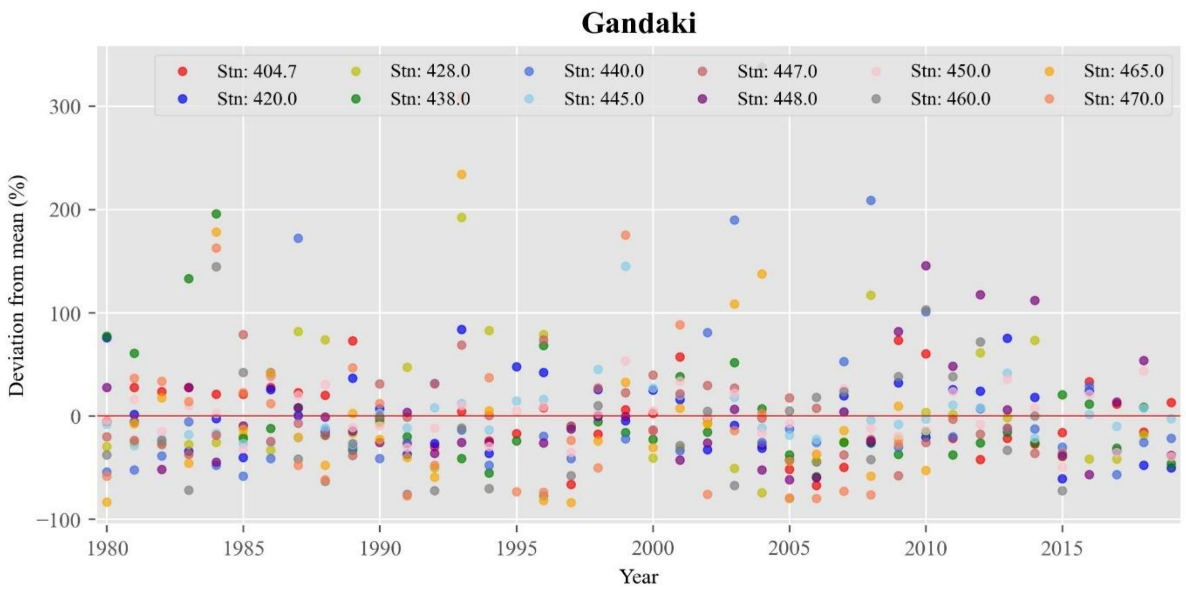


Figure 5-12 Deviation of instantaneous floods from the average-Gandaki Basin

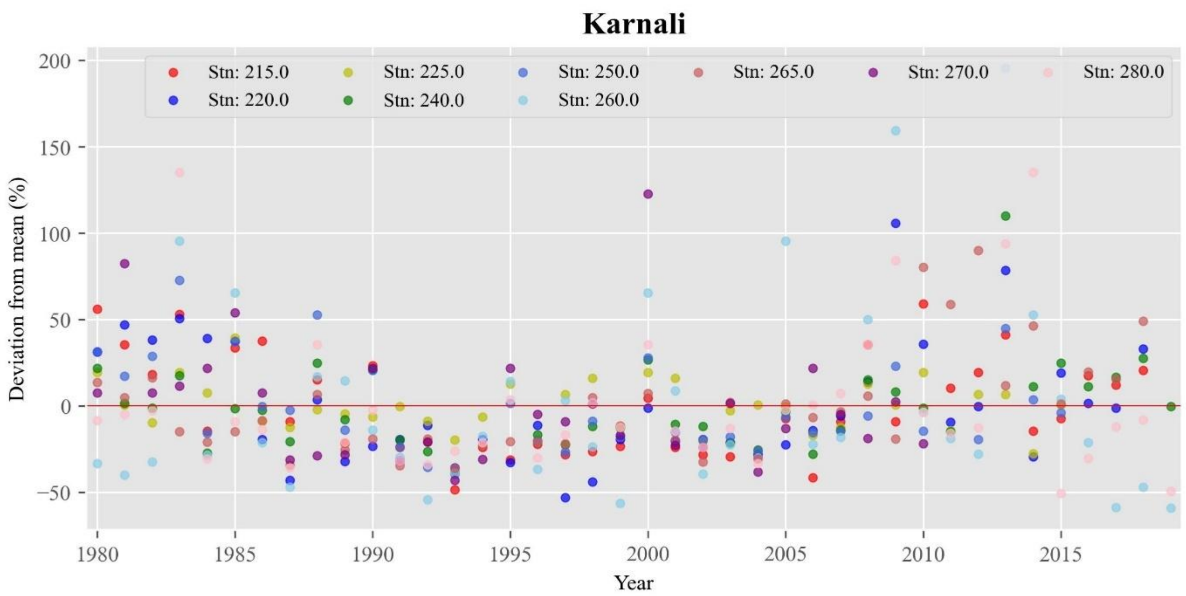


Figure 5-13 Deviation of instantaneous floods from the average-Karnali Basin

Table 5-11 Decadal average deviation percentage of IMFs of major river basins

Decade	Mahakali	Karnali	Babai	West Rapti	Gandaki	Bagmati	Koshi	Kankai
1980-1989	-45	8	51	29	3	6	16	-8
1990-1999	-21	-18	-1	-3	1	-5	3	2
2000-2009	10	0	-19	-10	-2	8	-9	9
2010-2019	52	9	-6	-10	-5	-17	-10	-13

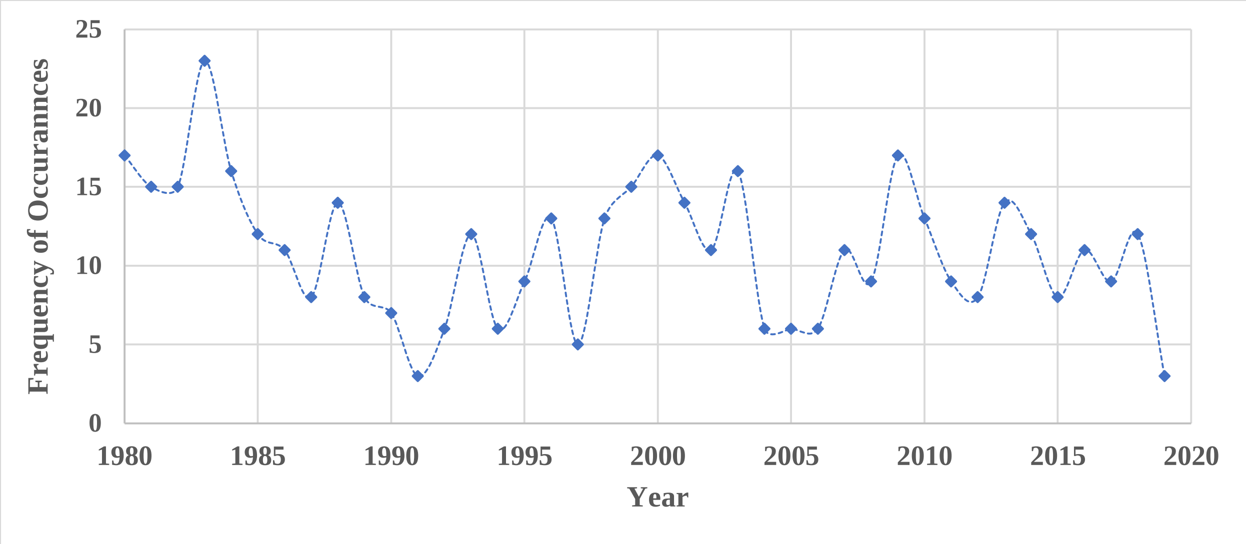


Figure 5-14 Occurrences of top ten instantaneous flood all over Nepal

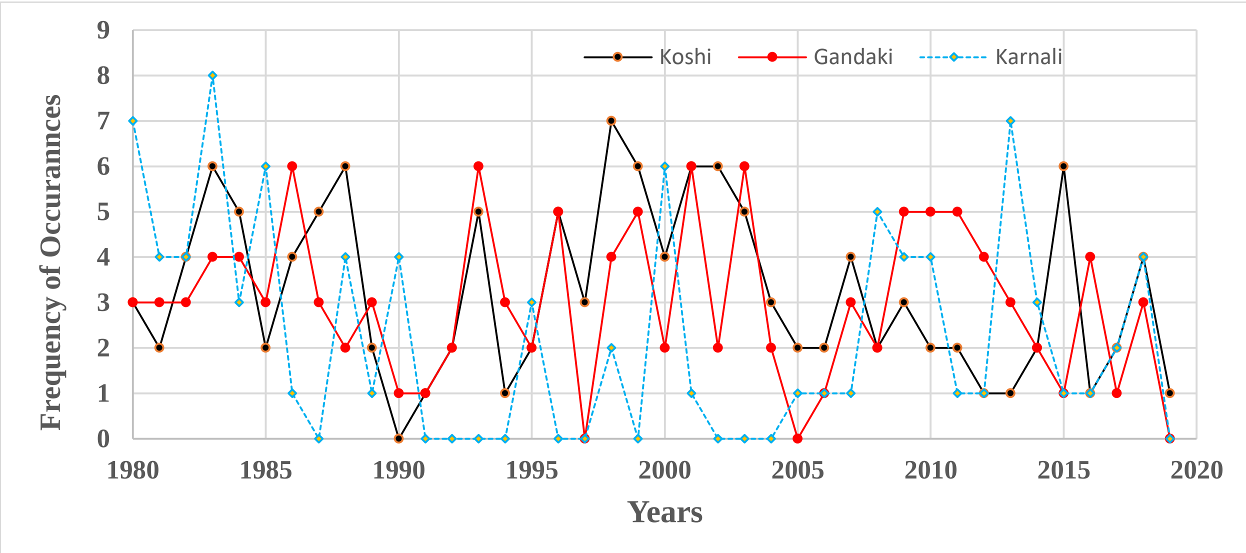


Figure 5-15 Occurrences of top ten instantaneous floods in Koshi, Gandaki and Karnali Basins

5.4 Flood Estimation of Ungauged Rivers

River basins that lack flow gauging stations are referred to as ungauged river basins. Class C rivers, which mainly originate from the Churia Hills or the Terai, are considered ungauged basins. Although the Kamala River is classified as a Class B River, it also lacks measured flow data, and thus, is categorized as an ungauged basin. In such cases, regional flood estimation methods are typically employed. Commonly used empirical flood analysis methods in Nepal include WECS/DHM 1990, DHM 2004, and the Modified Dicken's method. These flood estimation methods are briefly described in the following sub-sections.

1. WECS/DHM 1990 method

A widely used regional approach is the WECS/DHM method which provides methodologies to compute instantaneous flood flows (WECS/DHM, 1990). **Equations (5-10a** and **5- 10b)** are used to compute flood of 2-year and 100-year return period respectively in the WECS/DHM method.

$$Q_2 = 1.8767(A_{3000})^{0.8783} \quad (5\text{-}10a)$$

$$Q_{100} = 14.639(A_{3000})^{0.7342} \quad (5\text{-}10b)$$

Where,
Q_2 = 2-year flood in m^3/s

Q_{100} = 100-year flood in m^3/s

A_{3000}= Catchment area below 3000 m in km^2.

Based on the algebraic evaluations of the equations used for lognormal distribution, **Equation (5-11)** (WECS/DHM, 1990) is used to estimate floods at other return periods.

$$Q_T = \exp(lnQ_2 + S\sigma) \quad (5\text{-}11)$$

Where,

$\sigma = \ln{(Q_{100}/Q_2)}/2.326$

S = Standard normal variate, given in **Table 5-12.**

Table 5-12 Standard normal variate's values for different return period

Return Period (T-years)	S
2	0.000
5	0.842
20	1.645
25	1.759
50	2.054
100	2.326
200	2.576
500	2.878

2. DHM 2004 method

The 2- and 100-year return period flood estimation in the ungauged basins by this method uses **Equations (5-12a** and **5-12b)** (Sharma and Adhikari, 2004).

$$Q_2 = 2.29(A_{3000})^{0.86} \quad (5\text{-}12a)$$

$$Q_{100} = 20.7(A_{3000})^{0.72} \quad (5\text{-}12b)$$

Where,

Q_2 = 2-year flood in m^3/s
Q_{100} = 100-year flood in m^3/s
A_{3000}= Catchment area below 3000 m in km^2.

Flood estimation for other return periods, the method is similar to the WECS/DHM 1990 method.

3. Modified Dicken's method

The T year flood discharge (Q_T) in m^3/s is determined by using **Equation (5-13)**.

$$Q_T = C_T A^{0.75} \quad (5\text{-}13)$$

Irrigation Research Institute, Roorkee (India) has conducted frequency studies on Himalayan Rivers and suggested **Equation (5-14)** to compute Dickens constant C_T for desired return period (T) as:

$$C_T = 2.342 \log(0.6T) \log\left(\frac{1185}{p}\right) + 4 \quad (5\text{-}14)$$

Where,

$$p = \frac{a+6}{A+a} 100$$

Here,

a = Perpetual snow area in km^2
A = Total basin area in km^2.

5.4.1 Estimated Floods of Kamala River

The catchment area of the Kamala River at the junction of East-West Highway is 1,597 km^2. The estimated flood of Kamala River at this section by the three methods discussed above are given in **Table 5-13**.

Table 5-13 Estimated floods of Kamala River for different return periods

Unit: m^3/s

Return Period (years)	DHM2004	WECS/DHM 1990	Modified Dicken's
2	1,302	1,222	1,174
5	1,988	1,749	1,998
10	2,480	2,110	2,621
20	2,977	2,462	3,245
50	3,656	2,931	4,068
100	4,191	3,291	4,691
200	4,752	3,661	5,315
500	5,531	4,163	6,138

5.4.2 Estimated Floods of Class C Rivers

Floods of Kandra, Man Khola, Banganga, Tinau, Lothar, Tilabe, Bakaiya, Lokhandehi, Rato, Balan, Budhi, Bakraha, Birin and Mechi rivers (**Figure 5-16**) were estimated using the above-described methods. The estimated flood at the junction of East-West Highway with these rivers by all these methods is provided in **Table 5-14** (DHM 2004 method), **Table 5-15** (WECS 1990 method) and **Table 5-16** (Modified Dicken's method). The flood estimate from the DHM 2004 method has been selected, as it gave the higher flood values in most of the cases.

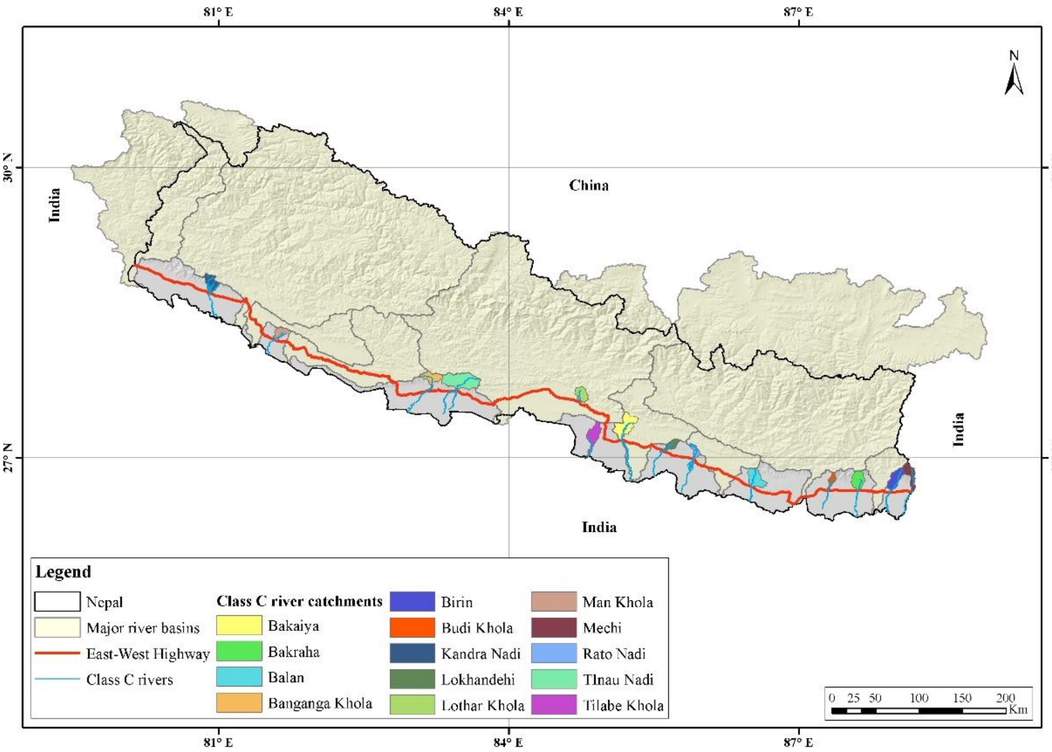


Figure 5-16 Location maps of Class C Rivers

Table 5-14 Flood estimation of Class C rivers by DHM 2004 method

Unit: m^3/s

DHM 2004 Method										
SN	River Name	Catchment Area (km^2)	Q_2	Q_5	Q_{10}	Q_{20}	Q_{50}	Q_{100}	Q_{200}	Q_{500}
1	Kandra Nadi	202.5	220	374	492	618	799	948	1,108	1,339
2	Man Khola	139.3	160	276	367	465	607	724	851	1,036
3	Banganga Khola	194.4	213	362	477	599	775	920	1,077	1,302
4	Tinau Khola	552.5	523	842	1,080	1,327	1,673	1,952	2,249	2,668
5	Lothar Khola	168.6	188	322	427	538	698	830	974	1,181
6	Tilabe Khola	267.3	280	468	612	764	980	1,157	1,348	1,621
7	Bakaiya Khola	394.6	391	641	830	1,027	1,306	1,532	1,774	2,118
8	Lokhandehi Khola	111.6	132	231	309	393	515	617	728	890
9	Rato Nadi	89.3	109	193	259	331	437	525	622	763
10	Balan Nadi	279.3	291	485	633	790	1,013	1,194	1,390	1,670
11	Budhi Khola	83.9	103	183	247	316	418	502	596	731
12	Bakraha Khola	224.5	241	406	534	669	862	1,021	1,192	1,438
13	Birin Khola	231.7	248	417	547	685	882	1,044	1,219	1,469
14	Mechi Nadi	198.2	216	367	484	608	787	933	1,092	1,320

Table 5-15 Flood estimation of Class C rivers by WECS 1990 method

Unit: m^3/s

WECS/DHM 1990 Method										
SN	River Name	Catchment Area (km^2)	Q_2	Q_5	Q_{10}	Q_{20}	Q_{50}	Q_{100}	Q_{200}	Q_{500}
1	Kandra Nadi	202.5	200	319	407	497	623	725	832	984
2	Man Khola	139.3	144	234	302	372	472	552	637	758
3	Banganga Khola	194.4	193	308	394	482	605	703	808	956
4	Tinau Khola	552.5	482	728	904	1,081	1,322	1,511	1,708	1,982
5	Lothar Khola	168.6	170	274	351	431	544	634	730	866
6	Tilabe Khola	267.3	255	401	507	616	767	888	1,015	1,194
7	Bakaiya Khola	394.6	359	552	692	833	1,027	1,181	1,342	1,567
8	Lokhandehi Khola	111.6	119	195	253	314	400	469	544	650
9	Rato Nadi	89.3	98	163	212	264	339	399	464	557
10	Balan Nadi	279.3	265	415	525	637	793	917	1,048	1,231
11	Budhi Khola	83.9	93	155	202	252	323	381	444	534
12	Bakraha Khola	224.5	219	347	441	538	673	782	896	1,057
13	Birin Khola	231.7	225	356	453	552	690	800	917	1,081
14	Mechi Nadi	198.2	196	313	400	489	614	714	820	969

Table 5-16 Flood estimation of Class C rivers modified Dicken's method

Unit: m^3/s

Modified Dicken's Mehod										
SN	River Name	Catchment Area (km^2)	Q_2	Q_5	Q_{10}	Q_{20}	Q_{50}	Q_{100}	Q_{200}	Q_{500}
1	Kandra Nadi	202.5	241	371	469	568	698	796	895	1,025
2	Man Khola	139.3	181	273	342	412	504	574	644	736
3	Banganga Khola	194.4	233	359	453	548	674	769	863	989
4	Tinau Khola	552.5	520	843	1,087	1,331	1,653	1,897	2,141	2,464
5	Lothar Khola	168.6	209	319	402	485	595	679	762	872
6	Tilabe Khola	267.3	298	466	593	719	887	1,014	1,141	1,309
7	Bakaiya Khola	394.6	402	640	821	1,001	1,240	1,420	1,601	1,839
8	Lokhandehi Khola	111.6	152	227	284	341	416	472	529	604
9	Rato Nadi	89.3	128	189	235	281	342	388	434	495
10	Balan Nadi	279.3	308	483	615	747	921	1,053	1,185	1,360
11	Budhi Khola	83.9	122	180	223	266	324	367	411	468
12	Bakraha Khola	224.5	260	404	512	620	763	871	980	1,123
13	Birin Khola	231.7	267	414	526	637	784	896	1,007	1,154
14	Mechi Nadi	198.2	237	364	461	557	685	782	878	1,006

5.5 Flood Disaster Events in Nepal

Flood incidents that have affected public lives and property in Nepal are recorded by the Ministry of Home Affairs (MoHA). Over the past 44 years (from 23/06/1980 to 30/09/2023), there have been 5,070 flood incidents in the country, resulting in fatalities and/or property damage at varying scales. This averages to about 115 flood incidents per year. The country-wide flood events for each year are shown in **Figure 5-17**. The highest number of flood events occurred in 2002, with 415 incidents, while the lowest number, recorded in 1992, was only 4. The frequency of flood incidents has increased since 1990, which could be attributed to the greater magnitude and higher number of floods in recent years. However, the analysis of past data discussed in the preceding sections does not support this conclusion. The increase in recorded incidents may instead be due to improved recording mechanisms at MoHA during this period, or a higher level of public awareness in recent years, upsurge by the growth of media (FM radios, TVs, newspapers, etc.).

The district-wise distribution (spatial distribution) of flood events is shown in **Figure 5-18**. Similarly, the districts that are affected by this flood events are listed in **Table 5-17**. It can be observed that four districts in the Terai region—Sarlahi (201), Morang (214), Rautahat (228), and Jhapa (270)—have experienced more than 200 flood disasters over the past 44 years. On the other hand, Terathum recorded only 8 flood incidents, the lowest among all districts, during this period.

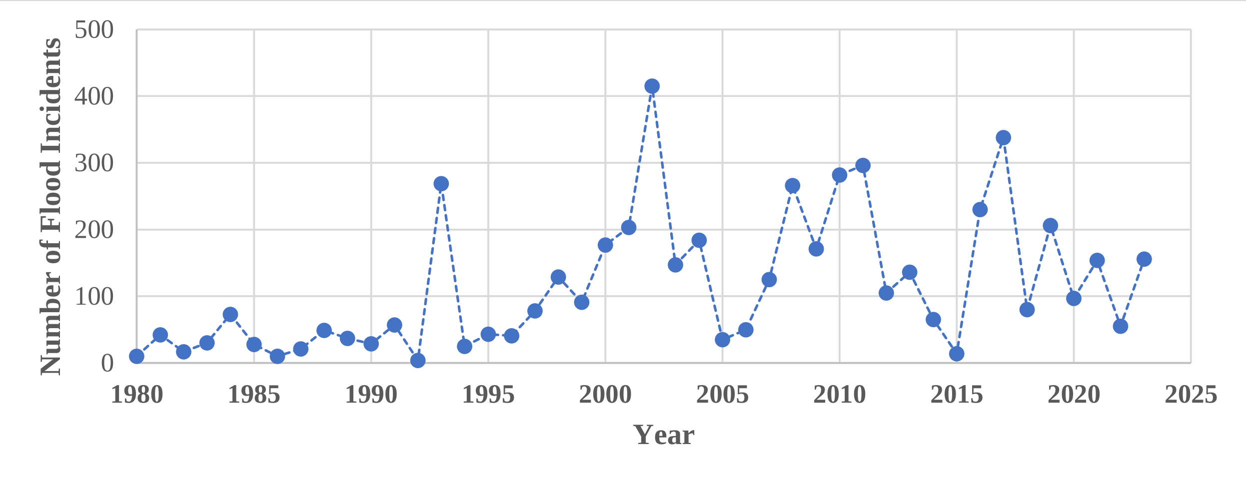


Figure 5-17 Temporal distribution of flood disaster events in Nepal

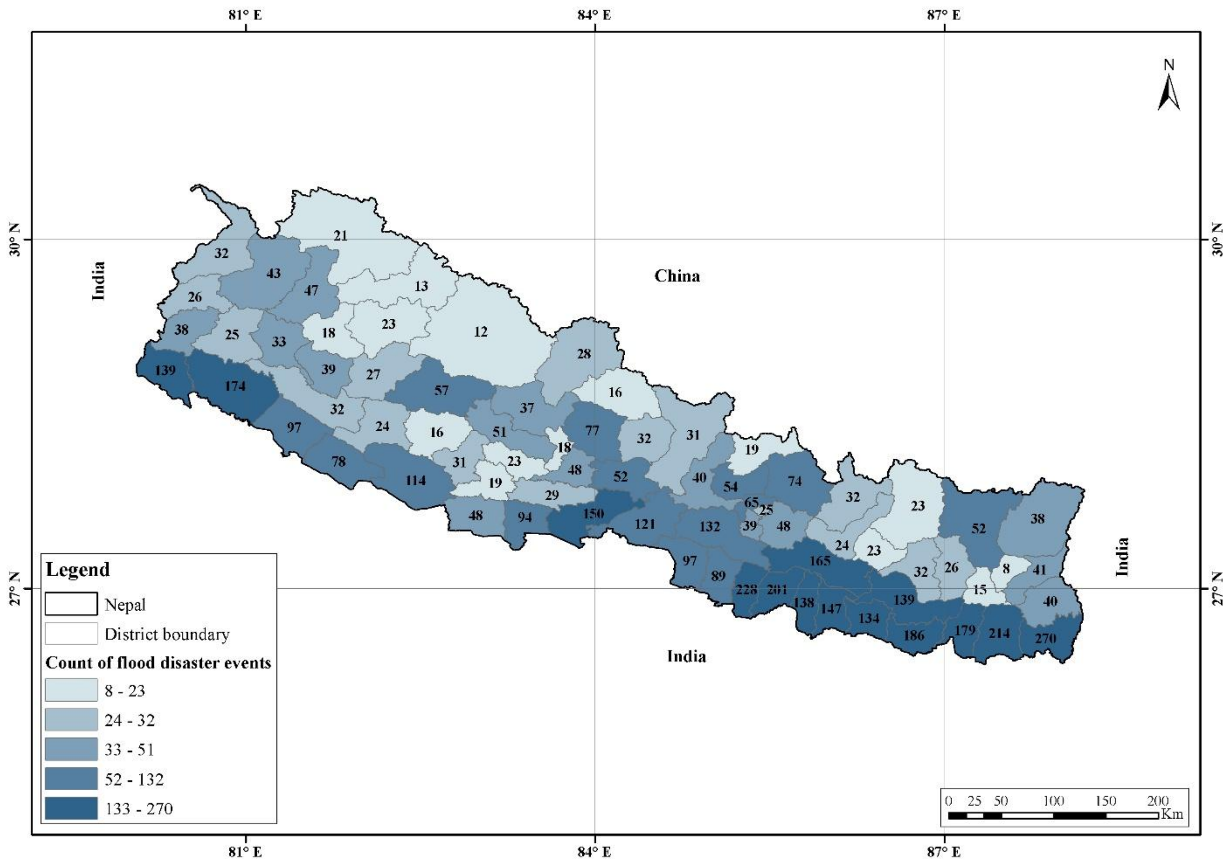


Figure 5-18 Spatial distribution of flood disaster events in Nepal

Table 5-17 List of districts with various flood disaster events

No. of Flood Incidents	No. of Districts	Name of Districts
< 10	1	Terhathum
11-25	18	Dolpa, Mugu, Dhankuta, Manang, Rolpa, Kalikot, Parbat, Arghakhanchi, Rasuwa, Humla, Gulmi, Jumla, Okhaldhunga, Solukhumbu, Ramechhap, Salyan, Bhaktapur, Doti
26-50	26	Baitadi, Bhojpur, Jajarkot, Mustang, Palpa, Gorkha, Pyuthan, Darchula, Dolakha, Khotang, Lamjung, Surkhet, Achhaam, Myagdi, Dadeldhura, Taplejung, Dailekh, Lalitpur, Dhading, Ilam, Panchthar, Bajhang, Bajura, Kapilbastu, Kavrepalanchowk, Shyanja
50-100	13	Baglung, Shankhuwasabha, Tanahu, Nuwakot, Rukum, Kathmandu, Sindhupalchowk, Kaski, Banke, Bara, Rupandehi, Bardiya, Parsa
101-200	13	Dang, Chitawan, Makawanpur, Siraha, Mahottari, Kanchanpur, Udayapur, Dhanusha, Nawalparasi, Sindhuli, Kailali, Sunsari, Saptari
>200	4	Sarlahi, Morang, Rautahat, Jhapa

The distribution of past flood disaster events based on human loss is presented in **Table 5-18**, which shows the number of events categorized by various scales of human deaths only, missing persons only, and both combined. Since these are flood events, the sum of deaths and missing persons may not necessarily equal the total of deaths plus missing persons. In a particular event, the number of deaths and missing persons might each be less than 100, but the combined total could exceed 100. For example, the flood disaster in Surkhet district on 14th August 2014 resulted in 34 deaths and 91 missing persons, making the combined total 125. This event is counted in the "Death + Missing" category as an event with more than 100 persons affected, but does not count as either only deaths or only missing persons.

There were four flood events in which more than 100 persons lost their lives. Six events claimed between 50 and 100 lives, while thirteen events caused between 25 and 50 deaths. Similarly, 49 events resulted in between 10 and 25 deaths. The total number of past flood incidents that caused human loss (either deaths or missing persons) is 1,758 out of a total of 5,071 events. This indicates that one in every three flood events led to at least one human life being lost in Nepal. The most devastating flood disaster occurred in Sarlahi district on 21st July 1993, claiming more than 237 lives in a single event.

Table 5-18 Distribution of flood disaster events based on human loss

Category	Death	Missing	Death + Missing
Loss of more than or equal to 100 persons	2	0	4
Loss of more than or equal to 50 persons	6	4	10
Loss of more than or equal to 25 persons	16	5	23
Loss of more than or equal to 10 persons	57	14	72
Loss of more than or equal to 5 persons	136	36	168
Loss of at least one person	1,435	426	1,758
No human loss	3,635	4,644	3,312
Maximum number of humans in a single event	237	91	237

5.6 Analysis of One-Day Annual Maximum Flood

5.6.1 Flood Zones Classification

The Government of Nepal devised flood hazard zone demarcation policy ‘Water Induced Disaster Management Policy 2072’ for flood control and management (WECS, 2019; DWIDM, 2072). In this policy, floodplain zones are classified based on the flood return periods (**Table 5-19**). The policy categorizes the level of risk into five categories and recommends the use of floodplains according to the level of risk.

Table 5-19 Flood zones classification

S.N.	Floodplain Zone	Level of Risk of Inundated Area	Return Period Flood (year)	Recommended Land Use	Remarks
1	Z0	Floodway	2	Floodway	Reserved for river flow
2	Z1	Highly Risk Area	2-5	Agriculture, forest, parking spot for vehicles, recreational spot etc.	Construction of private houses and development of residential area is prohibited.
3	Z2	Risky Area	5-25	Land use as in Z1 and construction of housing with high plinth level.	The area falls on level corresponding to 25-year return period flood + 50 cm
4	Z3	Moderately Risk Area	25-100	All activities stated in Z1 and Z2 and development of residential area, public houses, hospitals, school and emergency centres etc.	The area falls on level corresponding to 50-year return period flood + 50 cm
5	Z4	Riskless Area	>100	Strategic structures like emergency shelters, hydropower station, large industries etc. as Usual.	

5.6.2 Relationship between Instantaneous and One-Day Maximum Floods

There is only one instantaneous flood value per year in the gauged river basins. However, there can be more than one flood that is equal to or greater than a flood with a certain return period. From the perspective of resource allocation for flood management, the frequency, timing, and magnitude of floods are important. If a river system shows a high correlation between IMFs and one-day maximum floods, we can group the floods occurring at a particular gauging site based on different return periods. By doing so, we can create a flood inventory for that site in accordance with the flood hazard zone demarcation policy of the Government of Nepal (WECS, 2019; DWIDM, 2072), as outlined in **Table 5-19**.

The graphical relationships between IMFs and annual daily maximum floods are shown in **Figure 5-19**, and the performance statistics are provided in **Table 5-20**. A linear relationship between them is clearly seen from these figures. The value of the coefficient of determination (R^2) is well above 0.9 for all basins except for the Kankai River. Nevertheless, its value also falls in a very good category. From their relationships, it can be said that the instantaneous maximum floods in Class A Rivers is generally about 16% higher than the annual daily maximum floods. However, in the case of Class B Rivers, this value is about 60% for eastern rivers (Kankai and Bagmati) and 25% in western rivers (West Rapti and Babai).

Table 5-20 Relation and performance statistics of IMF and annual daily maximum floods

SN	Basin	Relationship	R^2
1	Koshi	$Q_{IMF} = 1.1554 Q_{DM}$	0.963
2	Gandaki	$Q_{IMF} = 1.1615 Q_{DM}$	0.982
3	Karnali	$Q_{IMF} = 1.1617 Q_{DM}$	0.967
4	Mahakali	$Q_{IMF} = 1.1901 Q_{DM}$	0.985
5	Kankai	$Q_{IMF} = 1.5971 Q_{DM}$	0.856
6	Bagmati	$Q_{IMF} = 1.5936 Q_{DM}$	0.936
7	West Rapti	$Q_{IMF} = 1.2889 Q_{DM}$	0.913
8	Babai	$Q_{IMF} = 1.2206 Q_{DM}$	0.962

5.6.3 Flood Frequency Analysis of One-Day Annual Maximum Floods

Flood frequency analysis of one-day annual maximum flood of the selected gauging locations was carried out using the Gumbel distribution method. Floods of 2-, 5-, 25- and 100-year return periods of the eight major locations are tabulated in **Table 5-21** while those for the whole of the county are given in **Appendix C (Table C-4)**. Moreover, flood magnitudes of 2-year, 5-year, 25-year and 100-year return periods are shown in **Figure 5-20**, **Figure 5-21**, **Figure 5-22** and **Figure 5-23** respectively.

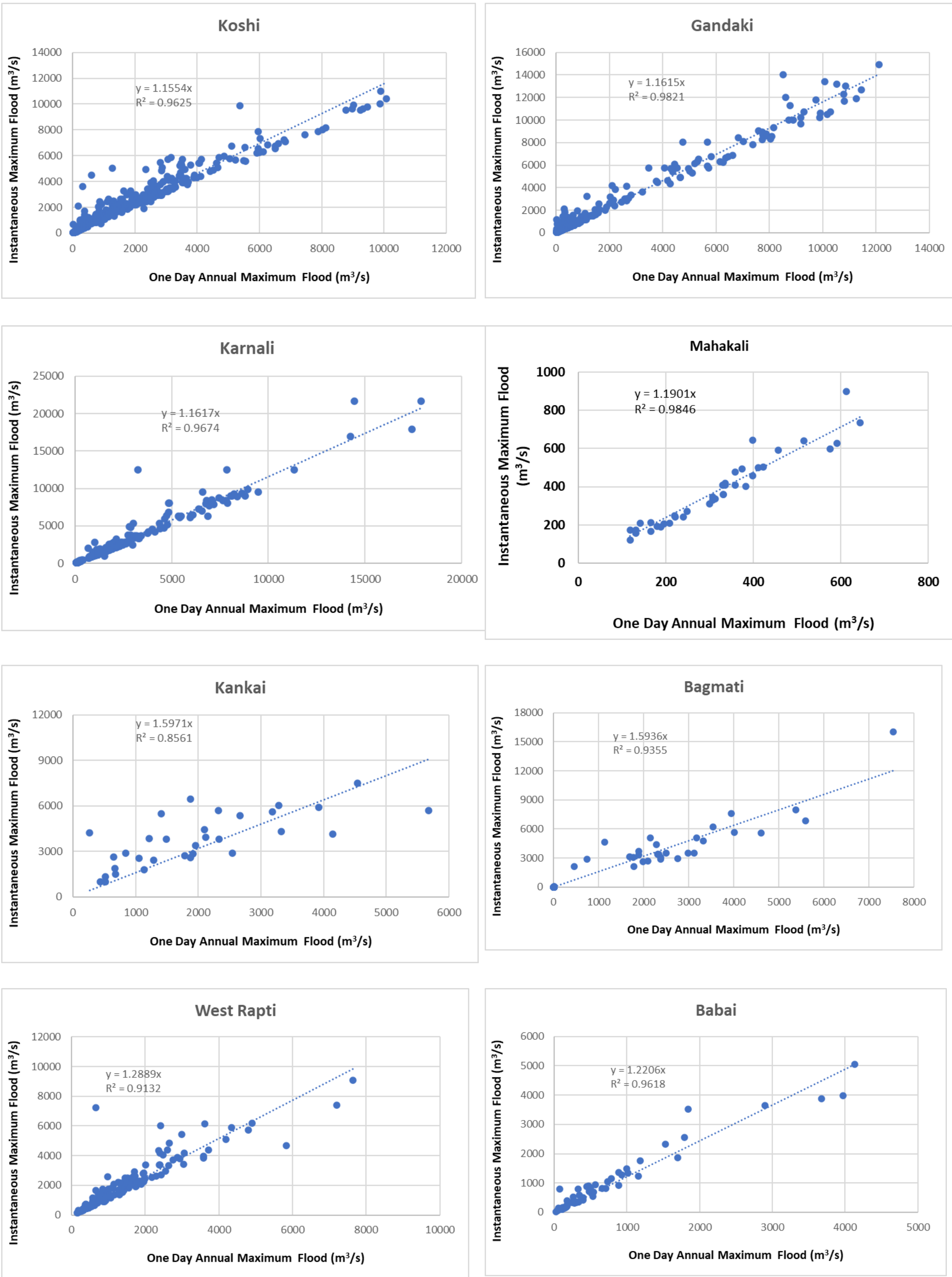


Figure 5-19 Relation between IMF and annual daily maximum floods

Table 5-21 One day flood of different return periods at eight major gauging sites

Unit: m^3/s

SN	St. No.	River	Location	n	Average	Std_Dev	Q_2	Q_5	Q_{25}	Q_{50}	Q_{100}	Q_{200}	Q_{500}
1	695	Koshi	Chatara	29	7,331	2,039	7,020	9,105	12,230	13,524	14,808	16,088	17,776
2	450	Gandaki	Devghat	40	8,520	1,856	8,232	10,075	12,836	13,980	15,115	16,246	17,738
3	280	Karnali	Chisapani	40	7,673	3,315	7,160	10,459	15,402	17,450	19,482	21,507	24,178
4	120	Chamelia	Nayalbadi	39	317	141	295	436	646	734	820	906	1,020
5	795	Kankai	Mainachuli	32	1,991	1,321	1,788	3,126	5,132	5,962	6,786	7,607	8,691
6	589	Bagmati	Pandherodovan	30	2,803	1,493	2,575	4,097	6,377	7,322	8,259	9,193	10,425
7	375	Rapti	Kusum	17	2,460	1,718	2,225	3,988	6,631	7,725	8,812	9,894	11,322
8	289.95	Babai	Chepang	29	1,208	1,114	1,038	2,177	3,884	4,591	5,292	5,991	6,913

Note: Q_x = Flood with return period of x year

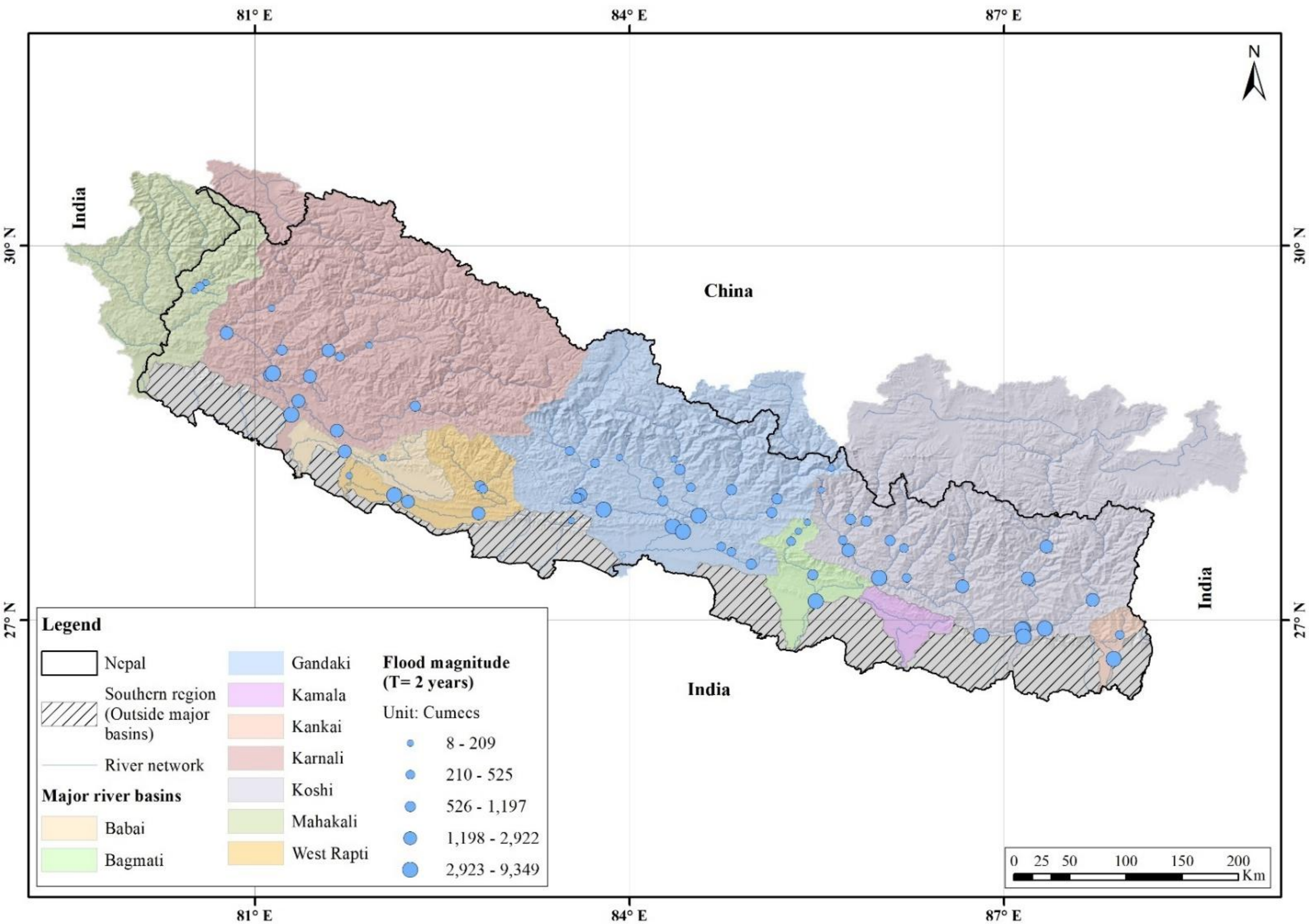


Figure 5-20 One day flood of 2-year return period at different gauging sites

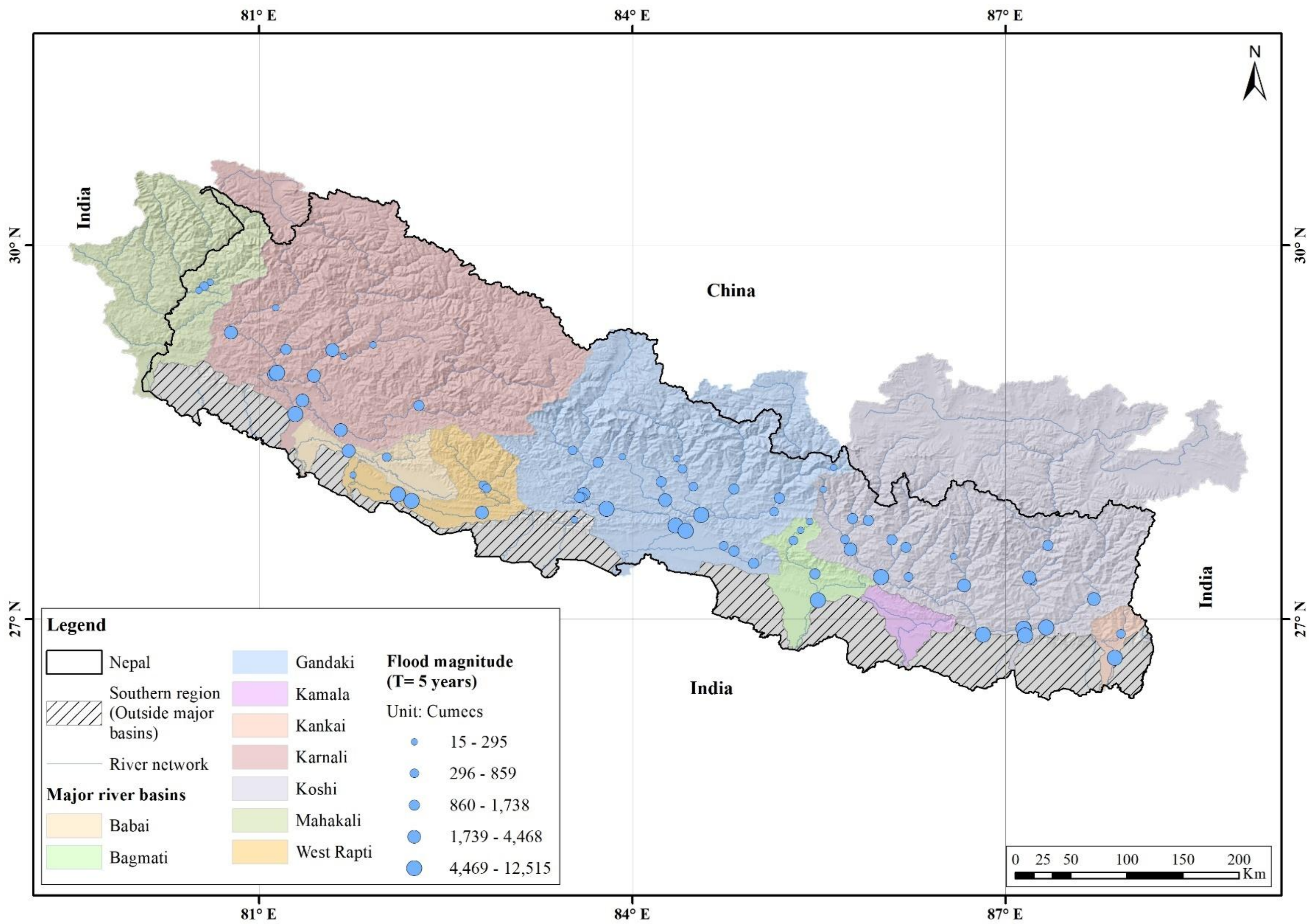


Figure 5-21 One day flood of 5-year return period at different gauging sites

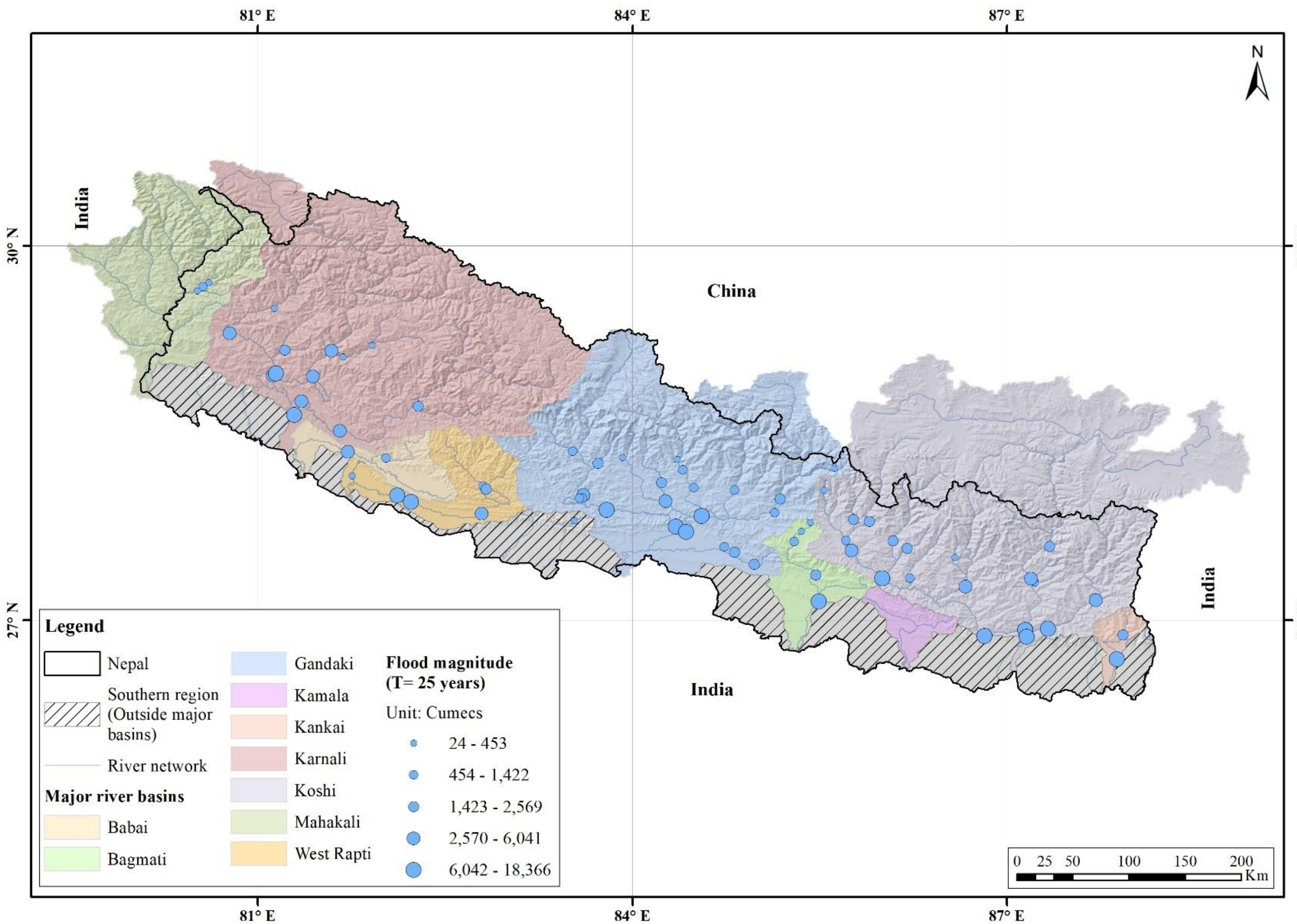


Figure 5-22 One day flood of 25-year return period at different gauging sites

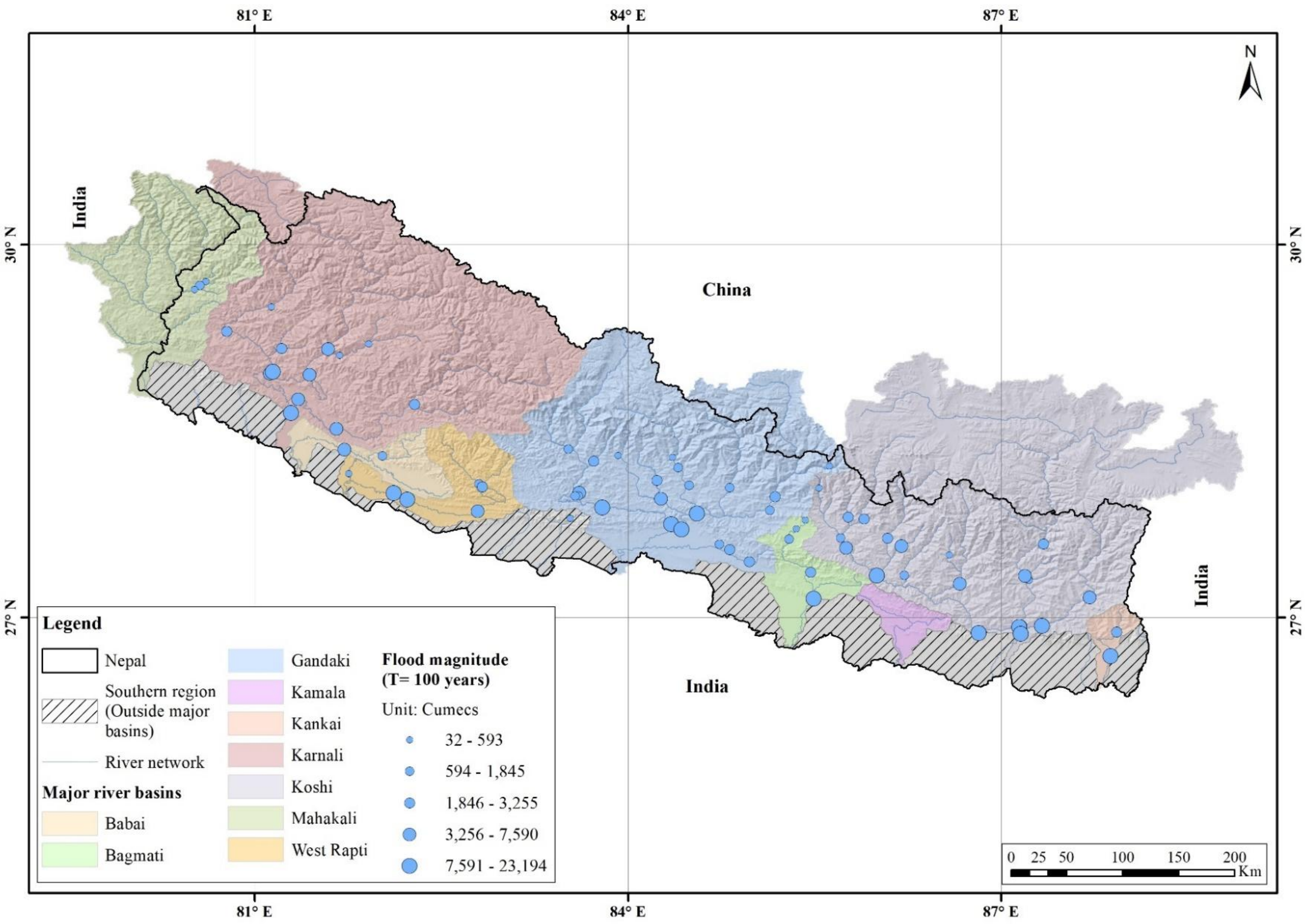


Figure 5-23 One day flood of 100-year return period at different gauging sites

5.6.4 Timing of One-Day Floods Occurrences

Timing of occurrence of the top 5 one-day floods in each year for the eight major rivers, namely, Kankai (Mainachuli), Koshi (Chatara), Bagmati (Pandherodovan), Gandaki (Devghat), West Rapti (Kusum), Babai (Chepang), Karnali (Chisapani) and Chamelia (Nayalbadi) were extracted and plotted against Gregorian Day of the year in **Figure 5-24** and **Figure 5-25**. In these graphs, the numerical designation '1' corresponds to the highest flood of the year, '2' indicates the second highest, and so forth, up to '5'. The first vertical lines of these figures (at 181st day of the year) represent the 1st Day of July and the second vertical lines (at 243rd day of the year) represent 31st of August. From these graphs, we can clearly see that majority of the floods in Nepal occur during July and August. A small number of such floods may occur in September. In other months, floods may occur, but rarely. No specific temporal trend is observed in one-day maximum floods.

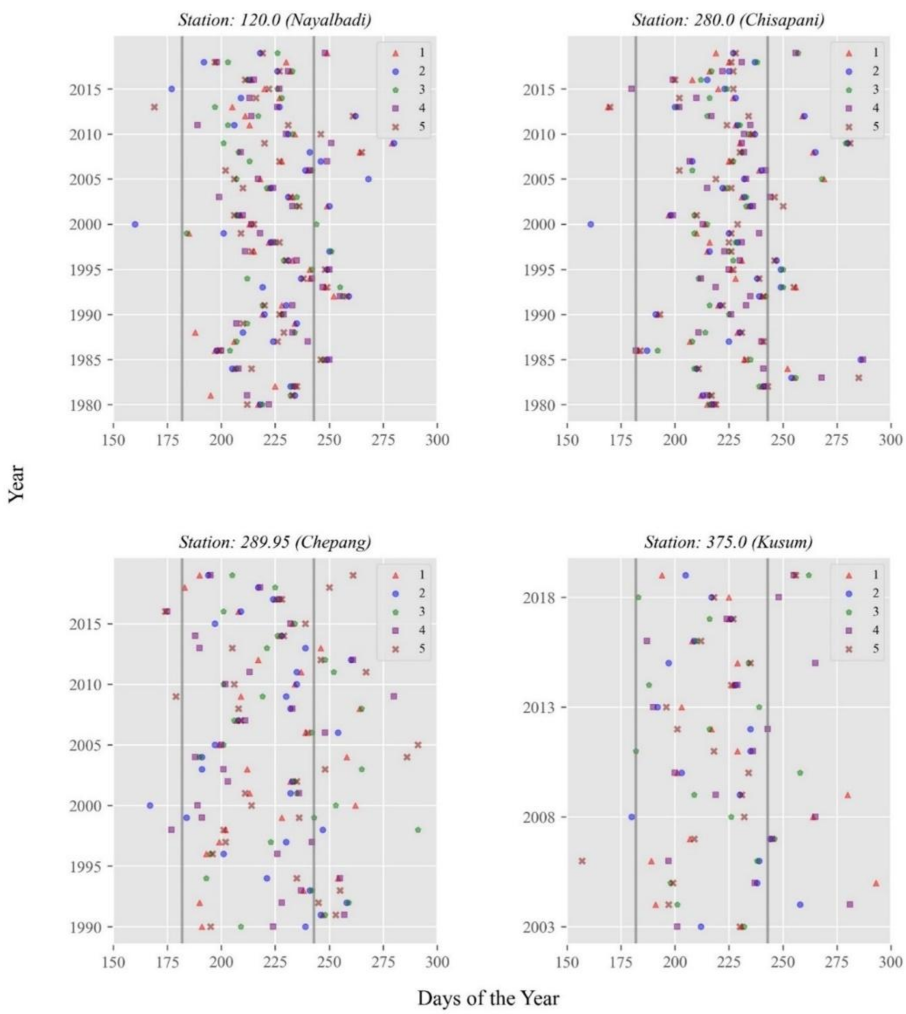


Figure 5-24 Timing of occurrence of floods of Chamelia, Karnali, Babai, and West Rapti Rivers

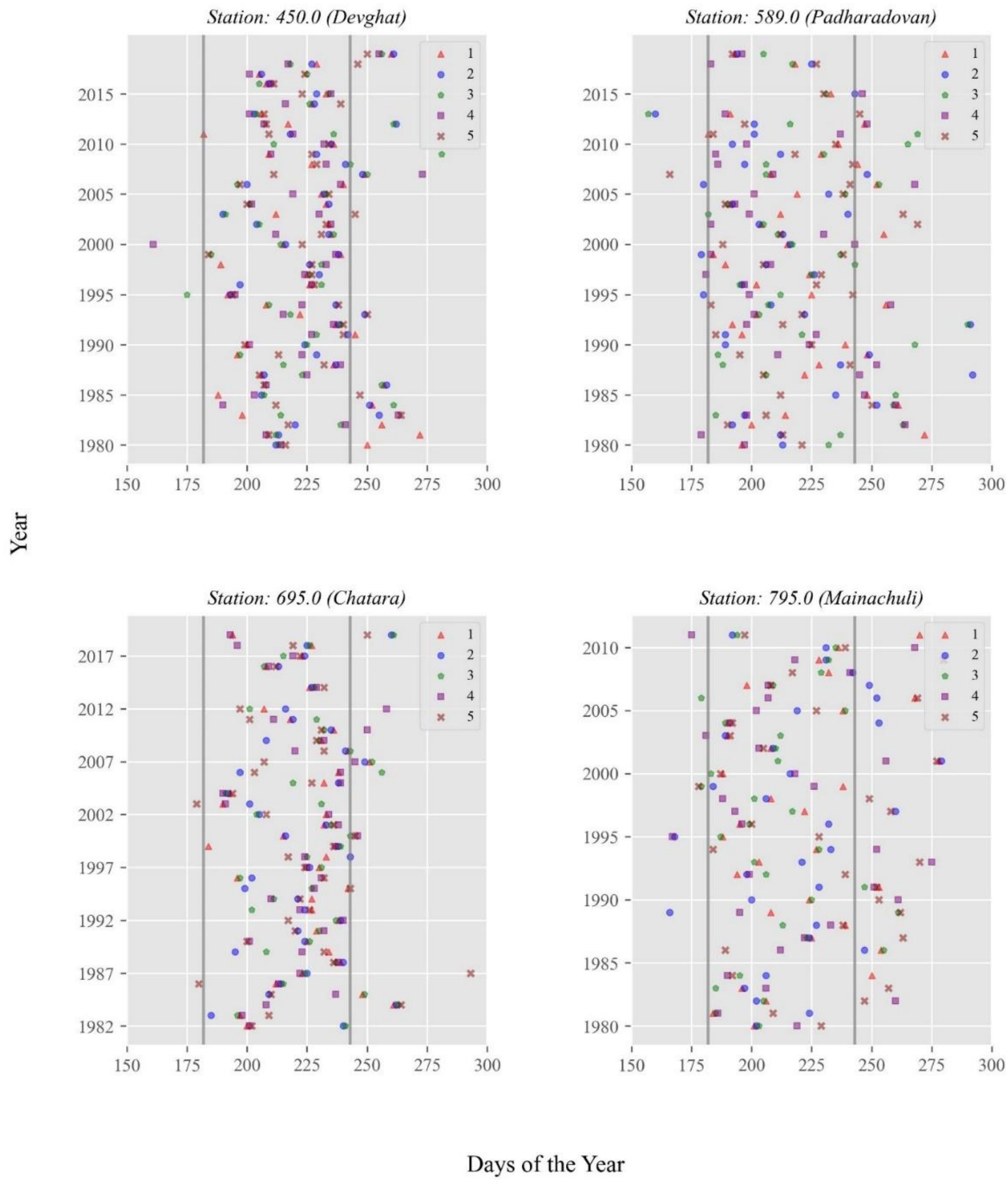


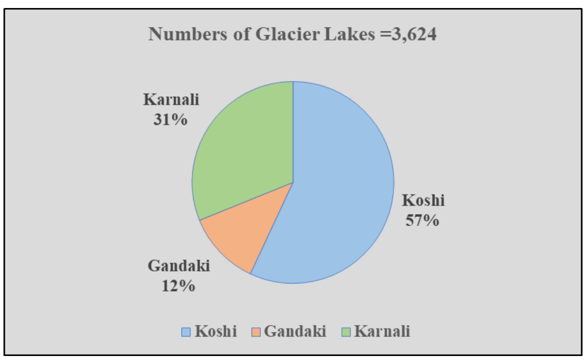
Figure 5-25 Timing of floods of Gandaki, Bagmati, Koshi, and Kankai Rivers

5.7 Glacial Lake Outburst Flood Estimation

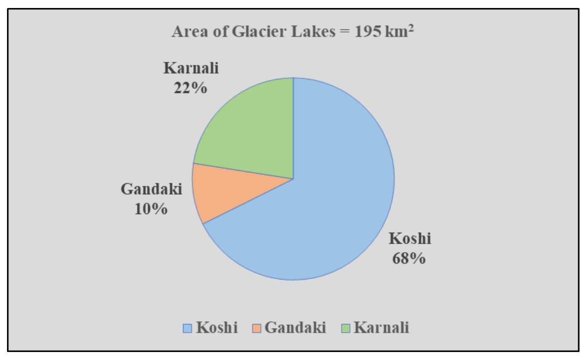
Glacial Lake Outburst Floods (GLOFs) pose a significant threat, causing great loss of life and property downstream due to the sudden release of large volumes of water. Studies have shown that several glacial lakes in Nepal are expanding rapidly, heightening the risk of GLOFs (ICIMOD, 2011). Notable past GLOF events in Nepal include the Dig Tsho GLOF in 1985 and the Bhote Koshi and Sun Koshi GLOFs in 1964 and 1981, respectively. The Dig Tsho GLOF destroyed the nearly completed Namche Small Hydroelectric Project and caused extensive damage downstream. The recent Thame flood, which occurred on the 16th of August 2024, was caused by the outburst of Thanbo Lake, sweeping a village downstream.

5.7.1 Number and Area of Glacial Lakes in Nepal

Bajracharya et al. (2020) stated that there are 3,624 glacial lakes in Nepal covering 195.4 km^2 area as of 2015. The Koshi basin has the largest number of glacial lakes (2,064), followed by the Karnali basin (1,128) and the Gandaki basin (432). The glacial lakes which spread over 0.02 km^2 are 1,410 (Koshi: 825, Gandaki: 171, and Karnali 414). Their distribution and area are presented at the sub-basin level in **Figure 5-26** and **Figure 5-27**. The distribution of lakes with their average sizes is given in **Table 5-22**.



a) Numbers of glacial lakes



b) Area of glacial lakes

Figure 5-26 Basin wise distribution of glacial lakes

5.7.2 Potentially Dangerous Glacial Lakes in Nepal

Currently, there are over 2,070 glacial lakes in Nepal which were mostly formed during the second half of the 20th century as a response to increasing temperatures (Maskey et al., 2020). As per Bajracharya et al. (2020), out of these glacial lakes, 21 are identified as Potentially Dangerous Glacial Lakes (PDGLs) (**Table 5-23**).

The danger levels of the PDGLs are categorized into three ranks, with Rank 1 being the highest as described hereunder and defined in Bajracharya et al. (2020).

Rank 1: Large Lake and possibility of expansion due to the caving of glacier; lake close to the loose moraine end; no overflow through the moraine; steep outlet slope; hanging source glacier; chances of snow and/or ice avalanches and landslides in the surroundings impacting the lake and dam.

Rank 2: Confined Lake outlets; lake outlets close to compact and old end-moraine; hanging lake; distinct seepage at the bottom of end-moraine dam; gentle outward slope of moraine.

Rank 3: Confined Lake outlet; gentle outward slope of the dam; large lake but shallow depth; moraine more than 200 m wide; old and compact moraine.

Further, the total glacial lake area of Nepal is found to increase from 179.56 km^2 in 2000 to 186.44 km^2 in 2005 and to 195.39 km^2 in 2015 (Bajracharya et al., 2020). It indicates that the glacial lakes have merged with each other in these years warning of increase in the number of PDGLs in the future. Locations of these PDGLs in Nepal are shown in **Figure 5-28**.

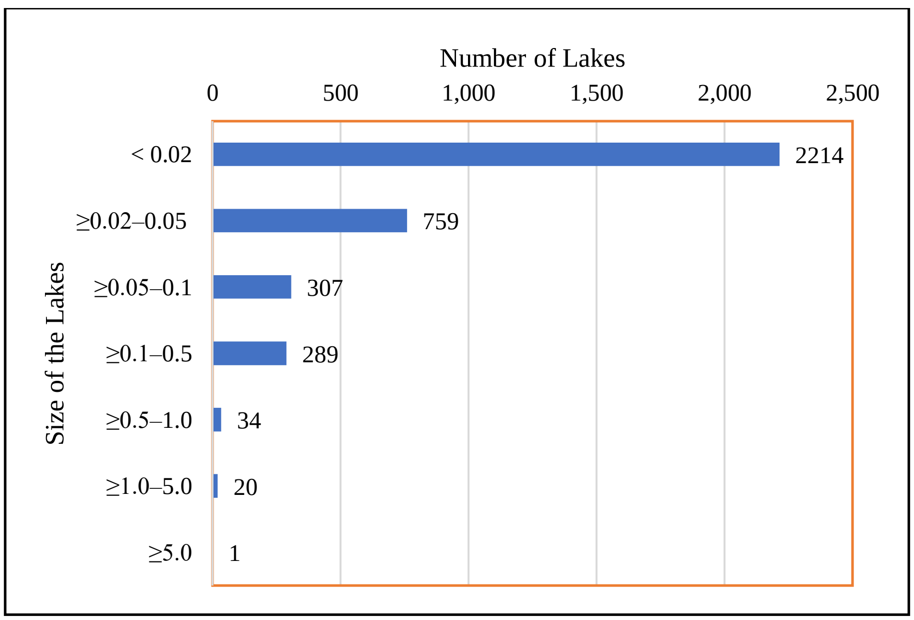


Figure 5-27 Distribution of glacial lakes with their average sizes

Table 5-22 Basin-wise glacial lakes and their areas

Main Basins	Sub-Basin	Count	Area (km²)	Average Area (km²)
Koshi	Tamor	283	9.12	0.03
	Arun	909	68.58	0.08
	Dudh Koshi	355	16.92	0.05
	Likhu	17	0.41	0.02
	Tama Koshi	307	14.68	0.05
	Sun Koshi	181	22.13	0.12
	Indrawati	12	0.16	0.01
	Sub-total	**2,064**	**132**	**0.06**
Gandaki	Trishuli	242	8.19	0.03
	Budhigandaki	49	1.58	0.03
	Marsyangdi	59	6.22	0.11
	Seti	4	0.15	0.04
	Kaligandaki	78	3.05	0.04
	Sub-total	**432**	**19.19**	**0.04**
Karnali	Bheri	164	9.2	0.06
	Tila	82	4.11	0.05
	Mugu	239	6.22	0.03
	Kawari	28	1.04	0.04
	West Seti	51	1.43	0.03
	Humla	498	20.21	0.04
	Kali	63	1.53	0.02
	Karnali	3	0.19	0.06
	Sub-total	**1128**	**43.93**	**0.04**
Nepal	**Total**	**3,624**	**195**	**0.05**

Source: Bajracharya et al. (2020)

Table 5-23 Number of potentially dangerous glacial lakes within Nepal

Basin	Sub-basin	Number of PDGL
Koshi	Tamor	4
	Arun	4
	Dudh Koshi	9
	Tama Koshi	1
Gandaki	Trishuli	1
	Marshyandi	1
Karnali	Humla Karnali	1
Nepal	Total	21

Source: Bajracharya et al. (2020)

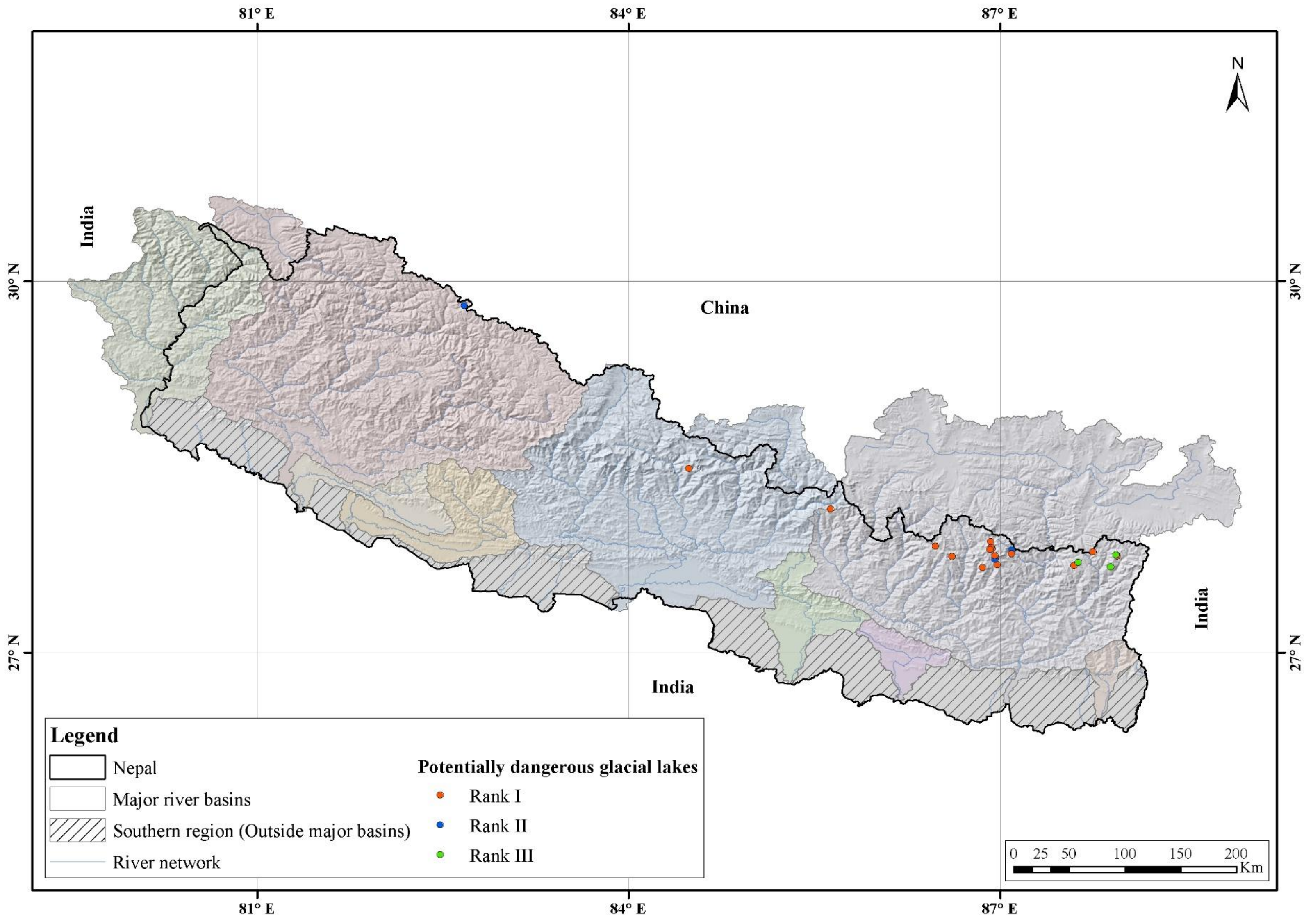


Figure 5-28 Locations of potentially dangerous glacial lakes within Nepal

5.7.3 Estimation of Volume and Peak Discharge of the Glacial Lakes

Conducting a bathymetric survey of glacial lakes is particularly challenging due to their locations in relatively inaccessible, physically demanding, and dangerous environments. Currently, no reliable technique exists for measuring lake bathymetry or volume using satellite imagery in cases where turbidity prevents the derivation of reflectance-depth relationships (Box and Ski, 2007; Cook and Quincey, 2015).

However, several studies have employed empirical approaches to estimate lake volumes from satellite imagery, based on established relationships between depth, area, and volume (Evans, 1986; O'Connor et al., 2001; Huggel et al., 2002; Yao et al., 2012; Fugita et al., 2013; Loriaux and Cassasa, 2013; Carrivick and Quincey, 2013; Messager et al., 2016; Cael et al., 2017; Rounce et al., 2017). Notably, some formulas with high correlation coefficients (Cook and Quincey, 2015) are as follows:

Equations for Estimation of Volume

(i) Evans (1986) for ice-dammed lakes

Evans' equation for estimating the volume of water in a lake based on the area of the glacial lake is presented in **Equation (5-15).**

$$V = 0.035A^{1.5} \quad (5\text{-}15)$$

where,

V = lake volume (m^3)

A = area of the lake (m^2)

(ii) O'Connor et al. (2001) for moraine-dammed lakes of the Central Oregon Cascade Range

The O'Connor et al.'s formula to estimate the volume of water is provided in **Equation (5-16)**.

$$V = 3.114A + 0.0001685A^2 \quad (5\text{-}16)$$

(iii) Huggel et al. (2002) for a combination of ice-dammed, moraine dammed lakes

The formula proposed by Huggel et al. for estimating water volume is presented in **Equation (5-17)**.

$$D = 0.104\, A^{0.42}$$

$$V = 0.104\, A^{1.42} \quad (5\text{-}17)$$

where,

D = depth of the lake (m)

(iv) Huggel et al. (2002) formula revised by Cook and Quincey (2015)

Cook and Quincey's revised formula for estimating the volume of water as a function of lake area is provided in **Equation (5-18).**

$$D = 0.1217\ A^{0.4129}$$

$$V = 0.1217\ A^{1.4129} \tag{5-18}$$

Estimation of Peak Discharges

i) Clague and Mathews formula

Clague and Mathews (1973) presented the relationship between the volume of water released from ice-dammed lakes and peak flood discharges as **Equation (5-19)**.

$$Q_p = 75(V_0 * 10^{-6})^{0.67} \tag{5-19}$$

where,

Q_p = Peak flood discharge (m^3/s)

V_0 = Total volume of water drained out from lake (m^3)

ii) Costa (1988) formula

The Clague and Mathews relationship was later modified by Costa (1988), as the peak discharge estimated by the original equation was higher than the measured discharge for Flood Lake in British Columbia during the August 1979 event. It is given in **Equation (5-20)**.

$$Q_p = 113(V_0 * 10^{-6})^{0.64} \tag{5-20}$$

Although these methods of discharge prediction are not physics-based, they seem to give reasonable results (Mool et al., 2001).

iii) Popov (1991) formula (as cited in Huggel (2002))

Popov’s formula to estimate peak flow is given by **Equation (5-21)**.

$$Q_p = 0.0048V^{0.896} \tag{5-21}$$

iv) Evans (1986) formula

Evan’s formula to estimate peak flow is given by **Equation (5-22)**.

$$Q_p = 0.72V^{0.53} \tag{5-22}$$

v) Huggel (2002) formula

Evan’s formula to estimate peak flow is given by **Equation (5-23)**.

$$Q_p = 0.00077V^{1.017} \tag{5-23}$$

vi) Walder and O’Connor 1997 formula

Evan’s formula to estimate peak flow is given by **Equation (5-24)**.

$$Q_p = 0.045V^{0.66} \quad (5\text{-}24)$$

The volume, depth, and peak flows estimated from the above equations are given in **Table 5-24**. The estimated peak flows range from less than 1,000 m^3/s to more than $40*10^6$ m^3/s. To choose the best model among them, the percentage deviation from the mean was used (Wang et al., 2008) as given by **Equation (5-25)**:

$$Q_{devi} = \frac{Q-\bar{Q}}{\bar{Q}}\% \quad (5\text{-}25)$$

Where,

Q_{devi}= Deviation from the mean (%)

Q = Estimated peak flow by a particular equation (m^3/s)

$\bar{Q}$= Average of all estimated peak flows (m^3/s)

The deviation percentage is given in **Table 5-25**. Based on the results in the table, the volume estimated by Huggel et al. (2002) and the peak flow estimated using Evans' equation exhibit the minimum deviation across all the lakes considered in this study, except for Tilicho Lake. However, even in this case, the value estimated by the Evans method is quite close to the minimum. Therefore, the peak flow estimated by the Evans method, using Huggel et al. (2002) volume estimation, is recommended.

The most likely peak flows of different lakes are:

Tso Rolpa: 9,800 m^3/s

Thulagi = 6,600 m^3/s

Imja= 8,600 m^3/s

Shey Phoksund = 22,000 m^3/s

Lower Barun = 11,000 m^3/s

Tilicho = 23,000 m^3/s and

Gokyo lakes = 12,000 m^3/s

It should also be noted that the Cook and Quincey (2015) method of volume estimation and Evans' method of peak flow estimation have yielded almost the same results.

Table 5-24 Volume and peak flow estimation of some of the glacial lakes

SN	Name of Lake	Methods/Formula	Area (km^2)	Volume (m^3)	Clague and Mathews (m^3/s)	Costa (m^3/s)	Popov (m^3/s)	Evans (m^3/s)	Huggel (m^3/s)	Walder and O'Connor (m^3/s)	Average Peak (m^3/s)	Max Peak (m^3/s)	Min Peak (m^3/s)
1	Tsho Rolpa												
	1	Evans (1986)	1.53	66237692	1245	1654	48860	10058	69272	6533	22937	69272	1245
	2	O'Connor et al. (2001)	1.53	399206070	4148	5222	244295	26060	430436	21380	121923	430436	4148
	3	Huggel et al. (2002)	1.53	62993418	1204	1602	46710	9794	65822	6320	21909	65822	1204
	4	Cook and Quincey (2015)	1.53	66625595	1250	1660	49116	10089	69684	6559	23060	69684	1250
2	Thulagi glacial												
	1	Evans (1986)	0.9	29883524	730	994	23946	6596	30832	3864	11160	30832	730
	2	O'Connor et al. (2001)	0.9	139287600	2049	2662	95101	14914	147520	10671	45486	147520	2049
	3	Huggel et al. (2002)	0.9	29652253	727	989	23780	6569	30590	3844	11083	30590	727
	4	Cook and Quincey (2015)	0.9	31480369	756	1028	25089	6781	32509	3999	11694	32509	756
3	Imja Tsho												
	1	Evans (1986)	1.28	50685414	1041	1394	38443	8728	52766	5476	17975	52766	1041
	2	O'Connor et al. (2001)	1.28	280056320	3271	4162	177817	21596	300151	16920	87319	300151	3271
	3	Huggel et al. (2002)	1.28	48895793	1016	1362	37224	8563	50872	5347	17398	50872	1016
	4	Cook and Quincey (2015)	1.28	51780656	1056	1413	39186	8828	53926	5553	18327	53926	1056
4	Shey Phoksundo												
	1	Evans (1986)	4.53	337454596	3707	4690	210147	23839	362815	19135	104055	362815	3707
	2	O'Connor et al. (2001)	4.53	3471878070	17670	20847	1696629	82003	3883692	89122	964994	3883692	17670

Table 5-24 Volume and peak flow estimation of some of the glacial lakes

SN	Name of Lake	Methods/Formula	Area (km²)	Volume (m³)	Clague and Mathews (m³/s)	Costa (m³/s)	Popov (m³/s)	Evans (m³/s)	Huggel (m³/s)	Walder and O'Connor (m³/s)	Average Peak (m³/s)	Max Peak (m³/s)	Min Peak (m³/s)
	3	Huggel et al. (2002)	4.53	294233953	3381	4296	185862	22169	315610	17480	91466	315610	3381
	4	Cook and Quincey (2015)	4.53	308810265	3493	4431	194091	22744	331518	18047	95721	331518	3493
5	Lower Barun												
	1	Evans (1986)	1.8	84523370	1466	1933	60787	11445	88762	7674	28678	88762	1466
	2	O'Connor et al. (2001)	1.8	551545200	5151	6422	326361	30929	597969	26464	165549	597969	5151
	3	Huggel et al. (2002)	1.8	79345134	1405	1857	57440	11068	83234	7360	27061	83234	1405
	4	Cook and Quincey (2015)	1.8	83823367	1458	1923	60336	11395	88014	7632	28460	88014	1458
6	Tilicho Lake												
	1	Evans (1986)	4.8	368069559	3929	4958	227151	24962	396316	20264	112930	396316	3929
	2	O'Connor et al. (2001)	4.8	3897187200	19093	22447	1881717	87183	4368021	96185	1079108	4368021	19093
	3	Huggel et al. (2002)	4.8	319444854	3573	4528	200069	23156	343132	18455	98819	343132	3573
	4	Cook and Quincey (2015)	4.8	335132327	3689	4669	208850	23752	360276	19048	103381	360276	3689
7	Gokyo Lake												
	1	Evans (1986)	1.962	96187037	1599	2100	68252	12257	101233	8357	32300	101233	1599
	2	O'Connor et al. (2001)	1.962	654740982	5779	7167	380574	33873	711924	29636	194825	711924	5779
	3	Huggel et al. (2002)	1.962	89673872	1525	2008	64096	11810	94265	7979	30281	94265	1525
	4	Cook and Quincey (2015)	1.962	94677112	1582	2079	67291	12155	99617	8271	31832	99617	1582

Table 5-25 Deviation percentage of peak flows from ensembled mean

Name of Lake	Methods/Formula	Clague and Mathews	Costa	Popov	Evans	Huggel	Walder and O'Connor
Tsho Rolpa							
1	Evans (1986)	-95	-93	113	-56	202	-72
2	O'Connor et al. (2001)	-97	-96	100	-79	253	-82
3	Huggel et al. (2002)	-95	-93	113	**-55**	200	-71
4	Cook and Quincey (2015)	-95	-93	113	-56	202	-72
Thulagi glacial							
1	Evans (1986)	-93	-91	115	-41	176	-65
2	O'Connor et al. (2001)	-95	-94	109	-67	224	-77
3	Huggel et al. (2002)	-93	-91	115	**-41**	176	-65
4	Cook and Quincey (2015)	-94	-91	115	-42	178	-66
Imja Tsho							
1	Evans (1986)	-94	-92	114	-51	194	-70
2	O'Connor et al. (2001)	-96	-95	104	-75	244	-81
3	Huggel et al. (2002)	-94	-92	114	-51	192	-69
4	Cook and Quincey (2015)	-94	-92	114	-52	194	-70
Shey Phoksundo							
1	Evans (1986)	-96	-95	102	-77	249	-82
2	O'Connor et al. (2001)	-98	-98	76	-92	302	-91
3	Huggel et al. (2002)	-96	-95	103	**-76**	245	-81
4	Cook and Quincey (2015)	-96	-95	103	-76	246	-81
Lower Barun							
1	Evans (1986)	-95	-93	112	-60	210	-73
2	O'Connor et al. (2001)	-97	-96	97	-81	261	-84
3	Huggel et al. (2002)	-95	-93	112	**-59**	208	-73
4	Cook and Quincey (2015)	-95	-93	112	-60	209	-73
Tilicho Lake							
1	Evans (1986)	-97	-96	101	-78	251	-82
2	O'Connor et al. (2001)	-98	-98	**74**	-92	305	-91
3	Huggel et al. (2002)	-96	-95	102	**-77**	247	-81
4	Cook and Quincey (2015)	-96	-95	102	**-77**	248	-82
Gokyo Lake							
1	Evans (1986)	-95	-93	111	-62	213	-74
2	O'Connor et al. (2001)	-97	-96	95	-83	265	-85
3	Huggel et al. (2002)	-95	-93	112	**-61**	211	-74
4	Cook and Quincey (2015)	-95	-93	111	-62	213	-74

5.8 Flood Inventory

Flood inventories are crucial for improving the understanding, preparedness, and response to flood hazards, ultimately reducing their impact on communities and economies. Some applications of flood inventories include:

- Identifying flood-prone areas for targeted risk assessments and mitigation measures, and aiding authorities in developing emergency response plans and resource allocation based on historical data.
- Assisting planners in establishing zoning regulations to prevent construction in high-risk areas.
- Helping engineers design flood-resilient infrastructure.
- Enabling researchers to study historical flood patterns and trends for future predictions and modeling.
- Allowing insurance companies to assess risk and determine flood insurance premiums.
- Guiding governments in developing and implementing policies to reduce flood risks based on inventory data.

5.8.1 Instantaneous Maximum Flood Based Flood Inventory

Instantaneous maximum floods (IMF)-based flood inventory of Nepal was prepared following flood plain zoning policy of the Government of Nepal, discussed in previous section**.** The flood inventory of main outlets of Class A rivers is given in **Table 5-26** while that of Class B rivers is given in **Table 5-27**. The inventory was grouped into the following four categories.

(i) **Category 1**: Floods equal to or greater than 100-year return period

(ii) **Category 2**: Floods equal to or greater than 25-year and less than 100-year return period

(iii) **Category 3**: Floods equal to or greater than 5-year and less than 25-year return period

(iv) **Category 4** Floods equal to or greater than 2-year and less than 5-year return period

In these tables, date of the flood magnitudes and return periods of those floods are given. For example, Q-695 represents flood magnitude of station 695 (i.e., at Chatara of the Koshi River) in m^3/s and T-695 represents return period of Q-695 in years and so on.

Flood inventory of all 44 stations based on IMF is given in **Appendix C (Table C-5)**.

Table 5-26 Flood inventory of Class A rivers based on instantaneous maximum flood

Class A River Basins (Units: Q in m³/s and T in years)												
River	**Koshi**			**Gandaki**			**Karnali River**			**Chamelia**		
Location	**Chatara**			**Devghat**			**Chisapani**			**Nayalbadi**		
Flood Categories	**Date**	**Q-695**	**T-695**	**Date**	**Q-460**	**T-460**	**Date**	**Q-280**	**T-280**	**Date**	**Q-120**	**T-120**
Floods ≥ 100 years	1980-06-25	24,000	233	2004-07-31	3,260	184						
Floods ≥ 25 and < 100 years							1983-09-11	21,700	62	2018-07-11	898	46
							2014-08-15	21,700	62			
Floods ≥ 5 and < 25 years				1984-09-17	1,820	13	2013-06-18	17,900	21	2016-08-01	734	17
				2010-08-24	1,510	8	2009-10-07	17,000	17	2000-06-08	643	10
				2012-08-03	1,280	5				2017-08-14	641	10
										2010-08-22	627	9
										2009-10-06	598	7
										2014-07-28	591	7
Floods ≥ 2 and < 5 years	2019-07-13	11,000	5	1985-09-05	1,060	4	1988-07-16	12,500	5	2011-08-01	504	4
	2018-08-15	10,400	4	1986-09-14	1,060	4	2000-08-01	12,500	5	1997-08-03	501	4
	2000-08-02	10,000	4	2009-08-05	1,030	3	2008-09-20	12,500	5	2019-08-06	495	4
	1999-07-03	9,930	3	2011-07-27	1,030	3	2007-08-13	9,900	3	1999-07-04	478	4
	2003-07-09	9,760	3	2007-08-17	921	3	1995-08-13	9,550	2	2013-07-24	458	3
	2017-08-11	9,640	3	2006-09-09	881	3	1998-08-04	9,400	2	1996-08-20	417	3
	2014-08-14	9,610	3	1998-07-25	820	3	2006-08-27	9,270	2	2015-08-08	410	3
	2002-08-21	9,550	3	2005-09-09	782	2	1990-07-11	9,010	2	2001-07-26	408	3
	2001-08-20	9,520	3	2002-07-23	779	2	2005-09-26	9,010	2	2008-09-20	408	3
	2016-07-26	8,180	2	2014-08-14	745	2	1982-08-28	8,980	2	1998-08-10	403	3
	2013-07-10	8,020	2	1990-08-27	740	2	2010-08-23	8,900	2	2006-08-28	360	2
	2010-08-24	7,630	2	1981-07-31	700	2	1981-07-31	8,790	2	2007-08-16	360	2
				1993-07-21	660	2				2003-08-21	347	2

Table 5-27 Flood inventory of Class B rivers based on instantaneous maximum flood

Class B River Basins (Units: Q in m³/s and T in years)												
River	**Kankai**			**Bagmati**			**West Rapti**			**Babai**		
Location	**Mainachuli**			**Padheredovan**			**Kusum**			**Chepang**		
Flood Categories	**Date**	**Q-795**	**T-**	**Date**	**Q-589**	**T-589**	**Date**	**Q-375**	**T-375**	**Date**	**Q-**	**T-**
Floods ≥ 100				1993-07-21	16,00	207						
Floods ≥ 25 and							2014-08-15	9,100	37	2017-08-13	5,060	37
Floods ≥ 5 and < 25 years	1990-08-12	7,500	20	2002-07-23	8,000	8	2016-07-26	6,160	8	2014-08-15	3,990	15
	1981-08-12	6,430	10	1984-09-17	7,630	7	2013-07-22	5,720	6	1995-08-09	3,870	13
	2002-07-28	6,050	8	2004-07-09	6,850	5				2007-07-26	3,640	11
	2003-07-09	5,920	8							1994-09-11	3,520	10
	1999-08-26	5,680	7									
	2009-08-16	5,680	7									
	2001-10-05	5,600	6									
	1983-07-15	5,500	6									
	1996-08-19	5,350	5									
Floods ≥ 2 and <5 years	2005-08-26	4,420	3	2000-08-02	6,200	4	2009-10-07	4,860	4	2006-08-27	2,550	4
	1985-07-28	4,330	3	1990-08-27	5,620	3	2017-08-13	3,950	3	2009-07-28	2,320	4
	1995-08-12	4,230	3	2005-08-07	5,580	3	2003-07-31	3,380	2	1996-07-11	1,870	3
	1987-08-13	4,150	3	1982-07-19	5,080	3	2005-10-20	3,380	2	1992-07-08	1,750	2
	2010-08-19	3,950	3	1999-07-03	5,080	3				2003-07-10	1,490	2
	1989-07-27	3,850	2	2010-08-24	4,780	2						
	2008-08-29	3,820	2	1998-08-18	4,660	2						
	1991-09-04	3,790	2	1989-09-05	4,410	2						

5.8.2 Inventory of Floods Based on Annual Maximum Daily Flow

The number of occurrences of floods greater than a 2-year, 5-year, 25-year, and 100-year return periods, their dates of occurrences, and the magnitudes are given in **Table C-6, Table C-7, Table C-8, and Table C-9** of **Appendix C** respectively. The summary results of flood inventory of 44 selected stations are presented in **Table 5-28**. A total number of daily flow data of these selected stations are 5,99,126. The number floods equal to or greater than 2-year return period is 4,255. It implies that there is a probability of 0.71% to have daily flows with the magnitude equal to or greater than 2-year return period flood in the rivers of Nepal. However, in some locations like Sangutar of Likhu Khola, this figure is 2.4% and in other locations, it is as less as 0.14% (Kusum of West Rapti River). Similarly, the total number of floods greater than or equal to 5-year return period are 664 (0.11% of total), greater than or equal to 25-year return period are 84 (0.01%) and greater than or equal to 100-year return period are 14 (.002% of the total).

5.8.3 Flood Inventory Based on Flood Disaster

A total of 5,070 flood disaster events occurred between 23rd June 1980 and 30th September 2023 are recorded in the Disaster Risk Reduction Portal of the Ministry of Home Affairs (http://drrportal.gov.np). Human loss is grouped into two categories: deaths and missing. Flood events with human combined human loss (deaths +missing) of more than 30 persons is given in **Table 5-29**. The inventory with events caused combined human loss of more than 10 persons is given in **Appendix C (Table C-10).**

It can be seen from the table that, two days of the August 1993 flood killed 415 people in Sarlahi. The highest number of missing people were from the floods of 2014 which occurred in Surkhet (91) and of 1981 which occurred in Rupandhehi (83). The number of deaths by these floods was also not less and exceeded the mark of 30 persons. These four flood events are the top four in view of combined death and missing people.

Table 5-28 Summary result of flood inventory based on one-day annual maximum floods

SN	Station	River	Location	Floods of Different Return Periods (m^3/s)				Number of Cases			
				Q_2	Q_5	Q_{25}	Q_{100}	$Q \geq Q_{100}$	$Q_{25} \leq Q < Q_{100}$	$Q_5 \leq Q < Q_{25}$	$Q_2 \leq Q < Q_5$
1	120	Chamelia	Nayalbadi	295	436	646	820	0	0	31	196
2	215	Humla Karnali	Tholtada	1,528	2,021	2,761	3,371	0	0	31	179
3	220	Tila Nala	Nagma	199	264	360	439	0	1	14	139
4	225	Sinja Khola	Diware	102	121	149	173	0	0	20	114
5	240	Karnali River	Asara Ghat	1,999	2,560	3,400	4,094	1	0	14	135
6	250	Karnali River	Benighat	2,426	3,066	4,025	4,816	0	1	11	88
7	260	Seti River	Banga	2,464	4,184	6,761	8,887	1	2	3	34
8	265	Thulo Bheri	Rimna	1,010	1,351	1,862	2,283	0	3	18	137
9	270	Bheri River	Jamu	1,928	2,744	3,966	4,974	0	3	10	74
10	280	Karnali	Chisapani	7,160	10,459	15,402	19,482	0	3	6	51
11	286	Sarada Khola	Daradhunga	166	335	587	795	1	0	7	31
12	289.95	Babai	Chepang	1,038	2,177	3,884	5,292	0	2	4	18
13	330	Mari Khola	Nayagaon	473	691	1,019	1,289	0	1	14	81
14	350	Rapti River	Bagasoti Gaon	1,221	2,026	3,231	4,225	0	1	12	38
15	360	Rapti River	Jalkundi	2,052	3,431	5,498	7,204	0	2	6	22
16	375	Rapti	Kusum	2,225	3,988	6,631	8,812	0	1	1	9
17	404.7	Myagdi Khola	Mangla Ghat	447	620	881	1,096	0	0	21	130
18	420	Kali Gandaki	Kotagaon Shringe	3,484	4,926	7,085	8,868	0	0	11	50
19	428	Mardi Khola	Lahachok	87	135	208	267	0	5	25	169
20	438	Madi River	Shisa Ghat	436	604	855	1,063	0	1	13	57
21	440	Chepe Khola	Garam Besi	200	373	632	845	1	1	8	34
22	445	Burhi Gandaki	Arughat	648	824	1,089	1,307	1	0	7	104
23	447	Trishuli	Betrawati	901	1,277	1,841	2,307	2	7	40	208
24	448	Tadi Khola	Tadipul Belkot	284	373	506	615	0	2	11	32
25	450	Gandaki	Devghat	8,232	10,075	12,836	15,115	0	0	13	31
26	460	Rapti River	Rajaiya	340	630	1,064	1,423	1	5	30	60
27	465	Manahari Khola	Manahari	321	553	900	1,187	1	1	10	72
28	470	Lothar Khola	Lothar	106	232	420	576	0	3	27	70
29	505	Bagmati River	Sundarijal	6	8	12	15	0	3	7	103
30	589	Bagmati River	Pandherodovan	2,575	4,097	6,377	8,259	0	1	6	24
31	602	Sabhaya Khola	Tumlingtar	143	215	322	410	0	1	6	57
32	602.5	Hinwa Khola	Pipletar	34	56	89	116	1	0	11	123
33	604.5	Arun River	Turkeghat	2,355	2,959	3,865	4,612	0	1	10	42
34	606	Arun River	Simle	2,952	3,870	5,246	6,382	0	1	8	43

SN	Station	River	Location	Floods of Different Return Periods (m^3/s)				Number of Cases			
				Q_2	Q_5	Q_{25}	Q_{100}	$Q \geq Q_{100}$	$Q_{25} \leq Q < Q_{100}$	$Q_5 \leq Q < Q_{25}$	$Q_2 \leq Q < Q_5$
35	620	Balephi Khola	Jalbire	289	430	640	814	2	4	23	120
36	630	Sun Kosi	Pachuwar Ghat	1,195	1,643	2,314	2,868	1	0	6	44
37	647	Tamakosi	Busti	817	986	1,239	1,448	0	3	7	52
38	650	Khimti Khola	Rasnalu Village	258	605	1,126	1,555	0	3	10	69
39	652	Sunkosi	Khurkot	2,957	4,291	6,291	7,940	0	1	11	67
40	660	Likhu Khola	Sangutar	244	330	459	565	0	1	17	265
41	670	Dudh Kosi	Rabuwa Bazar	1,340	2,168	3,409	4,432	1	4	6	58
42	690	Tamur River	Mulghat	2,475	3,462	4,941	6,162	0	1	15	52
43	695	Koshi	Chatara-Kothu	7,020	9,105	12,230	14,808	0	0	10	85
44	795	Kankai	Mainachuli	1,788	3,126	5,132	6,786	0	1	9	24
			Total					14	70	580	3,591

Note: Q_x: Flood of return period x

Table 5-29 Flood disaster events with higher human loss

SN	District	Incident Date	Total Death	Missing People	Affected Family	Death and Missing-Combined	Order based on number of Death and Missing-Combined	Order based on number of Deaths Only	Order based on number of Missing Only
1	Sarlahi	1993-07-21	237	0	4980	237	1	1	
2	Sarlahi	1993-07-20	178	0	2140	178	2	2	
3	Surkhet	2014-08-14	34	91	3866	125	3		1
4	Rupandehi	1981-09-10	35	83	14500	118	4		2
5	Sarlahi	1993-07-21	81	0	5783	81	5	3	
6	Sarlahi	1993-07-00	79	0	2626	79	6	4	
7	Kaski	2012-05-05	72	0	16	72	7	5	
8	Sindhupalchowk	1996-07-22	10	61	3	71	8		3
9	Makawanpur	1993-07-19	60	0	3321	60	9	6	
10	Sarlahi	1993-07-21	0	50	1364	50	10		4
11	Bardiya	2014-08-13	33	15	17376	48	11		
12	Morang	1999-08-22	45	0	0	45	12	7	
13	Chitawan	1990-08-26	32	12	0	44	13		
14	Rautahat	1993-07-00	44	0	1144	44	14	8	
15	Makawanpur	1993-07-19	39	0	5719	39	15	9	
16	Baglung	2020-09-03	22	16	100	38	16		
17	Rautahat	1993-07-00	36	0	3235	36	17	10	
18	Palpa	1981-10-10	4	27	0	31	18		5
19	Tanahu	1981-09-30	23	7	0	30	19		

5.9 Instantaneous Maximum Flood and Associated Climate

Flood is an interaction between climate (mainly rainfall and temperature), and basin characteristics (size, shape, relief, soil, and land use land cover). Basin characteristics can be considered more or less static for a basin and for a certain time window unless there is a rapid urbanization or deforestation. Climatic characteristics are dynamic, changing from one year to another, and even within a given year between seasons and months. In the South Asian Himalayan region, rainfall is the most dynamic among various other climatic factors. Characteristic of the rainfall (intensity, duration, and direction of movement of rainfall front) is, thus, the main contributing factor to instantaneous flood events. In some cases, LDOF and GLOF in the upstream can be the cause of instantaneous flood at the outlet of a basin.

Annual maximum daily flow and the average daily flow on the day when instantaneous flood occurred were extracted from the average daily flow data from 1980 to 2019. Using this extracted dataset, the possible causes of instantaneous floods on specific days were analyzed.

Average Daily Flow:
The average of flow measurements taken multiple times throughout a particular day at a specific location.

Annual Maximum Daily Flow:
The highest flow value among the average daily flows recorded in a given year.

Annual Instantaneous Maximum Flood:
The maximum instantaneous flow value recorded at a specific location during a given year.

If the rainfall on the day of an instantaneous flood (in a small, circular basin with sharp relief) or one to two days prior (in a large, fern-shaped basin with gentle relief) is not significantly heavier than on other days of the year, the flood's cause is likely a Glacial Lake Outburst Flood (GLOF) or Landslide-Dammed Outburst Flood (LDOF) event upstream of the gauging station. Conversely, even if the heaviest rainfall occurs on a particular day, the flood on that day may not be the year's highest if antecedent soil moisture is low. In such cases, high soil infiltration due to low antecedent moisture reduces surface runoff, diminishing the flood's magnitude. Furthermore, if the ratio of the instantaneous maximum flood to the annual maximum average flow for a particular year is significantly high, it strongly indicates the likelihood of a GLOF or LDOF event upstream of the flow gauging station. In such cases, floods can occur even on days with minimal precipitation. The possible cases of flood are explained in **Table 5-30** based on the following three variables defined above.

Q_{inst} = Instantaneous maximum flood occurred on a given day of a particular year

Q_{dmax}= Annual maximum flow of that particular year

$\bar{Q}$= Average flow of the day on which Q_{inst} occurred in a particular year

Table 5-30 Possible causes of floods

SN	Cases	Conditions	Probable Causes of Floods	Remarks
1	Impossible Case	$Q_{inst} < Q_{dmax}$ $Q_{inst} < \bar{Q}$		Problem in data (discussed in Chapter 3)
2	Possible Case-1 (All happened on the same day)	$Q_{inst} = Q_{dmax} = \bar{Q}$	i. Heavy rainfall occurred throughout the day than other days of the year. It can be • Over the whole basin • Major part of the basin	Almost same rainfall intensity over the whole day and it should be the highest on that day.
3	Possible Case – 2 (Q_{inst} and Q_{dmax} occurred on the same day)	$Q_{inst} > Q_{dmax}$	i. Heavy rainfall than other days of the year of short duration. It can be over the whole basin or in a major part of the basin ii. Heavy rainfall movement from u/s to d/s (max. flow time) or d/s to u/s during other period of the day of Q_{inst}. iii. LDOF and/or GLOF on the u/s iv. Any combination of the above	Related to cause ii Surface runoff reaching the outlet and rainfall occurring nearby area of the outlet simultaneously. Heavy rainfall occurring in the max flow time and the front moving away from the outlet.
4	Possible Case – 3 (Q_{inst} and Q_{dmax} occurred on different days)	$Q_{inst} > Q_{dmax}$	i. Occurrence of very heavy rainfall on the day of Q_{inst} than other days of the year for short duration. It should be near the outlet of the basin ii. Heavy rainfall movement from u/s to d/s (max. flow time) or d/s to u/s during other period of the day of Q_{inst}. iii. LDOF and/or GLOF on the u/s iv. Any combination of the above	Related to cause ii Surface runoff reaching the outlet and rainfall occurring nearby area of the outlet simultaneously. Heavy rainfall occurring in the max flow time and the front moving away from the outlet

5.9.1 Floods and Associated Climate

The top five instantaneous maximum flows/floods (IMF) across eight river basins were extracted from the instantaneous flow data series. For each flood event, the average precipitation on the day of the IMF occurrence (Day 0) and the preceding four days (Day 1 refers to one day before IMF occurrence, up to Day 4, four days before) was calculated by taking the arithmetic average of rainfall recorded at selected rain-gauge stations within the basin. This analysis aimed to assess antecedent soil moisture conditions. Similarly, cumulative precipitation for up to three days and two days preceding the flood event was calculated for Class A and Class B River Basins, respectively, to determine whether preceding rainfall contributed to the floods. The minimum cumulative precipitation values were identified, and the ratio of cumulative precipitation for each flood event to the corresponding minimum cumulative precipitation was computed. These ratios were used to rank cumulative precipitation and explore whether the magnitude of precipitation corresponded to the magnitude of floods.

Additionally, the ratio of the instantaneous flood to the annual maximum flood for the same year was calculated to examine variations between these two types of floods, aiding in identifying potential causes.

The following sub-sections briefly discuss floods and associated climatic conditions in each of Nepal's eight river basins. While temperature and precipitation are key climatic factors, only precipitation was considered in this analysis for two reasons:

1. The role of temperature is generally less significant than precipitation in causing IMF.
2. Temperature variations during monsoon seasons across years are not substantial enough to cause significant differences in evapotranspiration.

1. Koshi Basin Floods and Associated Climate

Top five IMFs at Chatara of Koshi River are given in **Table 5-31**. The topmost flood occurred on 25th of June 1980, which was 24,000 m^3/s. The second to fifth highest past floods were 11,000; 10,400; 10,000 and 9,930 m^3/s, which occurred on 13th July 2019, 15th August 2018, 2nd August 2000 and 3rd July 1999, respectively. The one-day annual maximum floods also occurred on the same day of occurrence of IMFs in all the five cases.

The precipitation and maximum and minimum temperatures on the days of the top five instantaneous maximum floods (IMFs) and the four preceding days for each flood event recorded within the basin are summarized in **Appendix C (Table C-11).** Both the maximum and minimum temperatures are almost same in all these five flood events (see **Table C-11b**).

The average precipitation on the day of each flood event shows an inconsistent relationship with flood magnitudes:

- The second-highest flood corresponds to the highest average precipitation (72 mm).

- The fifth-highest flood corresponds to the second-highest precipitation (46 mm).
- The fourth-highest flood corresponds to the third-highest precipitation.
- The third-highest flood corresponds to the fourth-highest precipitation (28 mm).
- Notably, the highest flood occurred on a day with only 13 mm of precipitation.

Only two rain gauge stations (Stations 1016 and 1058) recorded rainfall exceeding 46 mm on the day of the highest flood, and one station (Station 1078) recorded higher rainfall the day before the flood. These values suggest that basin-average precipitation alone does not adequately explain the flood magnitude at the river's outlet. The cumulative rainfall in the consecutive three days (day of flood and two previous days) also follow the same trend (**Table 5-31**). From these precipitation patterns, it can be inferred that antecedent moisture conditions were relatively consistent across all events.

Further, the flow-to-precipitation ratio for the highest flood is exceptionally higher than for the other cases. This suggests that the highest flood event on June 25, 1980, was not driven solely by rainfall. Instead, it was most likely triggered by a Landslide-Dammed Outburst Flood (LDOF) or Glacial Lake Outburst Flood (GLOF) upstream. This hypothesis is supported by the ratio of instantaneous to one-day maximum flood for that year, which is 2.02. It is mentioned here that on June 23, 1980 Nagma Pokhari (a glacial lake) burst (see **Table 2-7**) causing the flood on June 25, 1980.

In contrast, the ratios of instantaneous to one-day maximum flood for the other four events are slightly greater than 1, indicating that heavy rainfall was likely the primary cause of those floods.

The spatial distribution of the precipitation across the basin during and prior to these flood days is shown in **Figure 5-29.**

Table 5-31 Top five past IMF occurred at Chatara of Koshi River

Rank IMF	Date	IMF (m^3/s)	Day of IMF	P_{avg} (mm)	Cumulative P ($\sum P_{avg}$, mm)	$\frac{\sum P_{avg}}{\sum P_{avg-min}}$	Rank of $\sum P_{avg}$	$\frac{Q_{inst}}{Qdmax}$
1	**6/25/1980**	**24,000**	0	13	13	1.0	5	**2.02**
			1	13	26	1.0	5	
			2	13	39	1.0	5	
			3	10	49			
			4	8	57			
2	**7/13/2019**	**11,000**	0	72	72	5.4	1	**1.11**
			1	76	148	5.6	1	
			2	35	183	4.7	1	
			3	15	198			
			4	27	225			
3	**8/15/2018**	**10,400**	0	28	28	2.1	4	**1.03**
			1	23	51	1.9	4	
			2	40	91	2.3	4	
			3	22	113			
			4	21	133			
4	**8/2/2000**	**10,000**	0	46	46	3.4	3	**1.01**
			1	23	69	2.6	3	
			2	24	92	2.4	3	
			3	11	104			
			4	17	121			
5	**7/3/1999**	**9,930**	0	46	46	3.4	2	**1.10**
			1	37	83	3.2	2	
			2	23	106	2.7	2	
			3	15	121			
			4	14	134			

Note: P= Precipitation, P_{avg}= Arithmetic average of the basin P of a particular day, $\sum P_{avg}$= Cumulative value of P_{avg} of particular flood events up to four days before from the IMF occurred day (0: IMF occurred day, 1: one day before IMF occurred day and so on in col. Day of IMF), $P_{avg-min}$ = Minimum of cumulative P ($\sum P_{avg}$) among considered five cases (shaded values up to two days before IMF occurred day, Rank of $\sum P_{avg}$ is based on the ratio of $\sum P_{avg}$ to $\sum P_{avg-min}$ (Highest: 1, Lowest: 5).

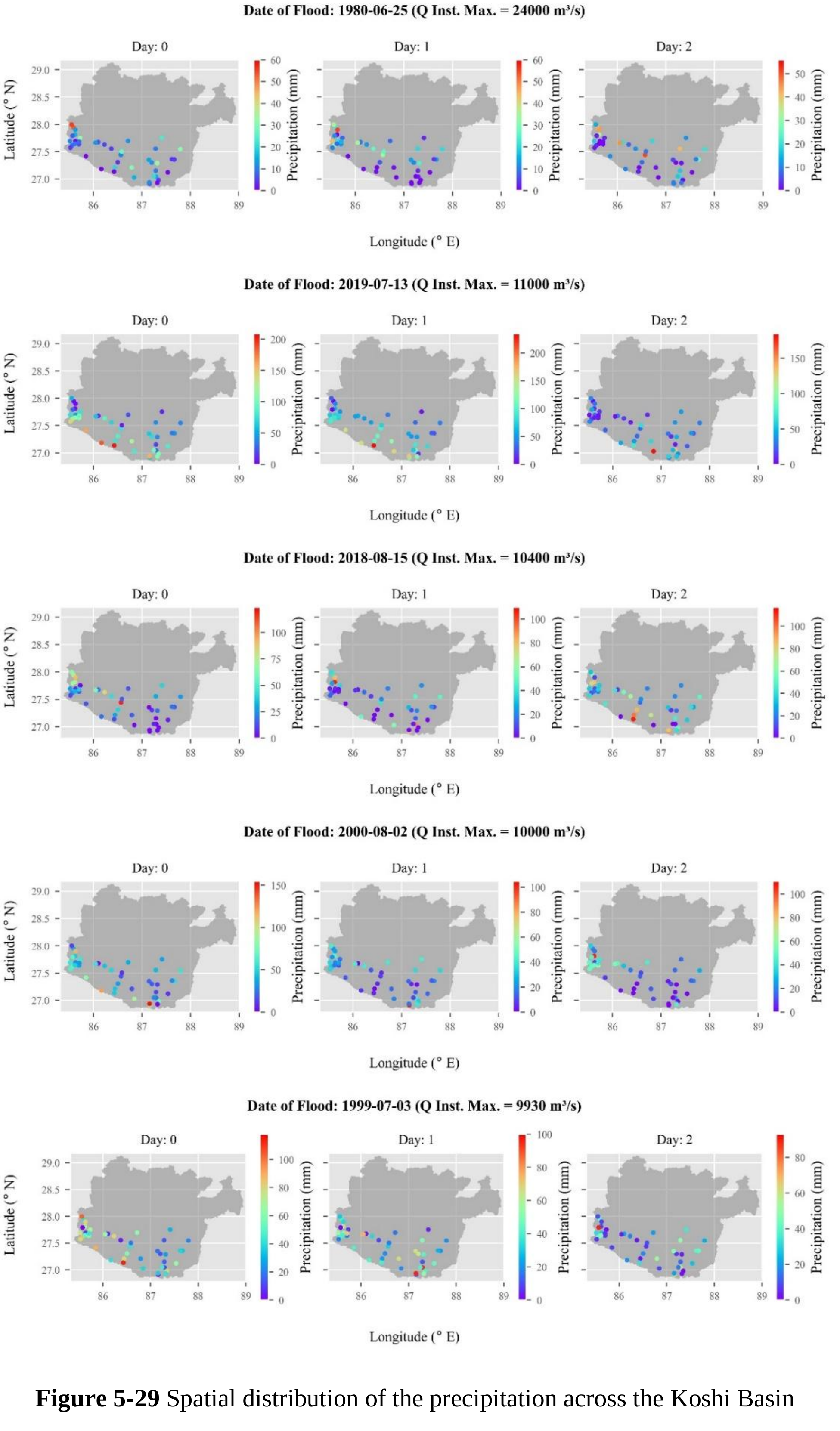


Figure 5-29 Spatial distribution of the precipitation across the Koshi Basin

2. Gandaki Basin Floods and Associated Climate

The past top five IMFs that occurred at Devghat in Gandaki River are given in **Table 5-32**. The topmost flood occurred on 27th August 1999, which was 14,900 m^3/s. The second to fifth highest flood magnitude (14,000; 13,400; 13,200 and 13,000 m^3/s) occurred on 17th August 2018, 14th September 1986, 22nd July 2013 and 23rd August 2001, respectively. The annual maximum one-day average floods also occurred on the same day of occurrence of IMF in four cases. But, in 2013, this flood occurred 3 days later (on 25th of July).

The precipitation, along with the maximum and minimum temperatures on the flood days and the preceding four days for the top five instantaneous maximum floods (IMFs) recorded within the basin, are detailed in **Appendix C (Table C-12).**

The average precipitation on the flood occurrence days reveals an interesting pattern:

- The highest precipitation (81 mm) corresponds to the fourth-highest flood.
- The second-highest precipitation (46 mm) corresponds to the fifth-highest flood.
- The third-highest precipitation (44 mm) corresponds to the third-highest flood.
- The fourth-highest precipitation (17 mm) corresponds to the second-highest flood.
- The lowest precipitation (16 mm) occurred on the day of the highest flood.

However, the two-day cumulative rainfall shows a different trend:

- The highest two-day cumulative rainfall corresponds to the fifth-highest flood.
- The lowest two-day cumulative rainfall corresponds to the second-highest flood.
- The second, third, and fourth highest two-day cumulative rainfall correspond to the fourth, third, and first highest floods, respectively.

The maximum precipitation recorded at any single rain-gauge station within the basin during these events was as follows (**Table C-12**):

- 343 mm for the fourth-highest flood.
- 149 mm for the fifth-highest flood.
- 106 mm for the third-highest flood.
- 100 mm for the highest flood.
- 95 mm for the second-highest flood

It is noteworthy—and somewhat surprising—that the greatest flood magnitudes (the first and second highest floods) occurred with the lowest rainfall (second lowest and lowest, respectively), while smaller floods (such as the fourth and fifth highest) were associated with significantly higher rainfall (**Table 5-32**).

The flow-to-precipitation ratios are significantly higher for the first and second highest flows compared to the other three flows. Based on these ratios, along with the ratio of instantaneous to one-day annual maximum flows, there is a possibility that landslide dam failures or glacial lake outburst floods (GLOFs) upstream of Devghat may have contributed to the floods, in addition to the rainfall within the basin. The other three floods are most likely caused by heavy rainfall within the basin itself.

Additionally, a comparison of the maximum rainfall recorded at specific rain-gauge stations with the average rainfall for the basin shows considerable variation in rainfall across the basin. The spatial distribution of precipitation across the basin during and prior to these flood days is shown in **Figure 5-30**.

Table 5-32 Top five IMF occurred in the past at Devghat of Gandaki River

Rank IMF	Date	IMF (m^3/s)	Day of IMF	P_{avg} (mm)	Cumulative P ($\sum P_{avg}$, mm)	$\frac{\sum P_{avg}}{\sum P_{avg-min}}$	Rank of $\sum P_{avg}$	$\frac{Q_{inst}}{Qdmax}$
1	**8/27/1999**	**14,900**	1	16	16	1.0	5	**1.23**
			2	46	62	2.0	4	
			3	55	117	1.8	3	
			4	20	137			
			5	38	175			
2	**8/17/2018**	**14,000**	1	17	17	1.1	4	**1.64**
			2	14	31	1.0	5	
			3	34	65	1.0	5	
			4	26	91			
			5	24	114			
3	**9/14/1986**	**13,400**	1	44	44	2.8	3	**1.33**
			2	40	85	2.7	3	
			3	40	125	1.9	1	
			4	31	155			
			5	22	177			
4	**7/22/2013**	**13,200**	1	81	81	5.1	1	**1.24**
			2	11	91	2.9	2	
			3	22	113	1.7	4	
			4	49	162			
			5	16	178			
5	**8/23/2001**	**13,000**	1	46	46	2.9	2	**1.20**
			2	56	101	3.3	1	
			3	22	123	1.9	2	
			4	24	147			
			5	56	203			

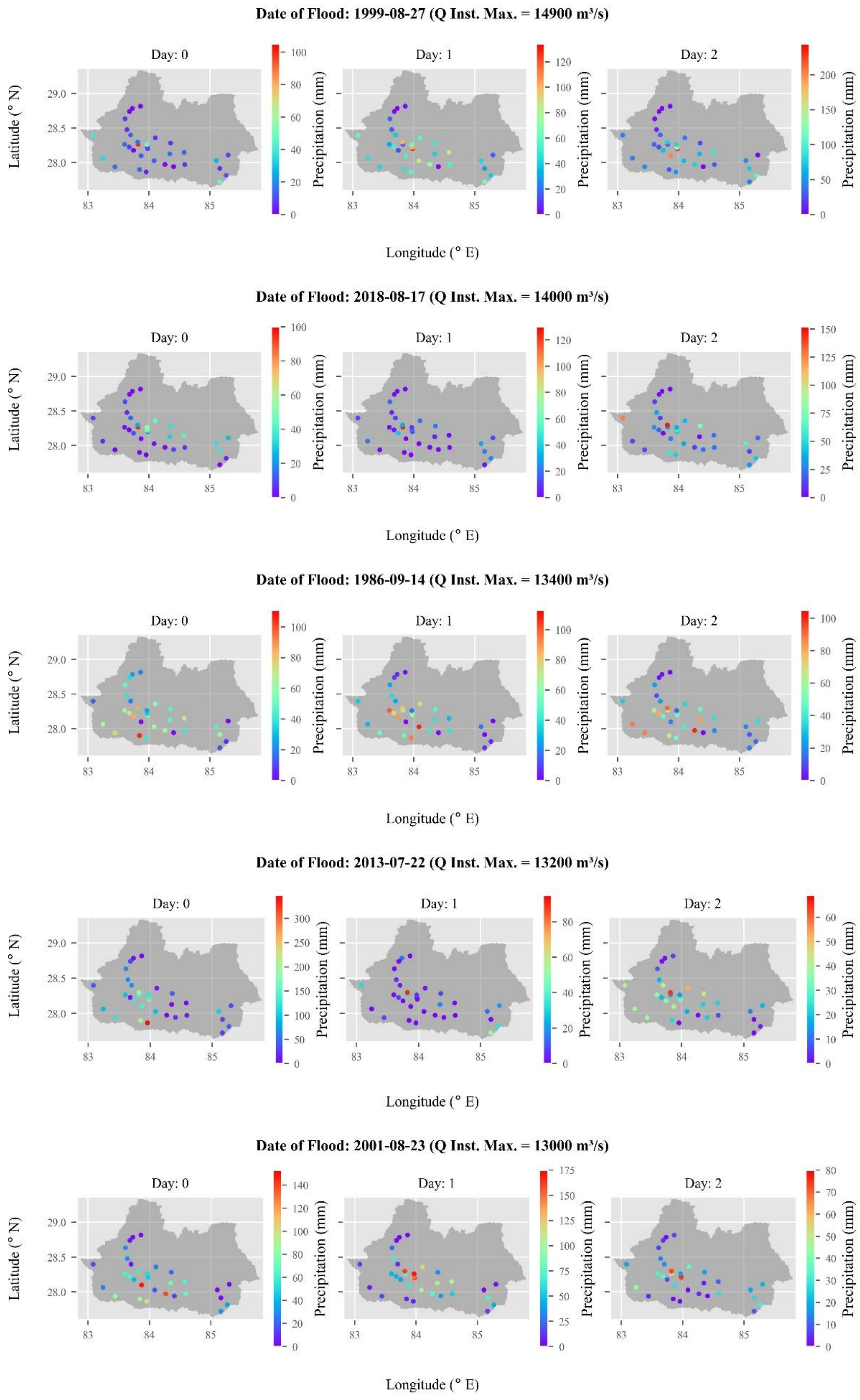


Figure 5-30 Spatial distribution of the precipitation map across the Gandaki Basin

3. Karnali Basin Floods and Associated Climate

Top five past IMFs of Karnali River at Chisapani are given in **Table 5-33**. The topmost floods at this gauging station were occurred on 11th September 1983 and on 15th August 2014, both with the magnitude of 21,700 m^3/s. The third, fourth and fifth largest floods were of magnitude of 17,900; 17,000 and 12,500 m^3/s which respectively occurred on 18th June 2013, 7th October 2009 and 1st August 2000. However, the annual maximum one day average floods of 1983 and 2009 did not occur on the day of occurrence of IMF. They occurred on 12th September 1983 and 18th August 2009 respectively.

The precipitation, maximum, and minimum temperatures on the days of the top five instantaneous maximum floods (IMFs) and the four preceding days for each flood event recorded within the basin are summarized in **Appendix C (Table C-13)**. Unlike at Devghat (Gandaki River) and Chatara (Koshi River), the lowest flow corresponds to the lowest precipitation. For the fifth-highest flood, the precipitation on the day of occurrence was 31 mm, with 47 mm of cumulative rainfall over two days and 60 mm over three days (**Table 5-33**).At this station, the highest basin average precipitation (82 mm) occurred on the day of the second-highest flood, while the second-highest precipitation (75 mm) occurred on the day of the third-highest flood. Similarly, the third and fourth-highest average precipitation values (74 mm and 68 mm, respectively) occurred on the days of the first and fourth-highest floods. However, the highest two-day cumulative rainfall occurred on the day of the fourth-highest flood. The second, third, and fourth-highest two-day cumulative rainfall values corresponded to the third, second, and first highest flood days, respectively.

The maximum precipitation recorded at any rain gauge station within the basin during these events was as follows:

- 500 mm for the second-highest flood.
- 240 mm for the third-highest flood.
- 220 mm for the highest flood.
- 197 mm for the fourth-highest flood.
- 86 mm for the fifth-highest flood (see **Table C-13)**

Once again, the highest rainfall did not contribute to the highest flood. The spatial distribution of precipitation across the basin during and prior to these flood days is shown in **Figure 5-31**.

The flow-to-precipitation ratios at this station are consistent across all cases. The ratios of instantaneous flood to one-day annual maximum flows range from 1.03 to 1.36. This suggests that the floods in this river basin are primarily rainfall-driven. However, it is surprising to observe that the highest floods occurred with lower rainfall in this basin as well.

Table 5-33 Top five IMF occurred in the past at Chisapani of Karnali River

Rank IMF	Date	IMF (m^3/s)	Day of IMF	P_{avg} (mm)	Cumulative P ($\sum P_{avg}$, mm)	$\frac{\sum P_{avg}}{\sum P_{avg-min}}$	Rank of $\sum P_{avg}$	$\frac{Q_{inst}}{Qdmax}$
1	**9/11/1983**	**21,700**	1	74	74	2.4	3	**1.36**
			2	18	93	2.0	4	
			3	8	101	1.7	4	
			4	4	105			
			5	11	116			
2	**8/15/2014**	**21,700**	1	82	82	2.6	1	**1.21**
			2	33	116	2.5	3	
			3	11	127	2.1	3	
			4	14	140			
			5	12	153			
3	**6/18/2013**	**17,900**	1	75	75	2.4	2	**1.03**
			2	43	118	2.5	2	
			3	8	127	2.1	2	
			4	5	132			
			5	6	138			
4	**10/7/2009**	**17,000**	1	68	68	2.2	4	**1.16**
			2	69	137	2.9	1	
			3	31	168	2.8	1	
			4	9	177			
			5	4	182			
5	**8/1/2000**	**12,500**	1	31.4	31.4	1.0	5	**1.10**
			2	19.8	51.1	1.0	5	
			3	12.4	63.5	1.0	5	
			4	12.0				
			5	15.2				

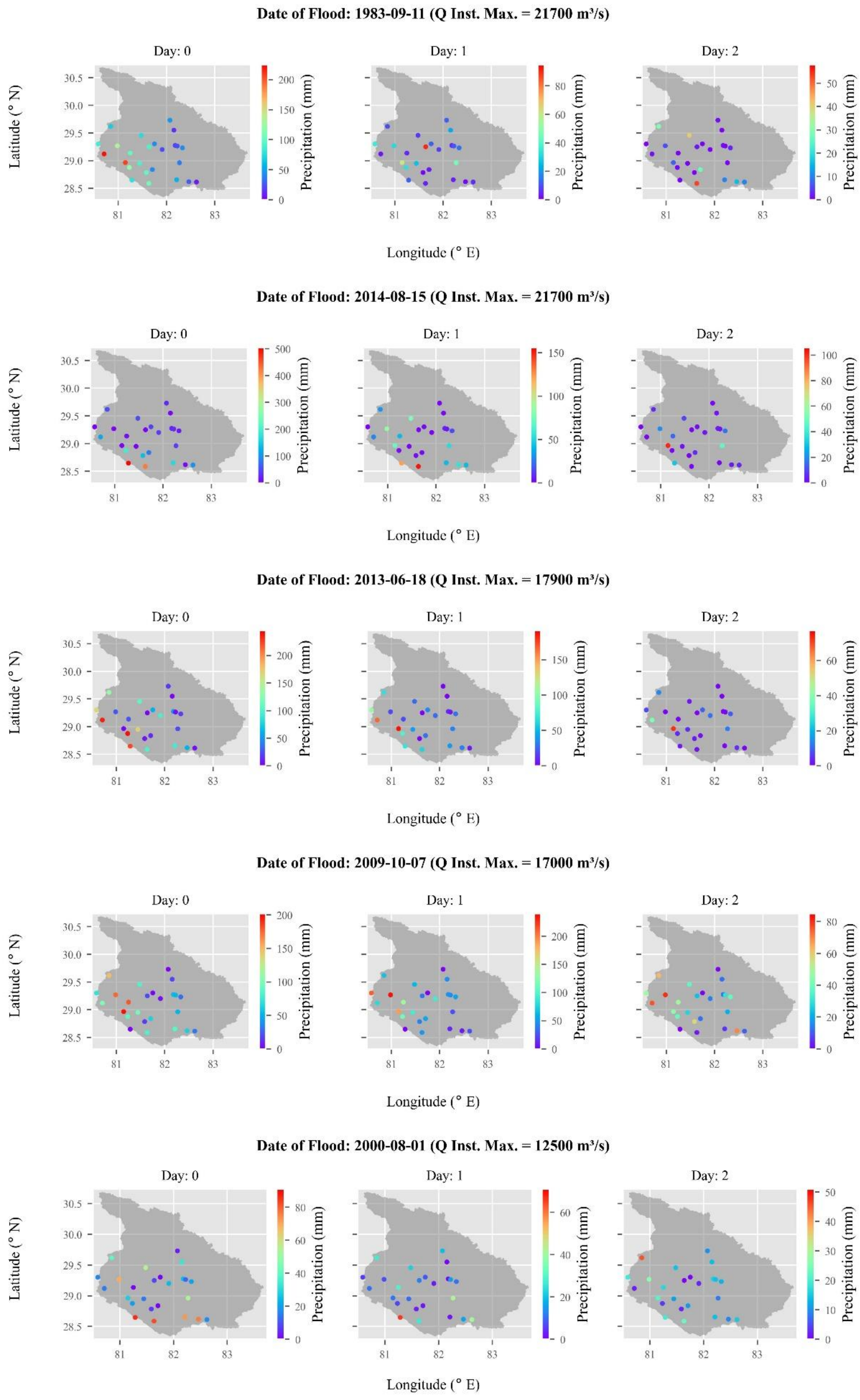


Figure 5-31 Spatial distribution of the precipitation across the Karnali Basin

4. Mahakali Basin Floods and Associated Climate

Top five past IMFs of Chamelia River at Nayalbadi are given in **Table 5-34**. On 11th July 2018 the highest flood (898 m^3/s) occurred at this gauging station. From second to fifth highest floods occurred on 1st August 2016, 8th June 2000, 14th August 2017 and 22nd August 2010 with their respective flood magnitudes of 734, 643, 641 and 627 m^3/s. However, the occurrence date of the annual maximum one day average floods and IMFs matches for only two floods of 2016 and 2010.

Table 5-34 Top five IMF occurred in the past at Nayalbadi of Chamelia river

Rank IMF	Date	IMF (m^3/s)	Day of IMF	P_{avg} (mm)	Cumulative P ($\sum P_{avg}$, mm)	$\frac{\sum P_{avg}}{\sum P_{avg-min}}$	Rank of $\sum P_{avg}$	$\frac{Q_{inst}}{Qdmax}$
1	**7/11/2018**	**898**	1	49	49	2.6	2	**1.40**
			2	52	101	2.7	2	
			3	43	143	2.6	1	
			4	11	154			
			5	0	154			
2	**8/1/2016**	**734**	1	19	19	1.0	5	**1.14**
			2	28	47	1.2	4	
			3	9	56	1.0	5	
			4	17	73			
			5	23	95			
3	**6/8/2000**	**643**	1	84	84	4.5	1	**1.32**
			2	26	110	2.9	1	
			3	2	112	2.0	2	
			4	24	136			
			5	0	136			
4	**8/14/2017**	**641**	1	27	27	1.4	4	**1.24**
			2	11	38	1.0	5	
			3	31	68	1.2	4	
			4	43.8	112.0			
			5	48.8	160.8			
5	**8/22/2010**	**627**	1	44.7	44.7	2.4	3	**1.06**
			2	32.0	76.7	2.0	3	
			3	12.0	88.6	1.6	3	
			4	48.4	137.0			
			5	83.8	220.8			

The precipitations, maximum and minimum temperatures of IMFs occurred on flood days and preceding four days of all these five flood events recorded within the basin are tabulated in **Appendix C (Table C-14)**. At this gauging station as well, the highest rainfall occurred during the third-highest flood event, while the first-highest flood event corresponded to the second-highest rainfall amount. Based on the ratios of floods to rainfall, and the ratio of instantaneous to one-day maximum floods, it can be concluded that the floods in this basin were primarily caused by heavy rainfall. The spatial distribution of precipitation across the basin during and prior to these flood days is shown in **Figure 5-32**. As any selected raingauge stations does not exist inside Chamelia basin, surrounding stations are shown in this figure.

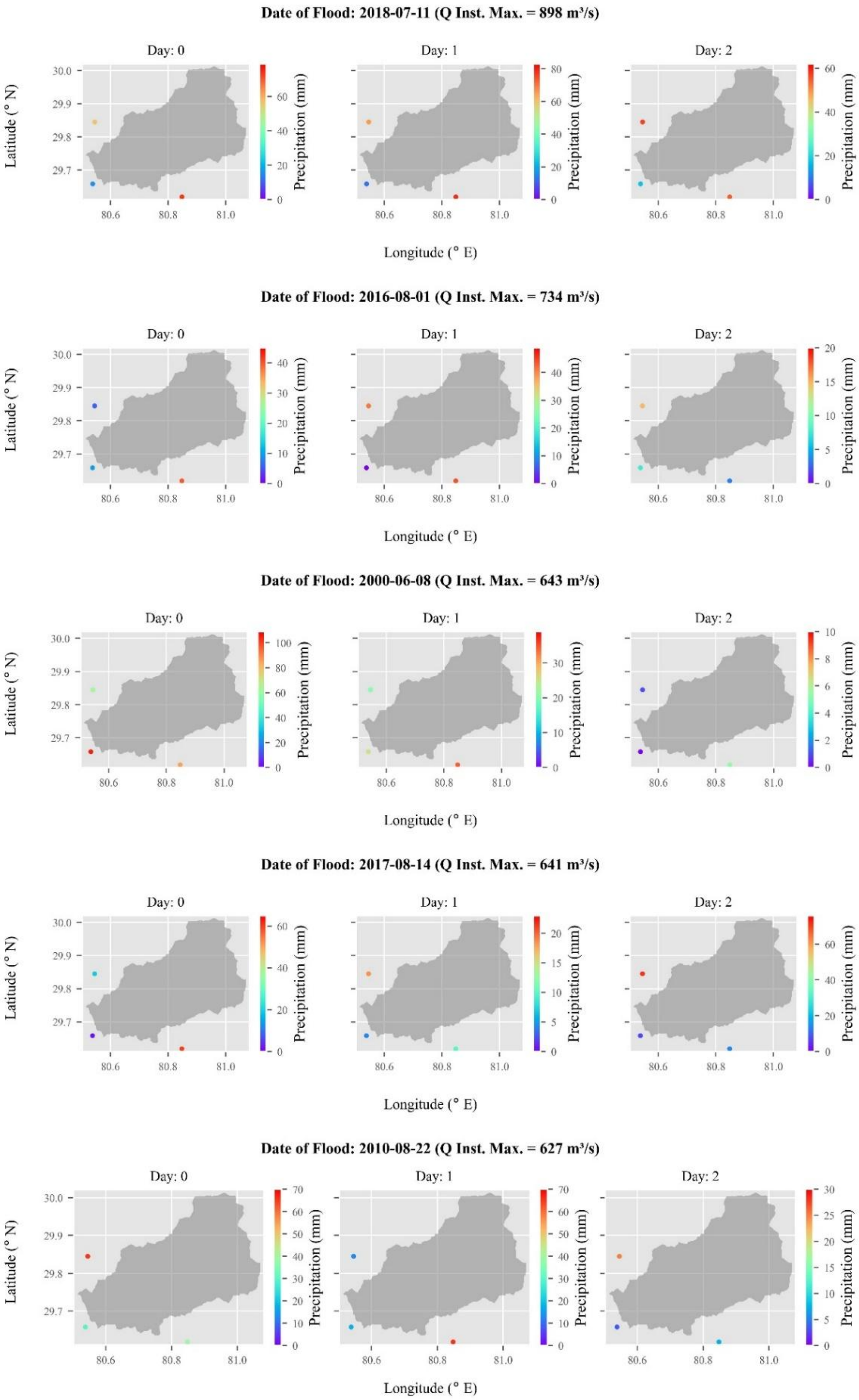


Figure 5-32 Spatial distribution of the precipitation across the Mahakali Basin

5. Kankai Basin Floods and Associated Climate

Top five past IMFs of Kankai River at Mainachuli are given in **Table 5-35**. The topmost floods at this gauging station occurred on 12th August 1990 with the magnitude of 7,500 m^3/s. The second, third, fourth and fifth largest floods were of magnitude of 6,430; 6050; 5,920 and 5,680 m^3/s respectively occurring on12th August 1981, 28th July 2002, 9th July 2003 and 16th August 2009. Further, the annual maximum one day average floods also occurred on the same day of occurrence of IMF in all five cases.

The precipitation, maximum, and minimum temperatures on the days of the top five instantaneous maximum floods (IMFs) and the four preceding days for each flood event recorded within the basin are provided in **Appendix C (Table C-15).** The rainfall rank is low for the highest flood in this basin as well. The ratios of flood magnitude to rainfall amount, and of instantaneous to one-day maximum flood, indicate a high probability that the causes of the first, second, third, and fourth highest floods were either short-duration high rainfall, a blockage upstream of the outlet that was breached, or a combination of both. The spatial distribution of precipitation across the basin during and prior to these floods is shown in **Figure 5-33**.

Table 5-35 Top five IMF occurred in the past at Mainachuli of Kankai River

<table>
<tr><th>Rank IMF</th><th>Date</th><th>IMF (m^3/s)</th><th>Day of IMF</th><th>P_{avg} (mm)</th><th>Cumulative P ($\sum P_{avg}$, mm)</th><th>$\frac{\sum P_{avg}}{\sum P_{avg-min}}$</th><th>Rank of $\sum P_{avg}$</th><th>$\frac{Q_{inst}}{Qdmax}$</th></tr>
<tr><td rowspan="5">**1**</td><td rowspan="5">**8/12/1990**</td><td rowspan="5">**7500**</td><td>1</td><td>1</td><td>1</td><td>1.0</td><td>5</td><td rowspan="5">**1.68**</td></tr>
<tr><td>2</td><td>16</td><td>17</td><td>1.0</td><td>5</td></tr>
<tr><td>3</td><td>0</td><td>17</td><td>1.0</td><td>5</td></tr>
<tr><td>4</td><td>55</td><td>72</td><td></td><td></td></tr>
<tr><td>5</td><td>0</td><td>72</td><td></td><td></td></tr>
<tr><td rowspan="5">**2**</td><td rowspan="5">**8/12/1981**</td><td rowspan="5">**6430**</td><td>1</td><td>136</td><td>136</td><td>136.2</td><td>2</td><td rowspan="5">**2.86**</td></tr>
<tr><td>2</td><td>33</td><td>170</td><td>10.0</td><td>4</td></tr>
<tr><td>3</td><td>0</td><td>170</td><td>10.0</td><td>4</td></tr>
<tr><td>4</td><td>5</td><td>174</td><td></td><td></td></tr>
<tr><td>5</td><td>13</td><td>187</td><td></td><td></td></tr>
<tr><td rowspan="5">**3**</td><td rowspan="5">**7/28/2002**</td><td rowspan="5">**6050**</td><td>1</td><td>81</td><td>81</td><td>81.4</td><td>4</td><td rowspan="5">**1.77**</td></tr>
<tr><td>2</td><td>186</td><td>268</td><td>15.7</td><td>1</td></tr>
<tr><td>3</td><td>10</td><td>278</td><td>16.3</td><td>1</td></tr>
<tr><td>4</td><td>2</td><td>280</td><td></td><td></td></tr>
<tr><td>5</td><td>44</td><td>324</td><td></td><td></td></tr>
<tr><td rowspan="5">**4**</td><td rowspan="5">**7/9/2003**</td><td rowspan="5">**5920**</td><td>1</td><td>101</td><td>101</td><td>100.8</td><td>3</td><td rowspan="5">**1.51**</td></tr>
<tr><td>2</td><td>124</td><td>225</td><td>13.2</td><td>2</td></tr>
<tr><td>3</td><td>3</td><td>228</td><td>13.4</td><td>3</td></tr>
<tr><td>4</td><td>0</td><td>228</td><td></td><td></td></tr>
<tr><td>5</td><td>12</td><td>240</td><td></td><td></td></tr>
<tr><td rowspan="5">**5**</td><td rowspan="5">**8/16/2009**</td><td rowspan="5">**5680**</td><td>1</td><td>203</td><td>203</td><td>203.3</td><td>1</td><td rowspan="5">**1.00**</td></tr>
<tr><td>2</td><td>5</td><td>209</td><td>12.3</td><td>3</td></tr>
<tr><td>3</td><td>20</td><td>229</td><td>13.4</td><td>2</td></tr>
<tr><td>4</td><td>10</td><td>239</td><td></td><td></td></tr>
<tr><td>5</td><td>13</td><td>251</td><td></td><td></td></tr>
</table>

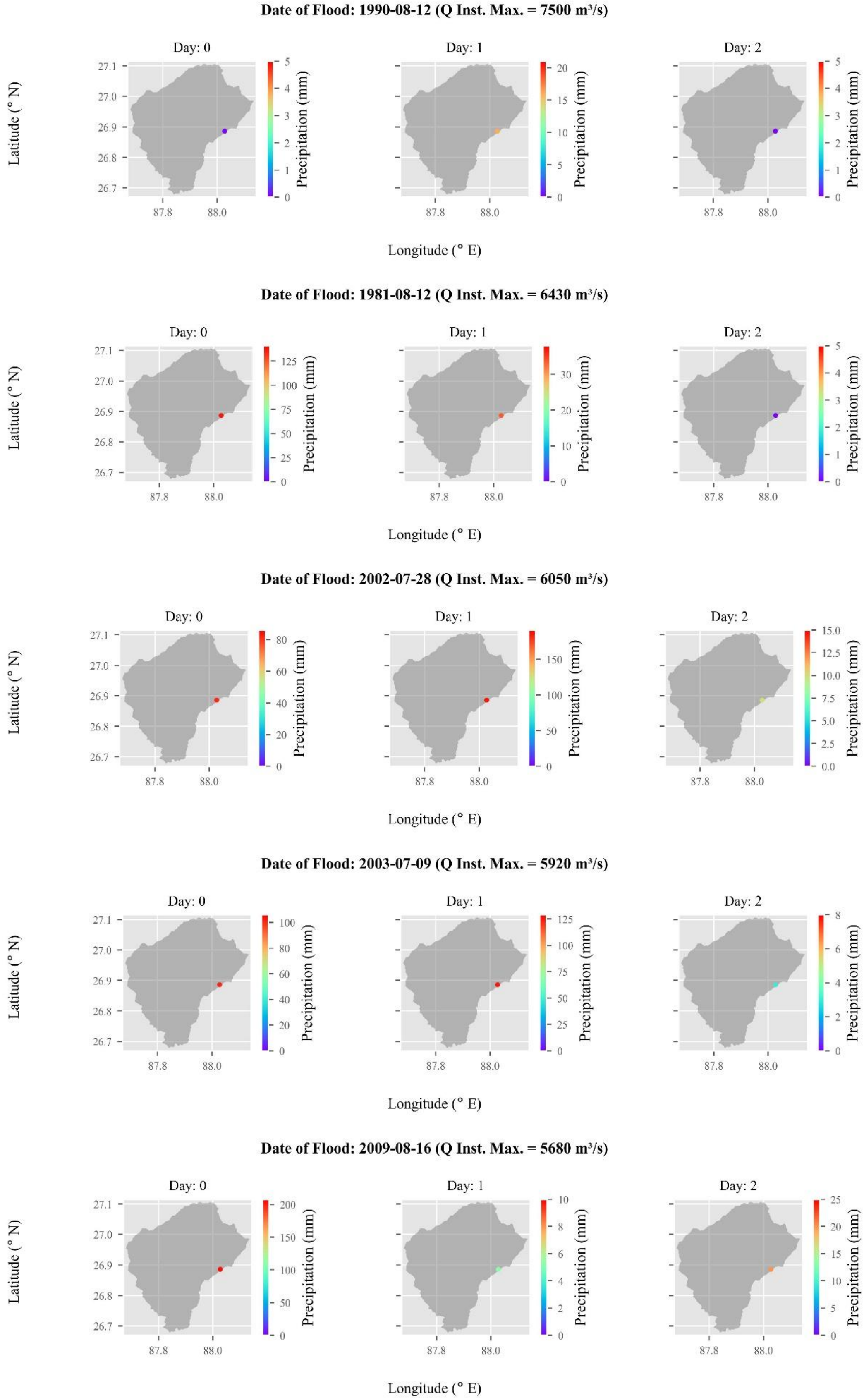


Figure 5-33 Spatial distribution of the precipitation across the Kankai Basin

6. Bagmati Basin Floods and Associated Climate

Top five past IMFs of Bagmati River at Pandherodovan are given in **Table 5-36**. The topmost flood occurred on 21st July 1993 whose magnitude was 16,000 m^3/s. The second, third, fourth and fifth largest floods occurred on 23rd July 2002, 17th September 1984, 9th July 2004 and 2nd August 2000 whose magnitudes were respectively 8,000; 7,630; 6,880 and 6,200 m^3/s. Further, the annual maximum one day average floods also occurred on the same day of occurrence of IMF in all the five cases in this basin. The precipitation, maximum, and minimum temperatures on the days of the top five instantaneous maximum floods (IMFs) and the four preceding days for each flood event recorded within the basin are presented in **Appendix C (Table C-16).** From this table, it is evident that the maximum rainfall upstream occurred one day before the highest flood day. In three rain gauge stations, the single-day rainfall recorded on the day before the highest flood exceeded 300 mm: Daman (St. 905) with 372 mm, Markhugaun (St. 915) with 386 mm, and Hariharpur (St. 1117) with 482 mm. The rainfall rank is lowest for the third-largest flood. Overall, heavy rainfall appears to be the primary cause of these top five floods in this basin. The spatial distribution of precipitation across the basin during and prior to these floods is shown in **Figure 5-34**.

Table 5-36 Top five IMF occurred in the past at Pandherodovan of Bagmati River

Rank IMF	Date	IMF (m^3/s)	Day of IMF	P_{avg} (mm)	Cumulative P ($\sum P_{avg}$, mm)	$\frac{\sum P_{avg}}{\sum P_{avg-min}}$	Rank of $\sum P_{avg}$	$\frac{Q_{inst}}{Qdmax}$
1	**7/21/1993**	**16000**	1	30	30	1.0	5	**2.12**
			2	157	186	3.5	2	
			3	22	208	2.0	2	
			4	11	219			
			5	18	237			
2	**7/23/2002**	**8000**	1	206	206	6.9	1	**1.49**
			2	91	297	5.6	1	
			3	19	316	3.1	1	
			4	38	355			
			5	1	356			
3	**9/17/1984**	**7630**	1	37	37	1.2	4	**1.93**
			2	16	53	1.0	5	
			3	50	103	1.0	5	
			4	9	112			
			5	2	114			
4	**7/9/2004**	**6850**	1	85	85	2.8	2	**1.22**
			2	44	129	2.4	3	
			3	19	148	1.4	3	
			4	10	158			
			5	4	162			
5	**8/2/2000**	**6200**	1	69	69	2.3	3	**1.75**
			2	39	108	2.0	4	
			3	12	120	1.2	4	
			4	9	130			
			5	17	146			

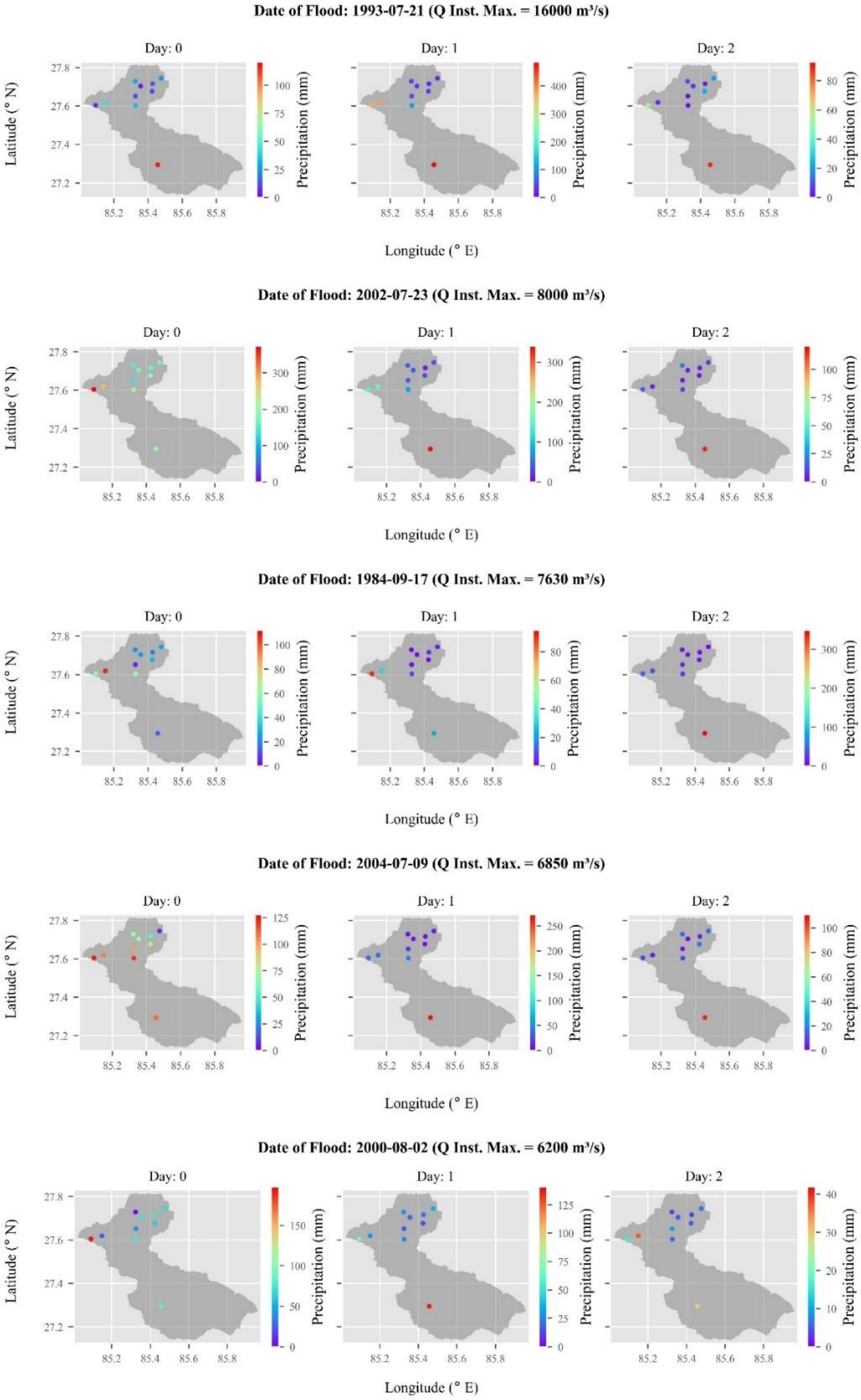


Figure 5-34 Spatial distribution of the precipitation across the Bagmati Basin

7. West Rapti Basin Floods and Associated Climate

Top five past IMFs at Kusum of West Rapti River are given in **Table 5-37**. The topmost flood magnitude was 9,100 m^3/s which occurred on 15th August 2014. The second, third, fourth and fifth largest floods occurred on 26th July 2016, 22nd Juy 2013, 7th October 2009 and 13th August 2017 whose magnitudes were respectively 9,100; 6,160; 5,720; 4,860 and 3,950 m^3/s. Further, the annual maximum one day average floods also occurred on the same day of occurrence of IMF in all cases. The ratios of instantaneous floods to one day maximum floods from 1st highest to 5th highest events are 1.19, 1.70, 1.19, 1.83 and 1.10 respectively. The precipitation, maximum, and minimum temperatures on the days of the top five instantaneous maximum floods (IMFs) and the four preceding days for each flood event recorded within the basin are provided in **Appendix C (Table C-17).** In this basin, rainfall and floods generally follow the same pattern—heavier rainfall corresponds to higher flood magnitudes. The rainfall on the day of occurrence appears to be the dominant factor for the largest floods. The spatial distribution of precipitation across the basin during and prior to these floods is shown in **Figure 5-35.**

Table 5-37 Top five IMF occurred in the past at Kusum of West Rapti River

Rank IMF	Date	IMF (m^3/s)	Day of IMF	P_{avg} (mm)	Cumulative P ($\sum P_{avg}$, mm)	$\frac{\sum P_{avg}}{\sum P_{avg-min}}$	Rank of $\sum P_{avg}$	$\frac{Q_{inst}}{Qdmax}$
1	**8/15/2014**	**9100**	1	165	165	11.4	1	**1.19**
			2	12	176	8.8	1	
			3	0	176	8.8	1	
			4	0	176			
			5	0	176			
2	**7/26/2016**	**6160**	1	114	114	7.9	2	**1.70**
			2	33	147	7.3	2	
			3	5	151	7.6	2	
			4	19	170			
			5	140	310			
3	**7/22/2013**	**5720**	1	43	43	3.0	3	**1.19**
			2	0	43	2.2	3	
			3	26	70	3.5	3	
			4	61	131			
			5	30	161			
4	**10/7/2009**	**4860**	1	27	27	1.9	4	**1.83**
			2	0	27	1.4	4	
			3	1	28	1.4	4	
			4	4	31			
			5	0	31			
5	**8/13/2017**	**3950**	1	14	14	1.0	5	**1.10**
			2	6	20	1.0	5	
			3	0	20	1.0	5	
			4	0	20			
			5	4	24			

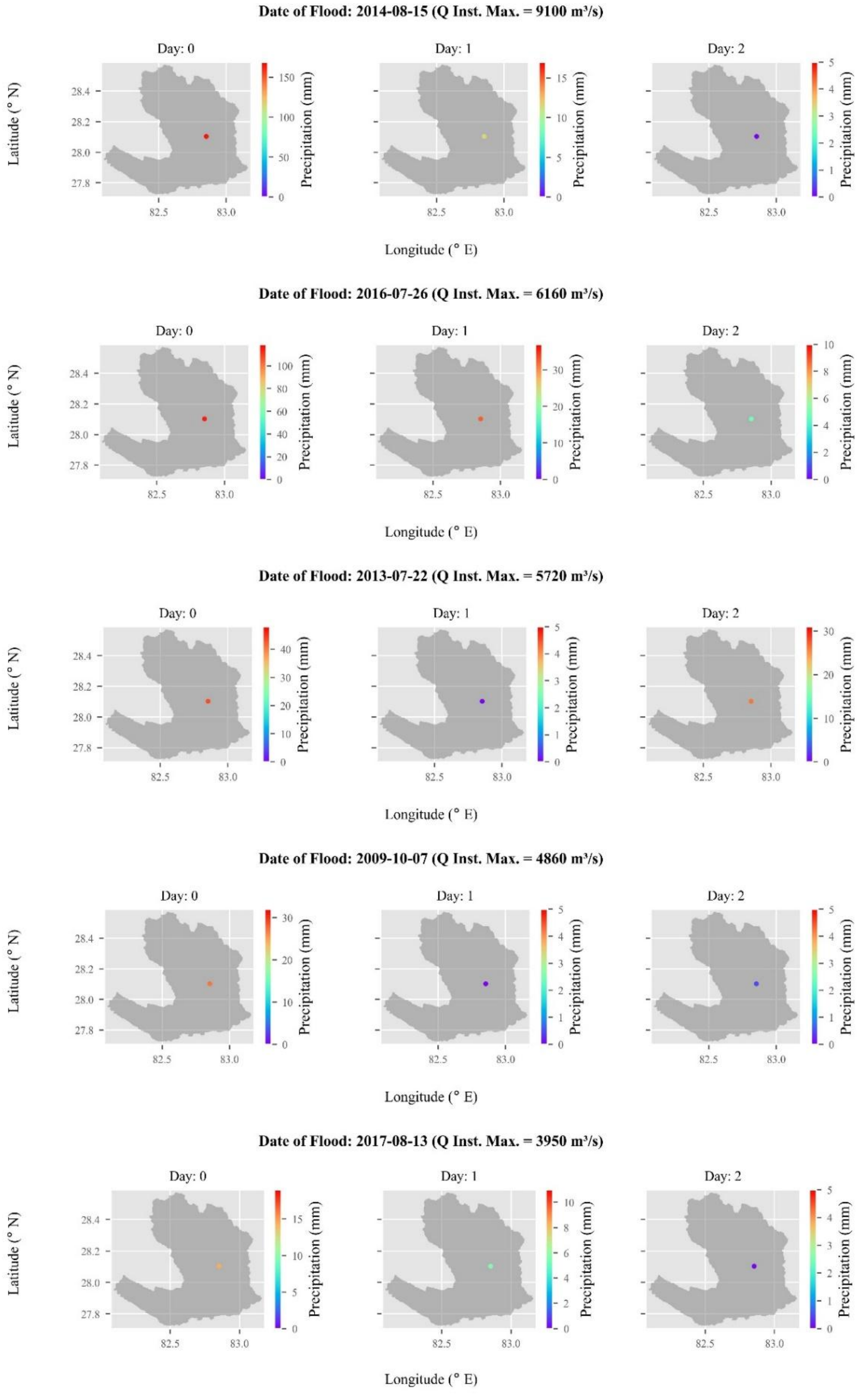


Figure 5-35 Spatial distribution of the precipitation across the West Rapti Basin

8. Babai Basin Floods and Associated Climate

Top five past IMFs of Babai River at Chepang are given in **Table 5-38.** The topmost flood occurred on 13th August 2017, whose magnitude was 5,060 m^3/s. The second, third, fourth and fifth largest floods occurred on 15th August 2014, 9th August 1995, 26th July 2007 and 11th September 1994 whose magnitudes were 3,994; 3,870, 3,640 and 3,520 m^3/s respectively. Further, the annual maximum one day average floods also occurred on the same day of occurrence of IMF in four cases in this basin except in 1995. In the year of 1995, one day maximum flood occurred on 13th August, four days after the IMF of the year. The precipitation, maximum, and minimum temperatures on the days of the top five instantaneous maximum floods (IMFs) and the four preceding days for each flood event recorded within the basin are presented in **Appendix C (Table C-18**). The rainfall on the day of occurrence appears to be the dominant factor for the largest floods. The rainfall rank is lowest for the third-largest flood, suggesting that there may have been a blockage that was breached, causing this flood. In the other cases, heavy rainfall seems to be the primary cause of the floods in this basin. The precipitation maps for these floods are shown in **Figure 5-36**.

Table 5-38 Top five IMF occurred in the past at Chepang of Babai River

Rank IMF	Date	IMF (m^3/s)	Day of IMF	P_{avg} (mm)	Cumulative P ($\sum P_{avg}$, mm)	$\frac{\sum P_{avg}}{\sum P_{avg-min}}$	Rank of $\sum P_{avg}$	$\frac{Q_{inst}}{Qdmax}$
1	**8/13/2017**	**5,060**	1	97	97	7.1	2	**1.23**
			2	67	165	7.5	2	
			3	5	170	7.8	2	
			4	29	199			
			5	4	203			
2	**8/15/2014**	**3,990**	1	269	269	19.8	1	**1.00**
			2	120	389	17.8	1	
			3	4	394	18.0	1	
			4	9	403			
			5	5	408			
3	**8/9/1995**	**3,870**	1	14	14	1.0	5	**1.05**
			2	8	22	1.0	5	
			3	0	22	1.0	5	
			4	20	42			
			5	49	91			
4	**7/26/2007**	**3,640**	1	47	47	3.4	3	**1.26**
			2	29	76	3.5	3	
			3	43	119	5.4	3	
			4	20	138			
			5	12	150			
5	**9/11/1994**	**3,520**	1	19	19	1.4	4	**1.91**
			2	19	37	1.7	4	
			3	22	60	2.7	4	
			4	1	60			
			5	0	60			

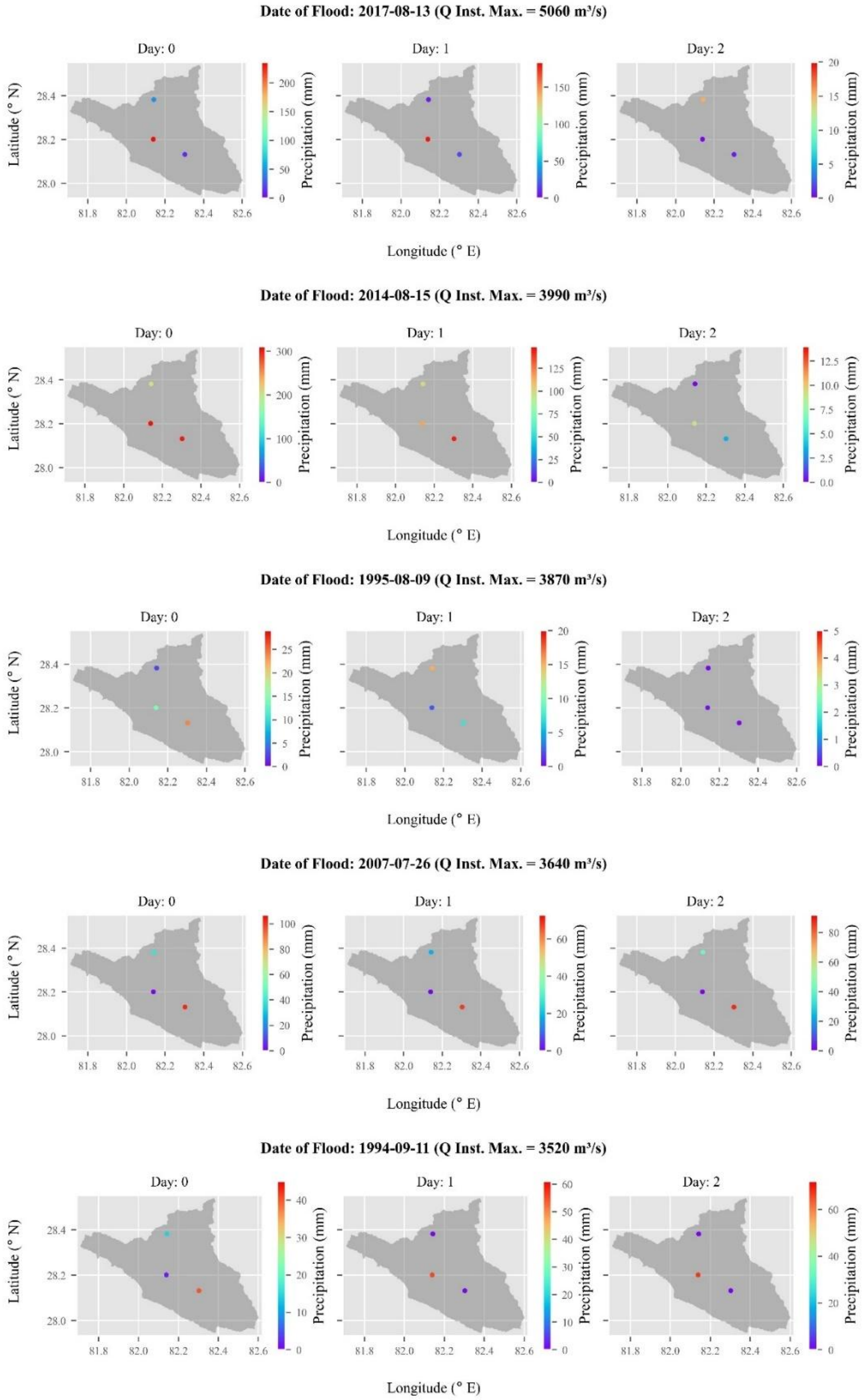


Figure 5-36 Spatial distribution of the precipitation across the Babai Basin

5.9.2 Affinity of Flood to Precipitation Location

In this study, the level of affinity of IMF with precipitation occurring at certain locations was assessed. It was done by calculating the Pearson correlation coefficients between IMF of a location (say IMF of 29 years at Chatara of Koshi River) and the precipitation occurring in the observation stations upstream of Chatara within the basin considering one station at a time. While calculating this coefficient, three cases of rainfall were considered: (i) rainfall occurring on the day of IMF (ii) rainfall one day ahead of the IMF event day and (iii) sum of the rainfall of these two days. This was done not to lose any combination of rainfall contributing to flood at the outlet. The summary of the results is given in **Table 5-39**.

Except for some stations of Karnali basin and Bagmati basin which showed the good correlation with the flood at Chisapani and Pandherodovan respectively, the rainfall occurring in the other locations did not show any significant affinity to the floods at the outlet of other rivers. For example, rainfall occurring in 5 raingauge stations showed better correlation with the floods at Chisapani of the Karnali River than that of other stations. They are stations 204 (Bajura/Martadi), 214 (Kotagaun), 304 (Guthichaur), 401 (Pusma) and 513 (Chaurjhari). Among these stations, rainfall occurring at Chaurjhari has the highest correlation coefficient (r= 0.78). Floods of Bagmati River at Padherodovan are influenced by the precipitation occurring a day prior to the flood at Stations 905 (Daman) and 915 (Markugaun).

Table 5-39 Affinity of IMF to precipitation location

SN	**River**	**Location of IMF**	**Rainfall at the IMF Event Day**		**Rainfall One Day Before IMF Event Day**		**Sum of the Rainfall of Two Days**	
			Avg	Max	Avg	Max	Avg	Max
1	Koshi	Chatara	0.082	0.367	0.107	0.379	0.096	0.354
2	Gandaki	Devghat	0.128	0.324	0.191	0.377	0.170	0.376
3	Karnali	Chisapani	0.437	0.780	0.217	0.531	0.415	0.743
4	Chamelia	Nayalbadi	0.182	0.323	-0.038	0.133	0.112	0.312
5	Kankai*	Mainachuli	0.294	0.294	0.268	0.268	0.351	0.351
6	Bagmati	Padheredovan	0.237	0.292	0.474	0.854	0.413	0.741
7	West Rapti*	Kusum	0.568	0.568	-0.014	-0.014	0.545	0.545
8	Babai	Chepang	0.351	0.376	0.322	0.500	0.395	0.498

* Only one station within the basin

5.9.3 Flood Disaster Events and Associated Climate

The following two criteria were used to select the ten flood events for assessing their association with precipitation:

1. Flood events with the maximum number of human casualties (deaths and/or missing persons).
2. Special attention was given to covering different locations (districts) if the minimum loss of human lives at a given location was greater than five persons.

The selected ten flood events, their dates of occurrence, human losses, and associated rivers (if they were near the site of the incident) are listed in **Table 5-40**. The deadliest flood among these occurred in Sarlahi on 21st July 1993, causing a total of 237 human casualties (deaths and missing). Even the 10th deadliest flood, which occurred on 3rd September 2020 in Baglung, claimed 38 lives.

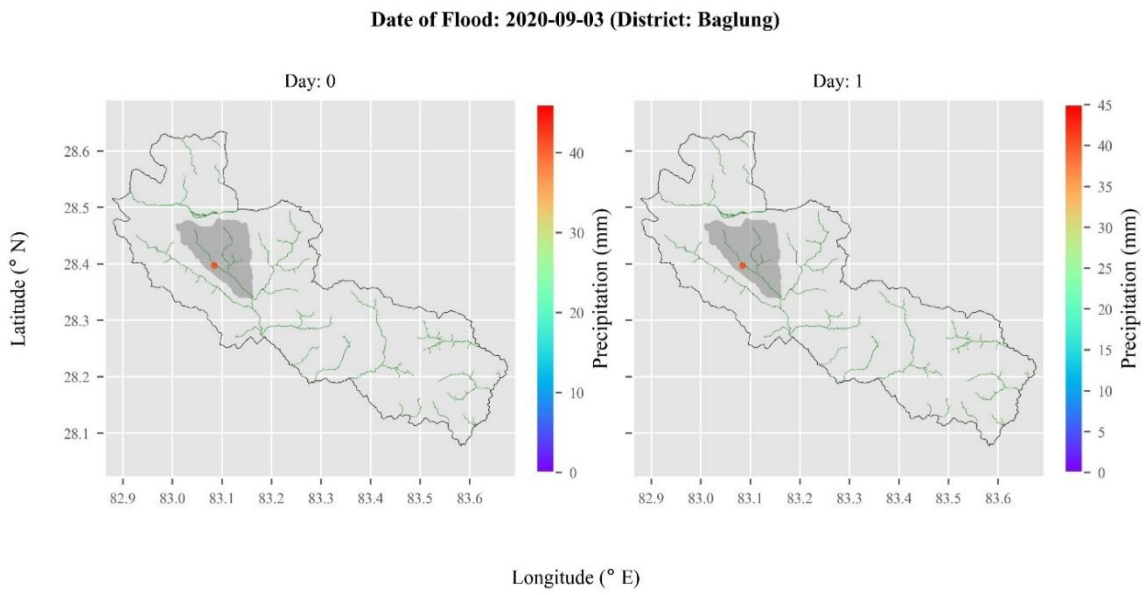
The average precipitation for the day of the flood and the cumulative precipitation from the two preceding days upstream of the location were also calculated and are provided in **Appendix C (Table C-19).** In most cases, the cause of the floods was heavy precipitation on the day of the event or one or two days prior. The recorded ten deadliest floods are briefly discussed below:

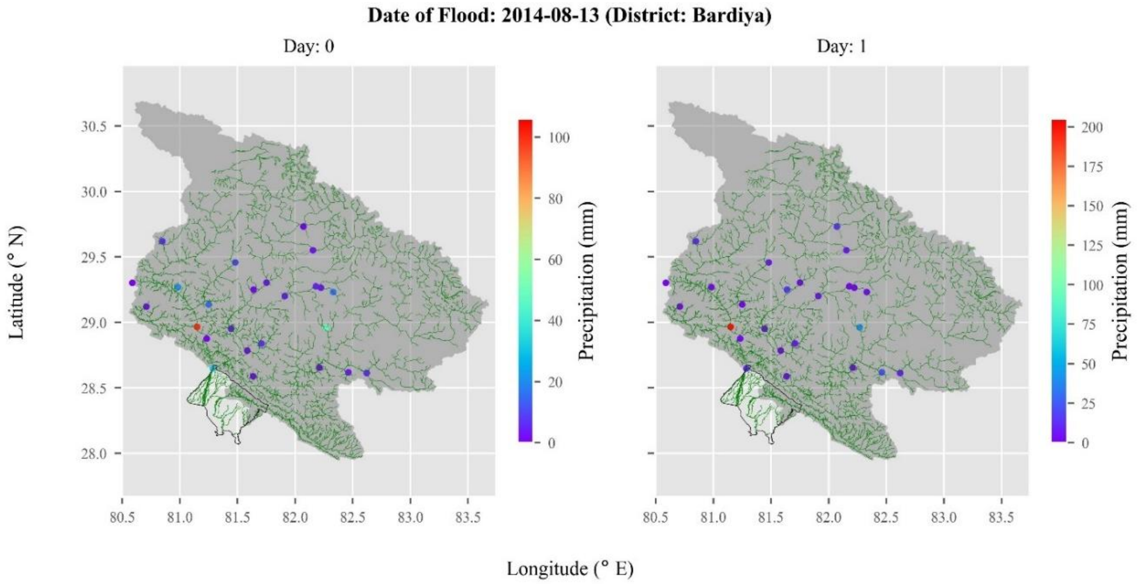
1. **Sarlahi Flood:** This flood was caused by heavy rainfall near the Kulekhani region (e.g., Daman/St. 905: 372 mm, Markhugaun/St. 915: 386 mm, and Hariharpur/St. 1117: 482 mm) that occurred the day before the flood.
2. **Surkhet Flood**: The flood was caused by incessant rainfall on the day of the disaster and the previous day. Although the rainfall was not exceptionally high, a blocked drainage channel caused by the rain triggered the flood, according to local reports.
3. **Tinau (Rupandehi) Flood**: This flood was attributed to a landslide outburst in the Tinau watershed, Palpa district, triggered by heavy precipitation on the day of the flood (e.g., St. 702/Palpa: 84 mm).
4. **Kaski District Flash Flood**: Although there was no significant rainfall on the day, a landslide near Machhapuchre Mountain blocked the river flow. When the landslide dam breached, a massive flash flood occurred in the Seti River, killing 72 people.
5. **Sindupalchwok Flood**: No significant rainfall was recorded in the Sindupalchwok district on the day or the days leading up to the flood, yet 71 people were killed. The disaster was caused by a catastrophic debris flow powered by the Bhairab Kunda stream.
6. **Makawanpur Flood**: This flood was the result of a cloudburst near the Kulekhani area.
7. **Bardiya Flood**: The incessant rainfall from the 13th to 15th August 2014 caused floods in the Karnali, Babai, Geruwa, Bhada, and Man Khola rivers, leading to widespread inundation in Bardiya.
8. **Morang Flood**: This flood, which caused 45 deaths, was likely influenced by rainfall in the Damak area (e.g., St. 1408: 43 mm on the day of the flood and 49 mm the day before).
9. **Chitwan Flood**: The flood was caused by heavy rainfall on the day of the disaster and the preceding day, particularly in the Daman and Hetauda areas. Rainfalls of 104 mm (St. 904/Daman) and 60 mm (St. 906/Hetauda) were recorded.
10. **Baglung Flood**: A combination of landslides and torrential rainfall caused significant losses in Dhorpatan Municipality-9, Baglung district, resulting in a major disaster.

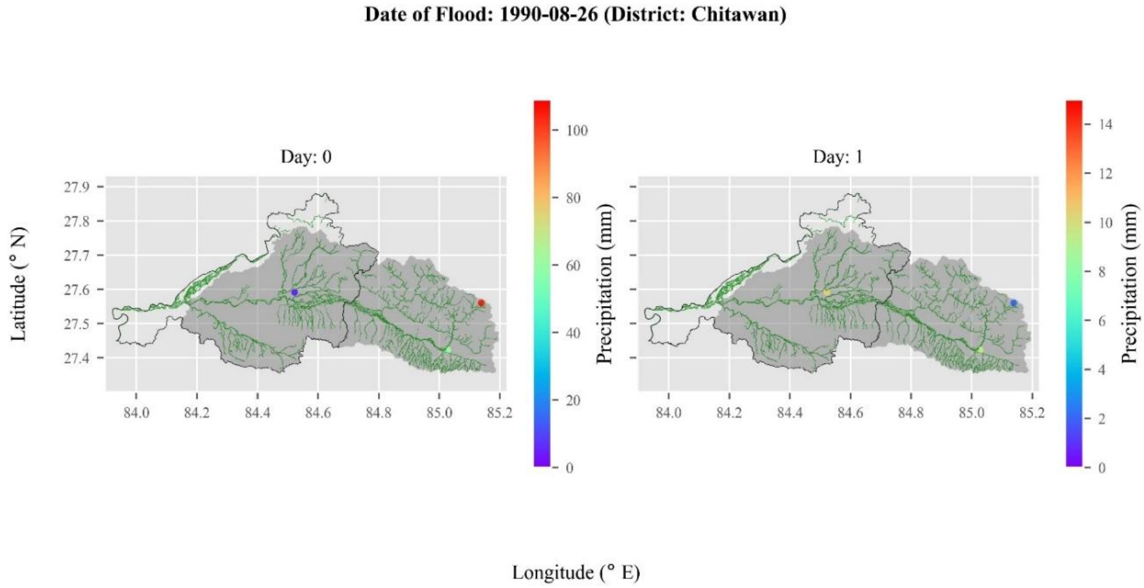
Table 5-40 Ten past flood events with severe human losses

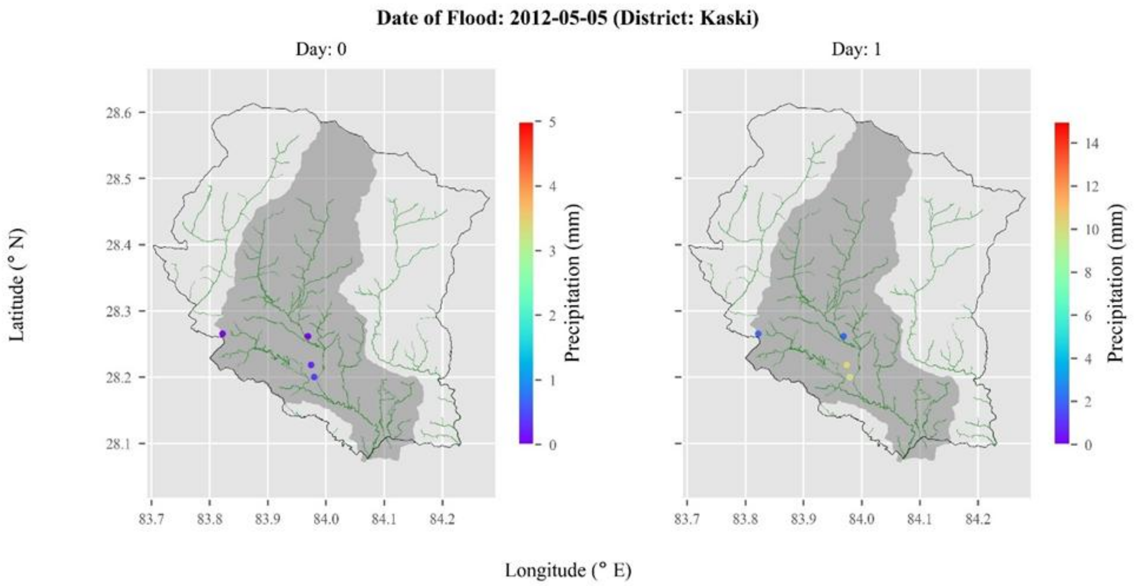
SN	District	Incident Date	Total Death	Missing People	Death and Missing-Combined	Closest River
1	Sarlahi	1993-07-21	237	0	237	Bagmati Barrage
2	Surkhet	2014-08-14	34	91	125	Bheri Nadi
3	Rupandehi	1981-09-10	35	83	118	Tinau
4	Kaski	2012-05-05	72	0	72	Seti
5	Sindhupalchowk	1996-07-22	10	61	71	Bhotekoshi Nadi
6	Makawanpur	1993-07-19	60	0	60	Kulekhani
7	Bardiya	2014-08-13	33	15	48	Man Khola, Babai, Karnali
8	Morang	1999-08-22	45	0	45	Bakraha, Das, Lohandra, Gachhiya, Budhi
9	Chitawan	1990-08-26	32	12	44	Rapti Nadi
10	Baglung	2020-09-03	22	16	38	Bhuji khola

The spatial distribution of the precipitation across the basin during and prior to these flood days is shown in **Figure 5-37**.

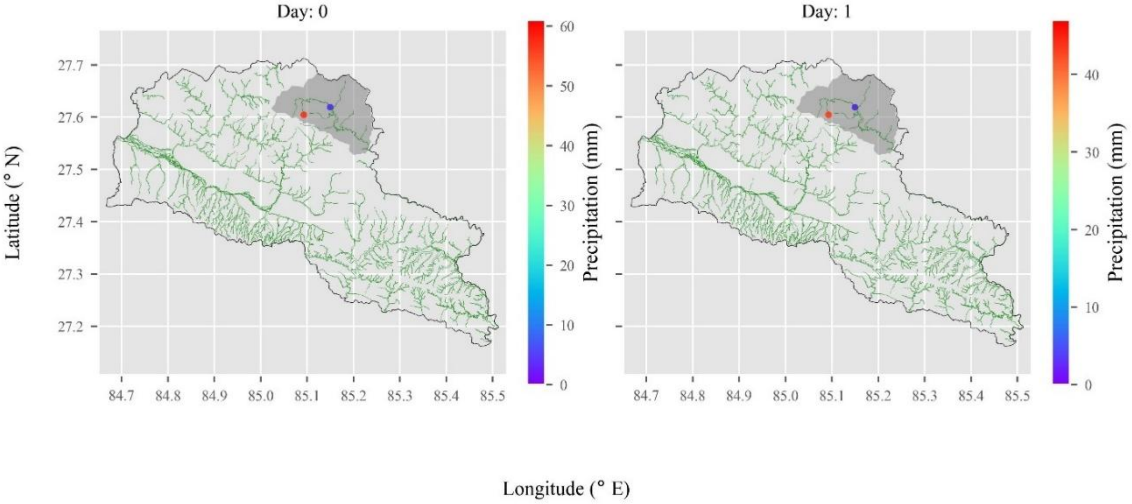



Date of Flood: 2014-08-13 (District: Bardiya)
Day: 0
Day: 1
Latitude (° N)
Precipitation (mm)
Longitude (° E)

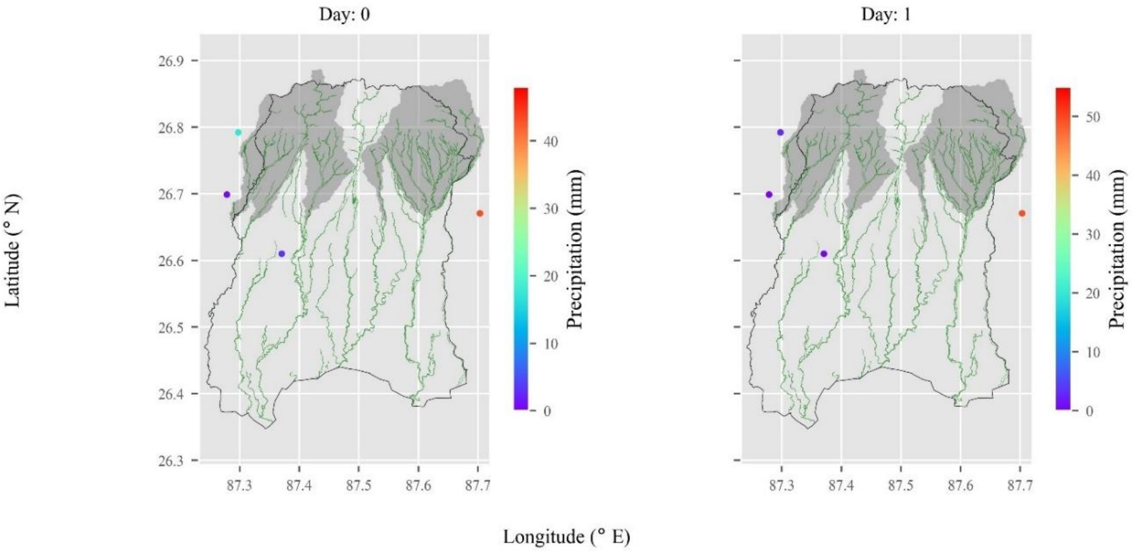

Date of Flood: 1990-08-26 (District: Chitawan)
Day: 0
Day: 1
Latitude (° N)
Precipitation (mm)
Longitude (° E)


Date of Flood: 2012-05-05 (District: Kaski)
Day: 0
Day: 1
Latitude (° N)
Precipitation (mm)
Longitude (° E)

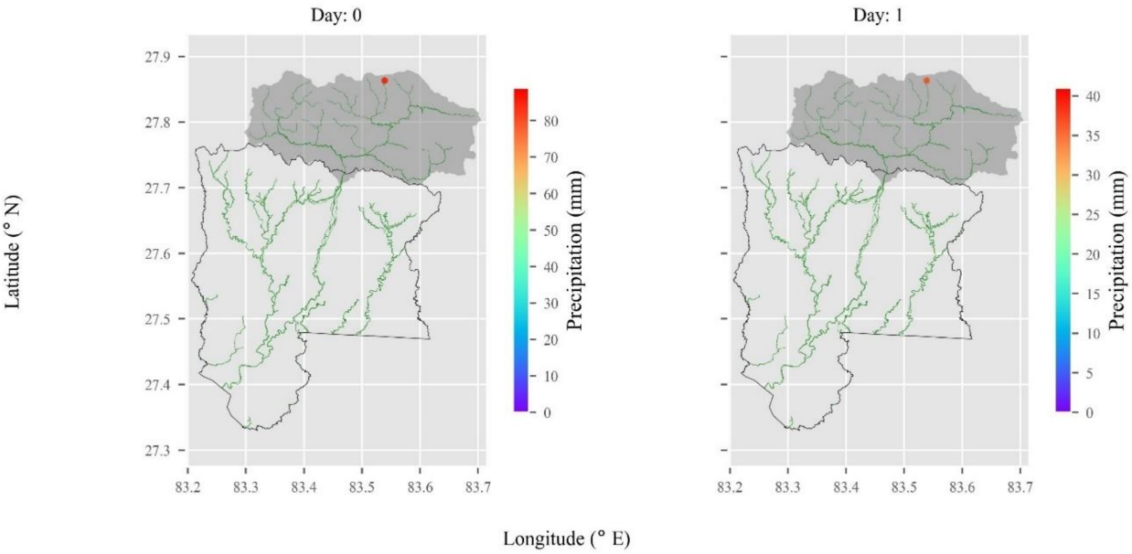
Date of Flood: 1993-07-19 (District: Makawanpur)



Date of Flood: 1999-08-22 (District: Morang)



Date of Flood: 1981-09-10 (District: Rupandehi)



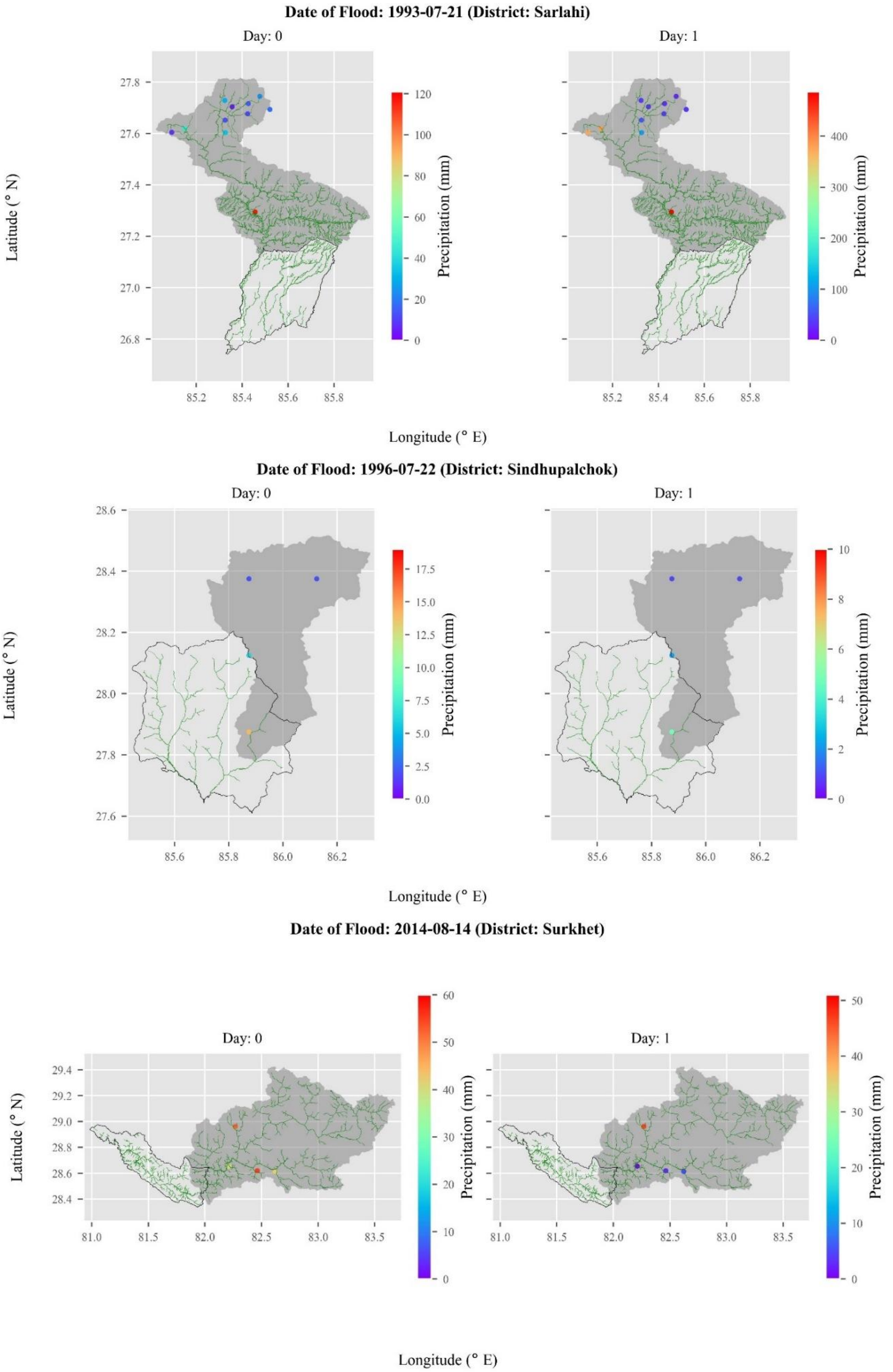


Figure 5-37 Flood disasters events and associated precipitation

5.10 Field Verification of Floods

5.10.1 Locations of Field Visits

The objective of the field visits was to observe the sites and interact with local people/key informants to gather first-hand information on past flood events. A total of 54 locations were visited during the field visits to verify the occurrence of any floods in these areas. The visited locations are listed in **Figure 5-38**. One of the queries with the local representatives/people was to know about their experiences on disastrous flood events in the past (**Appendix E: Table E-1):** Survey questionnaire on flood). The years of such floods as responded by the respondents are given in **Table 5-42**. Blank cells in the "Response of Respondents on Past Flood Events" column indicate that either the respondent could not recall the year of the flood or did not experience any significant floods in that municipality.

Out of the visited locations, only one (Kageshowri-Manohara Ward Number 8 in Kathmandu) reported no flood problems up until the date of the survey. The remaining 53 sites had experienced some form of flooding, whether large or small. A total of 105 flood events were reported by the respondents. A comparison was made between these reported flood events and the flood records available in the government's disaster portal (covering the period from 1980 to 2023). Of the 105 reported events, 12 occurred before the study period (before 1980). Seventy-two of the reported events matched the recorded events in the disaster portal, and these matching years are listed in the "Present in DRR Portal Record" column.

Table 5-41 List of field verification sites

SN	River_Name	District	Municipality	Ward No.	Latitude	Longitude	Type of Local Government
1	Karmanas River	Doti	Jorayal Rural	4	29.090723	80.661983	Gaunpalika
2	Dudhuwa River	Banke	Dudhuwa Rural	3	28.046065	81.69792	Gaunpalika
3	West Rapti River	Banke	Narainapur Rural	6	27.956599	81.783305	Gaunpalika
4	Bheri River	Surkhet	Bheri Ganga Rural	8	28.435416	81.814239	Nagarpalika
5	West RaptiRriver	Dang	Rapti Rural	3	27.83793	82.762964	Gaunpalika
6	Tinau River	Rupandehi	Titotama	14	27.583997	83.437563	Nagarpalika
7	Babai River	Bardiya	Thakurbaba	5	28.396839	81.295967	Nagarpalika
8	Karnali River	Kailali	Tikapur	8	28.434626	81.054637	Nagarpalika
9	Pathari River	Kailali	Bhajani	8	28.473154	80.962099	Nagarpalika
10	Mohana River	Kailali	Dhangadhi Sub-metropolitan City	19	28.603324	80.714644	Upamahanagarpalika
11	Mahakali River	Kanchanpur	Bhimduttanagar	9	29.051766	80.144049	Nagarpalika
12	Banara River	Kanchanpur	Krishnapur	1	28.909916	80.424188	Nagarpalika
13	Mahakali River	Kanchanpur	Bhimduttanagar	12	28.920406	80.105692	National Park
14	Seti River	Doti	Dipayal Silgadhi	5	29.26211	80.973174	Nagarpalika
15	Dordi Khola	Lamjung	Dordi Rural	6	28.229179	84.452119	Gaunpalika
16	Malekhu Khola	Dhading	Benighat Rorang	2	27.811287	84.827628	Gaunpalika
17	Pangthali Khola	Makwanpur	Raksirang Rural	8	27.584915	84.733057	Nagarpalika
18	Indrawati River	Sindupalanchowk	Indrawati Rural	12	27.832528	85.575133	Nagarpalika
19	Bagmati River	Kathmandu	Kajeshwori Manohara Rural	8	27.711554	85.372539	Nagarpalika
20	Gandaki River	Nawalparasi East	Madhya-Bindu	15	27.580581	83.993318	Nagarpalika
21	Rewa Khola	Chitwan	Madi	3	27.455258	84.318453	Nagarpalika
22	Thulo Syandi	Chitwan	Ichchhakamana Rural	7	27.728736	84.543785	Gaunpalika
23	Babai River	Dang	Ghorahi	17	28.001477	82.499611	Upamahanagarpalika
24	Babai River	Bardiya	Gulariya	4	28.263911	81.364286	Nagarpalika
25	Mahakali River	Darchula	Mahakali	4	29.838571	80.535243	Nagarpalika
26	Chamelia River	Darchula	Shailyashikhar	9	29.665743	80.543981	Nagarpalika
27	BhoteKoshi River	Sindupalanchowk	Balefi	8	27.763914	85.876558	Gaunpalika
28	BhoteKoshi River	Dolalghat	Bhumlu	10	27.63893	85.7058	Gaunpalika

SN	River_Name	District	Municipality	Ward No.	Latitude	Longitude	Type of Local Government
29	Bagmati River	Rautahat	Madhav Narayan	8	26.87983889	85.35002778	Nagarpalika
30	Mai Khola	Ilam	Mai	2	26.76465278	87.85678611	Nagarpalika
31	Tantin Khola	Jhapa	Arjundhara	4	26.70258056	87.96150556	Nagarpalika
32	Kankaimai River	Jhapa	Gauriganj Rural	1	26.65623056	87.87311944	Nagarpalika
33	Kankaimai River	Jhapa	Kankai	5	26.59918056	87.88021389	Nagarpalika
34	Surunga Khola	Jhapa	Kankai	3	26.63858056	87.89095	Nagarpalika
35	Saptakoshi River	Sunsari	Baraha	2	26.85535833	87.14984444	Nagarpalika
36	Budhi Khola	Sunsari	Itahari Submetero Politan	10	26.65845278	87.28593056	Upamahanagarpalika
37	Ratuwa Khola	Morang	Ratumai	3	26.65901111	87.70541667	Nagarpalika
38	Baluwa River	Dhanusa	Dhanusadham	4	26.87602778	86.06609444	Nagarpalika
39	Marin River	Sindhuli	Kamalamai	2	27.26155	85.87496944	Nagarpalika
40	Dhansar River	Bara	Nijgadh	1	27.21233889	85.26460556	Nagarpalika
41	Bakaiya River	Rautahat	Gaur	6	26.79941944	85.24941944	Nagarpalika
42	Flood plain area	Rautahat	Rajdevi	8	26.75233333	85.31146111	Nagarpalika
43	Khado River	Saptari	Rajbiraj	7	26.52306389	86.78668611	Nagarpalika
44	Banara Khola	Saptari	Kanchanrup	8	26.651	86.91901667	Nagarpalika
45	Surunga Khola	Saptari	Surunga	6	26.68558056	86.54665278	Nagarpalika
46	Kamala River	Siraha	Kalyanpur	2	26.71648056	86.19189444	Nagarpalika
47	Mainawati River	Siraha	Siraha	2	26.64762778	86.2108	Nagarpalika
48	Badahar River	Siraha	Siraha	15	26.61388333	86.15578333	Nagarpalika
49	Maulahi Khola	Saptari	Tirahut	2	26.60030556	86.86845	Gaunpalika
50	Lakhandehi River	Sarlahi	Hariwan	4	27.07876389	85.57689722	Nagarpalika
51	Kamala River	Sinduli	Kamalamai	8	27.12971111	85.94846389	Nagarpalika
52	Ratu Khola	Sinduli	Mithila	11	27.07508889	85.93923889	Nagarpalika
53	Soni River	Mahottari	Gaushala	1	26.94923056	86.38111111	Nagarpalika
54	Balan Khola	Saptari	Surunga	4	26.70179444	86.51075556	Nagarpalika

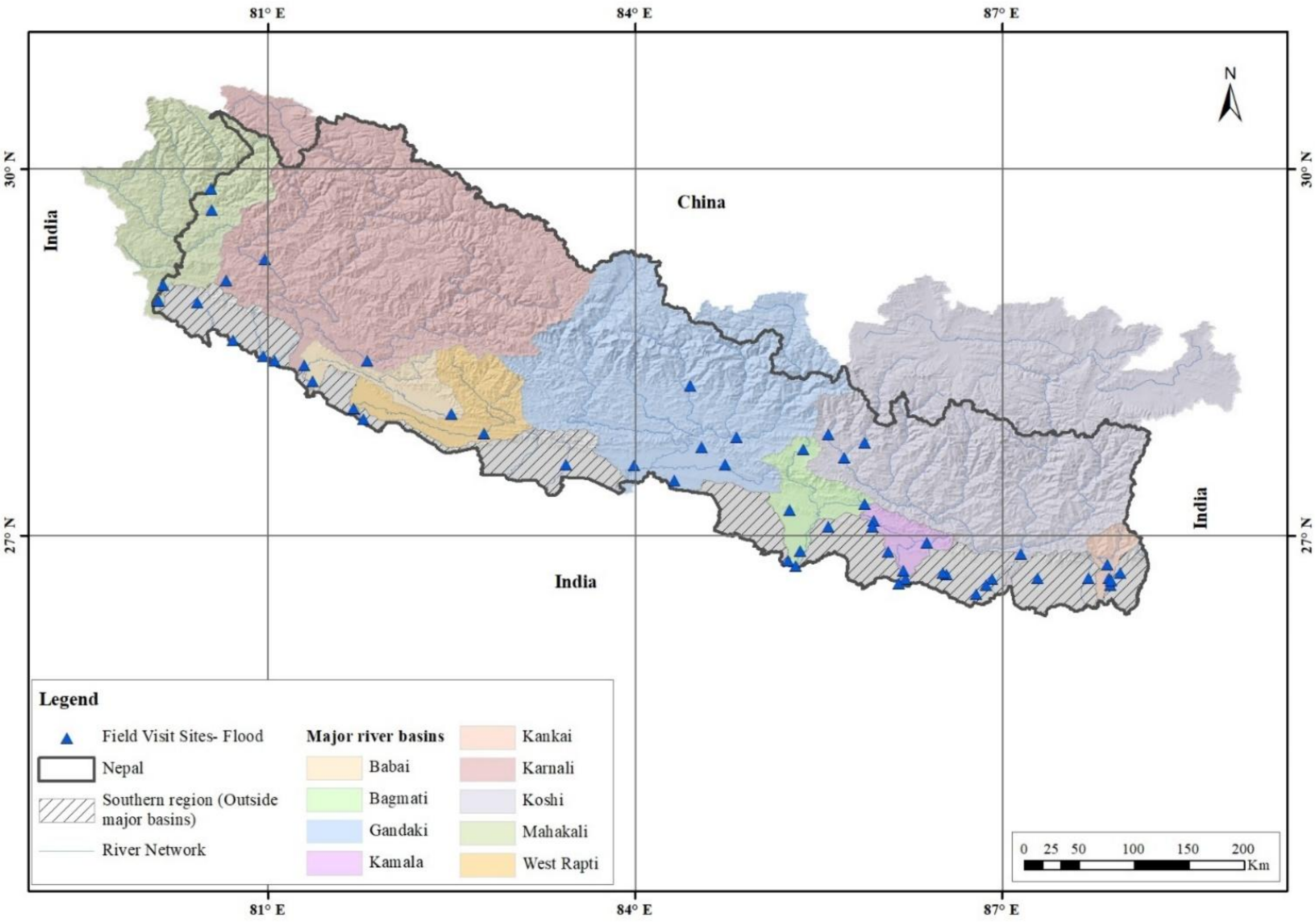


Figure 5-38 List of field verification sites

Table 5-42 Past major floods at different locations in the country

SN	River Name	District	Municipality	Ward No.	Response of Respondents on Past Flood Events	Present in DRR Portal Records	Not in DRR Portal Records	Flood Before 1980
1	Dudhuwa River	Banke	Dudhuwa	3	2015, 2017	2017	2015	
2	West Rapti River	Banke	Narainapur	6	1907, 2007, 2014, 2017, 2022	2007,2014,2017	2022	1
3	Dhansar River	Bara	Nijgadh	1	1993, 2017, 1893, 1917	1993, 2017		2
4	Babai River	Bardiya	Thakurbaba	5	2014	2014		
5	Babai River	Bardiya	Gulariya	4	2021	2021		
6	Rewa Khola	Chitawan	Madi	3	2001, 2002, 2020,2004, 2005	2001,2002, 2020,2004	2005	
7	Thulo Syandi	Chitawan	Ichchhakamana	7	1982, 1993, 1994,2002, 2017	1993,2002,2017	1982,1994	
8	West Rapti Rriver	Dang	Rapti	3	1961, 2003, 2004	2003,2004		1
9	Babai River	Dang	Ghorahi	17				
10	Mahakali River	Darchula	Mahakali	4	2021	2021		
11	Chamelia River	Darchula	Shailyashikhar	9	2021	2021		
12	Malekhu Khola	Dhading	Benighat Rorang	2	1974, 1984, 1993, 2021	1993,2021	1984	1
13	Baluwa River	Dhanusha	Dhanusadham	4	2021	2021		
14	Bhotekoshi River	Sindhupalchowk	Bhumlu	10	2023, 2002	2023,2002		
15	Karmanas River	Doti	Jorayal	4	2022, 2021, 2007, 1983, 1970	2021,2007,1983	2022	1
16	Seti River	Doti	Dipayal Silgadhi	5	2021, 1983, 1921, 1987	2021,1983	1987	1
17	Mai Khola	Ilam	Mai	2	1964			1
18	Tantin Khola	Jhapa	Arjundhara	4	1995, 1996	1995,1996		
19	Kankaimai River	Jhapa	Gauriganj	1	2020, 2017	2020,2017		
20	Kankaimai River	Jhapa	Kankai	5				
21	Surunga Khola	Jhapa	Kankai	3	1988, 1989	1988	1989	

SN	River Name	District	Municipality	Ward No.	Response of Respondents on Past Flood Events	Present in DRR Portal Records	Not in DRR Portal Records	Flood Before 1980
22	Karnali River	Kailali	Tikapur	8	1999, 2008, 2009, 2021	1999,2008,2009,2021		
23	Pathari River	Kailali	Bhajani	8	1983, 2021, 1983, 2021, 2019	2021,2021,2019	1983,1983	
24	Mohana River	Kailali	Dhangadhi	19	2021, 1985	2021	1985	
25	Mahakali River	Kanchanpur	Bhimduttanagar	9	2021	2021		
26	Banara River	Kanchanpur	Krishnapur	1	2021, 2023	2021	2023	
27	Mahakali River	Kanchanpur	Bhimduttanagar	12	2021, 1921	2021		1
28	Bagmati River	Kathmandu	Kajeshwori Manohara	8				
29	Dordi Khola	Lamjung	Dordi	6	2022, 2019	2022,2019		
30	Soni River	Mahottari	Gaushala	1				
31	Pangthali Khola	Makawanpur	Raksirang	8	2002, 2020	2002,2020		
32	Ratuwa Khola	Morang	Ratumai	3				
33	Gandaki River	Nawalparasi	Madhya-Bindu	15	2022, 2019, 1992, 1994, 1981, 2017, 2007	1981,2017,2007	2022,2019, 1992,1994	
34	Bagmati River	Rautahat	Madhav Narayan	8	2023, 2002	2023,2002		
35	Bakaiya River	Rautahat	Gaur	6	2021	2021		
36	Flood plain area	Rautahat	Rajdevi	8	2021	2021		
37	Tinau River	Rupandehi	Titotama	14	2011	2011		
38	Khado River	Saptari	Rajbiraj	7				
39	Banara Khola	Saptari	Kanchanrup	8	2021	2021		
40	Surunga Khola	Saptari	Surunga	6	2021, 2021	2021,2021		
41	Maulahi Khola	Saptari	Tirahut	2				
42	Balan Khola	Saptari	Surunga	4				
43	Lakhandehi River	Sarlahi	Hariwan	4				
44	Marin River	Sindhuli	Kamalamai	2	2017, 2020	2017,2020		

SN	River Name	District	Municipality	Ward No.	Response of Respondents on Past Flood Events	Present in DRR Portal Records	Not in DRR Portal Records	Flood Before 1980
45	Kamala River	Sindhuli	Kamalamai	8	1981, 1984, 1993, 2002	1984,1993,2002	1981	
46	Ratu Khola	Sindhuli	Mithila	11				
47	Indrawati River	Sindhupalchowk	Indrawati	12	2000, 2001, 2021	2000,2001,2021		
48	Bhotekoshi River	Sindhupalchowk	Balefi	8	1893, 1917, 1993, 2017	2017	1993	2
49	Kamala River	Siraha	Kalyanpur	2				
50	Mainawati River	Siraha	Siraha	2				
51	Badahar River	Siraha	Siraha	15	2021		2021	
52	Saptakoshi River	Sunsari	Baraha	2	1979			1
53	Budhi Khola	Sunsari	Itahari	10	2017, 2021	2017,2021		
54	Bheri River	Surkhet	Bheri Ganga	8	2015, 2023	2023	2015	
				Total	**105**	**72**	**21**	**12**

5.10.2 Observations Made During Field Verification Visit

1. Major Causes of floods

(i) **Overtopping of riverbanks**: Riverbanks and embankments overtopped in several areas, leading to floods.

(ii) **Breaching of banks/embankments**: Some banks and embankments were breached, contributing to floodwater spread.

(iii) **Rainwater accumulation**: Accumulation of rainwater in various areas exacerbated flooding.

(iv) **Sheet flow from the Siwalik hills**: Water runoff from the Siwalik range flowed into foothill towns and villages, causing flooding.

(v) **Inadequate drainage systems**: Some urban areas lacked proper drainage or had systems that were too small to handle the rainwater.

(vi) **Lack of side drains**: Many locations lacked continuous side drains along north-south roads.

(vii) **Backwater effects**: High flows in main rivers caused backwater effects in smaller tributaries and irrigation canals.

(viii) **Blockage by highways**: Highways obstructed the natural flow of water, contributing to floods.

(ix) **Blockage from Indian embankments**: Embankments constructed on the Indian side near the Nepal-India border blocked water flow into Nepal.

2. Sediment transport, deposition, and flow

(i) **Sediment and debris deposition**: All three types of rivers transport sediment, debris, and even boulders from upstream, depositing them in the riverbed, especially after entering the plains.

(ii) **Rising water levels due to sediment deposition**: As sediment accumulates in the riverbed, the water surface level rises, causing the river to overflow its banks, even if there is no increase in discharge.

(iii) **Formation of sediment islands**: Sediment islands frequently form in the middle of the river channel in most rivers.

(iv) **River meandering**: The presence of sediment islands often leads to river meandering, particularly in the Terai region. This makes predicting the river's flow path more challenging.

3. Bank cutting

(i) **Bank cutting**: Rivers flowing along or on both sides of the banks cause bank erosion, which in turn adds sediment to the river.

(ii) **Sand mining**: Sand mining, especially near the riverbanks, weakens the banks, making them more prone to erosion and sloughing.

(iii) **Soil composition and erosion**: The soil composition in the banks is primarily sand and silt, with layers only one or two feet below the surface. This makes the banks susceptible to undercutting, which creates steeply sloped banks. The soil mass above these undercut areas is prone to collapsing, forming sloughs (or falls).

4. Inundation and high flow

(i) **Duration and impact of inundation**: In certain areas, locals reported that the effects of inundation can last for up to 2-3 months in some years, with flood depths exceeding 1 meter. This leads to blocked transportation and submerged paddy fields. However, in most other areas, the flooding is of much shorter duration, typically lasting only a few hours.

(ii) **Flow after high flood**: In some rivers of Terai plains, there is a noticeable lack of flow after 2-3 hours of a high flood event.

5. Embankments and spurs

(i) **Lack of embankments**: Many small rivers do not have any embankments at all.

(ii) **Discontinuity of embankments**: Even in rivers that do have embankments, these structures are often not continuous, leaving sections vulnerable to flooding.

(iii) **Side-cutting issues**: In areas with earthen embankments, side-cutting problems are common, weakening the integrity of the embankments.

(iv) **Insufficient spurs**: The number of spurs is often inadequate to effectively divert the flow of the river.

(v) **Damaged or missing spurs**: In some locations, spurs have either been damaged or washed away, further compromising the ability to control the flow.

6. Early warning system and awareness about flood disaster

(i) **Absence of an early warning system**: In nearly all the visited areas, there was a noticeable lack of an effective early warning system to alert residents about upcoming floods.

(i) **Lack of flood preparedness awareness**: The absence of proper awareness and preparedness for floods has resulted in significant loss of human and animal lives, as well as widespread property damage.

7. Socio-economic impacts

(i) **Agricultural Land Loss and Degradation**:

- **Sideward seepage** of river water into adjacent agricultural land leads to waterlogging, making the land unsuitable for farming.
- **Bank cutting** in areas without embankments results in annual losses of agricultural land.
- **Breaching of embankments** can flood agricultural areas, reducing land value and causing crop damage.

(ii) **River Shifting and Associated Issues:**

- **River shifting** is common in plains, with rivers changing their course and flowing through private land, leading to the loss of agricultural land. Landowners pay taxes on these areas, hoping for compensation or the river to shift elsewhere.
- **River shifting** also damages homes, forcing people to migrate, creating social and economic challenges.
- **Infrastructure damage**: River shifting and bank cutting damage infrastructure such as electric poles, transmission lines, roads, and bridges.

(iii) **Urban and Rural Flooding Impacts:**

- **Inadequate drainage systems** in urban areas cause floodwater to enter settlements and commercial areas, leading to significant financial losses.
- In **rural areas**, floods damage basic livelihood materials, including clothes, food, cattle sheds, and poultry. Floods also kill fish in fish ponds.

(iv) **Psychological Stress:**

- People living in flood-prone areas experience constant psychological stress, especially during the flood season.

8. Social harmony

(i) Community Harmony and Infrastructure Development:

- The lack of community harmony has hindered efforts to construct or expand drains to effectively manage floodwater. This has led to widespread inundation in affected areas.

(ii) Relocation and Housing Efforts:

- In some locations, community or local government-led initiatives have involved shifting people to higher ground and constructing houses for those affected by floods. This helps mitigate the immediate impacts of flooding but requires continued support and planning.

5.10.3 Local People's Perception of Hydro-climatic Phenomena

Here is a summary of the key points shared by local people regarding hydro-climatic changes:

1. **Rainfall and Floods**: Rainfall is identified as the primary cause of floods in the region.
2. **Changes in Rainfall Characteristics**: Rainfall patterns have drastically changed in recent years compared to 20-25 years ago:
   - Rain is no longer continuous for extended periods (7-10 days) as it used to be in the past.
   - High rainfall events are no longer restricted to the monsoon season.

- The intensity of rainfall has significantly increased in recent years.
- Rainfall is localized, with some areas receiving rainfall while nearby locations (even 2-3 km away) remain dry.
- Total annual rainfall has decreased in recent years compared to the past.

3. **Increased Temperatures**: Temperatures and the consequent hotness have risen drastically over the past 20-25 years.
4. **Floods Outside Monsoon**: Flooding is no longer confined to the monsoon period. Flood events can occur at any time of the year, though there were mixed opinions regarding changes in the frequency of floods over the years.
5. **Climate Change Perception**: Many respondents attributed these observed changes in hydro-climatic phenomena to climate change.

CHAPTER 6: LOW FLOW ANALYSIS

Water supply that may be for drinking or irrigation or hydropower generation requires the quantification of low flows of different return periods for its optimal management. In this chapter, low flow frequency analysis of instantaneous minimum flow is carried out. Log Pearson Type III (LP III) distribution was fitted to the flow series for low flow frequency analysis in this study.

6.1 Low Flow Frequency Analysis

6.1.1 Low Flow Magnitude Estimation

The procedure used to estimate the low flow discharge of a given return period is as follows:

(i) The given flow data series is converted into their logarithms as given by **Equation (6-1)**.

$$q_i = logQ_i \tag{6-1}$$

(ii) The mean ($\bar{q}$), standard deviation (q_s) and the skewness coefficient (g) series are estimated.

(iii) For the given return period (T) and skewness coefficient, the value of frequency factor is selected from the table of frequency factor made for LP III distribution. It can be found in any standard textbook of hydrology (e.g. Reddi, 2001).

(iv) The logarithm of the low flow corresponding to the given T is calculated using **Equation (6-2)**.

$$q_T = \bar{q} + K_T . q_s \tag{6-2}$$

(v) The low flow magnitude corresponding to a given return period is calculated by **Equation (6-3)**.

$$Q_T = antilog(q_{T)} = 10^{q_T} \tag{6-3}$$

A sample calculation made for Instantaneous Low Flow (ILF) at Karnali-Chisapani gauging station is presented in **Table 6-1.**

Table 6-1 Sample low flow estimation for different return period

Return Period (T-years)	Frequency Factor (K_T)	q_T	Flood (Q_T) (m^3/s)
2	0.157	2.369	234
5	-0.759	2.295	197
10	-1.325	2.249	178
25	-2.022	2.193	156
50	-2.528	2.152	142
100	-3.022	2.112	129

$\bar{q}$= 2.356, q_s= 0.081, and g= -0.161

The low flow statistics (mean and standard deviation) of Class A and Class B rivers were calculated for ILFs of selected 41 stations. Flood magnitudes were estimated using **Equations (6-3)** for the return periods of 2, 5, 10, 25, 50 and 100 years at these stations. The estimated low flow magnitudes of all selected stations are given in **Table 6-2**.

The 2-, 5-, 10-, 25-, 50-, and 100-year low flows of three major Class A rivers are as follows: Koshi at Chatara has flows of 273, 234, 214, 193, 180, and 169 m^3/s; Gandaki at Devghat has flows of 206, 176, 164, 153, 147, and 142 m^3/s; and Karnali at Chisapani has flows of 234, 197, 178, 156, 142, and 130 m^3/s, respectively (**Table 6-2**)**.** The flow at Chatara is the highest among these three locations. Except for the 50- and 100-year flows, the Gandaki basin's flows are lower than those of the Karnali. In general, the larger the catchment area, the greater the low flow. However, the flow per unit basin area follows the opposite trend for all return periods: the highest flow occurs at Devghat, while the lowest is at Chatara. Groundwater and snowmelt contributions are primarily responsible for the low flow in these rivers. The low flows per unit catchment area in Class B rivers (Pandherodovan of Bagmati, Kusum of West Rapti, and Chepang of Babai) are therefore lower than those in Class A rivers, as there is no snowmelt contribution to the dry season flow in these rivers. However, at Mainachuli of the Kankai River, the minimum flow per unit catchment area is higher than at Chisapani and Chatara. No hydro-climatic reason can be identified to explain this result. We suspect this anomaly may be due to the quality of the observed flow data.

The flows per unit catchment area are lower at the most downstream locations—i.e., at Chatara on the Koshi, Devghat on the Gandaki, and Chisapani on the Karnali—compared to the respective averages of all sub-basins within these basins. This highlights the importance of snow cover for lean period flows.

Table 6-2 Minimum flow of different return periods at various gauging sites

Unit: m^3/s

SN	Station	River	Location	n	Average	Std_Dev	Q_2	Q_5	Q_{10}	Q_{25}	Q_{50}	Q_{100}
1	120	Chamelia	Nayalbadi	38	15.9	3.5	17.2	13.3	10.7	7.6	5.8	4.3
2	215	Humla Karnali	Tholtada	38	67.3	11.1	67.0	57.8	53.4	48.7	45.8	43.2
3	220	Tila Nala	Nagma	39	12.4	1.5	12.4	11.1	10.5	9.8	9.4	9.0
4	225	Sinja Khola	Diware	34	4.2	1.1	4.2	3.2	2.7	2.2	1.9	1.7
5	240	Karnali River	Asara Ghat	39	106.2	11.2	105.7	96.7	92.3	87.7	84.8	82.2
6	250	Karnali River	Benighat	34	123.1	12.0	124.8	113.6	107.0	99.2	93.9	88.9
7	260	Seti River	Banga near Belgaon	40	58.6	7.9	59.5	52.1	47.9	43.1	39.8	36.9
8	265	Thulo Bheri	Rimna	38	26.8	9.1	26.5	18.5	14.9	11.4	9.4	7.8
9	270	Bheri River	Jamu	31	73.8	15.0	76.6	61.8	53.1	43.4	37.2	31.8
10	280	Karnali	Chisapani	40	230.9	40.6	233.9	197.3	177.6	156.0	141.9	129.5
11	286	Sarada Khola	Daradhunga	36	1.2	0.5	1.1	0.8	0.6	0.5	0.4	0.4
12	289.95	Babai	Chepang	28	4.7	2.0	4.4	2.9	2.3	1.7	1.4	1.2
13	330	Mari Khola	Nayagaon	40	6.9	1.9	6.7	5.2	4.5	3.9	3.5	3.1
14	350	Rapti River	Bagasoti Gaon	39	8.4	2.9	8.1	5.8	4.8	3.8	3.3	2.8
15	360	Rapti River	Jalkundi	40	6.4	3.5	5.9	3.3	2.3	1.5	1.1	0.8
16	375	Rapti	Kusum	17	6.0	3.1	5.7	3.3	2.3	1.5	1.1	0.8
17	404.7	Myagdi Khola	Mangla Ghat	35	10.0	2.0	9.8	8.4	7.7	7.1	6.8	6.5
18	420	Kali Gandaki	Kotagaon Shringe	38	66.0	13.9	63.8	54.5	50.6	46.9	44.8	43.0
19	428	Mardi Khola	Lahachok	35	1.7	0.7	1.9	1.1	0.7	0.4	0.2	0.1
20	438	Madi River	Shisa Ghat	36	12.4	2.8	12.3	10.0	8.8	7.6	6.9	6.3
21	440	Chepe Khola	Garam Besi	39	3.3	0.9	3.3	2.5	2.2	1.8	1.6	1.4
22	445	Burhi Gandaki	Arughat	38	25.9	4.3	25.2	22.3	21.1	20.0	19.4	18.8
23	447	Trishuli	Betrawati	35	38.0	4.7	37.7	34.0	32.2	30.4	29.2	28.2

SN	Station	River	Location	n	Average	Std_Dev	Q_2	Q_5	Q_{10}	Q_{25}	Q_{50}	Q_{100}
24	448	Tadi Khola	Tadipul Belkot	40	2.5	1.3	2.4	1.3	0.9	0.6	0.4	0.3
25	450	Gandaki	Devghat	40	214.8	47.8	205.9	175.9	164.0	153.1	146.9	141.8
26	460	Rapti River	Rajaiya	30	4.0	1.6	3.7	2.6	2.1	1.7	1.4	1.2
27	505	Bagmati River	Sundarijal	35	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1
28	589	Bagmati River	Pandhera Dobhan	30	9.6	3.0	9.1	7.0	6.1	5.3	4.8	4.4
29	602	Sabhaya Khola	Tumlingtar	39	3.8	0.9	3.9	3.0	2.6	2.2	1.9	1.6
30	602.5	Hinwa Khola	Pipletar	34	1.0	0.3	0.9	0.7	0.5	0.4	0.4	0.3
31	604.5	Arun River	Turkeghat	40	86.1	11.8	85.0	76.1	72.1	68.1	65.7	63.6
32	606	Arun River	Simle	32	158.7	35.8	154.8	128.1	116.2	104.6	97.5	91.6
33	620	Balephi Khola	Jalbire	38	9.5	2.2	9.5	7.6	6.7	5.8	5.2	4.7
34	630	Sun Kosi	Pachuwar Ghat	38	41.3	11.1	38.8	32.6	30.3	28.3	27.2	26.4
35	647	Tamakosi	Busti	31	22.3	2.5	21.9	20.2	19.4	18.7	18.2	17.9
36	650	Khimti Khola	Rasnalu Village	36	3.6	1.0	3.5	2.7	2.3	2.0	1.8	1.6
37	652	Sunkosi	Khurkot	32	71.2	11.3	71.3	61.6	56.7	51.5	48.1	45.2
38	670	Dudh Kosi	Rabuwa Bazar	38	26.1	9.0	26.2	17.9	14.0	10.3	8.3	6.6
39	690	Tamur River	Mulghat	38	42.2	15.6	42.7	27.6	20.7	14.3	10.9	8.2
40	695	Sapta Koshi	Chatara-Kothu	29	273.0	46.2	272.8	233.6	214.1	193.4	180.2	168.5
41	795	Kankai Mai River	Mainachuli	32	7.6	1.5	7.5	6.3	5.7	5.2	4.8	4.5

Note: n= Number of data points, Qx = Low flow of return period x year

6.2 Occurrence Timing of Instantaneous Minimum Flows

Month wise distribution of instantaneous minimum flows (total number of data: 1,459) of selected 41 stations is shown in **Figure 6-1** and given in **Table 6-3**. From these table and figure, we can observe that almost all of these flows in Class A rivers (i.e., > 99%) occurred during the non-monsoon season, as expected. However, in the Class B River system, the pattern is mixed. In Kankai, 100% of such flows occurred during the non-monsoon season, while in Bagmati it was 91%, in West Rapti 62%, and in Babai 48%. Most of the instantaneous low flows (ILF) occurred in February, March, and April (average: 88%, range: 84–92% for Class A rivers). Additionally, it was found that the highest number of these low flows in Class A rivers occurred in March. However, this was not the case for Class B rivers. In Kankai and Bagmati, the peak occurred in April, while in West Rapti, it occurred in May. For the Babai River, it was found to occur in June.

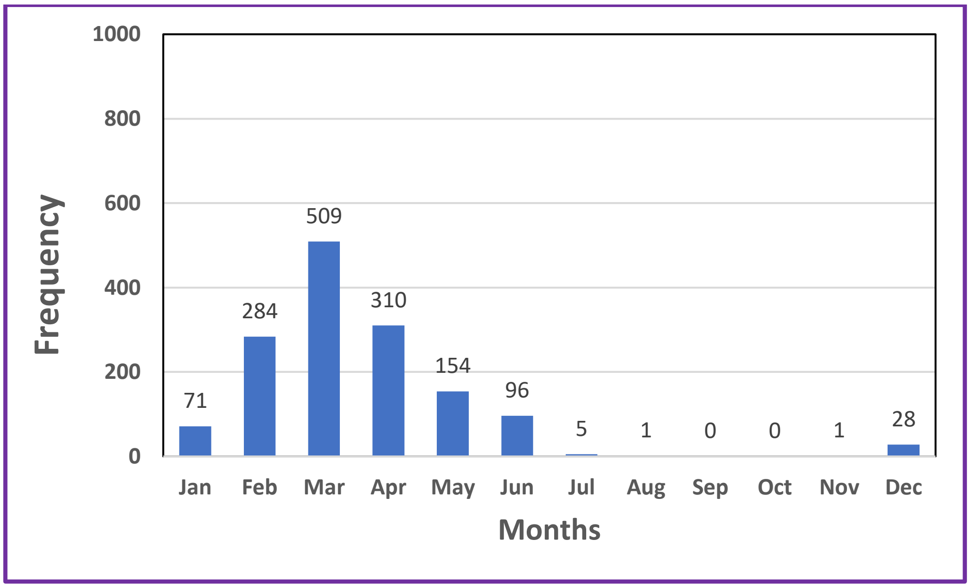


Figure 6-1 Occurrence timing of instantaneous low flows

Table 6-3 Distribution of occurrence of low flows events in different river basins

Month	Total Frequency	Koshi	Gandaki	Karnali	Mahakali	Kankai	Bagmati	West Rapti	Babai
Jan	71	30	8	28	2	0	2	0	1
Feb	284	68	72	123	16	2	3	0	0
Mar	**509**	**178**	**143**	**137**	**18**	12	13	4	4
Apr	310	119	94	35	1	**15**	**31**	9	6
May	154	10	38	3	0	3	9	**71**	20
Jun	96	3	4	2	0	0	6	51	**30**
Jul	5	0	1	0	0	0	0	1	3
Aug	1	0	1	0	0	0	0	0	0
Sep	0	0	0	0	0	0	0	0	0
Oct	0	0	0	0	0	0	0	0	0
Nov	1	1	0	0	0	0	0	0	0
Dec	28	16	5	5	1	0	1	0	0
Total	1459	425	366	333	38	32	65	136	64

Table 6-4 presents the basin-wise distribution of past instantaneous low flow (ILF) events that occurred on a single day. Similarly, the locations of occurrence of ILF on the same day of all 41 selected stations were depicted in **Figure 6-2**. In both the table and figure, only the ILF events that occurred in at least four of the 41 locations on the same day are presented. These events occurred at most in 6 locations on a single day. It is natural that there is a higher probability of high flows occurring on the same day if heavy rainfall affects many areas on that day. Since groundwater contribution is more significant in the case of low flows—depending on the geology of the groundwater-contributing areas—there is a lower probability of experiencing low flows on the same day across multiple locations.

Table 6-4 Basin wise distribution of past ILF events that occurred on a single day

Basins	Mahkali	Karnali	Babai	West Rapti	Gandaki	Bagmati	Koshi	Kankai	Nepal
Total Basins No./ Date	1	9	2	4	10	2	12	1	41
1981-3-15		3			1		2		6
1985-3-22	1	4							5
1996-2-18	1	3			1				5
1996-4-15					1	1	2	1	5
1997-3-26		2				1	1	1	5
1998-2-23		4			1				5
2000-3-22		2			2		1		5
1981-3-13					2	1	1		4
1986-3-4		2			2				4
1995-3-16		3	1						4
1996-2-24		2			1		1		4
1997-3-27		2			2				4
1997-3-28		1			2		1		4
1999-3-15		1			1	1	1		4
2003-2-16		4							4
2004-3-31	1				2		1		4
2006-3-8	1				1		2		4
2007-2-2		2			2				4
2008-3-31		2			1			1	4
2013-1-17		4							4
2017-3-9		1					3		4
2018-3-26							4		4

Basins	M	Karnali									Babai		West Rapti				Gandaki										Bagm		Koshi												K	
Year	120	215	220	225	240	250	260	265	270	280	286	289.95	330	350	360	375	404.7	420	428	438	440	445	447	448	450	460	505	589	602	602.5	604.5	606	620	630	647	650	652	670	690	695	795	Total
1981-3-15				*		*	*																		*										*		*					6
1985-3-22	*				*	*	*		*																																	5
1996-2-18	*		*		*	*																	*																			5
1996-4-15																		*										*		*						*					*	5
1997-3-26		*				*																						*					*								*	5
1998-2-23			*		*	*			*											*																						5
2000-3-22				*					*														*	*										*								5
1981-3-13																				*				*				*												*		4
1986-3-4						*	*															*	*																			4
1995-3-16					*	*				*		*																														4
1996-2-24							*			*												*											*									4
1997-3-27			*		*													*					*																			4
1997-3-28										*														*	*															*		4
1999-3-15		*																						*			*										*					4
2003-2-16					*		*		*	*																																4
2004-3-31	*																	*		*																	*					4
2006-3-8	*																*																*				*					4
2007-2-2						*	*												*			*																				4
2008-3-31			*	*																*																					*	4
2013-1-17			*		*		*			*																																4
2017-3-9										*																										*	*			*		4
2018-3-26																																	*	*	*					*		4

Figure 6-2 Spatial distribution of occurrences of past ILF events in a single day

6.3 Temporal Trend of Instantaneous Minimum Flows

Temporal trend on the instantaneous minimum flows was assessed by calculating the deviation percentage as in the case of IMFs from the average of the ILF series for each basin. The deviation of ILFs of Koshi, Gandaki and Karnali basin/sub-basins are plotted in **Figure 6-3**, **Figure 6-4** and **Figure 6-5** respectively. From these figures, no specific trend is observed in these basins. The decadal average deviation percentage of ILFs of major river basins are given in **Table 6-5**. The statistics of this table also show no trend.

In **Figure 6-6**, occurrence frequencies of bottom ten low flows from 1980 to 2019 of all over the country is depicted. It shows slight increase in low flows in recent years. In **Figure 6-7**, frequencies of occurrence of bottom 10 low flows in Koshi, Gandaki and Karnali basins are shown. From these figures, clustering of these low flows during a particular period of time are not seen. It implies that there is no clear observable temporal trend in the low flows in the rivers of Nepal.

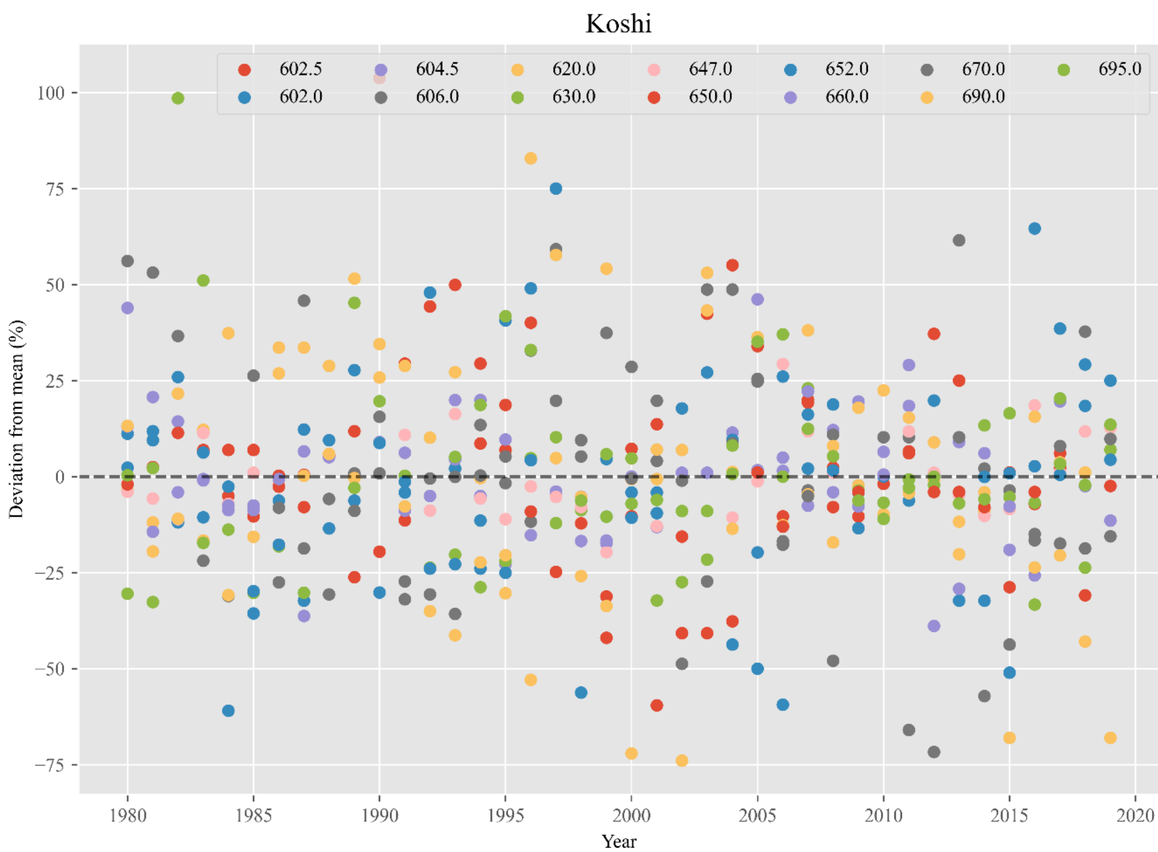


Figure 6-3 Deviation of instantaneous low flows from the average-Koshi Basin

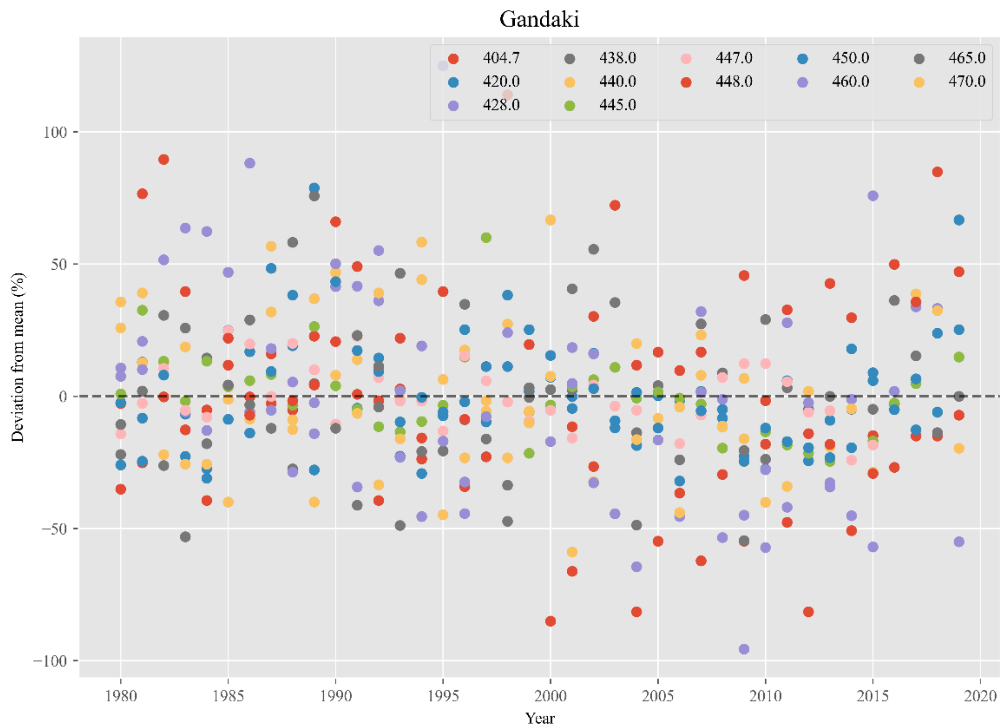


Figure 6-4 Deviation of instantaneous low flows from the average-Gandaki Basin

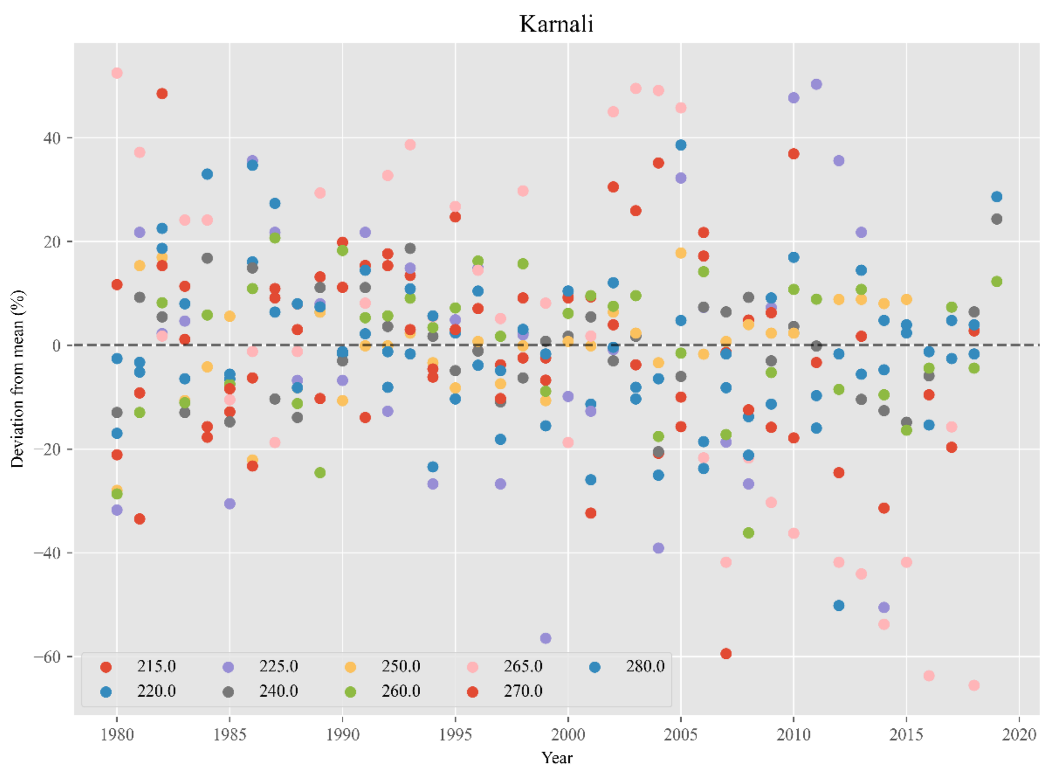


Figure 6-5 Deviation of instantaneous low flows from the average-Karnali Basin

Table 6-5 Decadal average deviation percentage of ILFs of major river basins

Decade	Mahakali	Karnali	Babai	West Rapti	Gandaki	Bagmati	Koshi	Kankai
1980-1989	7.4	2.4	13.7	4.9	8.6	-5.2	0.5	-6.4
1990-1999	5.9	2.1	0.5	1.1	4.5	4.1	3.7	-0.1
2000-2009	8.5	-1.1	3.7	3.9	-10.4	12.1	-1.3	6.2
2010-2019	-23.4	0.6	-13.0	-9.5	-5.1	-18.2	-4.0	1.0

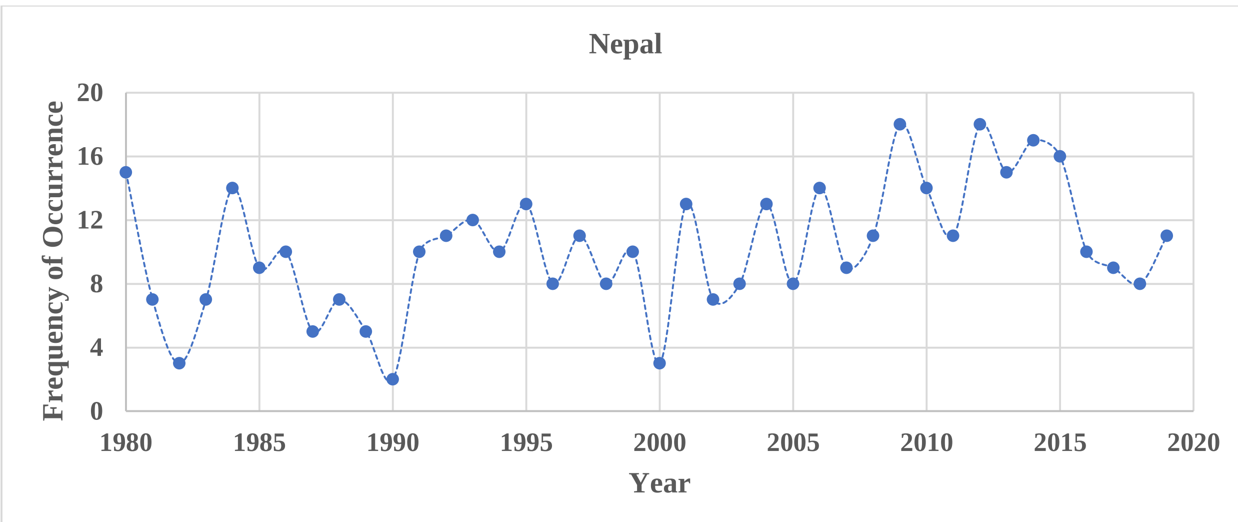


Figure 6-6 Occurrences of bottom ten instantaneous minimum flows for Nepal

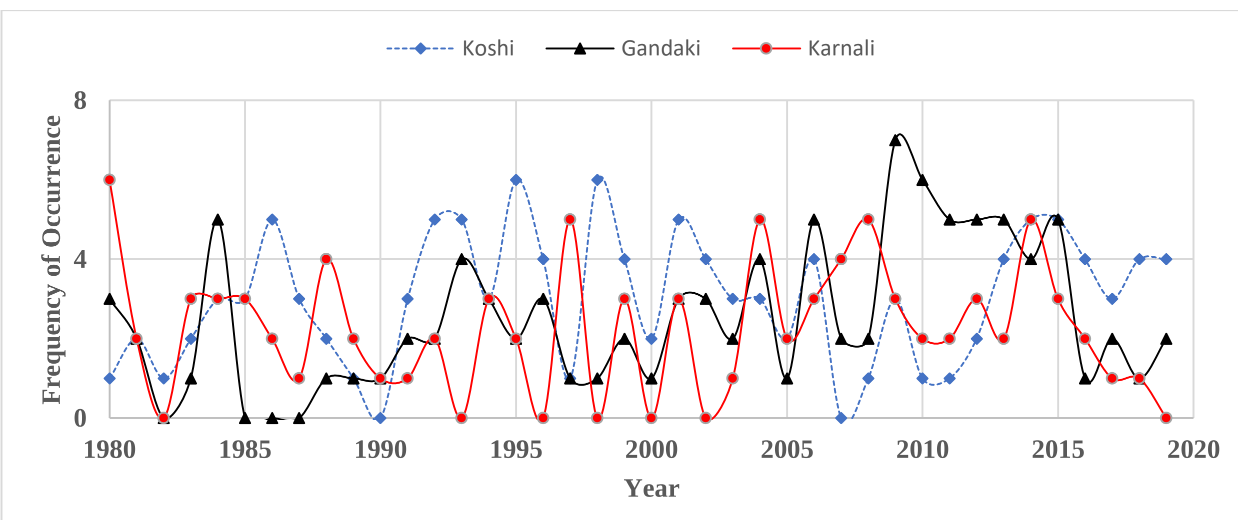


Figure 6-7 Occurrences of bottom ten instantaneous ILF in Koshi, Gandaki and Karnali Basins

6.4 Low Flows and Associated Climate

The bottom five instantaneous low flow (ILF) of eight river basins were extracted from the instantaneous minimum flow data series. For each low flow event, the monthly average precipitation on the month of occurrence of ILF (Month: 0) and preceding five months (Month: 1 refers to one month before the month of occurrence of ILF to Month: 5 refers to five months before the month of occurrence of ILF) were calculated taking arithmetic average of the rainfall occurring in the selected rain-gauge stations within the basin. It is to be mentioned here that instead of using daily rainfall, monthly averages were used in this case because of two reasons: (i) rainfall during the day and a few days before the instantaneous low flows are very insignificant (close to zero in most of the cases) and (ii) low flows are mainly attributed to snowmelt and groundwater flow in case of Class A rivers and groundwater in case of Class B rivers.

The cumulative precipitation up to three months were calculated for all the five low flow events of each basin to assess if the rainfall of preceding months contributes to the low flow of the given month. Maximum values of such cumulative precipitation were marked and the ratio of cumulative precipitations of each flood event to the corresponding maximum cumulative precipitation was calculated. Based on these ratios, the ranking of cumulative precipitation was done to explore if magnitude of the precipitation is in the same order as the magnitude of low flows. In the following paragraphs, ILF and associated climate are discussed in brief for each of the eight basins of Nepal. Although, temperature and precipitation are two major climatic components, only precipitation had been considered hereunder as in the case of IMF.

1. Koshi Basin

Bottom five ILF occurred in the past at Chatara of Koshi River and the monthly average precipitation, cumulative precipitation of monthly averages and rank of precipitation are given in **Table 6-6**. Rank of IFL and precipitation are not matching in this basin. It implies that in addition to precipitation, other parameters like temperature, vegetation, soil condition of the basin may play important role in flow phenomena of the basin.

2. Gandaki Basin

Bottom five ILF occurred in the past at Devghat of Gandaki River and the monthly average precipitation, cumulative precipitation of monthly averages and rank of precipitation are given in **Table 6-7**. Rank of IFL and precipitation are not matching in this basin similar to Koshi basin.

Table 6-6 Bottom five ILF occurred in the past at Chatara of Koshi River

Rank of ILF	Date	IFL (m^3/s)	Month Before IFL	Monthly P_{avg} (mm)	Cumulative Monthly P ($\sum P_{avg}$, mm)	$\frac{\sum P_{avg}}{\sum P_{avg-max}}$	Rank of $\sum P_{avg}$
1	4/14/2016	182	0	10	10	0.89	3
			1	39	50	0.76	4
			2	11	61	0.69	4
2	3/28/2001	185	0	11	11	1	5
			1	21	32	0.49	3
			2	7	39	0.44	2
3	3/3/2002	198	0	2	2	0.14	1
			1	17	19	0.29	1
			2	33	52	0.59	3
4	3/11/2003	214	0	2	2	0.21	2
			1	63	66	1	5
			2	23	89	1	5
5	2/25/1983	226	0	11	11	0.94	4
			1	21	32	0.48	2
			2	3	34	0.39	1

Table 6-7 Bottom five ILF occurred in the past at Devghat of Gandaki River

Rank of ILF	Date	IFL (m^3/s)	Month Before IFL	Monthly P_{avg} (mm)	Cumulative Monthly P ($\sum P_{avg}$, mm)	$\frac{\sum P_{avg}}{\sum P_{avg-max}}$	Rank of $\sum P_{avg}$
1	3/30/2006	146	0	65	65	1.0	5
			1	4	69	0.8	4
			2	0	69	0.8	3
2	4/14/1984	156	0	19	19	0.3	3
			1	17	36	0.4	3
			2	11	47	0.5	2
3	3/19/1980	159	0	41	41	0.6	4
			1	41	82	1.0	5
			2	8	90	1.0	5
4	3/15/1981	162	0	12	12	0.2	1
			1	12	24	0.3	2
			2	46	71	0.8	4
5	3/25/2009	162	0	13	13	0.2	2
			1	5	17	0.2	1
			2	1	19	0.2	1

3. Karnali Basin

Bottom five ILF occurred in the past at Chisapani of Karnali River and the monthly average precipitation, cumulative precipitation of monthly averages and rank of precipitation are given in **Table 6-8**. Rank of IFL and precipitation are not matching in this basin similar to Koshi basin.

Table 6-8 Bottom five ILF occurred in the past at Chisapani of Karnali River

Rank of ILF	Date	IFL (m^3/s)	Month Before IFL	Monthly P_{avg} (mm)	Cumulative Monthly P ($\sum P_{avg}$, mm)	$\frac{\sum P_{avg}}{\sum P_{avg-max}}$	Rank of $\sum P_{avg}$
1	2/15/2012	115	0	32	32	1	5
			1	56	88	1	5
			2	6	94	1	5
2	3/21/2001	171	0	13	13	0.4	3
			1	33	47	0.5	4
			2	25	71	0.8	3
3	3/10/2006	176	0	5	5	0.1	1
			1	7	12	0.1	1
			2	6	18	0.2	1
4	3/25/2008	182	0	16	16	0.5	4
			1	7	24	0.3	2
			2	27	51	0.5	2
5	3/28/1997	189	0	13	13	0.4	2
			1	16	29	0.3	3
			2	53	82	0.9	4

4. Chamelia Basin

Bottom five ILF occurred in the past at Nayalbadhi of Chamelia River and the monthly average precipitation, cumulative precipitation of monthly averages and rank of precipitation are given in **Table 6-9**. Rank of IFL and precipitation are not matching in this basin similar to other basins.

5. Kankai Basin

Bottom five ILF occurred in the past at Mainachuli of Kanakai river and the monthly average precipitation, cumulative precipitation of monthly averages and rank of precipitation are given in **Table 6-10**. The first IFL occurred in the month of lowest precipitation unlike other basins discussed above. However, other flows do not follow this sequence.

Table 6-9 Bottom five ILF occurred in the past at Nayalbadi of Chamelia River

Rank of ILF	Date	IFL (m^3/s)	Month Before IFL	Monthly P_{avg} (mm)	Cumulative Monthly P ($\sum P_{avg}$, mm)	$\frac{\sum P_{avg}}{\sum P_{avg-max}}$	Rank of $\sum P_{avg}$
1	12/22/17	4.34	0	15	15	1	5
			1	0	15	0.2	2
			2	24	38	0.3	4
2	1/17/19	5.14	0	1	1	0	2
			1	2	2	0	1
			2	13	15	0.1	1
3	3/9/16	10.8	0	2	2	0.1	3
			1	25	27	0.3	3
			2	8	35	0.3	3
4	3/12/11	10.9	0	9	9	0.6	4
			1	79	88	1	5
			2	28	116	1	5
5	3/17/09	13.4	0	0	0	0	1
			1	31	31	0.3	4
			2	2	33	0.3	2

Table 6-10 Bottom five ILF occurred in the past at Mainachuli of Kanakai River

Rank of ILF	Date	IFL (m^3/s)	Month Before IFL	Monthly P_{avg} (mm)	Cumulative Monthly P ($\sum P_{avg}$, mm)	$\frac{\sum P_{avg}}{\sum P_{avg-max}}$	Rank of $\sum P_{avg}$
1	4/19/94	4.46	0	7	7	0.2	1
			1	22	28	0.4	1
			2	50	79	0.9	4
2	3/20/80	5.3	0	34	34	1	5
			1	5	39	0.5	3
			2	2	41	0.5	2
3	3/29/82	5.5	0	24	24	0.7	3
			1	13	37	0.5	2
			2	0	37	0.4	1
4	5/10/85	5.83	0	28	28	0.8	4
			1	46	74	1	5
			2	13	87	1	5
5	4/10/81	6.18	0	15	15	0.4	2
			1	45	60	0.8	4
			2	10	70	0.8	3

6. **Bagmati Basin**

Bottom five ILF occurred in the past at Pandherodovan of the Bagmati River and the monthly average precipitation, cumulative precipitation of monthly averages and rank of precipitation are given in **Table 6-11**. This river's characteristics are similar to Koshi, Gandaki and Karnali basin in terms of concurrency in the rank of flow and precipitation.

Table 6-11 Bottom five ILF occurred in the past at Pandherodovan of Bagmati River

Rank of ILF	Date	IFL (m^3/s)	Month Before IFL	Monthly P_{avg} (mm)	Cumulative Monthly P ($\sum P_{avg}$, mm)	$\frac{\sum P_{avg}}{\sum P_{avg-max}}$	Rank of $\sum P_{avg}$
1	4/18/2006	4.9	0	72	72	0.7	4
			1	30	102	0.9	3
			2	0	102	0.7	2
2	4/24/1991	5.1	0	52	52	0.5	3
			1	42	94	0.8	2
			2	14	107	0.7	3
3	5/27/1982	6.25	0	50	50	0.5	2
			1	64	114	1	5
			2	44	157	1	5
4	4/30/2012	6.26	0	96	96	1	5
			1	10	107	0.9	4
			2	36	143	0.9	4
5	5/7/1995	6.65	0	0	0	0	1
			1	11	11	0.1	1
			2	35	46	0.3	1

7. **West Rapti Basin**

Bottom five ILF occurred in the past at Kusum of West Rapti River and the monthly average precipitation, cumulative precipitation of monthly averages and rank of precipitation are given in **Table 6-12**. Its characteristic is similar to that of Bagmati River.

8. **Babai Basin**

Bottom five ILF occurred in the past at Chepang of Babai River and the monthly average precipitation, cumulative precipitation of monthly averages and rank of precipitation are given in **Table 6-13**. In this river, the lowest flow occurs when the monthly precipitation is also low. However, second lowest flow and other low flows do not follow this pattern.

Table 6-12 Bottom five ILF occurred in the past at Kusum of West Rapti River

Rank of ILF	Date	IFL (m^3/s)	Month Before IFL	Monthly P_{avg} (mm)	Cumulative Monthly P ($\sum P_{avg}$, mm)	$\frac{\sum P_{avg}}{\sum P_{avg-max}}$	Rank of $\sum P_{avg}$
1	6/3/2009	1.12	0	28	28	0.4	3
			1	271	298	1	5
			2	1	299	1	5
2	6/21/2005	2.06	0	11	11	0.2	2
			1	12	24	0.1	2
			2	16	40	0.1	1
3	6/20/2019	3.19	0	56	56	0.8	4
			1	60	115	0.4	3
			2	24	140	0.5	3
4	6/5/2007	3.36	0	0	0	0	1
			1	0	0	0	1
			2	43	43	0.1	2
5	6/26/2018	3.75	0	74	74	1	5
			1	47	121	0.4	4
			2	112	234	0.8	4

Table 6-13 Bottom five ILF occurred in the past at Chepang of Babai River

Rank of ILF	Date	IFL (m^3/s)	Month Before IFL	Monthly P_{avg} (mm)	Cumulative Monthly P ($\sum P_{avg}$, mm)	$\frac{\sum P_{avg}}{\sum P_{avg-max}}$	Rank of $\sum P_{avg}$
1	6/16/1999	1.15	0	184	184	1	5
			1	182	367	1	5
			2	5	371	1	5
2	3/24/2016	1.83	0	9	9	0.1	1
			1	28	37	0.1	1
			2	9	46	0.1	1
3	5/30/1991	2.61	0	16	16	0.1	4
			1	32	48	0.1	2
			2	40	88	0.2	3
4	6/21/2005	3.01	0	12	12	0.1	2
			1	44	56	0.2	3
			2	16	72	0.2	2
5	6/8/1993	3.09	0	14	14	0.1	3
			1	87	102	0.3	4
			2	36	138	0.4	4

6.5 Concurrency between Instantaneous Maximum and Minimum Flows

The years of occurrence for the top 10 instantaneous maximum flows (IMF) and the bottom 10 minimum flows (ILF) were analyzed at the selected flow gauging stations to assess the likelihood of high and low flows (leading to floods and hydrological droughts) occurring in the same year. The ranking of floods (highest IMF) based on instantaneous flood magnitudes, along with the minimum flows of all selected gauging sites and their corresponding years of occurrence, is presented in **Appendix C (Table C-20)**. A summary of concurrency (i.e., the number of matches between these two sets for a given flow-measuring station) across the eight basins is provided in usum and Chepang respectively.

Table 6-14. Out of 410 cases, 129 matches were identified, indicating approximately a one-third probability that a wet year may also coincide with a dry year. In other words, the country faces more than a 30% likelihood of experiencing both flood disasters and drought conditions in the same year, particularly in Class A River Basins. **Figure 6-8** and **Figure 6-9** illustrate the comparison of floods and low flows at eight major locations in Class A and Class B River Basins, respectively. From these figures, the matches between top and bottom 10 flows are respectively 4, 2, 3 and 5 at Chatara, Devghat, Chisapani and Nayalbadi gauging stations and are 1, 2, 7 and 0 at Mainachuli, Pandherodovan, Kusum and Chepang respectively.

Table 6-14 Concurrency between floods and hydrological droughts

Basins	Nepal	Koshi	Gandaki	Karnali	Mahakali	Kankai	Bagmati	West Rapti	Babai
Total	410	120	100	90	10	10	20	40	20
Matches	129	40	28	33	5	1	7	12	3

6.6 Hydrological Flood and Drought Years

Based on the spatial coverage of IMF and ILF, hydrological flood and drought affected years were identified. If at least 13 gauging stations out of 41 (i.e., one third of the total selected stations) experienced top 10 floods in a single year, those years are termed as hydrological flood years. With the same criteria with bottom 10 low flows, hydrological drought years are also identified. On this basis, identified hydrological flood and drought years are presented in

Table 6-15.

The most flooded years in Nepal, in descending order, are: 1983, 2000, 1980, 2009, 2003, 1981, 1988, 2013, 1992, 1984, 1996, and 2010.

Similarly, the driest years, also in descending order, are: 2009, 2012, 2014, 2015, 1980, 2013, 1984, 2010, 2006, 2001, 1995, and 2004.

Notably, five years—1980, 1984, 2009, 2010, and 2013—are highlighted as experiencing both flood and drought conditions, as indicated in the figure.

Koshi-Chatara

Order-IMF	Year-IMF-695		Year-ILF-695	Order-ILF
1	1980		2016	1
2	2019		2001	2
3	2018		2002	3
4	2000		2003	4
5	1999		1983	5
6	2003		2010	6
7	2017		2013	7
8	2014		1998	8
9	2002		2009	9
10	2001		2014	10
Total Match	4		4	Total Match

Gandaki-Devghat

Order-IMF	Year-IMF-450		Year-ILF-450	Order-ILF
1	1999		2006	1
2	2018		1984	2
3	1986		1980	3
4	2013		1981	4
5	2001		2009	5
6	1988		2013	6
7	2007		1983	7
8	2011		2012	8
9	2003		2014	9
10	2016		2011	10
Total Match	2		2	Total Match

Karnali-Chisapani

Order-IMF	Year-IMF-280		Year-ILF-280	Order-ILF
1	1983		2012	1
2	2014		2001	2
3	2013		2006	3
4	2009		2008	4
5	1988		1997	5
6	2000		2011	6
7	2008		1999	7
8	2007		1995	8
9	1995		2003	9
10	1998		1988	10
Total Match	3		3	Total Match

Chamelia-Nayalbadi

Order-IMF	Year-IMF-120		Year-ILF-120	Order-ILF
1	2018		2017	1
2	2016		2019	2
3	2000		2016	3
4	2017		2011	4
5	2010		2009	5
6	2009		2012	6
7	2014		1987	7
8	2011		2015	8
9	1997		1985	9
10	2019		2004	10
Total Match	5		5	Total Match

Figure 6-8 Concurrence of maximum flood and minimum instataneous flows of Class A Rivers

Kankai-Mainachuli

Order-IMF	Year-IMF-795		Year-ILF-795	Order-ILF
1	1990		1994	1
2	1981		1980	2
3	2002		1982	3
4	2003		1985	4
5	1999		1981	5
6	2009		1986	6

Bagmati-Padheredovan

Order-IMF	Year-IMF-589		Year-ILF-589	Order-ILF
1	1993		2006	1
2	2002		1991	2
3	1984		1982	3
4	2004		2012	4
5	2000		1995	5
6	1990		2011	6

7	2001	1993	7	7	2005	2013	7
8	1983	1992	8	8	1982	1985	8
9	1996	1991	9	9	1999	1984	9
10	2005	2007	10	10	2010	2009	10
Total Match	1	1	Total Match	Total Match	2	2	Total Match

West Rapti-Kusum				Babai-Chepang			
Order-IMF	Year-IMF-375	Year-ILF-375	Order-ILF	Order-IMF	Year-IMF-289.95	Year-ILF-289.95	Order-ILF
1	2014	2009	1	1	2017	1999	1
2	2016	2005	2	2	2014	2016	2
3	2013	2019	3	3	1995	1991	3
4	2009	2007	4	4	2007	2005	4
5	2017	2018	5	5	1994	1993	5
6	2003	2012	6	6	2006	2012	6
7	2005	2006	7	7	2009	1997	7
8	2006	2013	8	8	1996	2001	8
9	2019	2003	9	9	1992	2008	9
10	2012	2010	10	10	2003	2010	10
Total Match	7	7	Total Match	Total Match	0	0	Total Match

Figure 6-9 Concurrence of maximum flood and minimum instataneous flows of Class B Rivers

Table 6-15 Flood and hydrological drought years

Flooded Years			Drought Years		
SN	Year	IMF-Coverage-Count	SN	Year	ILF-Coverage-Count
1	1983	21	1	2009	18
2	2000	17	2	2012	18
3	1980	16	3	2014	17
4	2009	16	4	2015	16
5	2003	15	5	1980	15
6	1981	14	6	2013	15
7	1988	14	7	1984	14
8	2013	14	8	2010	14
9	1982	13	9	2006	14
10	1984	13	10	2001	13
11	1996	13	11	1995	13
12	2010	13	12	2004	13

Note: Total Count = 41

The five driest years in Nepal include 2009, 2012, 2014, 2015, and 1980. For these years, the spatial distribution of annual and monthly rainfall anomalies has been shown in **Figure 6-10** followed by an explanation. The rainfall anomalies are computed as the percentage deviation of the precipitation sum (both monthly and annual) from their respective long-term averages.

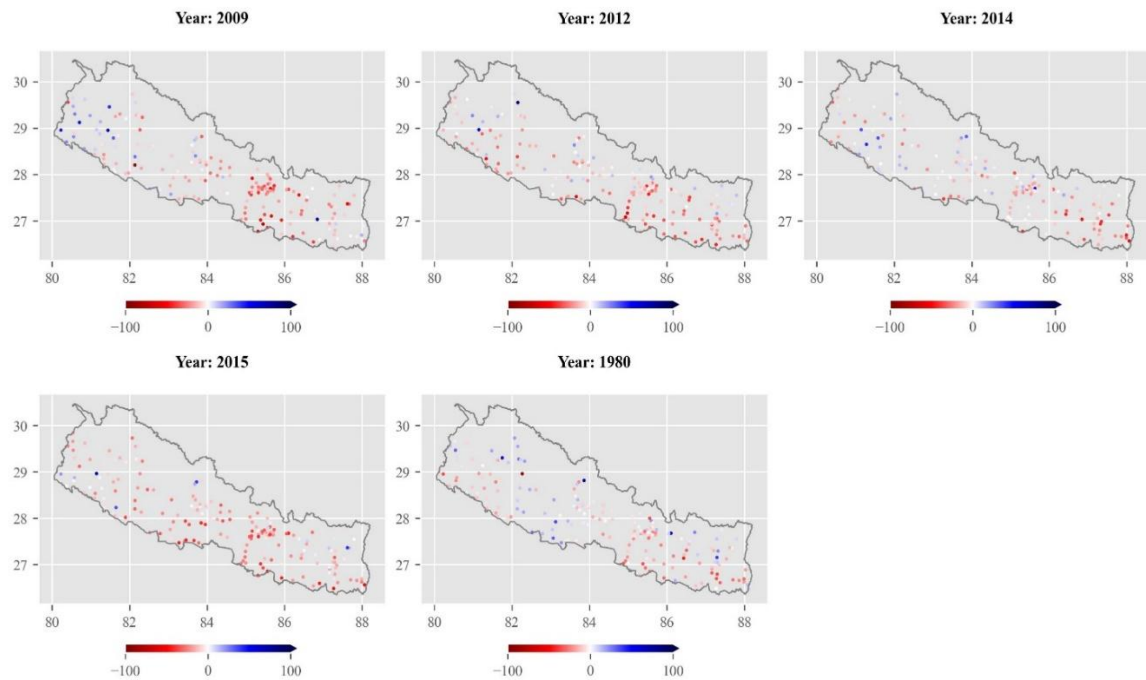


Figure 6-10 Annual rainfall anomalies for the five most dry years

Note: Rainfall anomalies are in %

Figure 6-10 shows the percentage deviation of annual precipitation from the long-term averages at different stations across the country for different years. The darker the red, the lower the precipitation than the long-term average and the darker the blue, the higher the precipitation than the long-term average. The figure shows that in those five years, the annual precipitation was less, especially in the eastern side of the country, with the western region highly drier in the year 2015. In the other four years apart from 2015, the annual precipitation is at the higher side at some stations in the western regions of the country. In central Nepal, the annual precipitation was less in 2009 and 2015 among these five years. The average change in precipitation for these years with respect to their long-term average was by -12.1%, -13.3%, -7.8%, -15.8% and -5% for the years 2009, 2012, 2014, 2015 and 1980 respectively. It is also worthy to note that in these five years, the years 2000 and 1980 were also the most flooded years, despite the decline in annual precipitation in many stations of the country, which indicates the distortion of the intra-distribution of rainfall.

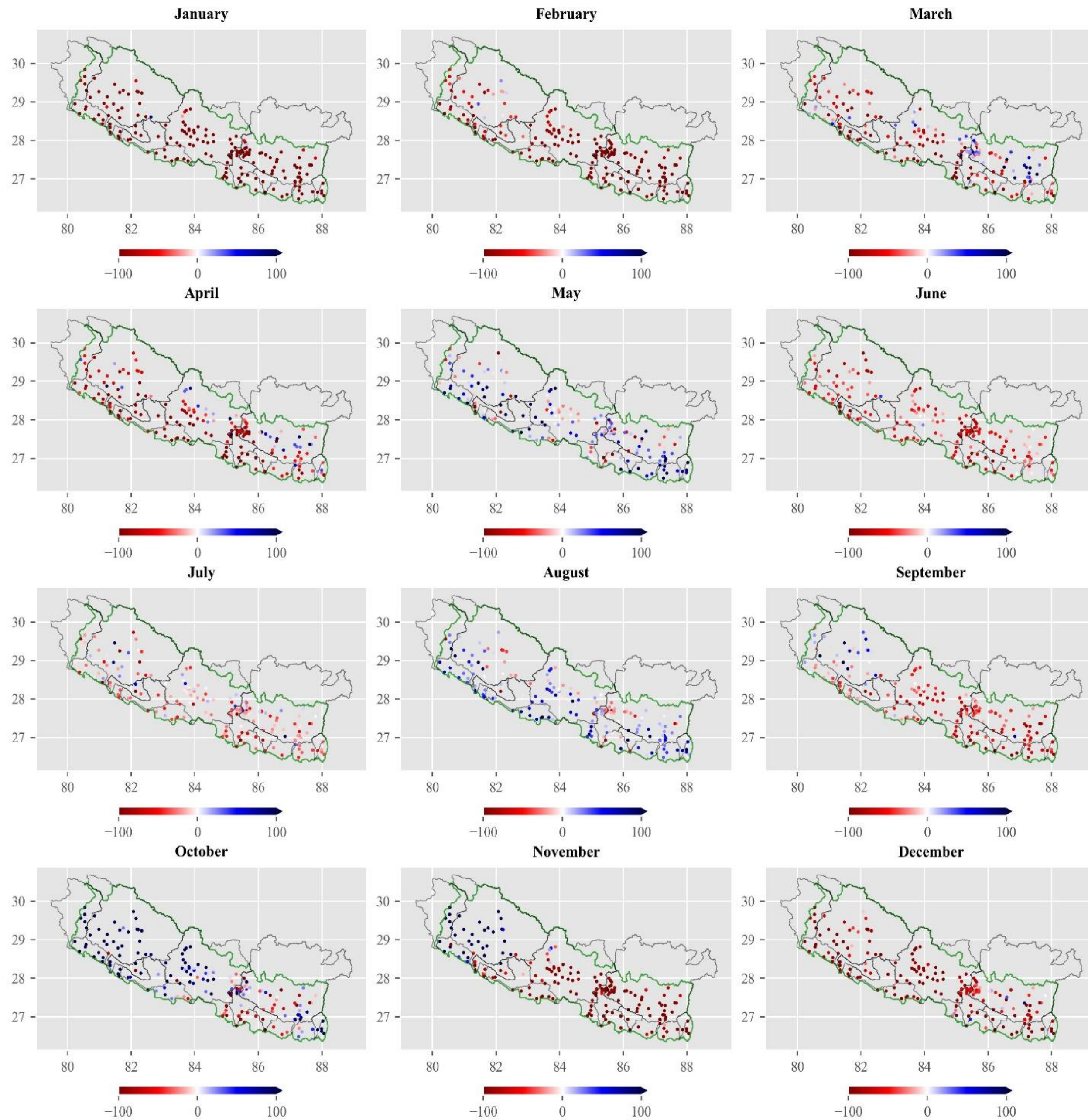
The percentage deviation of the precipitation from their long-term monthly averages for the stations across the country in 2009 is shown in the **Figure 6-11.** For the winter months (December, January, and February), there was very little rainfall in the country in comparison to the long-term averages, with no or little rainfall at most of the stations. In the months of March and April, the rainfall was higher at the stations in the eastern region of Nepal within the Koshi basin, while most of the other regions were drier than usual. In May, the rainfall was higher than average at most of the stations in the country, while the following monsoon months of June and July were relatively drier. A catastrophe struck when there was a high level of rainfall in August, with more than 48% of rainfall stations (86 out of 179) recording the August rainfall as 20% higher than their monthly averages and 21% of stations (38 out of 179) recording the August rainfall as 50% higher than the monthly average. After the heavy rainfall in August, the following months were mostly dry periods except for the relatively wet western regions of the country. This explains why flood and drought years have been the same for some years in history, as the months are typically dry but when it rains, it pours heavily.

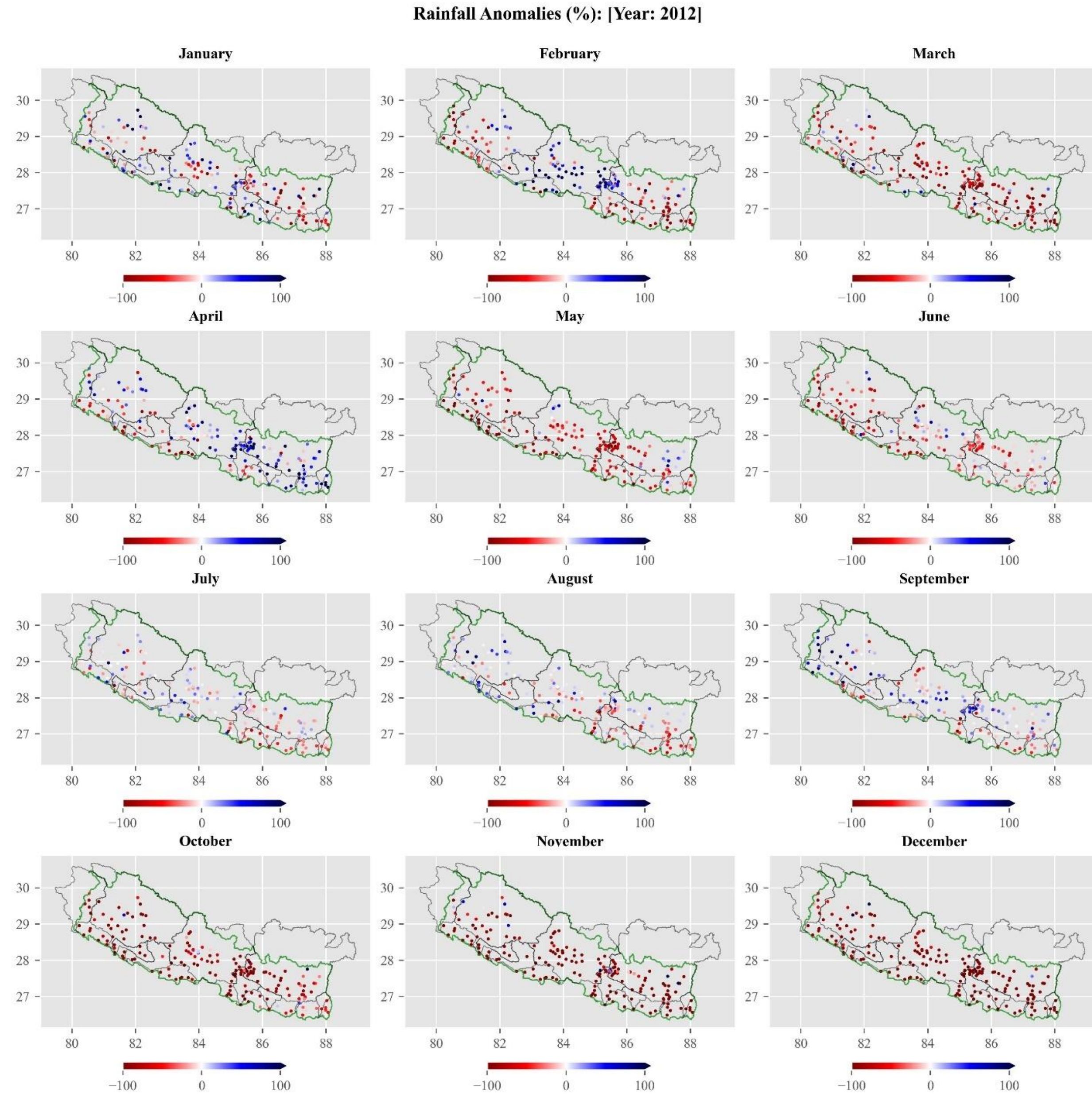
In 2012, the months of October, November, and December were drier across the country in comparison to their long-term averages, while in other months, there was mixed spatial variation in the country. In January and February, the rainfall stations in the central and western regions received rainfall higher than the averages, while the eastern Nepal was relatively drier than their mean states of rainfall. In the pre-monsoon months of March, April, and May, the precipitation was concentrated in April, with the other two months below their mean values. In the monsoon months of June, July, August, and September, the rainfall anomalies for the first three months were less in comparison to September, but the anomalies were stronger towards the positive side of change in September across the country, but excluding most of the Terai regions of the country. Except for the first two months of winter, April and September, this year received relatively lower precipitation than their averages most of the time.

The winter months of January and February of 2014 experienced the highest rainfall in the western regions, with relatively higher rainfall in the Terai belt in February. The eastern regions received less rainfall in these months. In the months of pre-monsoon, March received higher rainfall throughout various stations of the country, while the months of April and May were relatively drier. In the monsoon months, August received higher rainfall than their averages, while in other months, the rainfall was usually less across the country. However, in the months of October and December, the country received significantly higher rainfall than their mean states, while the months of November were drier relative to their long-term average.

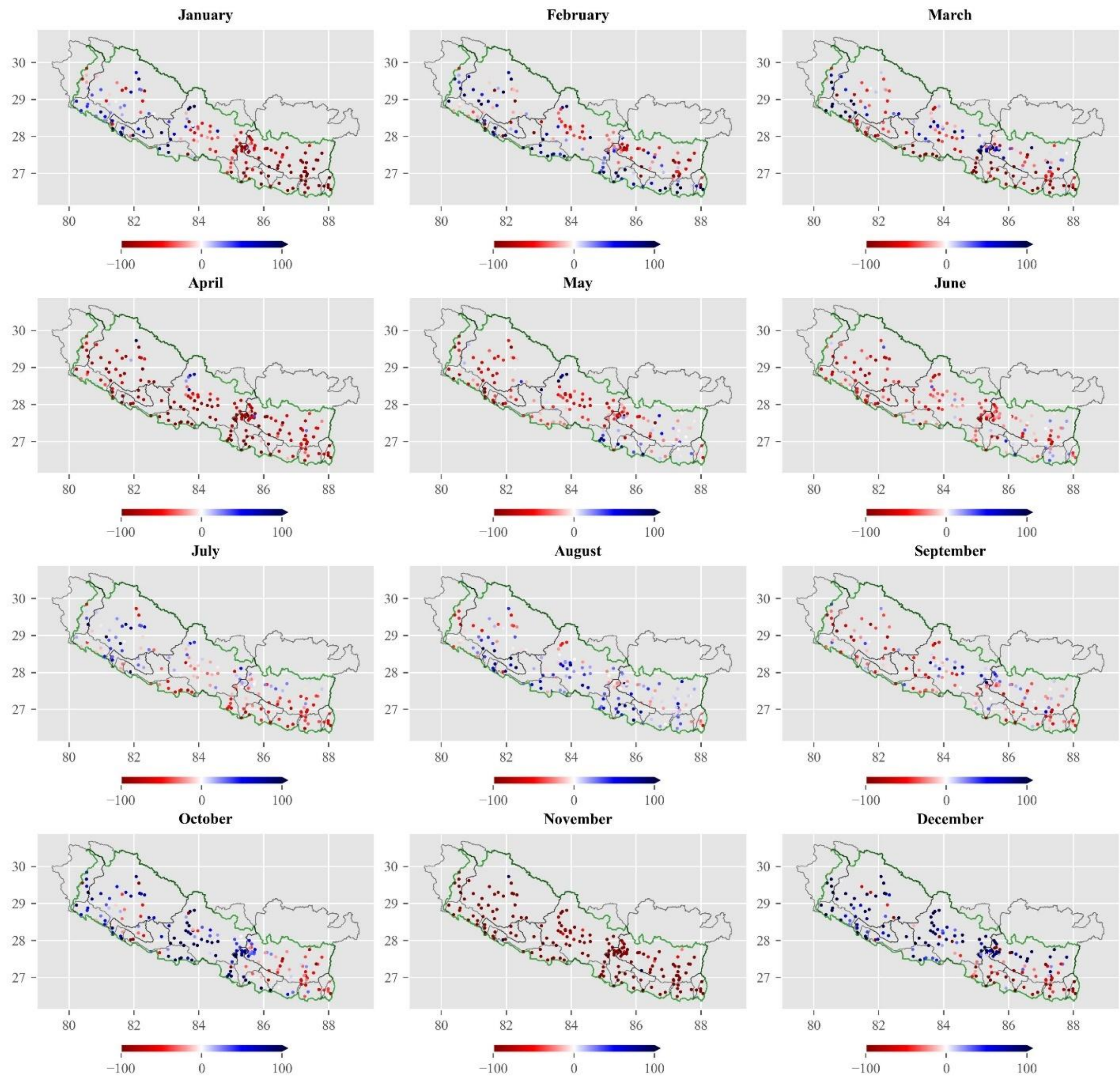
Also, the monthly variation of rainfall for other years have also been shown in the following figures which shows the similar nature of variation.

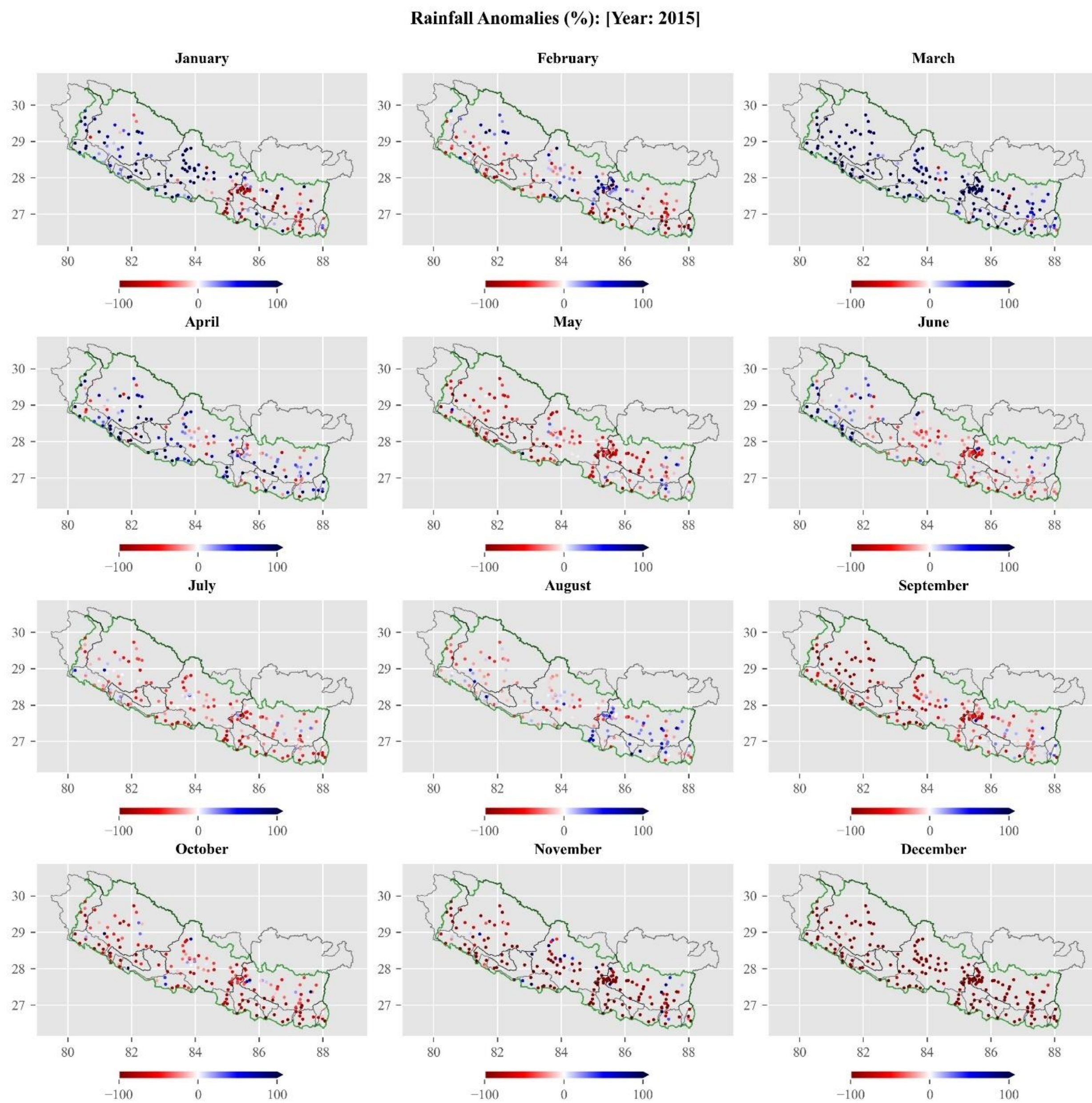
Rainfall Anomalies (%): [Year: 2009]




Rainfall Anomalies (%): [Year: 2012]
January
February
March
April
May
June
July
August
September
October
November
December
30
29
28
27
80
82
84
86
88
−100
0
100

Rainfall Anomalies (%): [Year: 2014]




Rainfall Anomalies (%): [Year: 2015]
January
February
March
April
May
June
July
August
September
October
November
December
30
29
28
27
80
82
84
86
88
−100
0
100

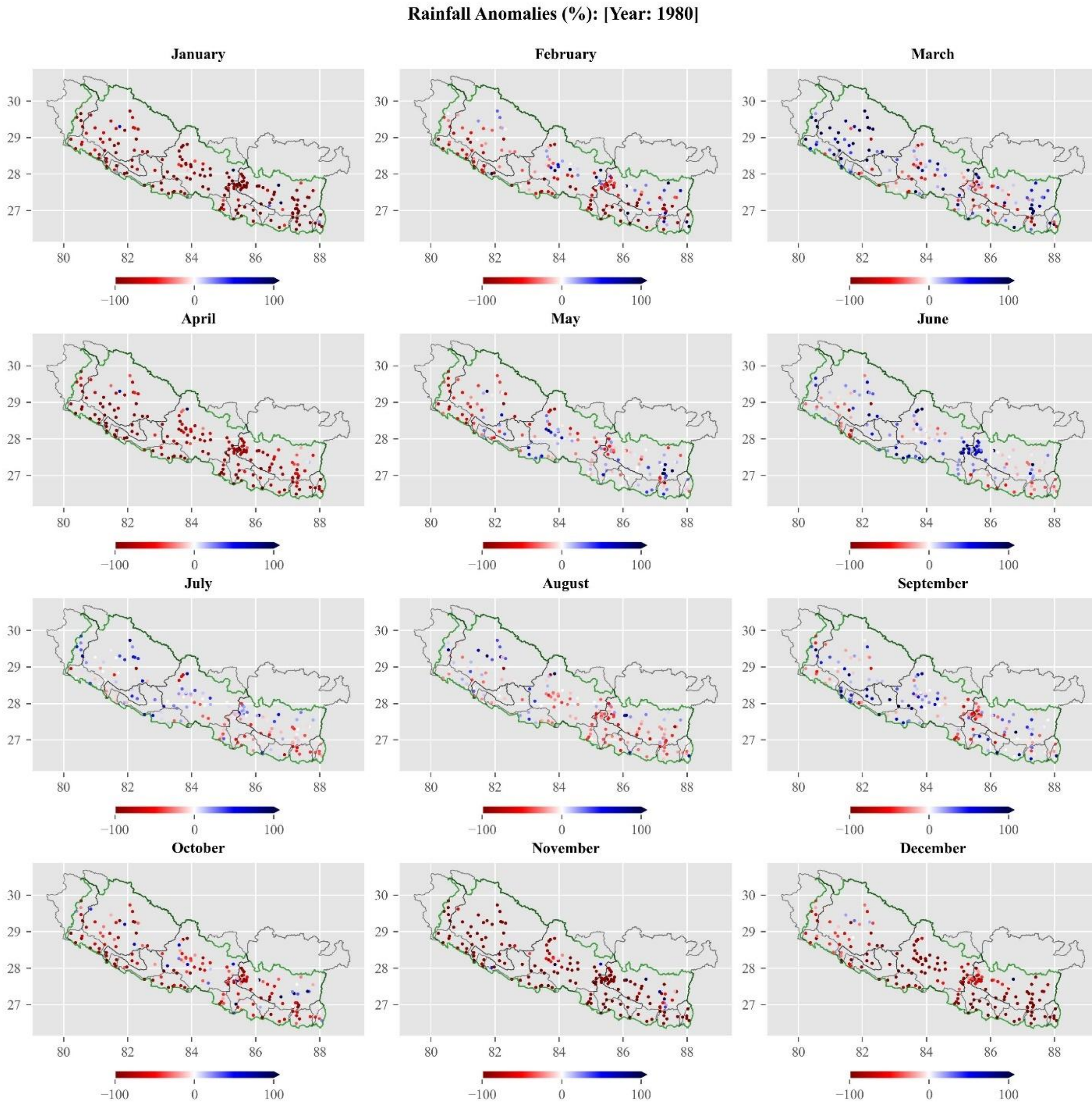


Figure 6-11 Monthly rainfall anomalies for the driest years

CHAPTER 7: DROUGHT ANALYSIS

7.1 Drought in General

Drought is a prolonged dry period in the natural climate cycle. It is a slow-onset disaster generally characterized by a lack of precipitation (WMO, 2023; WHO, 2023; National Geography, 2023). Droughts occur in virtually all climatic zones, such as high as well as low rainfall areas, and are mostly related to the reduction in the amount of precipitation received over an extended period of time (Mishra & Singh, 2010). Generally, drought frequency, severity, and duration for a given return period are used while analyzing the droughts (Wilhite and Glantz, 1987). When it occurs, drought can last for weeks, months, or years—sometimes, the effects last for decades (IRC, 2023). Over the past three decades, 1.8 billion people globally, or approximately 25 percent of humanity, have endured abnormal rainfall episodes each year, whether it was a particularly wet year or an unusually dry one (Damania et al. 2017). This variability has disproportionately impacted developing nations, with more than 85 percent of the affected people living in low- or middle-income countries (Damania et al. 2017). Drought causes a considerable hydrologic imbalance and, consequently, water shortages. Some of the key sectors that can be affected by drought are agriculture and food security, energy, water supply, health, tourism, government finances, etc.

Drought can broadly be grouped into six types, namely, Meteorological drought; Hydrological drought; Agricultural drought, Socio-economic drought, and Groundwater drought (Mishra & Singh, 2010).

i. Meteorological Drought

Meteorological drought is usually defined as a period of rainfall significantly less than the long-term average (Bordi et al., 2009). Definitions of meteorological drought must be considered region-specific since the atmospheric conditions that result in deficiencies of precipitation are highly variable from region to region (NDMC, 2023). It is one of the driving forces behind the occurrence of agricultural drought (Cao et al., 2022). Meteorological drought can be characterized on a decadal, yearly, monthly, and daily scale (Niaz et al., 2022). However, drought analysis may be challenging due to high temporal and spatial variability of precipitation, lack of monitoring stations, and other factors (Timilsina, 2021).

ii. Agricultural Drought

Agricultural drought occurs when soil moisture is depleted to the extent that crop and pasture yields are significantly affected (Li, 2021). As soil moisture is controlled by precipitation, evapotranspiration, and runoff fluxes (Sheffield & Wood, 2008), agricultural drought definition links various characteristics of meteorological drought to agricultural impacts (Cao et al., 2022).

iii. Hydrological Drought

The term hydrological drought refers to a lack of surface water and groundwater supply (Ndayiragije and Li, 2022). An abnormally low flow in rivers, as well as abnormally low water levels in lakes, reservoirs, and groundwater, are signs of a water shortage in the hydrological system. A hydrological drought is a period when a given water resource management system cannot use enough surface and groundwater water resources (Bordi et al., 2009).

iv. Groundwater Drought

Groundwater drought refers to the drop in groundwater availability that lasts for an extended period. This is attributed to the decreasing recharge over time (Goodarzi et al. 2022). Groundwater drought can occur naturally or because of human activities, but is frequently exacerbated by human activities (Thomas, 2017). Methods for monitoring and assessing groundwater droughts are based on time-series analyses of groundwater recharge or groundwater heads (Van Lanen & Peters, 2000; Li & Rodell, 2021). It is noted here that the groundwater drought is the consequence of other droughts i.e., meteorological to hydrological to agricultural droughts that impact groundwater storage.

v. Ecological Drought

Ecological drought is defined as a periodic shortage of water that drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedback in natural and/or human systems (Crausbay et al. 2017; Ndayiragije and Li, 2022). Ecological drought may be driven by natural phenomena, such as lack of rainfall or warming temperatures, and it may be exacerbated by multiple competing demands on existing limited water supply. Examples of drought impacts on ecological systems may include reduced plant growth over a season or permanently, freshwater ecosystems may change flow regimes, increased water temperature, and deteriorating water quality, which may result in the dying of fish, reduced opportunities for recreation, and decreased hydropower production.

vi. Socio-economic Drought

The socio-economic drought occurs when water resources are not enough to meet the water demand (Zhao et al., 2019). Droughts have a direct impact on domestic water supply and water-dependent economic sectors such as irrigation and hydropower production.

Drought indices are usually employed for the characterization of drought in a region (Tsakiris et al., 2007). Over the past few decades, several drought indices have been presented. The drought indices developed over time include indices such as the Effective Drought Index, Hybrid Drought Index, Keetch-Byram Drought Index, Palmer Drought Severity Index, Standard Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), Standardized Reconnaissance Drought Index (RDI), Standardized Soil Moisture Index (SMI), Standardized Streamflow Index (SSI), Deciles Index, Z-index, etc. (Palmer, 1965; Byun & Wilhite, 1999; Smakhtin & Hughes, 2004; Karamouz et al., 2009; Dikici, 2020). These drought indices can be defined for multiple time steps such as 1 month, 3 months, and 6 months, among others. Usually, the time frame is defined from 1 up to 24 months (Almeida-Ñauñay et al., 2022). However, it is challenging to ascertain the exact time step of droughts to best illustrating the drought status (Jain et al. 2015). As a general convention, negative values of drought indices signify drought conditions, while positive values indicate wetness.

7.2 General Methodology of Drought Assessment

The general methodology of drought assessment in this study is given in **Figure 7-1**. Five popularly used drought indices (SPI, SPEI, RDI, SMI, and SSI) are estimated in this study. One set of those indices (SPI, SPEI, and RDI) are based on meteorological variables viz. precipitation and temperature. These indices can, hence, be taken as meteorological drought indices. SMI is estimated from soil moisture data. As soil moisture affects agricultural productivity, SMI can be taken as an agricultural drought index. Similarly, SSI, which is estimated from river flow data, can be considered as hydrological drought index. Details of the estimation of these indices are described below.

7.2.1 Standardized Precipitation Index

Standardized Precipitation Index (SPI) was developed by McKee et al. (1993, 1995) to examine drought conditions. The long-term precipitation data for the relevant time scales can be employed to calculate SPI (Khan et al., 2008; McKee et al., 1993; Bagale et al., 2021).

SPI can determine the degree of wetness or drought in the area of interest. Depending on the time scales employed in the investigation, several SPI interpretations may be possible (Wu et al., 2001). For instance, the 1-month SPI can be used to assess recent drought conditions that may be associated with soil moisture. However, the 3-month SPI can estimate seasonal precipitation, while the 6- and 9-month SPI reveal trends at the mesoscale for precipitation. Similarly, the 12-month SPI depicts the long-term variability in precipitation (Karabulut, 2015). Various SPI durations, the phenomena they reflect, and the applications of this index have been listed in **Table 7-1**, as given by Zargar et al. (2011). Further, the SPI classification thresholds as per McKee et al. (1993) are given in **Table 7-2**. On the basis of SPI values, droughts are classified as mild, moderate, severe, and extreme droughts.

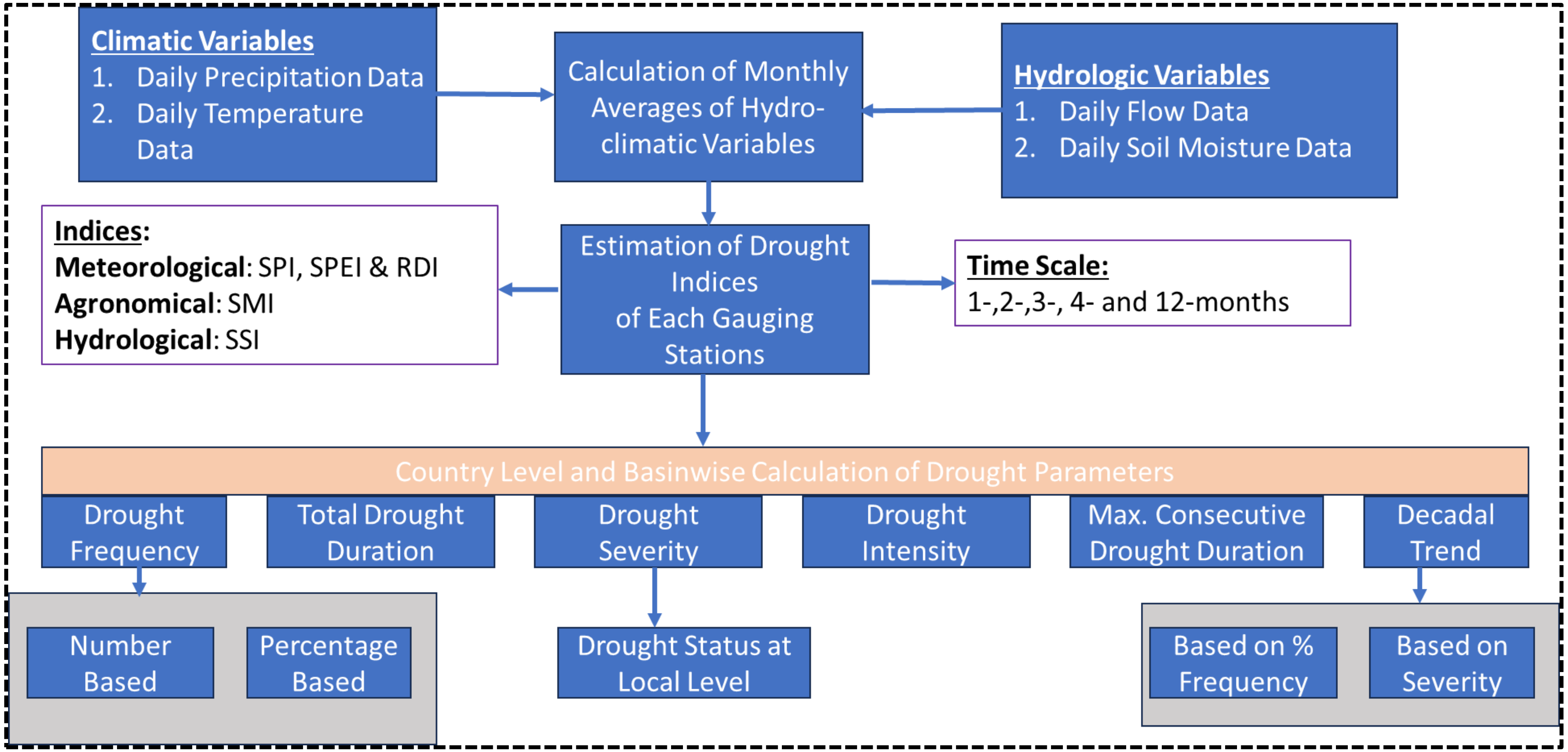


Figure 7-1 General methodology of drought assessment

Table 7-1 Phenomena reflected by specific-duration SPI and their applications

SPI duration	Phenomena reflected	Application
1-month SPI	Short-term conditions	Short-term soil moisture and crop stress (especially during the growing season)
3-month SPI	Short-term medium-term moisture conditions	A seasonal estimation of precipitation
6-month SPI	Medium-term trends in precipitation	Potential for effectively showing the precipitation over distinct seasons
9-month SPI	Precipitation patterns over a medium time scale	If $SPI_9 < -1.5$ then it is a good indication that substantial impacts can occur in agriculture (and possibly in other sectors)
12-month SPI	Long-term precipitation patterns	Possibly tied to stream flows, reservoir levels, and also groundwater levels

(Adapted from: Zargar et al., 2011)

Table 7-2 SPI classification thresholds

SPI Values	**Drought Category**
0 to -0.99	Mild Drought
-1.00 to -1.49	Moderate Drought
-1.50 to -1.99	Severe Drought
-2.00 or less	Extreme Drought

(Adapted from: McKee et al., 1993)

The following steps are followed in estimating SPI.

- Fit the prepared datasets into the Log-Logistic function to define the relationship of probability with precipitation.
- Use the probability of observed precipitation followed by the inverse normal to calculate precipitation deviation for a standard normal distribution. This value is the SPI for a particular precipitation data point as given in **Equation (7-1)**.

$$SPI = \frac{p_i - \bar{p}}{\sigma} \quad (7\text{-}1)$$

Where p_i is current rainfall, $\bar{p}$ is the long-term mean, and σ is the standard deviation of the long-term record.

Used Tools: *R* package as *SPEI* from *CRAN* (Includes both SPI and SPEI)

7.2.2 Standardized Precipitation Evapotranspiration Index

Since its inception in 2010, the Standardized Precipitation Evapotranspiration Index (SPEI) has been applied by a growing number of climatological and hydrological studies (Beguería et al., 2014). The SPEI is a variation of the WMO-recommended Standardized Precipitation Index (SPI). SPEI takes into consideration evapotranspiration effects in addition to precipitation to assess the drought severity. This index has been considered to be better for the tracking of the agricultural droughts (Yihdego et al., 2019). The classification of droughts based on this index is the same as that of SPI as shown in **Table 7-2** (Kurniasih et al., 2017).

The following steps are followed in estimating SPEI.

- Calculate the differences between precipitation (P_i) and PET for month i (D_i) and aggregate at different time scales (D_n^k) as given in **Equation (7-2a)** and **Equation (7-2b)**.

$$D_i = P_i - PET_i \tag{7-2a}$$

$$D_n^k = \sum_{i=0}^{k-1} P_{n-i} - PET_{n-i} \tag{7-2b}$$

Where, n is the calculation month, and k is the scale of aggregation.

- Fit the calculated datasets into the Log-Logistic function to define the relationship of probability with D^k series.
- Use the probability density function and the properties of Log-Logistic function to produce standardized normal values for SPEI as given in **Equation (7-3)**.

$$SPEI = W - \frac{c_0 + c_1 W + c_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3} \tag{7-3}$$

Where, $W = \sqrt{-2\ln(P)}\ for\ P \leq 0.5$

P is the probability of exceeding a determined Di value and is given as P= 1 – f(x), where f(x) is the probability density function of log-logistic function and $C_0 = 2.515517$, $C_1 = 0.802853$, $C_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$ and $d_3 = 0.001308$ are the constants.

Tools: *R* package as *SPEI* from *CRAN* (Includes both SPI and SPEI)

7.2.3 Reconnaissance Drought Index

Reconnaissance Drought Index (RDI) is based on both precipitation and potential evapotranspiration (PET). As RDI incorporates PET as a key variable, it is considered an improvement over SPI. Temperature and precipitation totals are the inputs for RDI. The drought classification based on RDI, as given by Cai et al. (2015), is listed in **Table 7-3**.

Table 7-3 RDI classification criteria

Drought Class	RDI Value		Drought Class	RDI Value
Extremely Wet	RDI ≥ 2.0		Moderate Drought	-1.5 ≤ RDI < -1.0
Very Wet	1.5 ≤ RDI < 2.0		Severe Drought	-2.0 ≤ RDI < -1.5
Moderately Wet	1.0 ≤ RDI < 1.5		Extreme Drought	RDI < -2.0
Near Normal	-1.0 ≤ RDI < 1.0			

(Adapted from: Cai et al., 2015)

The following steps are followed to calculate RDI.

- Calculate RDI using the following **Equation (7-4)** and **Equation (7-5)**.

$$RDI_{st}^{i} = \frac{y_k^i - \overline{y_k}}{\widehat{\sigma_{yk}}} \tag{7-4}$$

$$\alpha_k^i = \frac{\sum_{j=1}^{k} P_{ij}}{\sum_{j=1}^{k} PET_{ij}}, i = 1{:}N \tag{7-5}$$

where $\overline{y_k}$ and $\widehat{\sigma_{yk}}$ are the arithmetic mean and the standard deviation of y_k, respectively, and y_k equal $\ln(\alpha_k^i)$, P_{ij} and PET_{ij} are the amounts of precipitation and PET in month *jth* of the *ith* year throughout the N year of study, respectively.

Tools: DrinC Program

7.2.4 Standardized Soil Moisture Index

The SMI is generally used to quantify the agricultural drought as it is directly linked with the anomalies in the state of the water content in the soil. The computation of the Standardized Soil Moisture Index (SMI) follows a similar pathway to the Standardized Precipitation Index (SPI) with only a difference in the input data. In the case of SMI, the moisture data has to be used to quantify the drought. Such moisture data may be retrieved from various kinds of primary and secondary sources including field observations, satellite estimates, reanalysis products, etc.

7.2.5 Standardized Streamflow Index

The Standardized Streamflow Index (SSI), which has the advantages of simplicity and effectiveness, is the most often used index to measure streamflow-based hydrological droughts. In other words, SSI enables accurate comparisons of a stream's hydrological characteristics (Shamshirband, et al., 2020). This index is statistically similar to SPI. It is developed using monthly streamflow values and the methods of normalization are the same as those of SPI (Timilsina, 2021). The classification of drought based on the SSI is listed in **Table 7-4** (Ramadas et al., 2014).

Table 7-4 SSI classification criteria

Description	Range		Description	Range
Exceptional drought	(-∞ to -2.0]		Abnormally wet	[0.5 to 0.8)
Extreme drought	(-2.0 to -1.6]		Moderately wet	[0.8 to 1.3)
Severe drought	(-1.6 to -1.3]		Severely wet	[1.3 to 1.6)
Moderate drought	(-1.3 to -0.8]		Extremely wet	[1.6 to 2.0)
Abnormally dry	(-0.8 to -0.5]		Exceptionally wet	[2.0 to ∞)
Normal condition	(-0.5 to 0.5)			

(Adapted from: Ramadas et al., 2014).

The method of estimating SSI is the same as that of estimating SPI, except for the type of data used. In the case of the SSI calculation, flow data is used instead of precipitation data at different time scales of interest.

To have consistency of the various indices, the degree of severity of the drought (moderate, severe, and extreme) was assessed based on criteria used for SPI which is given in **Table 7-2**.

7.2.6 Drought Frequency

The number of droughts months for each drought type (moderate, severe, extreme and total) of a particular station during the study period was counted (see **Table 7-6**). The percentage of frequency of each drought type was then calculated by dividing this number by the total months of the study period (e.g., for SPI-1: study period=43 years = 516 months).

7.2.7 Total Drought Duration

The Total Drought Duration (TDD) is calculated as the total number of drought months for a considered station, i.e., the sum of the moderate, severe and extreme drought months.

7.2.8 Drought Severity

Drought Severity (DS) is the sum of the values of drought indices (≤ -1.0) of drought months for the considered station. For example, the DS of precipitation station i for SPI-1 is calculated as **Equation (7-6)**.

$$DS_i = \sum_j^N SPI1 \;\; \forall \, (SPI \leq -1.0) \tag{7-6}$$

Where, N = Number of total months of the study period. The higher the negative value, the more the drought severity.

7.2.9 Drought Intensity

Drought intensity (DI) is defined as the ratio of drought severity to the duration (unit: per month). DI can be of two types depending on the duration taken in the calculation, i.e., total months (N) based and TDD-based DI. They are calculated as

(i) Total months-based DI is calculated by **Equation (7-7)**

$$DI_N = \frac{DS}{N} \tag{7-7}$$

It tells the average intensity of drought severity for the whole duration of the study.

(ii) TDD-based DI is calculated by **Equation (7-8).**

$$DI_{TDD} = \frac{DS}{TDD} \tag{7-8}$$

It tells the average intensity of drought severity in the drought months. The higher the negative value, the more the drought severity.

7.2.10 Maximum Consecutive Drought Duration

It is the maximum number of consecutive drought months during the study period.

7.3 Assessment of Drought Indices and Drought Parameters

In order to assess the drought conditions of Nepal, five commonly used drought indices, viz. Standardized Precipitation Indices (SPI), Standardized Precipitation Evapotranspiration Indices (SPEI), Reconnaissance Drought Indices (RDI), Standardized Soil Moisture Indices (SMI) and Standardized Streamflow Indices (SSI), of all the selected rainfall, temperature, GLDAS Soil Moisture products at the root zone and flow

Box 7-1

Drought Indices and Time Steps

1.	SPI:	(i) SPI-1	(ii) SPI-2	(iii) SPI-3	(iv) SPI-4	(v) SPI-12
2.	SPEI:	(i) SPEI-1	(ii) SPEI-2	(iii) SPEI-3	(iv) SPEI-4	(v) SPEI-12
3.	RDI:	(i) RDI-1	(ii) RDI-2	(iii) RDI-3	(iv) RDI-4	(v) RDI-12
4.	SMI:	(i) SMI-1	(ii) SMI-2	(iii) SMI-3	(iv) SMI-4	(v) SMI-12
5.	SSI:	(i) SSI-1	(ii) SSI-2	(iii) SSI-3	(iv) SSI-4	(v) SSI-12

Drought Parameters

1. **Drought Frequency**
2. **Drought Severity**
3. **Drought Intensity**
4. **Maximum Consecutive Drought Duration**

gauging stations were estimated in this study. The time scales of these drought indices are one, two, three, four and twelve-months. Hence, a total of 25 cases (5 types * 5 time scales) have been considered.

Four different drought parameters, viz. frequency, severity, intensity and maximum consecutive drought duration, were calculated for each location. These parameters were averaged over the 10 selected basins of Nepal. Drought years were also identified for all these cases based on the severity. A brief discussion of the results of the 25 cases is given below. Similarly, decadal trends of the drought events of the 10 basins (Class A River Basins: Koshi, Gandaki, Karnali and Chamelia (Mahakali); Class B River Basins: Kankai, Kamala, Bagmati, West Rapti and Babai; and Class C River Basin: not covered by Class A and Class B River Basins within the territory of Nepal), and of Nepal were also calculated based on the drought frequency and severity for all the 25 cases. Here, it should be remembered that the basin average of these indices or parameters implies the values obtained from the analysis of data of the hydro-climatic stations falling within the considered basin. Similarly, country-level average implies the values calculated from the data of all hydro-climatic stations selected in this study.

The nomenclature used for drought parameters in this study is given in **Table 7-5**. To explain the method better, an example of the calculation of different drought parameters, and estimated drought indices for SPI-1 is given in **Table 7-6**. Drought parameters based on other indices were also done similarly.

Table 7-5 Drought parameters and their nomenclature

SN	Description	Symbol
1	Total No. of Data Points	N
2	Number of Moderate Drought out of N	n_M
	Number of Severe Drought out of N	n_S
	Number of Extreme Drought out of N	n_E
	Total Drought Duration (Number of Total Drought out of N)	TDD
3	Percentage of Moderate Drought Period	M%
	Percentage of Severe Drought Period	S%
	Percentage of Extreme Drought Period	E%
	Percentage of Total Drought Duration	TDD%
4	Drought Severity	DS
5	Drought Intensity (N-based)-Unit: per month	DI_N
	Drought Intensity (TDD)-based)- Unit: per month	DI_{TDD}
6	Maximum Consecutive Drought Duration	MaxCDD

Table 7-6 An example of calculation of different drought parameters

Date	1004	1007	1008	1009	101	1016	1018	1020	1023	1024	1029	…	…	….	…	…..	104	1043	1049	105	1405	1408	1409	1410	1415	1420	1421
1980-01-31	-1.0	-1.2	-1.1	-1.1	-1.3	-1.2	-1.1		-1.1			-1.3			-1.1				-1.0		-1.1						
1980-02-29																				-1.2							
1980-03-31																											
1980-04-30	-1.1	-1.6	-1.4			-1.0		-1.4	-1.3	-1.2	-1.4	-1.0	-1.3	-1.4	-1.1	-1.4		-1.2	-1.3			-1.4	-1.4	-1.7	-1.4		-1.4
1980-05-31	-1.3				-1.2		-1.0		-1.0			-1.5					-1.1		-1.1								
1980-06-30																								-1.2			
1980-07-31																				-2.1		-1.0			-1.1		
1980-08-31								-2.0	-1.6	-1.5	-1.7				-1.9	-1.1			-1.7							-2.2	
1980-09-30	-1.7		-1.1		-1.1		-1.5	-1.7						-1.6					-1.2								
1980-10-31							-1.1	-1.2		-1.1																	
1980-11-30																											
1980-12-31																											
1981-01-31														-1.0													
1981-02-28		-1.3	-1.2		-1.2	-1.4			-1.3	-1.2	-1.3		-1.3	-1.2		-1.2		-1.2	-1.3		-1.6					-1.2	
…...																											
…...																											
…...																		-1.1									
2022-10-31																											
2022-11-30																											
2022-12-31																											

	516	516	516	516	516	516	516	516	516	516	516	516	516	516	516	516	516	516	516	516	516	516	516	516	516	516	516
Number Based Frequency																											
Moderate	3	2	4	1	4	3	4	2	4	3	2	3	2	3	2	3	1	3	5	1	1	2	1	1	2	1	1
Severe	1	1	0	0	0	0	0	1	1	1	1	0	0	1	1	0	0	0	1	0	1	0	0	1	0	0	0
Extreme	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0
Total Drought Duration(TDD)	4	3	4	1	4	3	4	4	5	4	3	3	2	4	3	3	1	3	6	2	2	2	1	2	2	2	1
% Based Frequency																											
M%	0.6	0.4	0.8	0.2	0.8	0.6	0.8	0.4	0.8	0.6	0.4	0.6	0.4	0.6	0.4	0.6	0.2	0.6	1.0	0.2	0.2	0.4	0.2	0.2	0.4	0.2	0.2
S%	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.0	0.0	0.2	0.2	0.0	0.0	0.0	0.2	0.0	0.2	0.0	0.0	0.2	0.0	0.0	0.0
E%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.2	0.0
Total (%)	0.8	0.6	0.8	0.2	0.8	0.6	0.8	0.8	1.0	0.8	0.6	0.6	0.4	0.8	0.6	0.6	0.2	0.6	1.2	0.4	0.4	0.4	0.2	0.4	0.4	0.4	0.2
Severity	-5.1	-4.2	-4.9	-1.1	-4.8	-3.6	-4.7	-6.3	-6.3	-5.0	-4.3	-3.9	-2.7	-5.2	-4.0	-3.6	-1.1	-3.5	-7.6	-3.3	-2.6	-2.4	-1.4	-2.9	-2.5	-3.4	-1.4
N based Intensity-(Int-N)	-0.01	-0.01	-0.01	0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	-0.01	-0.01	-0.01	-0.01	0.00	0.00	-0.01	0.00	-0.01	0.00
TDD based Intensity-(Int-TDD)	-1.29	-1.38	-1.21	-1.10	-1.21	-1.20	-1.18	-1.59	-1.25	-1.25	-1.44	-1.28	-1.34	-1.30	-1.35	-1.21	-1.06	-1.18	-1.27	-1.66	-1.32	-1.19	-1.35	-1.46	-1.27	-1.69	-1.42
Maximum Cosucutive Drougth Duration	2	1	1	1	1	1	2	3	2	1	1	2	1	2	1	1	1	1	2	1	1	1	1	1	1	1	1

(red)	Extreme Drought
(yellow)	Severe Drought
(green)	Moderate Drought

7.3.1 SPI-1 Based Drought Parameters and Decadal Trend

SPI-1-based drought parameters are given in **Table 7-7** (Nepal and Class A River Basins) and **Table 7-8** (Class B and Class C River Basins). The total number of data points used in SPI-1 calculations is 516 months. Of these 516 months, the average number of months experiencing moderate, severe, and extreme drought in Nepal, based on this index, are 61, 14, and 2 months, respectively. In other words, approximately 15% of the months in Nepal have historically experienced either moderate (11.86%), severe (2.72%), or extreme (0.46%) droughts. However, some stations have nearly 20% of the months affected (e.g., St. 1317), while others have less than 10% (e.g., St. 922). All basins show a similar percentage of total drought duration, implying a 15% probability of any one of the three types of droughts occurring in Nepal.

The average drought severity (DS) of Nepal is -102. It gives the drought intensity of -0.20 based on total months (N) and -1.32 based on total drought duration (TDD). The first figure indicates that the overall intensity of drought severity is not that high in Nepal. However, it falls under the moderate category (i.e., ≤ -1.0) on average, when drought occurs. Similarly, the average number of the maximum consecutive drought duration (MaxCDD) in Nepal is 4. This range is the highest in the rainfall stations of the Karnali River basin, where it spans from 2 to 9 months.

Average of the total drought duration of Koshi, Gandaki, Karnali, and Mahakali are respectively 80, 81, 78 and 89 months. It implies that the probability of experiencing drought in Koshi, Gandaki, Karnali and Mahakali basins are about 16%, 16%, 15% and 17% respectively. However, these values for Kankai, Kamala, Bagmati, West Rapti, Babai and Southern basins are respectively 15%, 15%, 15%, 13%, 16% and 14%.

The average value of the drought severity of Koshi, Gandaki, Karnali and Mahkali basins are -107, -108, -104, and -118 respectively. It gives the average drought intensity of -1.33, -1.34, -1.33 and -1.33 respectively during the drought months of these basins. All these values fall under moderate droughts. Maximum consecutive drought days of Koshi, Gandaki, Karnali and Mahkali basins are respectively 4, 4, 4 and 3.

The average drought severity of Kankai, Kamala, Bagmati, West Rapti, Babai and Southern basins are respectively -106, -97, -105, -90, -107 and -93. The drought intensity in these basins during the drought period are -1.34, -1.27, -1.32, -1.32, -1.27 and -1.29 respectively. These results show that the average drought intensity of Class A, Class B and Class C rivers are not so different.

Decadal values of SPI-1 of Nepal and the 10 major basins are given in **Table 7-9**. It is evident that no particular trend (increasing or decreasing) is seen over the country and even within each basin, in both the percentage of time-based drought events and the level of severity-based drought.

Table 7-7 SPI-1: Drought parameters of Nepal and Class A River Basins

Drought Parameters	Nepal			Koshi			Gandaki			Karnali			Chamelia		
	Avg.	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**
N	516	516	516	516	516	516	516	516	516	516	516	516	516	516	516
n_M	61	88	32	62	81	46	62	88	46	61	81	43	70	81	59
n_S	14	25	6	15	25	6	16	25	6	15	25	10	15	20	10
n_E	2	7	0	3	7	0	3	7	0	2	4	0	3	4	2
TDD	78	101	47	80	101	65	81	94	65	78	99	66	89	99	83
M%	11.86	17.1	6.2	12.1	15.7	8.9	12	17.1	8.9	11.79	15.7	8.3	13.63	15.7	11.4
S%	2.72	4.8	1.2	2.95	4.8	1.2	3.05	4.8	1.2	2.97	4.8	1.9	2.97	3.9	1.9
E%	0.46	1.4	0	0.53	1.4	0	0.57	1.4	0	0.36	0.8	0	0.6	0.8	0.4
TDD%	15.03	19.6	9.1	15.57	19.6	12.6	15.61	18.2	12.6	15.14	19.2	12.8	17.2	19.2	16.1
DS	-102.0	-134.8	-65.6	-106.6	-134.8	-85.4	-107.7	-119.9	-87.0	-104.0	-129.5	-89.9	-117.5	-129.5	-109.1
DI_N	-0.2	-0.26	-0.13	-0.21	-0.26	-0.17	-0.21	-0.23	-0.17	-0.2	-0.25	-0.17	-0.23	-0.25	-0.21
DI_{TDD}	-1.32	-1.4	-1.22	-1.33	-1.4	-1.26	-1.34	-1.4	-1.22	-1.33	-1.39	-1.27	-1.33	-1.37	-1.3
MaxCDD	4	9	2	4	8	3	4	7	3	4	9	2	3	4	3

Table 7-8 SPI-1: Drought parameters of selected Class B and Class C River Basins

Class B and Class C River Basins																		
Drought Parameters	**Kankai**			**Kamala**			**Bagmati**			**West Rapti**			**Babai**			**Southern Basins**		
	Avg.	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**
N	516	516	516	516	516	516	516	516	516	516	516	516	516	516	516	516	516	516
n_M	58	58	58	64	79	48	63	83	57	55	55	55	71	74	70	59	72	32
n_S	19	19	19	11	12	10	14	20	7	11	11	11	11	12	8	12	20	6
n_E	2	2	2	2	2	2	2	5	1	2	2	2	2	5	0	2	5	0
TDD	79	79	79	76	93	60	80	94	72	68	68	68	84	87	82	73	89	47
M%	11.2	11.2	11.2	12.3	15.3	9.3	12.25	16.1	11	10.7	10.7	10.7	13.83	14.3	13.6	11.42	14	6.2
S%	3.7	3.7	3.7	2.1	2.3	1.9	2.71	3.9	1.4	2.1	2.1	2.1	2.07	2.3	1.6	2.28	3.9	1.2
E%	0.4	0.4	0.4	0.4	0.4	0.4	0.44	1	0.2	0.4	0.4	0.4	0.47	1	0	0.39	1	0
TDD%	15.3	15.3	15.3	14.8	18	11.6	15.41	18.2	14	13.2	13.2	13.2	16.37	16.9	15.9	14.08	17.2	9.1
DS	-106	-106	-106	-97	-114	-79	-105	-121	-95	-90	-90	-90	-107	-110	-103	-93	-113	-66
DI_N	-0.2	-0.2	-0.2	-0.18	-0.22	-0.15	-0.2	-0.23	-0.18	-0.17	-0.17	-0.17	-0.21	-0.21	-0.2	-0.18	-0.22	-0.13
DI_{TDD}	-1.34	-1.34	-1.34	-1.27	-1.32	-1.23	-1.32	-1.35	-1.29	-1.32	-1.32	-1.32	-1.27	-1.29	-1.26	-1.29	-1.4	-1.22
MaxCDD	2	2	2	4	4	3	3	4	3	3	3	3	4	6	2	3	8	2

Table 7-9 Decadal Trend of SPI-1

Category	Time Frame	Nepal			Koshi			Gandaki			Karnali			Chamelia		
		Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min
Frequency Based (% of time)	1980-1990	14	30	5	15	30	8	16	28	8	13	19	8	17	18	15
	1991-2000	15	27	6	16	25	8	16	27	8	14	21	8	16	17	15
	2001-2010	16	31	8	17	31	10	17	26	10	19	28	14	19	23	16
	2011-2022	15	25	6	15	25	8	15	23	6	16	21	10	17	19	15
Severity Based	1980-1990	-23	-57	-8	-25	-57	-14	-28	-50	-14	-22	-34	-13	-29	-32	-26
	1991-2000	-24	-44	-8	-26	-41	-13	-25	-44	-12	-21	-34	-13	-25	-27	-23
	2001-2010	-26	-50	-13	-26	-50	-16	-26	-42	-14	-31	-48	-23	-30	-35	-26
	2011-2022	-29	-47	-10	-29	-47	-15	-28	-43	-10	-30	-43	-18	-33	-36	-31

Category	Time Frame	Kankai			Kamala			Bagmati			West Rapti			Babai			Southern Basin		
		Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min
Frequency Based (% of time)	1980-1990	13	13	13	14	17	11	14	17	8	14	14	14	14	16	11	12	19	5
	1991-2000	16	16	16	18	21	14	17	23	10	14	14	14	18	20	15	14	19	6
	2001-2010	18	18	18	15	17	13	15	22	9	16	16	16	18	23	16	15	22	8
	2011-2022	15	15	15	13	18	8	16	19	11	10	10	10	16	18	15	15	24	8
Severity Based	1980-1990	-23	-23	-23	-23	-27	-18	-24	-30	-13	-21	-21	-21	-23	-26	-19	-20	-33	-8
	1991-2000	-25	-25	-25	-27	-31	-22	-27	-36	-15	-23	-23	-23	-26	-30	-21	-22	-31	-8
	2001-2010	-28	-28	-28	-23	-23	-23	-24	-33	-13	-27	-27	-27	-28	-37	-24	-23	-34	-13
	2011-2022	-29	-29	-29	-24	-32	-16	-30	-36	-20	-20	-20	-20	-30	-36	-26	-28	-46	-14

7.3.2 SPI-2 Based Drought Parameters and Decadal Trend

SPI-2-based drought parameters are given in **Table 7-10** (Nepal and Class A River Basins) and **Table 7-11** (Class B and Class C River Basins). The total number of data points is 515 (516 months -1 month) for SPI-2 analysis. The probability of having a total drought of this kind in Nepal is 17.16%. The probability of having a moderate, severe and extreme drought of this kind in Nepal is respectively 12.92%, 3.63% and 0.56%. These figures are almost similar for all the considered basins too. Further, the values of SPI-2 are slightly higher than those of SPI-1. The average drought severity is about -120 with N-based intensity and TDD-based intensity of -0.23 and -1.35 respectively. As in SPI-1, TDD-based intensity falls in the moderate category. Similarly, the average number of the maximum consecutive drought duration of Nepal for this index is found to be 6 (ranging from 3 to 15 durations), both occurring in the Karnali River basin.

Decadal values of SPI-2 of Nepal and the 10 major basins are given in **Table 7-12**. Unlike SPI-1, SPI-2 shows a trend of increasing drought, especially in the major basins (Koshi, Gandaki and Karnali) in both frequency-based drought events and the severity-based drought.

7.3.3 SPI-3 Based Drought Parameters and Decadal Trend

Drought parameters based on SPI-3 indices are given in **Table 7-13** (Nepal and Class A River Basins) and **Table 7-14** (Class B and Class C River Basins). The series has 514 data points for this drought index. The average TDD is 91 (range: 78-105) months for Nepal. The percentages of occurrence of moderate, severe and extreme drought are 12.74%, 4.17% and 0.83% respectively. It implies that Nepal faces SPI-3 drought of either one of these three categories 18% of the time, on average. All basins have almost the same percentage of total drought events as that of an average of Nepal. The DS value is -126 for Nepal and close to this value, for all the other basins. The N-based DI is -0.25 and TDD based DI is -1.39. The TDD-based DI falls in the moderate category as SPI-1 and SPI-2. The MaxCDD ranges from 4 (in the Gandaki basin) to 15 (in the Karnali basin) with an average value of 7 for Nepal. The decadal trend of SPI-3, given in **Table 7-15**, shows an increasing trend, in general, both in drought in numbers and severity.

Table 7-10 SPI-2: Drought parameters of Nepal and Class A River Basins

Nepal and Class A River Basins															
Drought Parameters	**Nepal**			**Koshi**			**Gandaki**			**Karnali**			**Chamelia**		
	Avg.	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**
N	515	515	515	515	515	515	515	515	515	515	515	515	515	515	515
n_M	66	90	43	65	87	46	62	82	43	66	85	45	59	62	55
n_S	19	32	9	19	32	11	21	30	13	21	29	12	25	27	22
n_E	3	8	0	4	8	0	4	8	0	3	6	0	3	4	2
TDD	88	110	70	88	110	71	87	105	76	91	101	70	87	87	86
M%	12.92	17.5	8.3	12.65	16.9	8.9	11.96	15.9	8.3	12.88	16.5	8.7	11.47	12	10.7
S%	3.62	6.2	1.7	3.7	6.2	2.1	4.17	5.8	2.5	4.08	5.6	2.3	4.8	5.2	4.3
E%	0.65	1.6	0	0.77	1.6	0	0.75	1.6	0	0.69	1.2	0	0.6	0.8	0.4
TDD%	17.16	21.4	13.6	17.09	21.4	13.8	16.86	20.4	14.8	17.61	19.6	13.6	16.83	16.9	16.7
DS	-120	-143	-97	-120	-143	-97	-120	-139	-106	-123	-136	-100	-121	-122	-119
DI_N	-0.23	-0.28	-0.19	-0.23	-0.28	-0.19	-0.23	-0.27	-0.21	-0.24	-0.26	-0.19	-0.24	-0.24	-0.23
DI_{TDD}	-1.35	-1.48	-1.25	-1.37	-1.48	-1.29	-1.38	-1.46	-1.31	-1.36	-1.43	-1.28	-1.39	-1.42	-1.36
MaxCDD	6	15	3	6	10	4	6	8	4	6	15	3	5	6	5

Table 7-11 SPI-2: Drought parameters of Class B and Class C River Basins

Class B and Class C River Basins																		
Drought Parameters	**Kankai**			**Kamala**			**Bagmati**			**West Rapti**			**Babai**			**Southern Basin**		
	Avg.	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**
N	515	515	515	515	515	515	515	515	515	515	515	515	515	515	515	515	515	515
n_M	64	64	64	66	69	64	65	76	58	74	74	74	66	76	56	71	90	53
n_S	18	18	18	16	17	14	19	24	13	16	16	16	19	24	11	15	25	9
n_E	2	2	2	2	3	2	3	4	1	2	2	2	2	4	0	3	7	0
TDD	84	84	84	84	85	84	87	95	80	92	92	92	87	91	82	89	106	75
M%	12.4	12.4	12.4	12.9	13.4	12.4	12.63	14.8	11.3	14.4	14.4	14.4	12.77	14.8	10.9	13.82	17.5	10.3
S%	3.5	3.5	3.5	3	3.3	2.7	3.78	4.7	2.5	3.1	3.1	3.1	3.7	4.7	2.1	3	4.9	1.7
E%	0.4	0.4	0.4	0.5	0.6	0.4	0.54	0.8	0.2	0.4	0.4	0.4	0.4	0.8	0	0.52	1.4	0
TDD%	16.3	16.3	16.3	16.4	16.5	16.3	16.91	18.4	15.5	17.9	17.9	17.9	16.83	17.7	15.9	17.32	20.6	14.6
DS	-115	-115	-115	-112	-112	-112	-119	-127	-111	-121	-121	-121	-117	-120	-113	-118	-134	-104
DI_N	-0.22	-0.22	-0.22	-0.22	-0.22	-0.22	-0.23	-0.25	-0.22	-0.24	-0.24	-0.24	-0.23	-0.23	-0.22	-0.23	-0.26	-0.2
DI_{TDD}	-1.37	-1.37	-1.37	-1.33	-1.33	-1.33	-1.37	-1.39	-1.34	-1.32	-1.32	-1.32	-1.35	-1.37	-1.32	-1.33	-1.4	-1.25
MaxCDD	5	5	5	5	5	5	5	6	4	4	4	4	7	11	4	6	11	3

Table 7-12 Decadal Trend of SPI-2

Category	Time Frame	Nepal			Koshi			Gandaki			Karnali			Chamelia		
		Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min
Frequency Based	1980-1990	13	31	4	16	31	6	14	30	6	12	24	5	11	16	8
	1991-2000	18	32	8	17	27	10	18	32	10	17	24	11	16	18	13
	2001-2010	20	36	10	18	32	10	19	29	10	22	30	16	18	22	13
	2011-2022	18	31	7	17	31	8	17	28	7	19	29	12	22	26	19
Severity Based	1980-1990	-23	-60	-6	-27	-60	-10	-25	-57	-10	-21	-45	-7	-22	-30	-17
	1991-2000	-29	-58	-11	-29	-47	-15	-30	-58	-17	-27	-39	-17	-26	-31	-19
	2001-2010	-32	-55	-15	-30	-53	-16	-31	-51	-15	-38	-55	-26	-29	-36	-23
	2011-2022	-35	-67	-12	-34	-67	-14	-33	-53	-12	-37	-58	-20	-44	-51	-38

Category	Time Frame	Kankai			Kamala			Bagmati			West Rapti			Babai			Southern Basin		
		Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min
Frequency Based	1980-1990	15	15	15	14	15	13	13	20	8	12	12	12	12	14	9	12	23	4
	1991-2000	18	18	18	20	20	19	21	26	13	17	17	17	16	20	13	17	26	8
	2001-2010	18	18	18	20	23	18	17	20	13	23	23	23	19	24	15	20	36	11
	2011-2022	15	15	15	13	14	12	17	26	13	20	20	20	20	25	16	19	30	10
Severity Based	1980-1990	-25	-25	-25	-23	-25	-21	-24	-37	-12	-19	-19	-19	-20	-24	-16	-21	-40	-6
	1991-2000	-31	-31	-31	-32	-32	-31	-34	-42	-20	-26	-26	-26	-26	-33	-22	-28	-45	-11
	2001-2010	-29	-29	-29	-33	-35	-31	-27	-34	-20	-40	-40	-40	-33	-42	-26	-33	-54	-18
	2011-2022	-30	-30	-30	-24	-27	-22	-34	-49	-25	-37	-37	-37	-37	-49	-31	-37	-59	-18

Table 7-13 SPI-3: Drought parameters of Nepal and Class A river basins

Nepal and Class A River Basins															
Drought Parameters	**Nepal**			**Koshi**			**Gandaki**			**Karnali**			**Chamelia**		
	Avg.	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**
N	514	514	514	514	514	514	514	514	514	514	514	514	514	514	514
n_M	65	87	46	64	82	46	59	75	46	62	85	46	64	69	60
n_S	21	35	11	21	31	12	24	32	17	23	29	17	22	24	18
n_E	4	10	0	5	9	1	5	10	1	5	10	0	5	6	3
TDD	91	105	78	90	99	78	88	96	78	90	104	78	91	93	88
M%	12.74	16.9	8.9	12.45	16	8.9	11.48	14.6	8.9	12.09	16.5	8.9	12.53	13.4	11.7
S%	4.17	6.8	2.1	4.15	6	2.3	4.64	6.2	3.3	4.46	5.6	3.3	4.23	4.7	3.5
E%	0.83	1.9	0	0.95	1.8	0.2	0.96	1.9	0.2	0.92	1.9	0	0.93	1.2	0.6
TDD%	17.7	20.4	15.2	17.5	19.3	15.2	17.0	18.7	15.2	17.4	20.2	15.2	17.6	18.1	17.1
DS	-126	-139	-111	-126	-136	-112	-123	-111	-111	-126	-139	-117	-127	-129	-126
DI_N	-0.25	-0.27	-0.21	-0.24	-0.26	-0.22	-0.24	-0.21	-0.21	-0.25	-0.27	-0.23	-0.25	-0.25	-0.24
DI_{TDD}	-1.39	-1.51	-1.29	-1.4	-1.48	-1.31	-1.41	-1.35	-1.35	-1.41	-1.51	-1.33	-1.41	-1.43	-1.39
MaxCDD	7	25	4	7	12	5	7	12	4	8	25	5	7	9	5

Table 7-14 SPI-3: Drought parameters of Class B and Class C River Basins

Class B and Class C River Basins																		
Drought Parameters	**Kankai**			**Kamala**			**Bagmati**			**West Rapti**			**Babai**			**Southern Basin**		
	Avg.	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**
N	514	514	514	514	514	514	514	514	514	514	514	514	514	514	514	514	514	514
n_M	65	65	65	72	73	70	66	75	56	71	71	71	64	68	55	71	87	58
n_S	23	23	23	19	21	17	21	26	15	26	26	26	24	35	17	19	28	13
n_E	2	2	2	3	3	3	3	6	1	1	1	1	3	5	1	3	8	1
TDD	90	90	90	94	94	93	91	97	84	98	98	98	90	92	88	94	105	83
M%	12.6	12.6	12.6	13.9	14.2	13.6	12.9	14.6	10.9	13.8	13.8	13.8	12.37	13.2	10.7	13.85	16.9	11.3
S%	4.5	4.5	4.5	3.7	4.1	3.3	4.16	5.1	2.9	5.1	5.1	5.1	4.6	6.8	3.3	3.78	5.4	2.5
E%	0.4	0.4	0.4	0.6	0.6	0.6	0.68	1.2	0.2	0.2	0.2	0.2	0.6	1	0.2	0.7	1.6	0.2
TDD%	17.5	17.5	17.5	18.2	18.3	18.1	17.7	18.9	16.3	19.1	19.1	19.1	17.57	17.9	17.1	18.31	20.4	16.1
DS	-124	-124	-124	-125	-127	-123	-127	-135	-118	-132	-132	-132	-126	-130	-122	-128	-139	-115
DI_N	-0.24	-0.24	-0.24	-0.24	-0.25	-0.24	-0.25	-0.26	-0.23	-0.26	-0.26	-0.26	-0.24	-0.25	-0.24	-0.25	-0.27	-0.22
DI_{TDD}	-1.37	-1.37	-1.37	-1.34	-1.37	-1.31	-1.39	-1.42	-1.36	-1.34	-1.34	-1.34	-1.39	-1.43	-1.36	-1.36	-1.43	-1.29
MaxCDD	8	8	8	6	7	6	6	7	5	6	6	6	10	13	8	7	12	5

Table 7-15 Decadal Trend of SPI-3

Category	Time Frame	Nepal			Koshi			Gandaki			Karnali			Chamelia		
		Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min
Frequency Based	1980-1990	13	35	3	15	35	5	14	33	5	11	24	4	12	17	9
	1991-2000	17	33	6	17	29	8	17	33	10	15	24	8	15	19	10
	2001-2010	21	42	8	20	32	8	19	31	10	23	37	12	21	23	17
	2011-2022	20	40	8	18	31	8	19	29	8	21	29	13	23	28	18
Severity Based	1980-1990	-23	-67	-5	-28	-66	-9	-24	-67	-8	-20	-47	-6	-20	-29	-16
	1991-2000	-28	-61	-9	-29	-52	-13	-29	-61	-15	-26	-39	-14	-25	-34	-17
	2001-2010	-35	-65	-13	-33	-59	-13	-33	-57	-16	-40	-63	-19	-34	-38	-28
	2011-2022	-40	-80	-14	-37	-69	-14	-37	-56	-14	-41	-62	-22	-48	-57	-39

Category	Time Frame	Kankai			Kamala			Bagmati			W. Rapti			Babai			Southern Basin		
		Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min
Frequency Based	1980-1990	13	13	13	14	15	12	13	20	7	10	10	10	12	13	10	12	25	3
	1991-2000	21	21	21	22	23	21	20	25	13	14	14	14	15	20	13	17	25	6
	2001-2010	18	18	18	21	23	20	19	26	12	28	28	28	21	27	14	22	42	10
	2011-2022	19	19	19	17	17	17	19	26	15	24	24	24	22	29	17	22	40	13
Severity Based	1980-1990	-23	-23	-23	-24	-28	-20	-24	-40	-11	-18	-18	-18	-21	-24	-17	-21	-43	-5
	1991-2000	-35	-35	-35	-36	-37	-34	-35	-45	-19	-23	-23	-23	-26	-37	-20	-28	-44	-9
	2001-2010	-29	-29	-29	-35	-36	-34	-29	-43	-18	-45	-45	-45	-36	-49	-24	-36	-65	-17
	2011-2022	-36	-36	-36	-31	-31	-30	-38	-53	-27	-46	-46	-46	-43	-60	-34	-42	-80	-23

7.3.1 SPI-4 Based Drought Parameters and Decadal Trend

SPI-4-based drought parameters are given in **Table 7-16** (Nepal and Class A River Basins) and **Table 7-17** (Class B and Class C River Basins). The total number of data points is 513 for SPI-4 analysis. The probability of having a total SPI-4 drought is 17.43%. The probability of having a moderate, severe and extreme drought of this kind in Nepal are respectively 11.79%, 4.63 and 1.04%. These figures are almost similar in all basins too. Further, the values of SPI-4 are almost the same as those of SPI-3. The average TDD is 89 which is more or less equal in the large basins. However, the TDD of smaller basins is slightly greater than that of larger basins. The average drought severity is about -126 with N-based intensity and TDD-based intensity of -0.25 and -1.42 respectively. As in the other SPIs, TDD-based intensity falls in the moderate category. Similarly, the average number of the maximum consecutive drought duration of Nepal for this index is 8; ranging from a minimum of 5 to a maximum of 25 durations occurring in the Karnali River Basin.

Decadal values of SPI-4 of Nepal and the 10 major basins are given in **Table 7-18**. SPI-4 also shows increasing drought trends, especially in the major basins (Koshi, Gandaki and Karnali) for both N-based drought and the DS-based drought events.

7.3.2 SPI-12 Based Drought Parameters and Decadal Trend

The drought parameters based on SPI-12 are given in **Table 7-19** (Nepal and Class A River Basins) and **Table 7-20** (Class B and Class C River Basins). The total number of data points is 505 for the SPI-12 analysis. There is a 17% probability of this type of drought occurring in Nepal. The probabilities of having moderate, severe and extreme droughts of this type in Nepal are 10.64%, 4.73% and 1.52% respectively. These figures are similar to those of the major river basins. The average TDD is 85 which is more or less equal for all basins. The average drought severity is about -124 with N-based intensity and DRR-based intensity of -0.25 and -1.46 respectively. As in other SPIs, TDD-based intensity falls in the moderate category. Similarly, the average number of the maximum consecutive drought duration of Nepal for this index is 21. It is the highest among the considered five SPIs. Decadal values of SPI-12 of Nepal and other 10 major basins are given in **Table 7-21**. SPI-12 shows no clear trends in their series.

Table 7-16 SPI-4: Drought parameters of Nepal and Class A River Basins

Nepal and Class A River Basins															
Drought Parameters	**Nepal**			**Koshi**			**Gandaki**			**Karnali**			**Chamelia**		
	Avg.	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**
N	513	513	513	513	513	513	513	513	513	513	513	513	513	513	513
n_M	60	80	41	59	75	42	56	67	45	58	79	41	65	72	58
n_S	24	36	13	24	34	14	25	36	18	25	31	19	22	26	16
n_E	5	13	0	6	12	1	6	11	1	6	13	0	7	7	6
TDD	89	101	73	89	97	78	87	99	78	89	100	73	93	95	91
M%	11.79	15.6	8	11.51	14.6	8.2	10.84	13.1	8.8	11.35	15.4	8	12.6	14	11.3
S%	4.63	7	2.5	4.74	6.6	2.7	4.91	7	3.5	4.8	6	3.7	4.23	5.1	3.1
E%	1.04	2.5	0	1.11	2.3	0.2	1.17	2.1	0.2	1.14	2.5	0	1.33	1.4	1.2
TDD%	17.43	19.7	14.2	17.33	18.9	15.2	16.88	19.3	15.2	17.28	19.5	14.2	18.1	18.5	17.7
DS	-126	-139	-113	-126	-134	-116	-124	-137	-115	-127	-136	-113	-131	-132	-130
DI_N	-0.25	-0.27	-0.22	-0.25	-0.26	-0.23	-0.24	-0.27	-0.22	-0.25	-0.27	-0.22	-0.26	-0.26	-0.25
DI_{TDD}	-1.42	-1.56	-1.32	-1.42	-1.51	-1.34	-1.43	-1.5	-1.36	-1.44	-1.56	-1.33	-1.41	-1.43	-1.39
MaxCDD	8	24	5	9	17	6	8	17	5	9	24	5	9	11	6

Table 7-17 SPI-4: Drought parameters of Class B and Class C River Basins

Class B and Class C River Basins																		
Drought Parameters	**Kankai**			**Kamala**			**Bagmati**			**West Rapti**			**Babai**			**Southern Basin**		
	Avg.	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**
N	513	513	513	513	513	513	513	513	513	513	513	513	513	513	513	513	513	513
n_M	70	70	70	72	74	69	60	74	49	63	63	63	59	63	52	65	80	51
n_S	27	27	27	20	24	17	25	28	20	24	24	24	23	28	20	22	32	13
n_E	1	1	1	4	5	3	5	8	2	3	3	3	6	7	4	5	9	1
TDD	98	98	98	96	101	91	90	100	81	90	90	90	88	91	86	91	101	80
M%	13.6	13.6	13.6	13.95	14.4	13.5	11.69	14.4	9.6	12.3	12.3	12.3	11.5	12.3	10.1	12.59	15.6	9.9
S%	5.3	5.3	5.3	4	4.7	3.3	4.92	5.5	3.9	4.7	4.7	4.7	4.57	5.5	3.9	4.29	6.2	2.5
E%	0.2	0.2	0.2	0.8	1	0.6	0.92	1.6	0.4	0.6	0.6	0.6	1.13	1.4	0.8	0.93	1.8	0.2
TDD%	19.1	19.1	19.1	18.7	19.7	17.7	17.48	19.5	15.8	17.5	17.5	17.5	17.17	17.7	16.8	17.76	19.7	15.6
DS	-133	-133	-133	-131	-135	-128	-127	-135	-118	-126	-126	-126	-124	-127	-122	-127	-139	-117
DI_N	-0.26	-0.26	-0.26	-0.26	-0.26	-0.25	-0.25	-0.26	-0.23	-0.25	-0.25	-0.25	-0.24	-0.25	-0.24	-0.25	-0.27	-0.23
DI_{TDD}	-1.35	-1.35	-1.35	-1.37	-1.4	-1.34	-1.41	-1.48	-1.35	-1.4	-1.4	-1.4	-1.41	-1.44	-1.4	-1.4	-1.47	-1.32
MaxCDD	9	9	9	7	7	7	7	12	6	6	6	6	10	12	9	8	16	5

Table 7-18 Decadal Trend of SPI-4

Category	Time Frame	Nepal			Koshi			Gandaki			Karnali			Chamelia		
		Avg	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**	**Min**
Frequency Based	1980-1990	13	37	2	16	35	5	13	37	4	11	22	3	9	13	5
	1991-2000	16	36	4	16	29	5	17	36	7	15	25	5	14	18	8
	2001-2010	21	40	6	20	37	7	19	34	6	23	38	11	23	26	19
	2011-2022	20	40	6	18	32	6	18	28	7	20	29	13	26	29	22
Severity Based	1980-1990	-23	-76	-4	-28	-71	-7	-24	-76	-7	-19	-46	-4	-16	-22	-9
	1991-2000	-28	-67	-6	-27	-56	-9	-29	-67	-11	-25	-43	-9	-23	-33	-14
	2001-2010	-36	-68	-9	-33	-65	-11	-33	-63	-9	-41	-68	-18	-38	-43	-31
	2011-2022	-40	-85	-11	-37	-75	-11	-37	-55	-12	-42	-65	-22	-54	-60	-45

Category	Time Frame	Kankai			Kamala			Bagmati			W. Rapti			Babai			Southern Basin		
		Avg	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max.**	**Min**
Frequency Based	1980-1990	16	16	16	15	16	14	13	19	4	6	6	6	12	13	9	12	27	2
	1991-2000	21	21	21	21	23	19	19	26	10	12	12	12	15	20	10	16	25	4
	2001-2010	21	21	21	23	23	22	20	26	11	28	28	28	21	29	16	22	40	9
	2011-2022	19	19	19	17	19	15	19	26	13	24	24	24	20	26	15	21	40	8
Severity Based	1980-1990	-26	-26	-26	-26	-29	-22	-24	-40	-6	-12	-12	-12	-20	-22	-15	-21	-47	-4
	1991-2000	-36	-36	-36	-36	-40	-32	-33	-45	-17	-20	-20	-20	-26	-38	-16	-27	-48	-6
	2001-2010	-34	-34	-34	-38	-39	-37	-32	-41	-17	-48	-48	-48	-38	-55	-25	-37	-66	-16
	2011-2022	-37	-37	-37	-32	-34	-29	-38	-53	-25	-46	-46	-46	-41	-58	-30	-42	-85	-16

Table 7-19 SPI-12: Drought parameters of Nepal and Class A River Basins

Nepal and Class A River Basins															
Drought Parameters	**Nepal**			**Koshi**			**Gandaki**			**Karnali**			**Chamelia**		
	Avg.	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**
N	505	505	505	505	505	505	505	505	505	505	505	505	505	505	505
n_M	54	88	22	57	88	30	53	73	32	49	78	25	48	55	42
n_S	24	54	4	23	43	4	24	41	11	23	42	10	18	25	11
n_E	8	23	0	8	19	0	8	21	0	9	23	1	11	18	5
TDD	85	110	56	88	110	68	85	100	70	81	108	62	77	83	71
M%	10.64	17.4	4.4	11.21	17.4	5.9	10.42	14.5	6.3	9.68	15.4	5	9.57	10.9	8.3
S%	4.73	10.7	0.8	4.61	8.5	0.8	4.74	8.1	2.2	4.62	8.3	2	3.53	5	2.2
E%	1.52	4.6	0	1.55	3.8	0	1.68	4.2	0	1.82	4.6	0.2	2.27	3.6	1
TDD%	16.86	21.8	11.1	17.33	21.8	13.5	16.81	19.8	13.9	16.08	21.4	12.3	15.3	16.4	14.1
DS	-124	-148	-92	-126	-148	-107	-124	-139	-107	-120	-145	-100	-114	-122	-109
DI_N	-0.25	-0.29	-0.18	-0.25	-0.29	-0.21	-0.25	-0.27	-0.21	-0.24	-0.29	-0.2	-0.22	-0.24	-0.21
DI_{TDD}	-1.46	-1.73	-1.28	-1.45	-1.61	-1.28	-1.47	-1.6	-1.33	-1.49	-1.73	-1.34	-1.48	-1.53	-1.44
MaxCDD	21	59	11	24	59	12	22	35	12	19	49	11	17	21	12

Table 7-20 SPI-12: Drought parameters of Class B and Class C River Basins

Drought Parameters	Kankai			Kamala			Bagmati			West Rapti			Babai			Southern Basin		
	Avg.	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**
N	505	505	505	505	505	505	505	505	505	505	505	505	505	505	505	505	505	505
n_M	49	49	49	40	46	35	57	76	25	64	64	64	63	66	60	55	82	22
n_S	40	40	40	28	35	21	29	54	12	18	18	18	12	17	6	23	39	6
n_E	4	4	4	9	13	5	4	16	0	7	7	7	11	13	10	7	17	0
TDD	93	93	93	78	86	69	90	108	72	89	89	89	86	90	79	85	104	56
M%	9.7	9.7	9.7	8	9.1	6.9	11.36	15	5	12.7	12.7	12.7	12.5	13.1	11.9	10.88	16.2	4.4
S%	7.9	7.9	7.9	5.55	6.9	4.2	5.74	10.7	2.4	3.6	3.6	3.6	2.4	3.4	1.2	4.65	7.7	1.2
E%	0.8	0.8	0.8	1.8	2.6	1	0.82	3.2	0	1.4	1.4	1.4	2.2	2.6	2	1.37	3.4	0
TDD%	18.4	18.4	18.4	15.35	17	13.7	17.89	21.4	14.3	17.6	17.6	17.6	17	17.8	15.6	16.86	20.6	11.1
DS	-133	-133	-133	-117	-124	-111	-129	-148	-111	-125	-125	-125	-123	-127	-118	-123	-142	-92
DI_N	-0.26	-0.26	-0.26	-0.24	-0.25	-0.22	-0.26	-0.29	-0.22	-0.25	-0.25	-0.25	-0.24	-0.25	-0.23	-0.24	-0.28	-0.18
DI_{TDD}	-1.43	-1.43	-1.43	-1.52	-1.6	-1.45	-1.43	-1.55	-1.37	-1.4	-1.4	-1.4	-1.44	-1.49	-1.41	-1.45	-1.65	-1.33
MaxCDD	14	14	14	23	24	22	22	24	16	13	13	13	22	28	13	19	39	11

Table 7-21 Decadal Trend of SPI-12

Category	Time Frame	Nepal			Koshi			Gandaki			Karnali			Chamelia		
		Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min
Frequency Based	1980-1990	12	58	0	16	58	0	12	36	0	12	29	0	7	11	2
	1991-2000	17	48	0	15	33	0	18	48	1	16	33	1	16	33	5
	2001-2010	20	52	1	20	48	2	20	45	1	20	49	3	14	21	10
	2011-2022	19	43	1	19	43	1	17	35	1	17	38	1	22	33	11
Severity Based	1980-1990	-21	-110	0	-28	-110	0	-22	-79	0	-20	-60	0	-13	-20	-3
	1991-2000	-29	-90	0	-25	-66	0	-32	-89	-1	-29	-61	-1	-27	-61	-7
	2001-2010	-34	-91	-1	-34	-85	-2	-35	-81	-1	-36	-91	-3	-23	-36	-16
	2011-2022	-39	-93	-1	-39	-93	-1	-35	-72	-2	-35	-82	-3	-51	-70	-22

Category	Time Frame	Kankai			Kamala			Bagmati			W. Rapti			Babai			Southern Basin		
		Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max.	Min
Frequency Based	1980-1990	15	15	15	12	14	10	15	23	0	2	2	2	1	2	1	10	30	0
	1991-2000	22	22	22	23	37	8	17	38	0	11	11	11	24	34	10	17	33	0
	2001-2010	14	14	14	19	22	17	21	28	11	33	33	33	21	34	14	19	52	2
	2011-2022	22	22	22	9	11	7	19	37	7	24	24	24	21	26	17	21	42	1
Severity Based	1980-1990	-25	-25	-25	-23	-32	-14	-26	-46	0	-3	-3	-3	-2	-2	-1	-17	-59	0
	1991-2000	-41	-41	-41	-43	-70	-17	-31	-59	0	-17	-17	-17	-42	-68	-16	-30	-66	0
	2001-2010	-22	-22	-22	-35	-41	-29	-36	-48	-18	-57	-57	-57	-37	-68	-21	-33	-90	-3
	2011-2022	-46	-46	-46	-16	-21	-11	-36	-74	-11	-49	-49	-49	-43	-61	-33	-43	-87	-3

7.4 SPEI, RDI, SMI and SSI Based Drought Parameters and Decadal Trend

SPEI-1, SPEI-2, SPEI-3, SPEI-4 and SPEI-12 indices-based drought parameters and decadal trends are given in **Appendix D (Table D-1, D-2, D-3, D-4** and **D-5** respectively. Similarly, RDI-1, RDI-2, RDI-3, RDI-4 and RDI-12 indices-based drought parameters and decadal trends are given in **Appendix D-6, D-7, D-8, D-9** and **D-10** respectively. Likewise, SMI-1, SMI-2, SMI-3, SMI-4 and SMI-12 indices-based drought parameters and decadal trends are given in **Appendix D-11, D-12, D-13, D-14** and **D-15** respectively. Also, SSI-1, SSI-2, SSI-3, SSI-4 and SSI-12 indices-based drought parameters and decadal trends are given in **Appendix D-16, D-17, D-18, D-19** and **D-20** respectively. The general characteristics of the parameters based on these indices are almost similar to those of SPI.

7.5 Average Drought Parameters of Nepal

The average drought parameters of Nepal based on the different drought indices considered in this study (viz. SPI, SPEI, RDI, SMI and SSI) for 1-, 2-, 3-, 4- and 12-months are listed in **Table 7-22**. The average of SPI, SPEI and RDI are listed under the column Avg-Met. It is interesting to note here that all the drought parameters of all the months calculated from SPI and RDI are almost equal. However, parameters calculated from SPEI are slightly different. For example, 1-month TDD is slightly more in SPEI than that of RDI and SPI whereas it is the other way round for 2-month TDD. The percentage of TDD is about 17% in all cases except 1-month (15.5%) From these figures, it can be tentatively estimated that the occurrence probability of meteorological drought in Nepal is around 15-18%. Similarly, DS and DI are higher for SPEI-1 than RDI-1 and SPI-1. For the other months, these parameters are almost equal. Values of these parameters are slightly lower for a 1-month drought than that of other months. MaxCCDs are almost equal for all these three indices. As discussed in the previous section, the SMI can be considered to represent agricultural drought. The TDD percentage of SMI-1 is slightly more than SSI-1 and Met-1. But in the other months, this parameter has almost equal values. The calculated values of Drought Severity (DS) based on SMIs are the lowest for all drought scales (months) which is around -58. However, this value based on the other indices is quite high, i.e. less than -100. The drought intensity values are almost the same in all the cases which are around -0.24 (DI_N) and -1.41 (DI_{TDD}). The value of -1.41 of DI_{TDD} implies that, on average, droughts in Nepal are of moderate type. MaxCCDs are almost equal for all SSI and meteorological droughts, while it is higher for SMI.

A summary of the drought parameters of Nepal is presented in **Table 7-23**. From this table, it can be inferred that the probability of occurrence of moderate drought (M= 12%) is almost three times more than that of severe drought (S=4%). Extreme droughts are quite rare events in Nepal, which account for 1% of the total drought occurrences historically. In general, the average DI_{TDD} shows that the drought of Nepal is of moderate type. The MaxCDD of the country is about 11 in number.

Table 7-22 Different drought indices-based drought parameters of Nepal

Parameters	SPI-1	SPEI-1	RDI-1	Avg-Met-1	SMI-1	SSI-1		SPI-2	SPEI-2	RDI-2	Avg-Met-2	SMI-2	SSI-2
N	516	516	516	516	239	444		515	515	515	515	238	438
$\mathbf{n_M}$	61	58	62	60	28	46		66	59	68	64	29	46
$\mathbf{n_S}$	14	21	13	16	12	21		19	24	18	20	12	21
$\mathbf{n_E}$	2	5	2	3	2	6		3	5	3	4	2	5
TDD	78	84	78	80	42	73		88	87	89	88	42	72
M%	11.9	11.3	12.0	11.7	11.9	10.3		12.9	11.5	13.2	12.5	12.1	10.4
S%	2.7	4.1	2.6	3.1	5.1	4.7		3.6	4.6	3.5	3.9	5.0	4.8
E%	0.5	1.0	0.4	0.6	0.7	1.3		0.7	1.0	0.6	0.7	0.7	1.2
TDD%	15.0	16.3	15.0	15.5	17.7	16.4		17.2	17.0	17.3	17.1	17.7	16.5
DS	-102	-118	-101	-107	-59	-106		-120	-124	-119	-121	-59	-105
$\mathbf{DI_N}$	-0.20	-0.23	-0.20	-0.21	-0.25	-0.24		-0.23	-0.24	-0.23	-0.23	-0.25	-0.24
$\mathbf{DI_{TDD}}$	-1.32	-1.41	-1.31	-1.35	-1.41	-1.46		-1.35	-1.41	-1.35	-1.37	-1.40	-1.45
MaxCDD	4	4	3	4	11	7		6	6	6	6	12	8

Different drought indices-based drought parameters of Nepal (contd.)

Parameters	SPI-3	SPEI-3	RDI-3	Avg-Met-3	SMI-3	SSI-3		SPI-4	SPEI-4	RDI-4	Avg-Met-4	SMI-4	SSI-4
N	514	514	514	514	237	433		513	513	513	513	236	428
n_M	65	60	67	64	29	46		60	57	60	59	29	46
n_S	21	24	21	22	12	21		24	26	24	25	12	21
n_E	4	5	4	4	1	5		5	6	5	5	1	5
TDD	91	90	92	91	42	72		89	88	89	89	42	72
M%	12.7	11.7	13.0	12.5	12.2	10.6		11.8	11.0	11.7	11.5	12.2	10.7
S%	4.2	4.8	4.1	4.4	4.9	4.9		4.6	5.0	4.7	4.8	5.0	5.0
E%	0.8	1.0	0.8	0.9	0.6	1.1		1.0	1.2	1.0	1.1	0.5	1.1
TDD%	17.7	17.4	17.9	17.7	17.7	16.7		17.4	17.2	17.4	17.3	17.7	16.8
DS	-126	-127	-127	-127	-58	-104		-126	-127	-126	-126	-58	-103
DI_N	-0.25	-0.25	-0.25	-0.25	-0.25	-0.24		-0.25	-0.25	-0.25	-0.25	-0.25	-0.24
DI_{TDD}	-1.39	-1.42	-1.38	-1.40	-1.40	-1.45		-1.42	-1.44	-1.42	-1.43	-1.40	-1.44
MaxCDD	7	8	7	7	13	10		8	9	8	8	14	11

Parameters	SPI-12	SPEI-12	RDI-12	Avg-Met-12	SMI-12	SSI-12
N	505	505	505	505	228	392
n_M	54	54	53	54	31	45
n_S	24	25	25	25	10	18
n_E	8	7	7	7	1	4
TDD	85	86	85	85	42	67
M%	10.6	10.7	10.6	10.7	13.6	11.4
S%	4.7	4.9	5.0	4.9	4.3	4.8
E%	1.5	1.4	1.3	1.4	0.5	1.1
TDD%	16.9	17.0	16.9	16.9	18.4	17.2
DS	-124	-125	-124	-124	-57	-96
DI_N	-0.25	-0.25	-0.25	-0.25	-0.25	-0.25
DI_{TDD}	-1.46	-1.45	-1.45	-1.45	-1.38	-1.43
MaxCDD	21	21	20	21	24	22

Table 7-23 Summary of drought parameters of Nepal

Parameters	1-Month Drought			2-Month Drought			3-Month Drought		
	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min
n_M	51	62	28	54	68	29	53	67	29
n_S	16	21	12	19	24	12	20	24	12
n_E	3	6	2	4	5	2	4	5	1
TDD	71	84	42	76	89	42	77	92	42
M%	11.5	12	10	12.0	13	10	12.0	13	11
S%	3.8	5	3	4.3	5	3	4.6	5	4
E%	0.8	1	0	0.8	1	1	0.9	1	1
TDD%	16.1	18	15	17.1	18	16	17.5	18	17
DS	-97	-59	-118	-105.2	-59	-124	-108.6	-58	-127
DI_N	-0.22	-0.20	-0.25	-0.24	-0.23	-0.25	-0.25	-0.24	-0.25
DI_{TDD}	-1.38	-1.31	-1.46	-1.39	-1.35	-1.45	-1.41	-1.38	-1.45
MaxCDD	6	11	3	8	12	6	9	13	7

Parameters	4-Month Drought			12-Month Drought			Overall Avg
	Avg	Max	Min	Avg	Max	Min	
n_M	50	60	29	47	54	31	51
n_S	21	26	12	20	25	10	19
n_E	4	6	1	5	8	1	4
TDD	76	89	42	73	86	42	75
M%	11.5	12	11	11.4	14	11	12
S%	4.9	5	5	4.7	5	4	4
E%	1.0	1	1	1.2	2	1	1
TDD%	17.3	18	17	17.3	18	17	17
DS	-108	-58	-127	-105	-57	-125	-105
DI_N	-0.25	-0.24	-0.25	-0.25	-0.25	-0.25	-0.24
DI_{TDD}	-1.42	-1.40	-1.44	-1.43	-1.38	-1.46	-1.41
MaxCDD	10	14	8	22	24	20	11

7.6 Assessment of Drought Years of Nepal

The following criteria were applied while determining the drought years of Nepal.

1. The average of all drought indices (i.e., both positive and negative values) of each duration (e.g., for SPI-1: each of 516 months) of all locations (e.g., for SPI-1: 179 precipitation stations) were calculated. Then, their average over a given year was determined. It gives the drought year.
2. Calculate the TDD-based drought intensity.
3. Decide the drought type based on this drought intensity.

Meteorological Drought Years and Associated Climate

Precipitation data from 179 rain gauge stations are used in this study to calculate SPI. To calculate SPEI and RDI, both data from precipitation and temperature stations are required which are only 62. To have greater spatial coverage, SPI indices have been used to explore the meteorological drought years of the country. Seasonal drought conditions are assessed and drought years are also categorized based on seasonal drought conditions. Knowledge of monsoon drought is important for agricultural purposes, and winter and pre-monsoon droughts are important for the hydropower sector. In this study, a year is said to be a drought year, if the average of the SPIs of all 179 stations is less than -1.0. If SPI values lie in between -1.5 and -1.0, the year is termed a moderate drought year, if it lies between -2.0 and -1.5, it is termed a severe drought year and if its value is less than -2.0, the year is termed as an extreme drought year. Both winter and pre-monsoon seasons are of 3 months, the winter drought year was explored from SPI-3 for February (SPI-3: DJF). Similarly, the pre-monsoon drought year was also extracted from SPI-3 for May (SPI-3: MAM). Monsoon season, being 4 months, monsoon drought year was assessed from SPI-4 for September (SPI-4: JJAS). The post-monsoon drought year was decided based on SPI-2 for November (SPI-2: ON).

Winter Drought Years

The average SPI-3 for February is plotted against the year in **Figure 7-2**. From this figure, it can be seen that on average, Nepal experienced six winter drought years in the last 42 years (1981- 2022). They are 1999, 2006, 2008, 2018 and 2021. However, it is mentioned here that drought years may differ from these years for a particular location (gauging site). The average SPI values, the TDD, number of stations out of 179 with Extreme Wet (SPI >2.0), Severe Wet (1.5<SPI=<2.0), Moderate Wet ((1.0<SPI=<1.5), Normal (-1.0<SPI<=1.0), Moderate Drought (-1.5<SPI=<-1.0), Severe Drought (-1.5<SPI =<-2.0) and Extreme Drought (< -2.0) were calculated (**Table 7-24**). Here, it can also be seen that TDD and average SPI exhibit inverse relations in general. Although there are almost no stations with wet conditions in these years and there is a significant number of stations with severe drought, the SPI values of a significant number of stations under normal conditions moderated the overall SPI value. It resulted in the average value of SPI-3 in between -1.5 and -1.0; falling these drought years under the moderate drought years.

Pre-monsoon Drought Year

The average SPI-3 for May is plotted against year in **Figure 7-3**. There is only one pre-monsoon drought year (1996) in Nepal.

Monsoon and Post-monsoon Drought Years

The average SPI-4 for September is plotted against the year in **Figure 7-4**. Similarly, the average SPI-2 for November is plotted against the year in **Figure 7-5**. No drought years were found for monsoon and post-monsoon based on the criteria discussed above for Nepal.

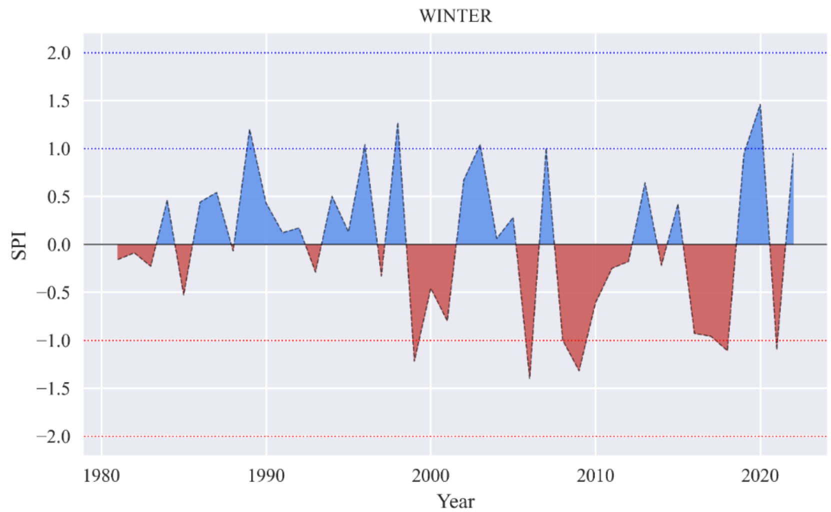


Figure 7-2 Average SPI-3 for winter of Nepal

Table 7-24 Seasonal drought years of Nepal

Year	Avg-SPI3	TDD	TWD	Normal	Ext-Wet	Sev-Wet	Mod-Wet	Normal	Mod-Drought	Sev-Drought	Ext-Drought
Winter Drought Years											
1999	-1.22	139	0	40	0	0	0	40	113	25	1
2006	-1.40	168	1	10	0	1	0	10	108	55	5
2008	-1.00	111	1	67	0	0	1	67	98	13	0
2009	-1.32	160	0	19	0	0	0	19	120	40	0
2018	-1.11	133	1	45	0	0	1	45	120	13	0
2021	-1.10	137	1	41	1	0	0	41	123	13	1
Pre-monsoon Drought Years											
1996	-1.16	125	3	51	0	0	3	51	58	58	9

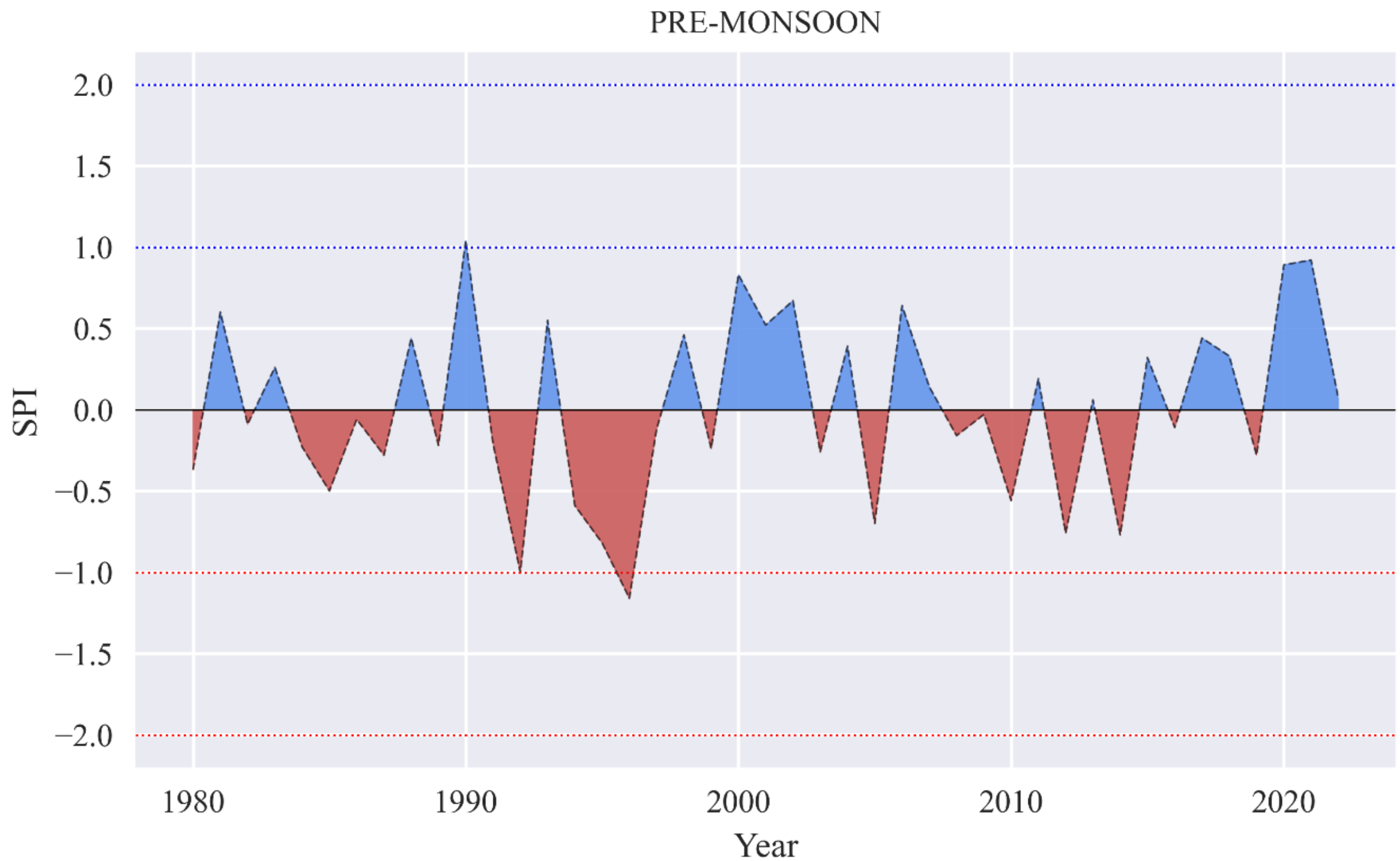


Figure 7-3 Average SPI-3 for pre-monsoon of Nepal

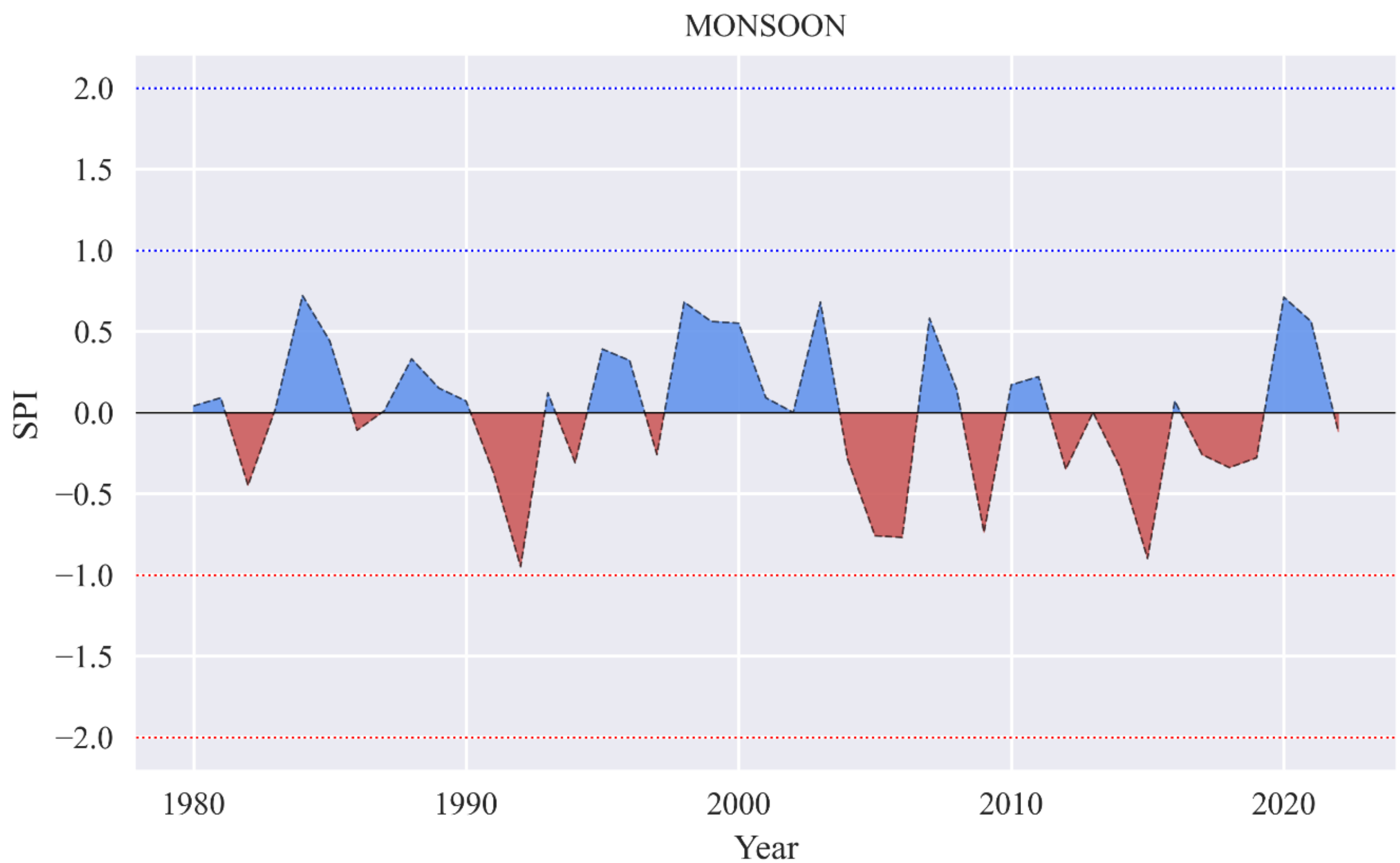


Figure 7-4 Average of SPI-4 for the monsoon of Nepal

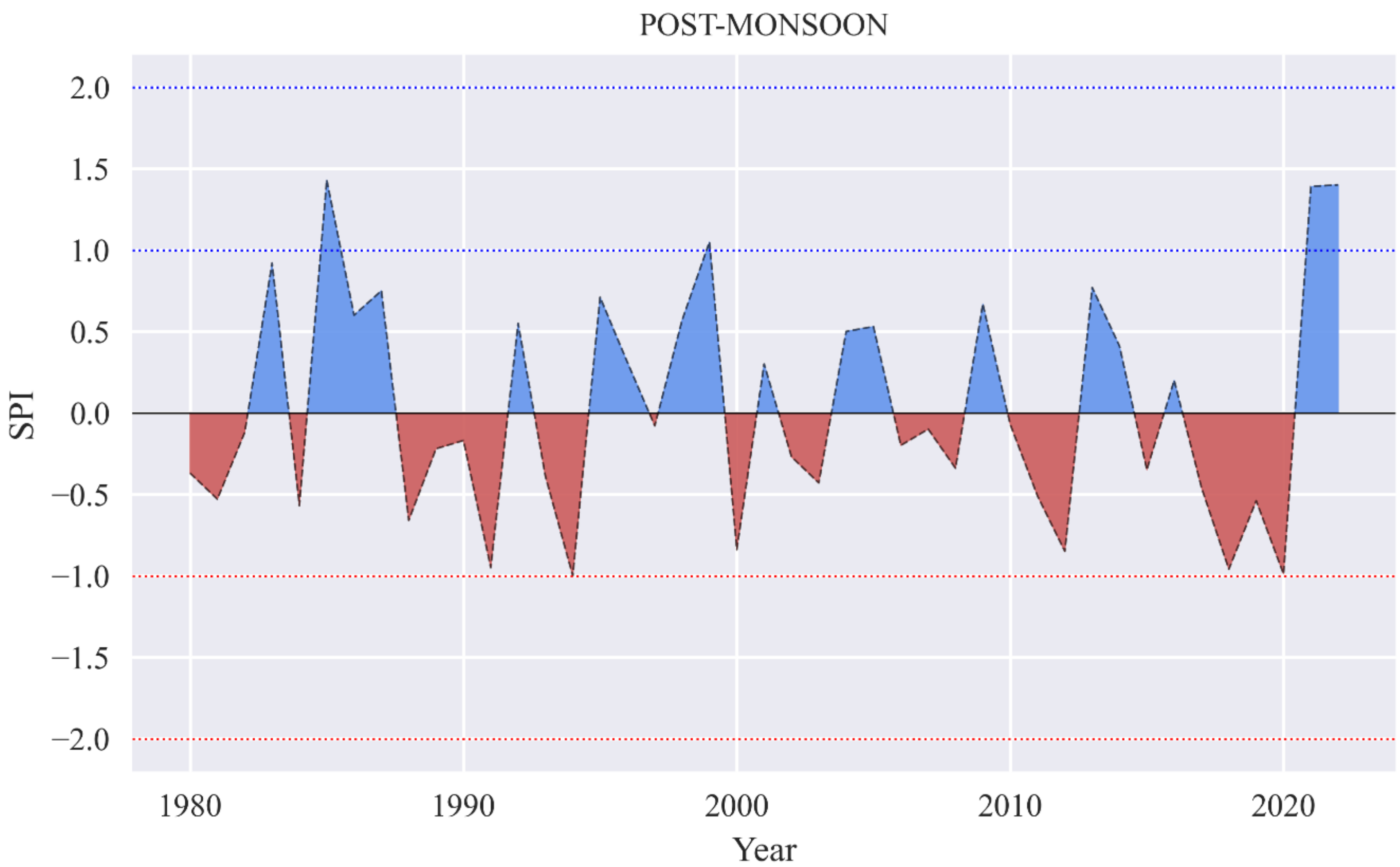


Figure 7-5 Average of SPI-2 for post-monsoon of Nepal

7.7 Field Verification of Drought

7.7.1 Locations of Field Visits

Field visits were made to assess the status of drought at various locations in the country. The location of field visits for the verification of drought is given in **Table 7-25** and shown in **Figure 7-6**.

Table 7-25 Location of field visits for the verification of drought

SN	District	Municipalities	Ward	Latitude	Longitude
1	Achham	Mangalsen	14	29.18333	81.36667
2	Achham	Bannigadhi Jayagadh	2	29.33333	81.40000
3	Achham	Turmakhad	3	29.53333	81.73333
4	Baitadi	Diasaini	6	29.65000	80.53333
5	Baitadi	Patan	6	29.76667	80.90000
6	Baitadi	Dashrathchand Municipality	5	29.91667	80.68333
7	Banke	Raptimari Rural Municipality	1	28.00000	82.00000
8	Banke	Nepalgunj Sub Metrpolitian Municipality	9	28.04902	81.62480
9	Banke	Rapti Sonari Rural Municipality	9	28.19257	81.77343
10	Banke	Kohalpur Municipality	13	28.20283	81.71851
11	Bara	Nijgadh Muncipalty	11	27.24670	85.10473
12	Bardiya	Barbardiya Municipality	2	28.35111	81.31765
13	Bardiya	Basghadi Municipality	1	28.35122	81.71641
14	Bardiya	Rajapur Municipality	4	28.43013	81.09411
15	Chitwan	Madi Municipality	3	27.45526	84.31845
16	Chitwan	Ichchhakamana Rural Municipality	7	27.72874	84.54379
17	Dang	Babali Rural Municipality	4	28.19000	82.13000
18	Ilam	Mai Municipality	2	26.76465	87.85679
19	Ilam	Suryodohya Municipality	11	26.88680	88.03784
20	Ilam	Ilam Municipality	5	26.94751	87.92087
21	Janakpur	Jankpurdham Sub-metropolitian City	12	26.71682	85.92991
22	Jhapa	Bhadrapur Municiplaity	9	26.59355	88.07496
23	Jhapa	Shivasatakshi Municipality	10	26.65806	87.86675
24	Kailali	Tikapur	9	28.75000	81.08333
25	Kailali	Tikapur	3	28.88333	81.18333
26	Kailali	Godawari	4	29.35000	80.95000
27	Kathmandu	Tarakeshwor	2	27.78881	85.30557
28	Mahottari	Pipra Rural Municipality	3	26.68319	85.85933
29	Morang	Birathnagar Metropolitan City	4	26.48717	87.27569
30	Nawalparasi East	Madhya-Bindu Municipality	15	27.58058	83.99332
31	Rautahat	Yemunamai Rural Municipality	4	26.82629	85.30584
32	Rautahat	Madav Narayan Municipality	8	26.87970	85.35038
33	Rautahat	Gadimai Municipality	3	26.93740	85.36875
34	Rupandehi	Titotama Municipality	14	27.58400	83.43756

SN	District	Municipalities	Ward	Latitude	Longitude
35	Saptari	Surunga Municipality	6	26.68558	86.54665
36	Sarlahi	Bagmati Municipality	2	27.10173	85.51964
37	Sindhuli	Kamalamai Municipality	13	27.08479	85.99094
38	Sindhuli	Marin Rural Municipality	2	27.27882	85.63050
39	Siraha	Siraha Municipality	15	26.61388	86.15578
40	Sunsari	Baju Rural Municipality	5	26.45724	87.18975
41	Surkhet	Lekhbesi Municipality	4	28.49000	81.76000
42	Udayapur	Katari Municipality	6	26.93423	86.42865
43	Udaypur	Belaka Municipality	7	26.89250	87.13284
44	Udaypur	Gadimai Municipality	5	26.93872	85.52100
45	Udaypur	Rautamai Rural Municipality	2	26.99926	85.66042

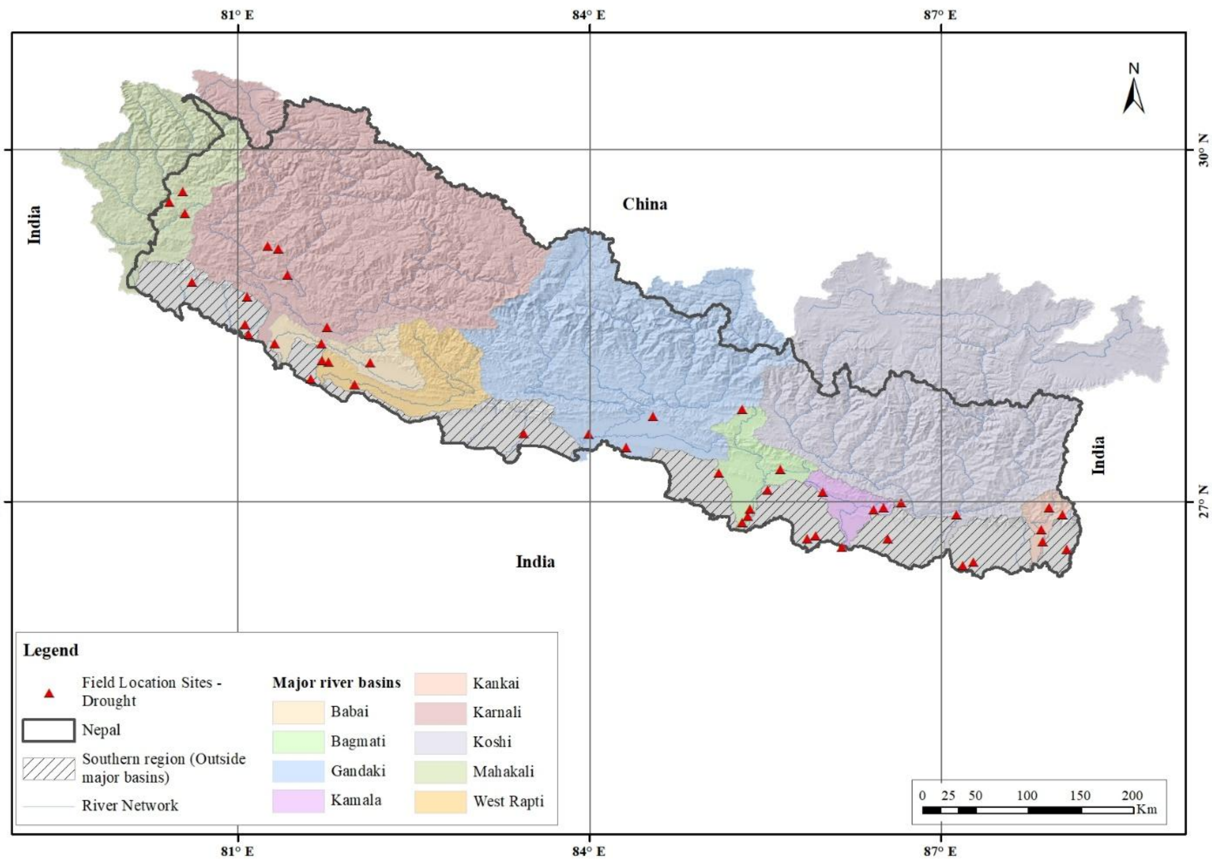


Figure 7-6 Location of field visits for the verification of drought

7.7.2 Sample Field Experiences

Marin Rural Municipality-Ward No 2

Marin Rural Municipality is one of the municipalities of the Sindhuli District. It lies in the Marin River basin which is a sub-basin of the Bagmati River basin. Its population is 28,808 with a population density of 89 per km^2. There are a total of 6,044 households in this municipality. The literacy rate of the municipality is only 68.3%. There are 7 wards in this municipality. Ward 2 was visited for field verification and to assess the drought conditions over there. The population of this ward as per the 2021 Census is 4,547.

According to the ward chairman of Ward Number 2 of the Marin Rural Municipality (**Figure 7-7**) and locals, their location has been experiencing dry climatic conditions due to rising temperatures and decreasing rainfall; this year they had the highest temperature they ever experienced. The locals said that they had been experiencing decreasing rainfall and increasing temperatures once every two years. It resulted in agricultural losses, a decrease in water level in the wells, decreased water availability in drinking water sources, and significantly reduced crop production. Even in the bazaar area, a couple of shopkeepers said that their sales had been reduced as people were not coming out of their homes due to the severe heat. They said that this year's hotness was the highest, maybe after 30 or 32 years.

Figure 7-7 Marin Rural Municipality-2

Kamalamai Municipality-Ward No 13

Kamalamai is one of the municipalities of the Sindhuli district, lying in the Kamala River basin. The population of Kamalamai is 71,016, with a population density of 147 per km^2. The total households in the municipality are 18,016. The literacy rate of this municipality is 77.8%. There are 14 wards in this

municipality. Ward No. 13, which was visited to verify the drought conditions and interact with the local representatives, has a population of 2,258 as per the CBS Census 2021.

According to locals, Kamalamai municipality has been experiencing dry climatic conditions. It is mainly due to high temperatures in recent years and decreased rainfall. They also said that this year has been the year of the highest temperature of their lifetime. A decrease in agricultural productivity and the drying up of some of the drinking water sources are a few examples of the impacts they had to experience in this ward too. However, in the area where an irrigation facility exists, the maize crop was found in quite good condition. It shows that the drought problem exists in locations where agriculture depends on rainfall.

Figure 7-8 Kamalamai Municipality -13

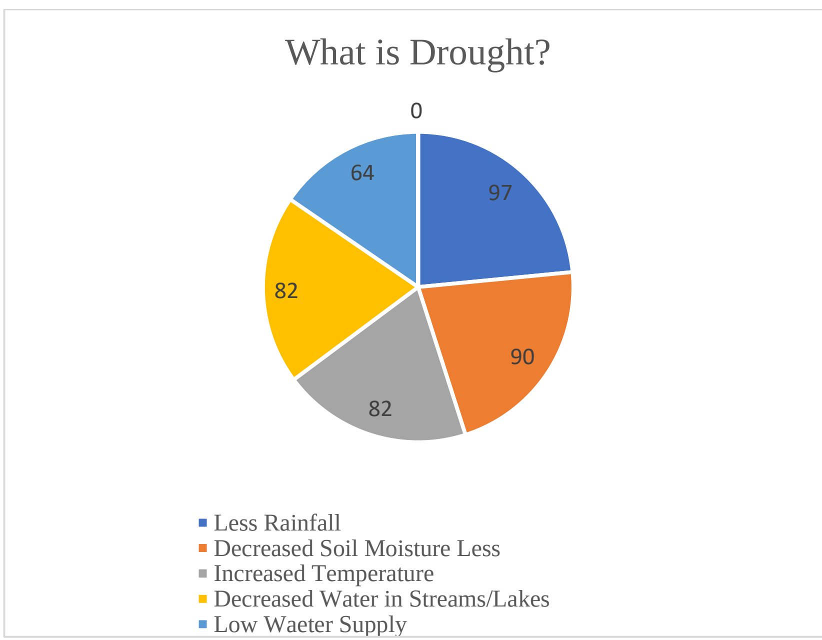
7.7.3 Analysis of Survey Data

During the field visits, a questionnaire survey was also carried out with local representatives from 45 locations. Very simple questions were asked to assess their understanding of what exactly drought is for

them, its causes, frequency, and effects in their localities. The questionnaire used for the survey is given in **Appendix E** (**Table E-2**).

i. Understanding of Drought

Almost all local respondents believed that drought occurs when an area receives less rainfall than usual at the required time (**Figure 7-9**). They also expressed the view that decreased soil moisture, increased temperatures, reduced water levels in streams and lakes, and consequently low water supply conditions are additional indicators of drought.



Unit: Percentage

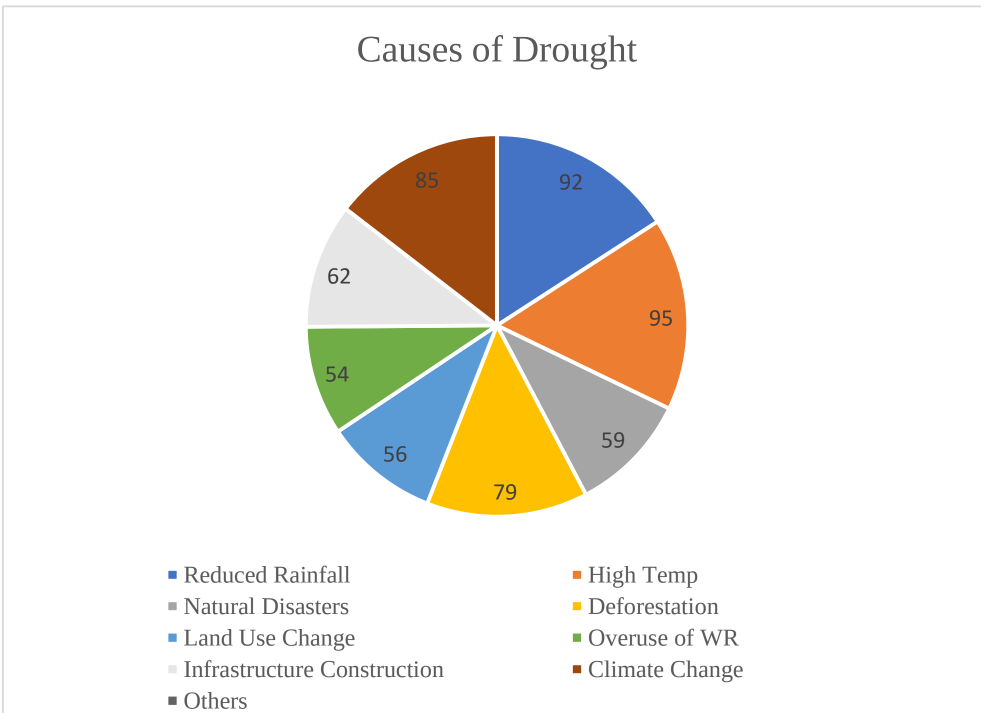
Figure 7-9 Understanding of drought

ii. Cause of Drought

The primary reason for the drought, according to the inhabitants, is decreased precipitation coupled with rising temperatures. Additionally, people believe the drought is influenced by factors such as earthquakes, deforestation, altered land use, and excessive water consumption. Many also attribute climate change as a significant contributing factor to this phenomenon. The total points assigned to each drought cause are visualized in **Figure 7-10**.

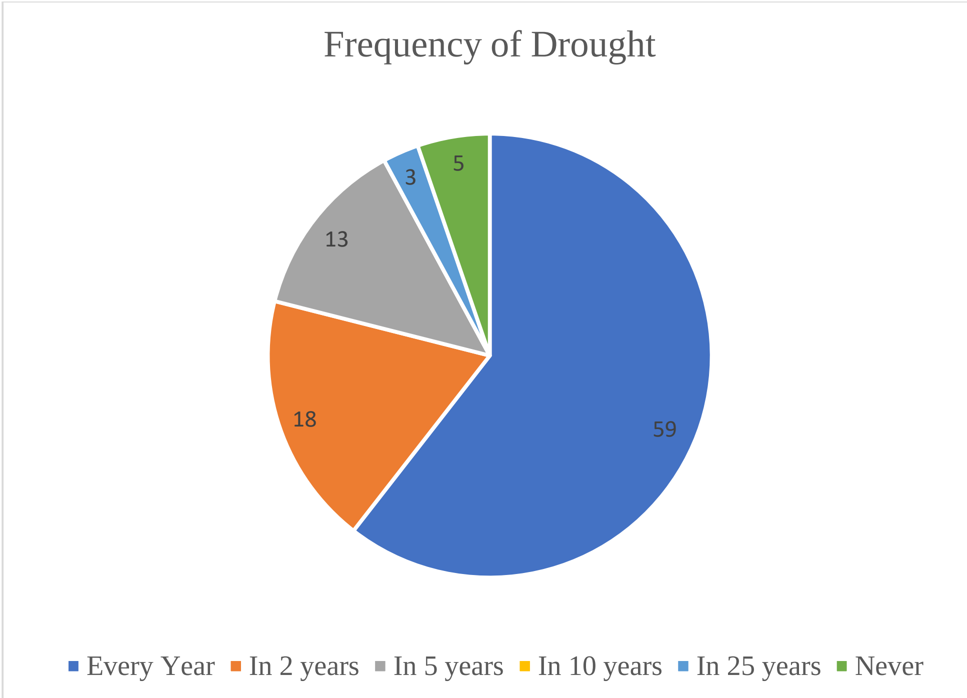
iii. Frequency of Drought

Almost two-thirds of the respondents reported experiencing drought every year, while one-fifth stated that it occurred once every two years. In some locations, however, the respondents mentioned that they had not experienced the effects of drought at all (**Figure 7-11**).



Unit: Percentage

Figure 7-10 Causes of drought



Unit: Percentage

Figure 7-11 Frequency of drought

iv. Damage by the Drought

About the question on damage assessment of the locals by the drought events in different sectors, a damage scale of 1 to 5 was assigned, 5 for very high level of damage and 1 for very low level of damage. The severity of damage is, then, categorized as given in **Table 7-26**.

Table 7-26 Severity of damage as per local representative

Range	Severity of Damage
<2	Mild
2 to < 3	Moderate
3 to <4	Severe
>4	Extreme

Based on these criteria, the extreme impact of drought felt by the locals was on agriculture and drinking water (**Table 7-27**). In other sectors, the impact is considered as mild to moderate.

Table 7-27 Impacts of drought as per local representative

SN	Kinds of Loss	Degree of Damage	Priority Rankings
1	Agriculture Loss	Extreme	4.67

2	Drinking water sources	Extreme	4.28
3	Energy Availability	Moderate	2.62
4	Disease and Health	Moderate	2.72
5	Loss of Animal	Moderate	2.46
6	Loss of Human	Mild	1.79
7	Loss of Properties	Moderate	2.38
8	Migration	Moderate	2.08
9	Others	Mild	0.79

CHAPTER 8: HYDROLOGICAL MODELING

8.1 General Background

A hydrologic model is a simplification of a real-world hydrological system. It is used to simulate the hydrological processes of a river basin, allowing for a better understanding of the cause-and-effect relationship between climatic factors and the bio-physical environment. Another main use of hydrological models is to predict basin hydrology in relation to potential changes in climatic and physical factors.

There are various types of hydrological models available for simulation, including those categorized by spatial discretization (lumped, semi-distributed, or fully distributed) and by process description (empirical, conceptual, or physical). In a lumped model, spatial variability is disregarded, treating the entire basin as one unit. In contrast, a distributed model is data-intensive and requires significant computational time. Semi-distributed models are variations of lumped models that incorporate some features of distributed models. Due to the lack of data required for fully distributed models and the need to address spatial variability, the semi-distributed Soil and Water Assessment Tool (SWAT) model, which includes the following features, was chosen for hydrological modeling in this study.

(i) **River Basin Approach**: SWAT operates on a river basin scale, dividing it into sub-basins and further into hydrological response units (HRUs), allowing for a detailed representation of land use, soil, and topographic characteristics.

(ii) **Integration of Multiple Hydrological Processes**: SWAT incorporates various hydrological processes.

(iii) **Consideration of Land Use and Land Cover Dynamics**: SWAT can account for land use and land cover changes and their effects on hydrological processes.

(iv) **Use in Climate Change Impact Studies**: SWAT can be used to assess the impact of climate change on river hydrology, incorporating projected future climate data.

(v) **User-Friendly Interface**: SWAT features a user-friendly interface.

(vi) **Open-Source Software**: SWAT is open-source software.

The workflow of the SWAT model is shown in **Figure 8-1**. SWAT simulates the various hydrological processes occurring in the river basin based on water balance calculations as given in **Equation (8-1)**:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (8\text{-}1)$$

Where SW_t is the final soil water content (mm), SW_0 is the initial soil water content (mm), t is the time in days, R_{day} is the amount of precipitation on the day i (mm), Q_{surf} is the amount of surface runoff on the day *i* (mm), E_a is the amount of evapotranspiration on the day i (mm), W_{seep} is the amount of water entering the vadose zone from soil profile on the day *i* (mm) and Q_{gw} is the amount of return flow on the day *i* (mm).

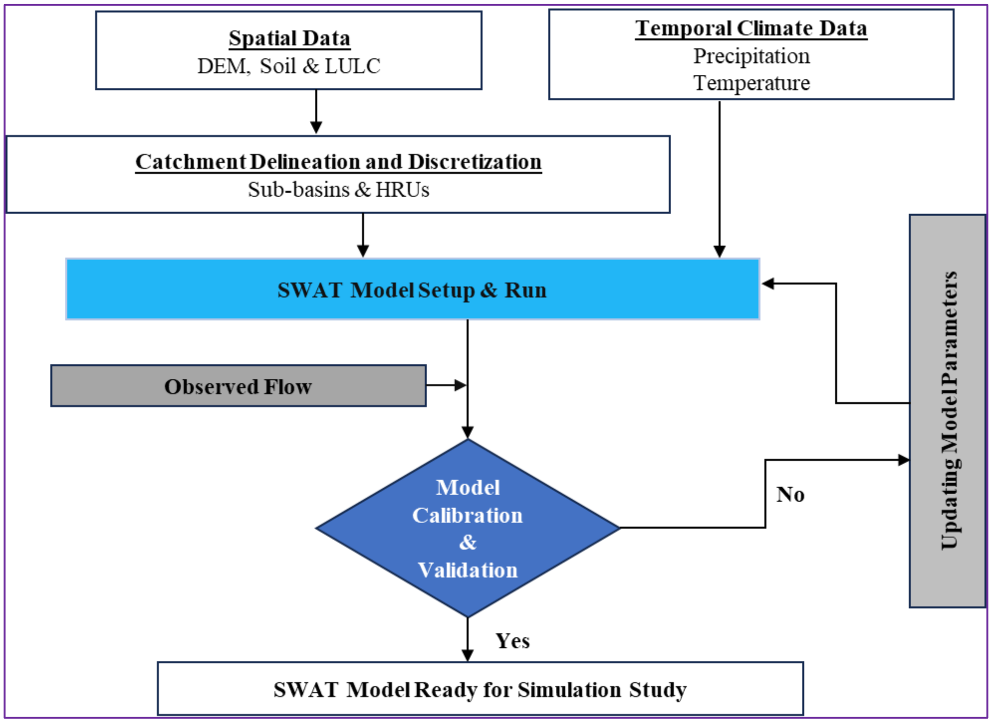


Figure 8-1 Workflow of SWAT hydrological model.

8.2 Major Steps in Hydrological Modeling

The major steps in modeling with SWAT are: (a) watershed delineation, (b) preparation of spatial input data (e.g., land use, soil, and slope classes), (c) preparation of temporal climate data (e.g., rainfall, temperature, etc.), (d) generation of hydrological response units (HRUs), (e) model initialization, (f) calibration and validation, and (g) application (i.e., to generate flow at different nodes). The steps followed in this study are briefly discussed below.

8.2.1 Watershed Delineation

The river networks, sub-basins, and outlets were generated in the SWAT platform within the GIS environment using the SRTM Digital Elevation Model (DEM). In addition to the auto-generated outlets at the river, DHM hydrological stations were manually added for the multi-site calibration of the model. The sub-basins delineated for the Karnali, Gandaki, Koshi, Chamelia (Mahakali), Babai, West Rapti, Bagmati, Kamala, and Kankai Basins are shown in **Figure 8-2**, **Figure 8-3**, **Figure 8-4**, **Figure 8-5**, **Figure 8-6**, **Figure 8-7**, **Figure 8-8**, **Figure 8-9** and **Figure 8-10** respectively.

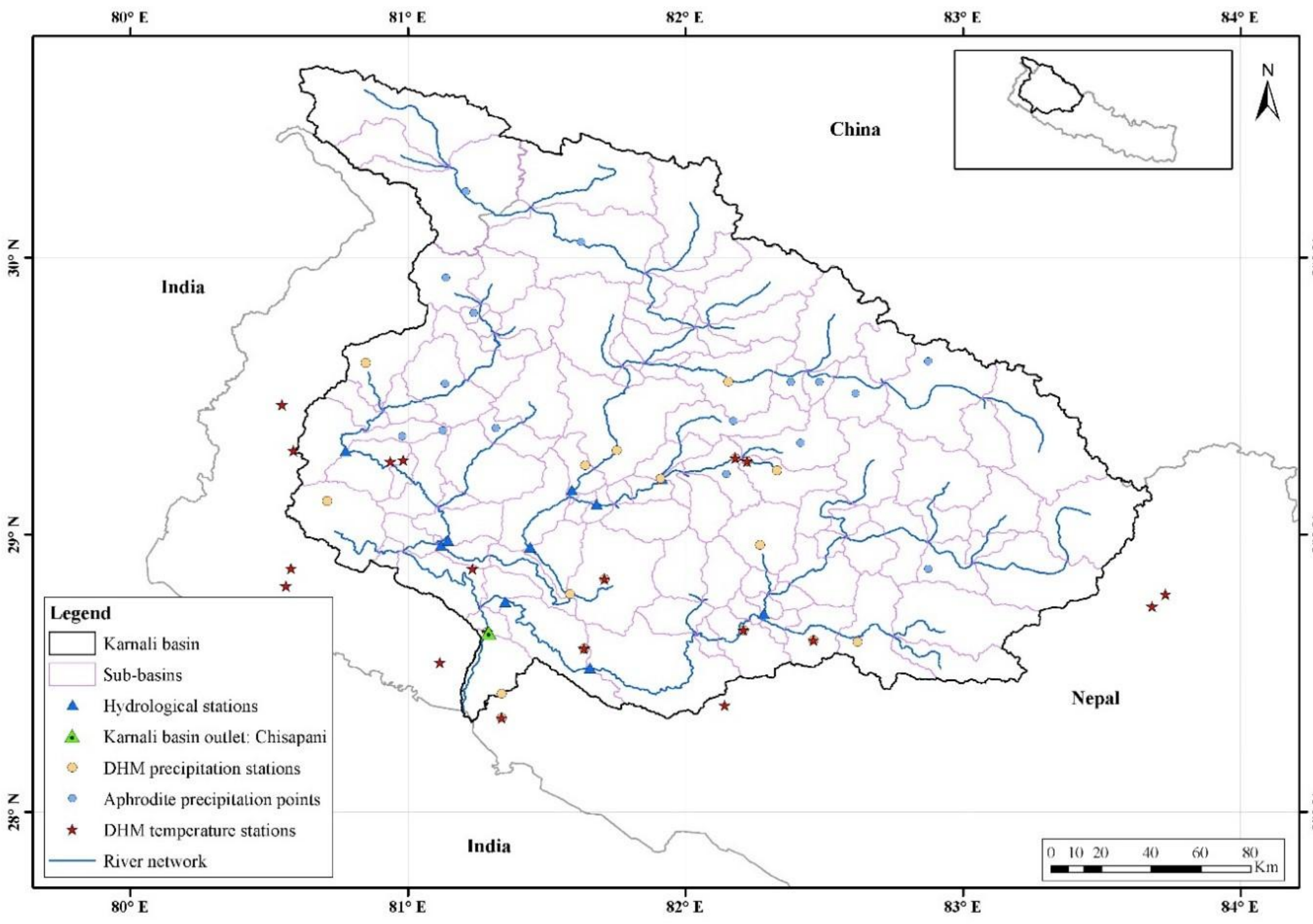


Figure 8-2 Delineated sub-basins of Karnali River Basin for SWAT modeling

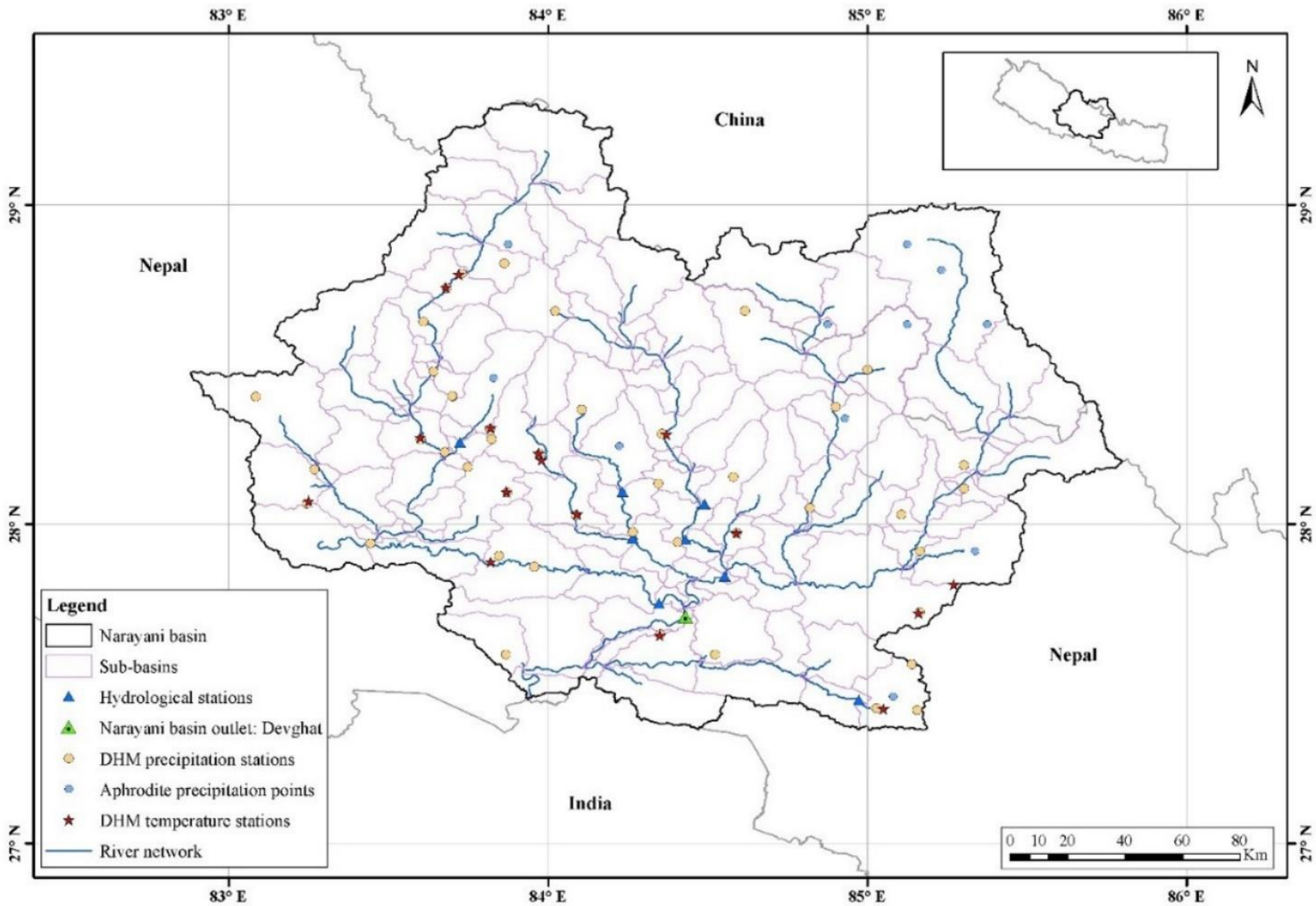


Figure 8-3 Delineated sub-basins of Gandaki River Basin for SWAT modelling

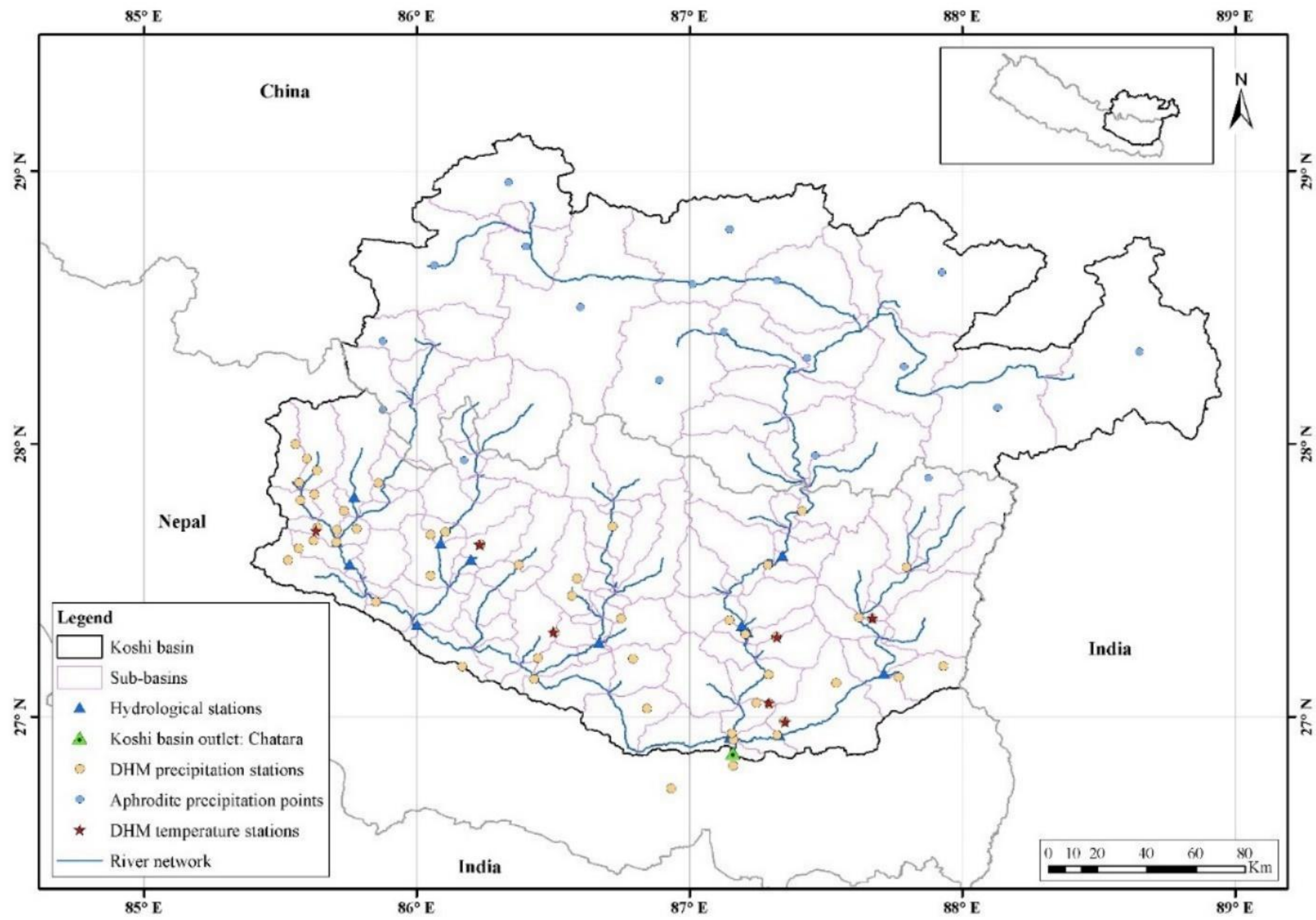


Figure 8-4 Delineated sub-basins of Koshi River Basin for SWAT modeling

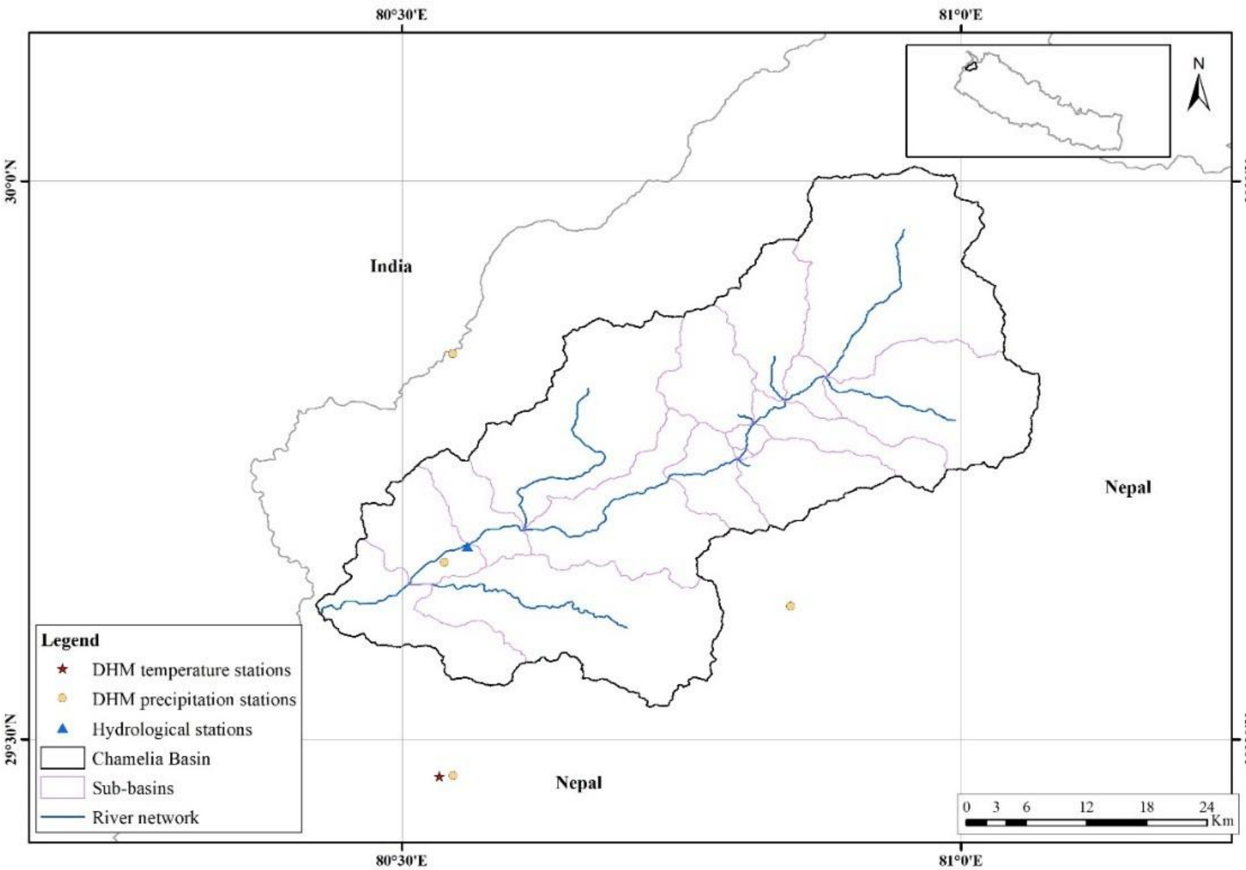


Figure 8-5 Delineated sub-basins of Chamelia River Basin for SWAT modeling

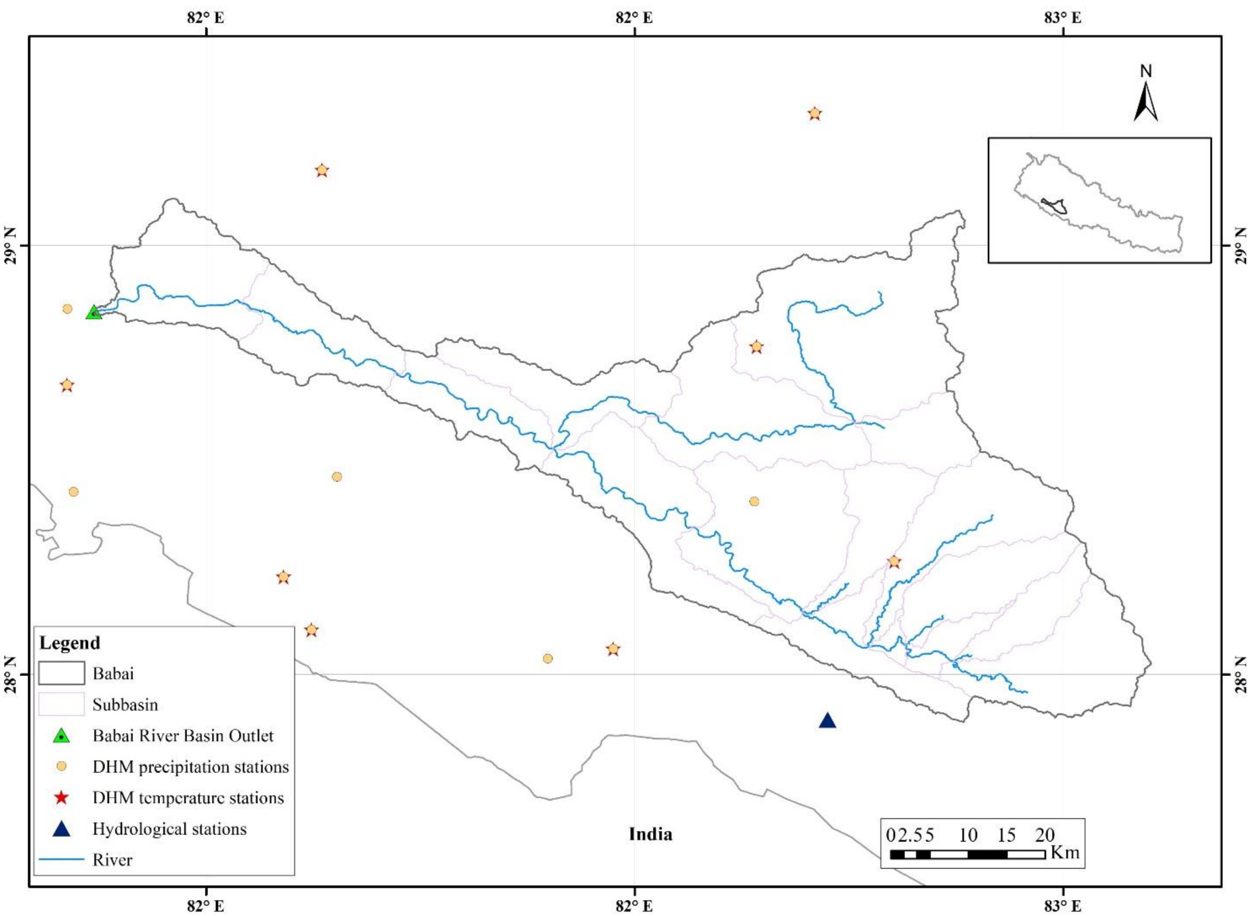


Figure 8-6 Delineated sub-basins of Babai River Basin for SWAT modeling

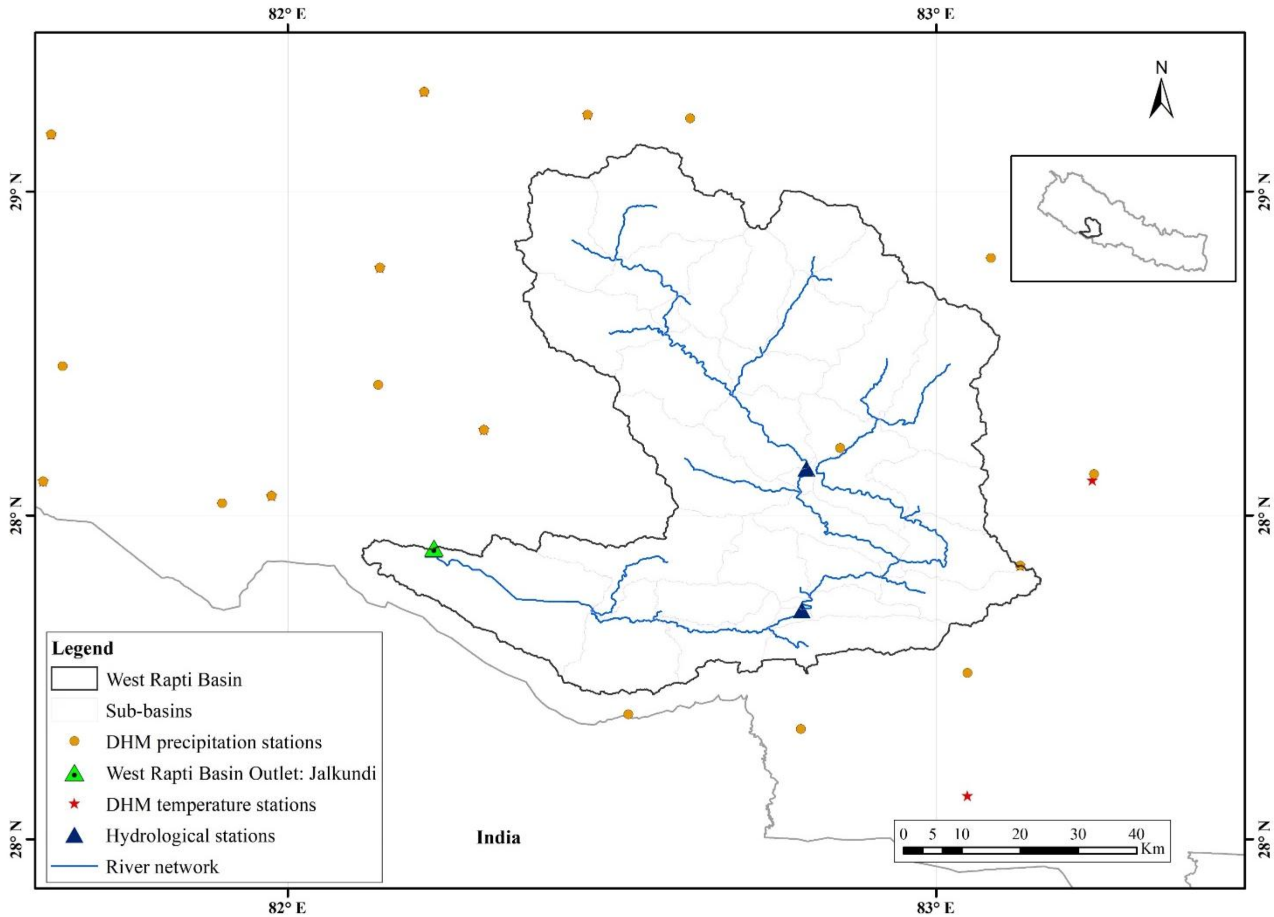


Figure 8-7 Delineated sub-basins of West Rapti River Basin for SWAT modeling

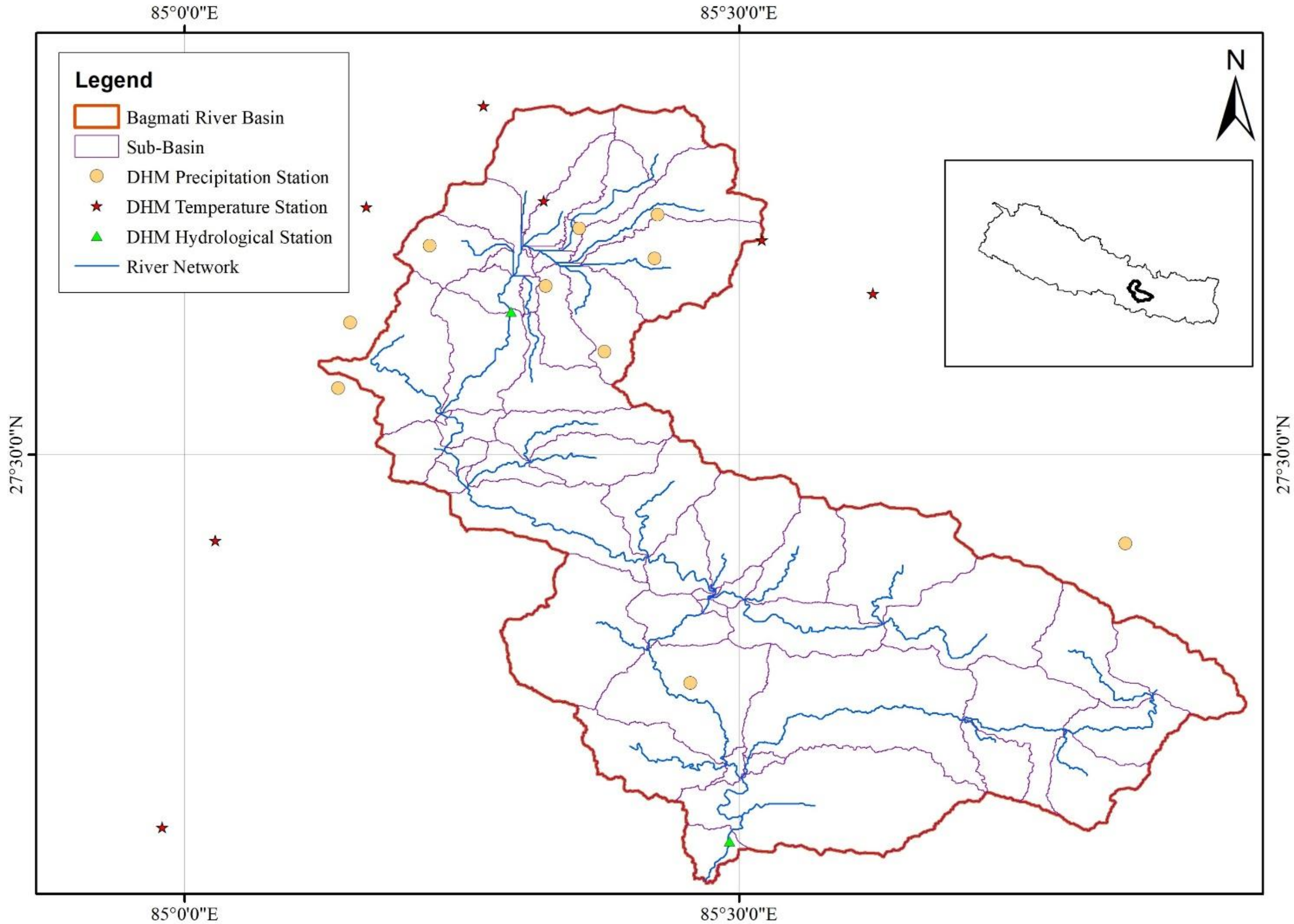


Figure 8-8 Delineated sub-basins of Bagmati River Basin for SWAT modeling

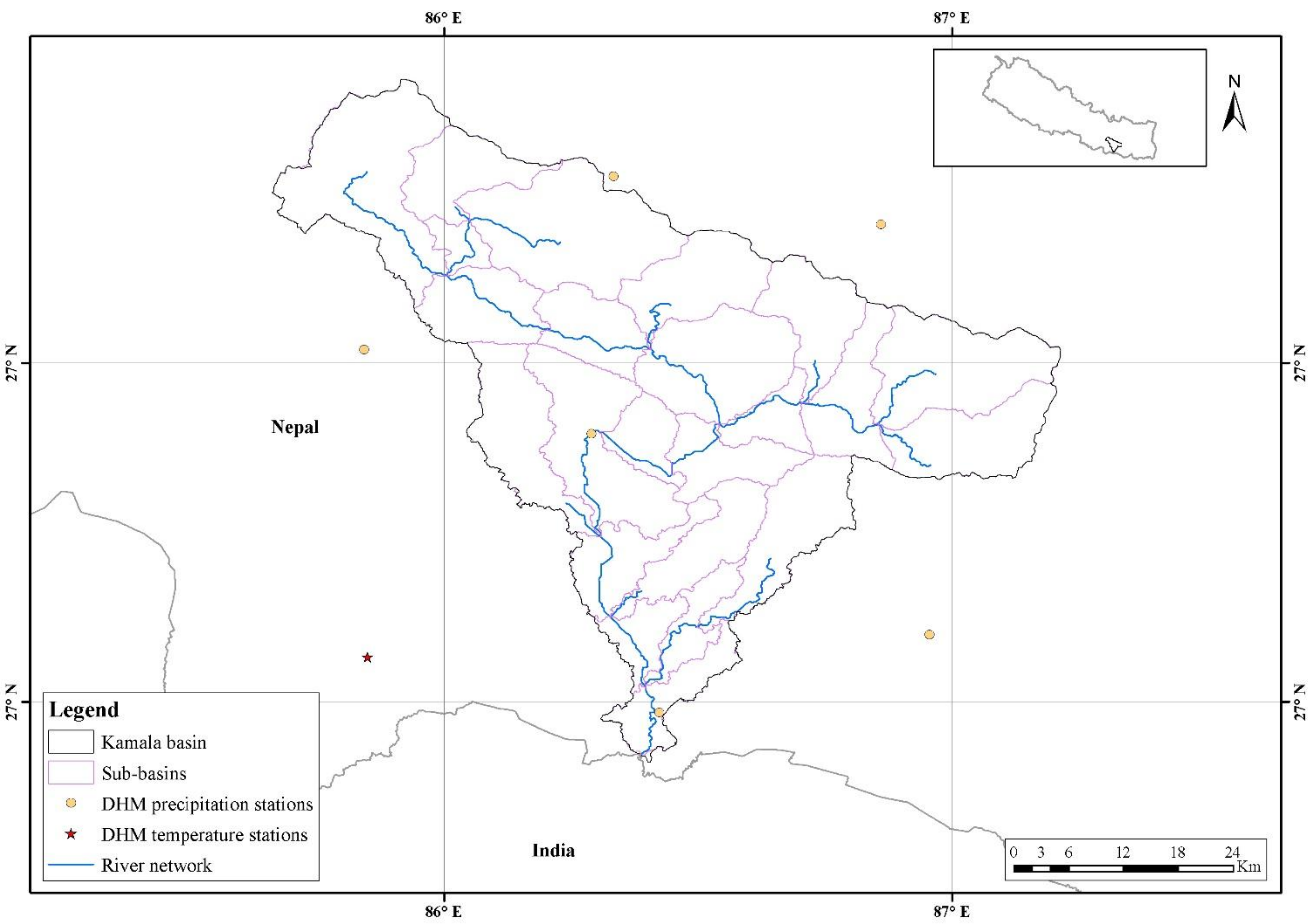


Figure 8-9 Delineated sub-basins of Kamala River Basin for SWAT modeling

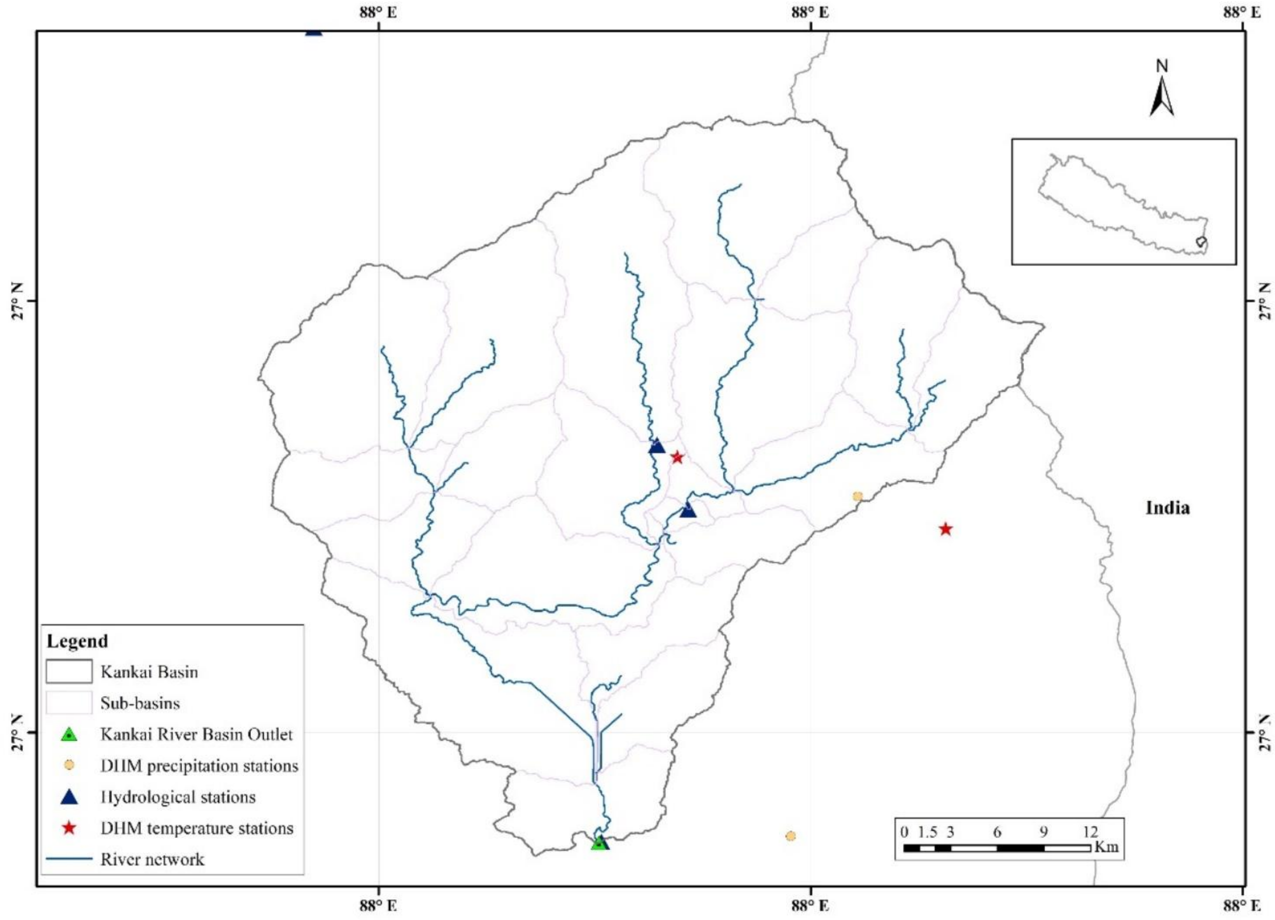


Figure 8-10 Delineated sub-basins of Kankai River Basin for SWAT modelling

8.2.2 Preparation of Soil, Land-use, and Slope Data

The general land use land cover and soil status in the basin are presented in **Table 8-1**. The slope raster for the model was generated from the DEM and five classes of slope were categorized based on the quantile method of classification**.**

Table 8-1 Details of the hydrological model setup for selected basins

SN	Basin Name	Number of Sub-basins	Number of HRUs	Basin Area (km^2)	Temporal Extent of Model	Warm-up Period (Years)	Slope Classes (%)	Soil Types	LULC Types
1	Koshi	123	2051	53,979	**1980-2019**	2	0-16 16-31 31-45 45-62 >62	• Chromic CAMBISOLS • Chromic LUVISOLS • Dystric REGOSOLS • Eutric CAMBISOLS • Eutric REGOSOLS, etc.	• Snow (only for Karnali, Gandaki, Koshi and Chamelia) • Water body • Forest • Cropland • Built-up-areas • Barren land • Grassland etc.
2	Narayani	135	2191	36,092			0-23 23-39 39-54 54-72 >72		
3	Karnali	104	2001	45,718			0-27 27-44 44-57 57-74 >74		
4	Chamelia	16	344	1,587			0-40 40-57 57-73 73-94 >94		
5	Babai	17	192	2,973			0-5 5-15 15-35 35-55 >55		
6	West Rapti	31	392	5,264			0-5 5-25 25-45 45-65 >65		
7	Bagmati	54	609	2,656			0-13 13-28 28-44 44-65 >65		
8	Kamala	23	299	2,188			0-6.5 6.5-15 15-30 30-45 >45		

SN	Basin Name	Number of Sub-basins	Number of HRUs	Basin Area (km^2)	Temporal Extent of Model	Warm-up Period (Years)	Slope Classes (%)	Soil Types	LULC Types
9	Kankai	23	279	1,163			0-7.6 7.6-27.2 27.2-39.1 39.1-53.3 >53.3		

8.2.3 Climate Data in SWAT

The climate variables: precipitation, maximum temperature and minimum temperature were used to define the climate system within the SWAT model. The daily climate series was used for the time period of 1980-2019.

8.2.4 Definition of Hydrologic Response Units

Hydrologic Response Units (HRUs) are the smallest spatial component of the SWAT model and represent a unique combination of land-use, soil and slope class. SWAT enables users to define the thresholds for land use, slope classes, and soil types for the formation of HRUs in order to improve simulation computing efficiency while preserving the essential landscape characteristics of a watershed during the hydrological modeling process (Kalcic et al., 2015; Her et al., 2015). With a threshold of 10% for each of the building blocks of HRUs, the HRUs were generated across the watershed and the counts of these units are given in **Table 8-1**.

8.2.5 Model Initialization, Calibration and Validation

Hargreaves's equation was used in this study to calculate potential evapotranspiration. Simulations were carried out at daily time steps, with the calibration and validation periods for each basin varying based on data availability. They are:

Koshi Basin at Chatara:

Calibration: 01/01/1999 - 12/31/2005 & Validation: 01/01/2006 - 12/31/2012

Gandaki Basin at Devghat:

Calibration: 01/01/2006 - 12/31/2010 & Validation: 01/01/2011 - 12/31/2014

Karnali Basin at Chisapani:

Calibration: 01/01/1990 - 12/31/1998 & Validation: 01/01/1999 - 12/31/2007

Chamelia Basin at Nayalbadi:

Calibration: 01/01/2001 - 12/31/2008 & Validation: 01/01/2009 - 12/31/2015

Kankai Basin at Mainachuli:

Calibration: 01/01/2000 - 12/31/2005 & Validation: 01/01/2006 - 12/31/2010

Bagmati at Padheredovan:

Calibration: 01/01/2002 - 12/31/2009 & Validation: 01/01/2010 - 12/31/2016

West Rapti at Kusum:

Calibration: 01/01/2003 - 12/31/2009 & Validation: 01/01/2010 - 12/31/2016

Babai at Chepang:

Calibration: 01/01/2001 - 12/31/2005 & Validation: 01/01/2006 - 12/31/2008

Since Kamala River Basin does not have a hydrological station, it was not possible to calibrate and validate the SWAT model for this basin. Instead, model parameters from the nearby Kankai Basin were borrowed to simulate the flow for this basin.

8.2.6 Model Performance Evaluation

Model performance evaluation for calibration and validation was conducted (i) through visual inspection of hydrographs, scatter plots, and flow duration curves (FDCs) to assess how closely the simulated results matched the observed flows, and (ii) through quantitative evaluation of the model results. For quantitative evaluation, four widely used statistical measures were employed in this study: Nash-Sutcliffe Efficiency (NSE), Kling-Gupta Efficiency (KGE), Percent Bias (PBIAS), and the Coefficient of Determination (R^2). The recommended performance rating statistics for the simulated results are provided in **Table 8-2**.

Table 8-2 Recommended general performance ratings statistics for hydrological modeling

Performance Rating	NSE	KGE	PBIAS	R^2
Very Good	$0.75 < NSE \leq 1.0$	$0.75 < KGE < 1.0$	$PBIAS \leq \pm 10$	$0.75 < R^2 \leq 1.0$
Good	$0.65 < NSE \leq 0.75$	$0.50 < KGE < 0.75$	$\pm 10 \leq PBIAS \leq \pm 15$	$0.65 < R^2 \leq 0.75$
Satisfactory	$0.50 < NSE \leq 0.65$	$0.0 < KGE \leq 0.5$	$\pm 15 \leq PBIAS \leq \pm 25$	$0.50 < R^2 \leq 0.65$
Unsatisfactory	$NSE \leq 0.50$	$KGE \leq 0$	$PBIAS \geq \pm 25$	$R^2 \leq 0.50$

Source: Moriasi et al. (2007), Gupta et al. (2009), Ewen (2011), Todini & Biondi (2017), Gupta and Kling (2011)

8.3 Model Performance

8.3.1 Model Performance for Koshi River Basin

The discharge data from hydrological stations 604.5 (Turkeghat), 606 (Simle), 610 (Barhbise), 629.1 (Dolalghat), 630 (Pachuwarghat), 647 (Busti), 650 (Rasnalu), 652 (Khurkot), 681 (Hampachuwar), 684 (Majhitar), and 695 (Chatara) were used to calibrate and validate the SWAT model for the Koshi River

Basin. The NSE, PBIAS, R^2, and KGE values for both the calibration and validation periods at each site are presented in **Table 8-3**.

These results demonstrate that the model is well-calibrated, highlighting its excellent ability to capture the hydrological dynamics of the Koshi Basin and its sub-basins. In **Figure 8-11**, shows the hydrograph, FDC, and scatter plot for hydrological station 695, which represents the primary outlet of the basin at Chatara.A visual examination of the hydrographs and flow duration curves (FDCs) further confirms that the model performs reasonably well in estimating both high and low flows.

However, the model still underestimates high flows to some extent. Despite this limitation, the developed SWAT model is sufficiently robust to effectively simulate the hydrology of the Koshi River Basin.

Table 8-3 Model performance for Koshi River Basin

SN	Station no.	Location	Period	NSE	PBIAS (%)	R^2	KGE
1	604.5	Turkeghat	Calibration	0.79	-9.0	0.80	0.68
			Validation	0.70	-14.4	0.72	0.61
2	606	Simle	Calibration	0.77	-7.8	0.80	0.78
			Validation	0.73	9.3	0.76	0.68
3	610	Barhbise	Calibration	0.73	14.9	0.76	0.71
			Validation	0.69	16.9	0.73	0.67
4	629.1	Dolalghat	Calibration	0.71	-0.6	0.77	0.75
			Validation	0.52	-26.7	0.86	0.66
5	630	Pachuwarghat	Calibration	0.79	6.9	0.81	0.75
			Validation	0.84	3.4	0.85	0.84
6	647	Busti	Calibration	0.72	-28.1	0.78	0.56
			Validation	0.72	3.7	0.74	0.64
7	650	Rasnalu	Calibration	0.58	0.5	0.59	0.57
			Validation	0.66	21.7	0.70	0.63
8	652	Khurkot	Calibration	0.61	26.4	0.81	0.54
			Validation	0.59	36.9	0.87	0.55
9	681	Hampachuwar	Calibration	0.88	-17.9	0.90	0.76
			Validation	0.92	3.3	0.92	0.91
10	684	Majhitar	Calibration	0.73	20.6	0.84	0.68
			Validation	0.81	14.3	0.85	0.77
11	695	Chatara	Calibration	0.91	6.0	0.95	0.83
			Validation	0.94	-7.9	0.95	0.9

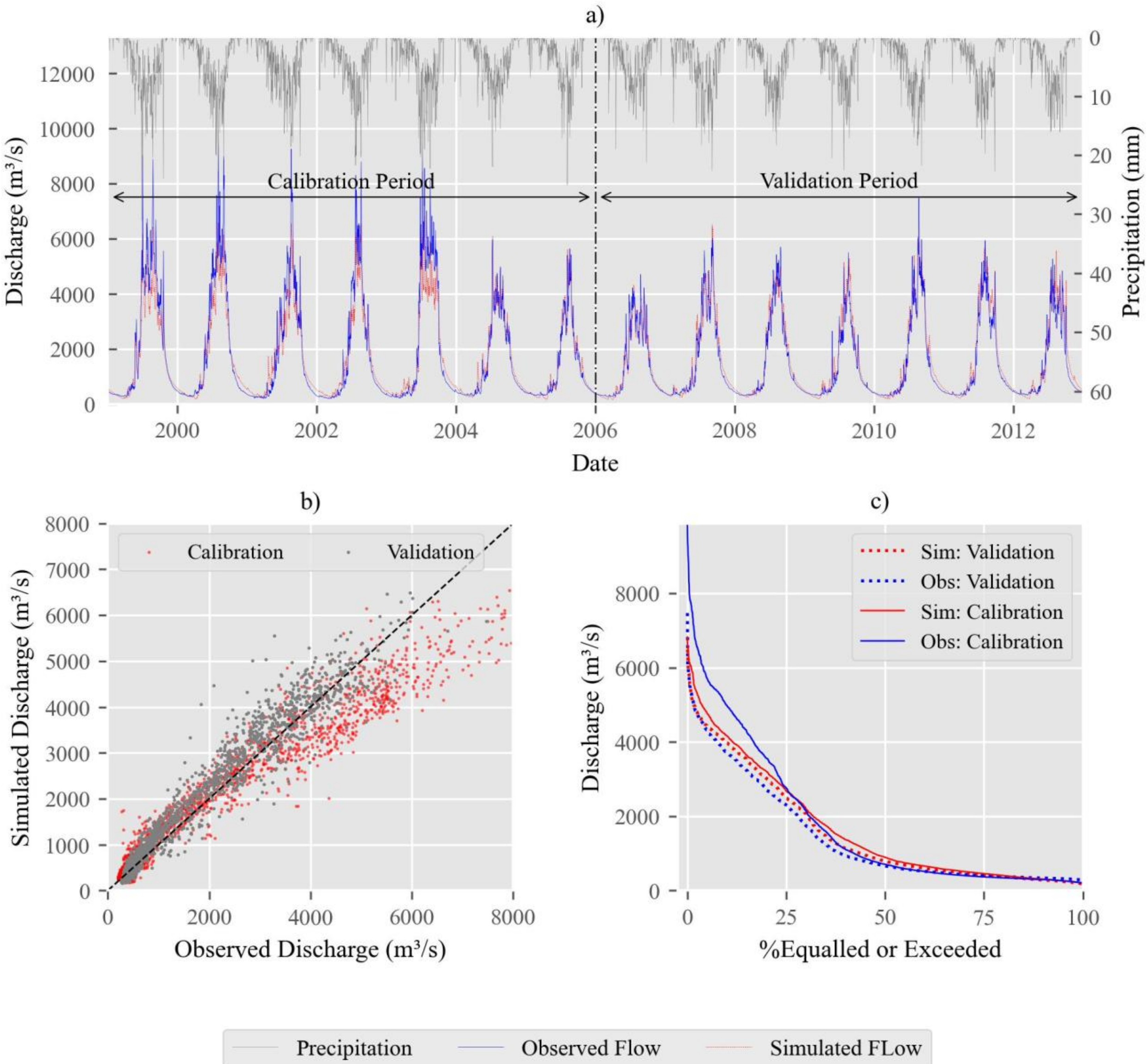


Figure 8-11 Performance of the model for Koshi River at Chatara

a) Observed and simulated daily hydrograph, b) Flow duration curves and c) Scatter plot of daily flows

8.3.2 Water Balance Components of Koshi Basin

The annual average values of water balance components were estimated for the baseline period (1980-2019). **Figure 8-12** illustrates the yearly average volume of water balance components for the Koshi River Basin at Chatara. The annual precipitation averages 1,191 mm, of which 390 mm (33% of the total precipitation) is lost as evapotranspiration. The remaining 781 mm (66% of the total precipitation) constitutes the water yield.

The water yield is further divided into 26% overland flow and 74% lateral and groundwater flows. A small portion of water is lost as deep percolation. The spatial distribution of the various water balance components is presented in **Figure 8-13**.

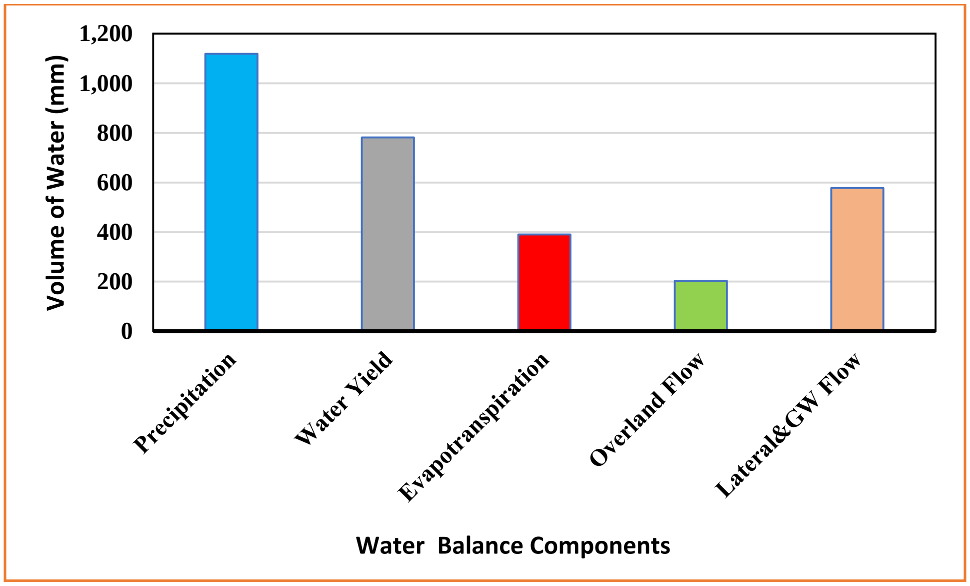


Figure 8-12 Water balance of Koshi Basin at Chatara

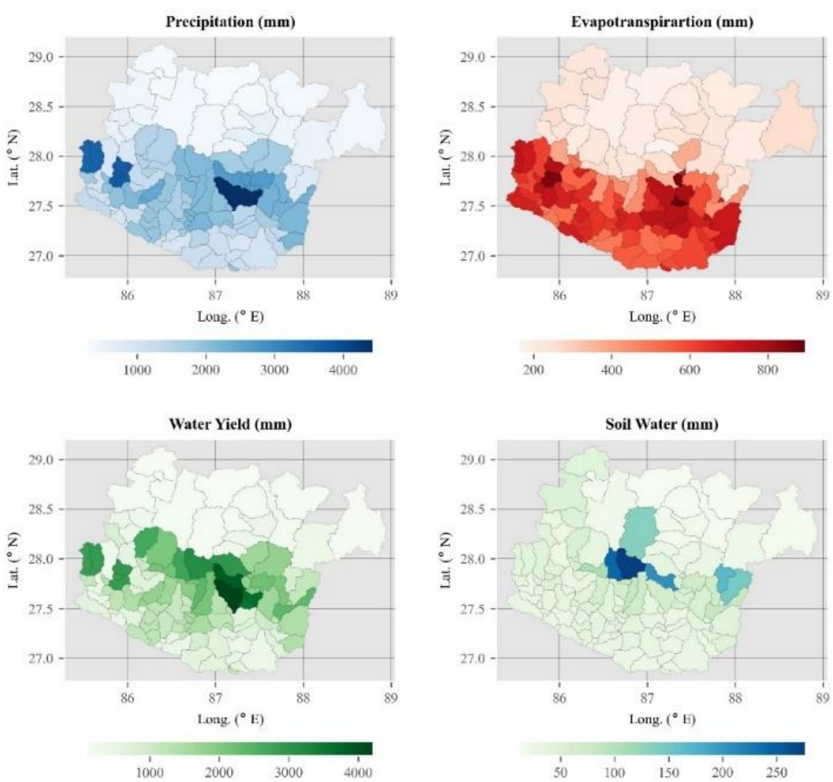


Figure 8-13 Spatial distribution of various water balance components in Koshi Basin

8.3.3 Model Performance for Gandaki Basin

The SWAT model of the Gandaki River Basin was calibrated and validated using discharge data from nine hydrological stations: St. Nos. 404.7 (Mangalghat), 419.1 (Ansing), 420 (Kotagaun), 438 (Shisaghat), 439.7 (Bimalnagar), 445 (Arughat), 447 (Betrawati), 449.91 (Kalikhola), and 450 (Devghat).

To statistically evaluate the model's performance, four performance metrics—NSE, PBIAS, R^2, and KGE—were computed for each station, as presented in **Table 8-4**. For Devghat (station no. 450), the NSE values for the calibration and validation periods are 0.87 and 0.88, respectively. Similarly, other performance metrics for this station are also excellent: KGE and R^2 are both 0.87 (calibration) and 0.88 (validation), while PBIAS values are 3.44% (calibration) and -1.0% (validation). These statistics are similarly satisfactory for other sub-stations.

The hydrograph, flow duration curve (FDC), and scatter plot for the basin's main outlet at Devghat are displayed in **Figure 8-14**. Analyzing the hydrographs and FDCs reveals that the model performs reasonably well in estimating both high and low flows. From the scatter plot of St. No. 450, it is evident that most points align closely with the centerline, indicating good agreement between observed and simulated flows.

However, the model slightly underestimates high flows. Despite this limitation, a comprehensive evaluation confirms that the model accurately represents the hydrology of the Gandaki River Basin.

Table 8-4 Model performance indicators for Gandaki Basin

SN	Station no.	Location	Period	NSE	PBIAS (%)	R^2	KGE
1	404.7	Mangalghat	Calibration	0.63	18.28	0.65	0.61
			Validation	0.6	3.86	0.62	0.62
2	419.1	Ansing	Calibration	0.84	2.22	0.84	0.84
			Validation	0.73	-11.66	0.8	0.77
3	420	Kotagaun	Calibration	0.68	0.045	0.72	0.72
			Validation	0.75	5.31	0.76	0.76
4	438	Shisaghat	Calibration	0.64	-16.59	0.72	0.67
			Validation	0.48	-24.9	0.79	0.65
5	439.7	Bimalnagar	Calibration	0.67	17.7	0.7	0.65
			Validation	0.6	31.4	0.67	0.6
6	445	Arughat	Calibration	0.66	29.23	0.75	0.58
			Validation	0.71	19.19	0.75	0.67
7	447	Betrawati	Calibration	0.57	-2.8	0.7	0.66
			Validation	0.68	14.27	0.71	0.65

SN	Station no.	Location	Period	NSE	PBIAS (%)	R^2	KGE
8	449.91	Kalikhola	Calibration	0.73	28.07	0.84	0.67
			Validation	0.74	26.42	0.85	0.68
9	450	Devghat	Calibration	0.87	3.44	0.87	0.87
			Validation	0.88	-1	0.88	0.88

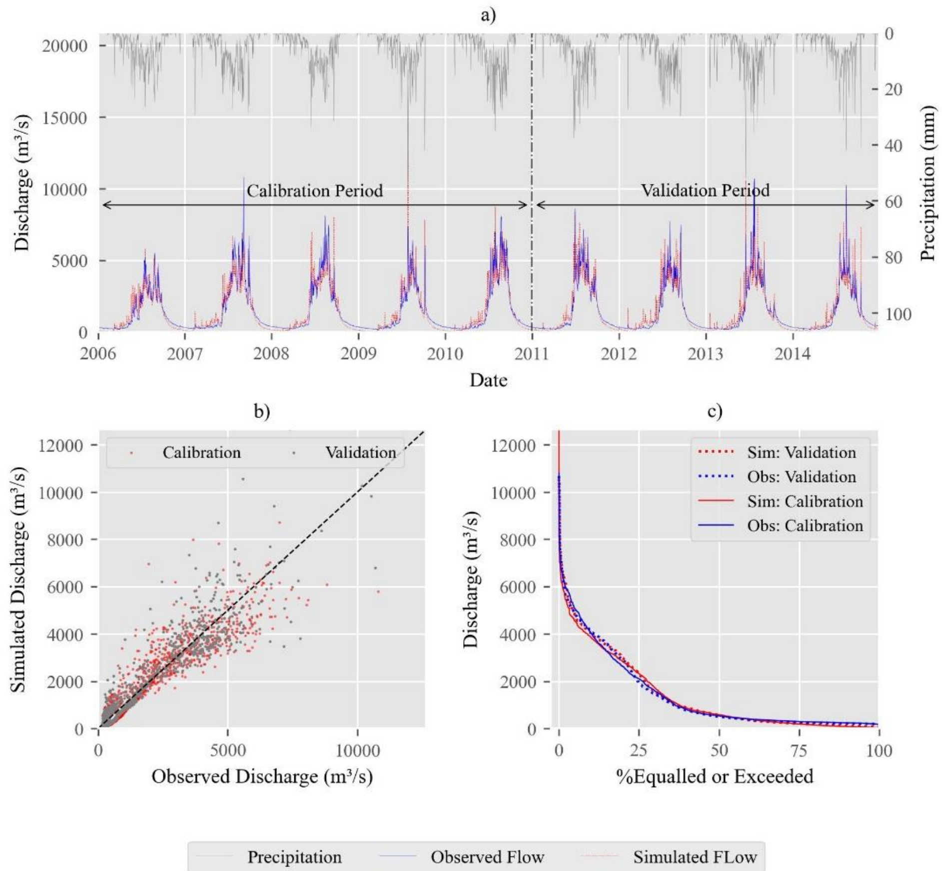


Figure 8-14 Performance of the model for Gandaki River at Devghat

a) Observed and simulated daily hydrograph, b) Flow duration curves and c) Scatter plot of daily flows

8.3.4 Water Balance Components of Gandaki Basin

The baseline volume of the water balance components for the basin is shown in **Figure 8-15**. The annual precipitation averages 1,714 mm, of which 401 mm (23% of the total precipitation) is lost as evapotranspiration. The remaining 1,285 mm (75% of the total precipitation) constitutes the water yield.

The net water yield, which includes the combined contributions of overland flow and base flow (lateral and groundwater flow), is further divided as follows: 27% of the water yield (350 mm) is from overland flow, while 73% (935 mm) is from base flow. The spatial distribution of various water balance components of Gandaki Basin is depicted in **Figure 8-16**

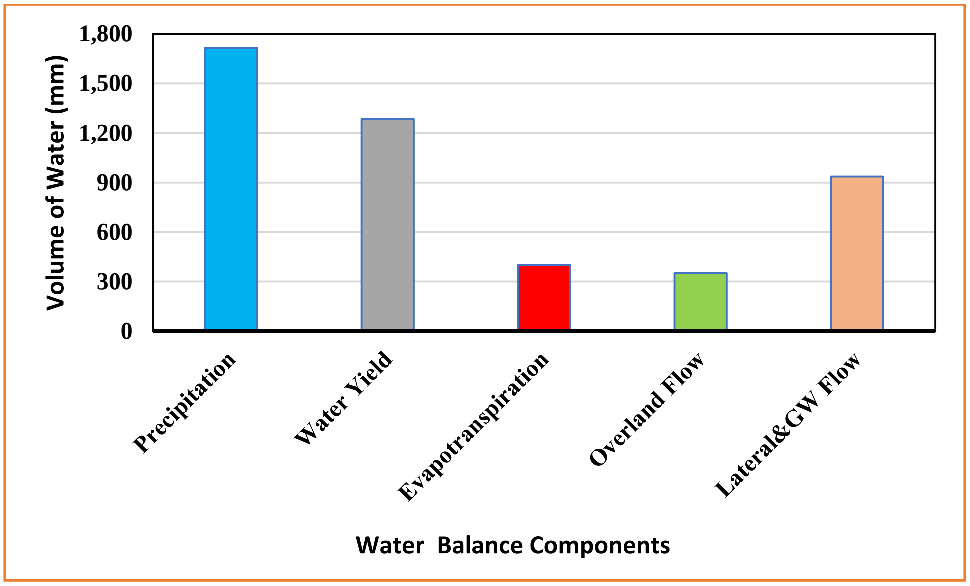


Figure 8-15 Water balance components of Gandaki Basin at Devghat

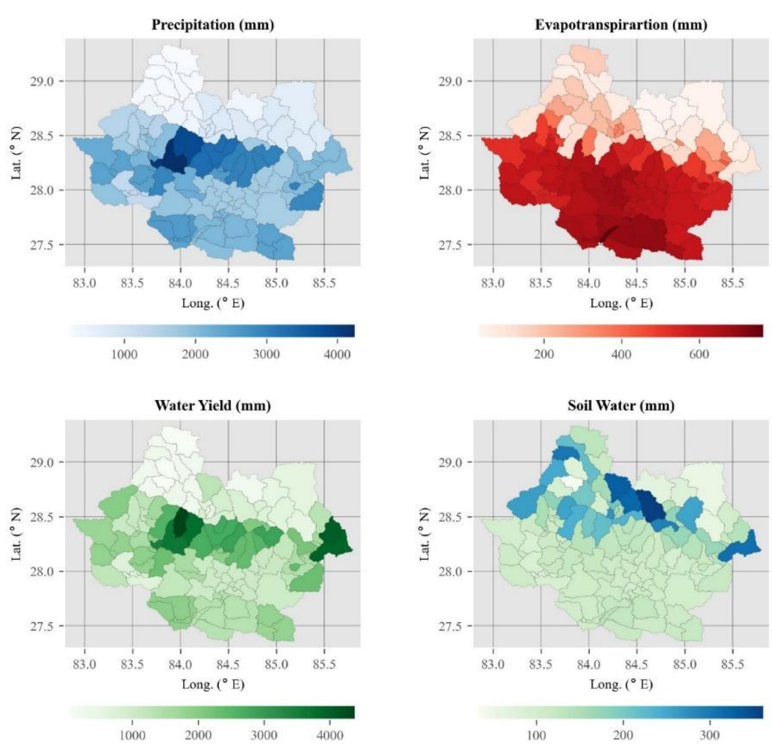


Figure 8-16 Spatial distribution of various water balance components of Gandaki Basin

8.3.5 Model Performance for Karnali River Basin

The calibration and validation of the SWAT model for the Karnali Basin were conducted using data from eight hydrological stations: St. 240 (Asaraghat), St. 250 (Benighat), St. 259.2 (Gopaghat), St. 260 (Bangga), St. 265 (Rimna), St. 269.5 (Samaijighat), St. 270 (Jamu), and St. 280 (Chisapani).

At most stations, NSE values exceeded 0.7 for both calibration and validation periods. Similarly, the R^2 and KGE values fall within the "good" to "very good" categories, indicating high model accuracy. Most stations also exhibited PBIAS values below 10%, suggesting satisfactory performance in discharge estimation (**Table 8-5**). The hydrograph, FDC, and scatter plot of observed and simulated flow at Chisapani, the main outlet of the Karnali basin is shown in **Figure 8-17**. A visual analysis of these graphs, along with the performance parameters, confirms that the model performs well, demonstrating its efficiency in simulating the hydrology of the Karnali River Basin.

Table 8-5 Model performance for Karnali River Basin

SN	Station No.	Location	Period	NSE	PBIAS (%)	R^2	KGE
1	240	Asaraghat	Calibration	0.63	4.8	0.78	0.60
			Validation	0.62	-5.6	0.77	0.69
2	250	Benighat	Calibration	0.72	1.5	0.80	0.72
			Validation	0.64	-5.5	0.78	0.71
3	259.2	Gopaghat	Calibration	0.56	-14.5	0.75	0.69
			Validation	0.51	-20.9	0.72	0.64
4	260	Bangga	Calibration	0.75	-1.6	0.76	0.76
			Validation	0.61	-2.1	0.62	0.60
5	265	Rimna	Calibration	0.74	14.6	0.78	0.68
			Validation	0.58	39.3	0.73	0.52
6	269.5	Samaijighat	Calibration	0.80	1.5	0.82	0.81
			Validation	0.82	6.9	0.82	0.81
7	270	Jamu	Calibration	0.79	-1.8	0.82	0.81
			Validation	0.73	5.6	0.74	0.73
8	280	Chisapani	Calibration	0.87	6.5	0.87	0.85
			Validation	0.88	4.2	0.88	0.87

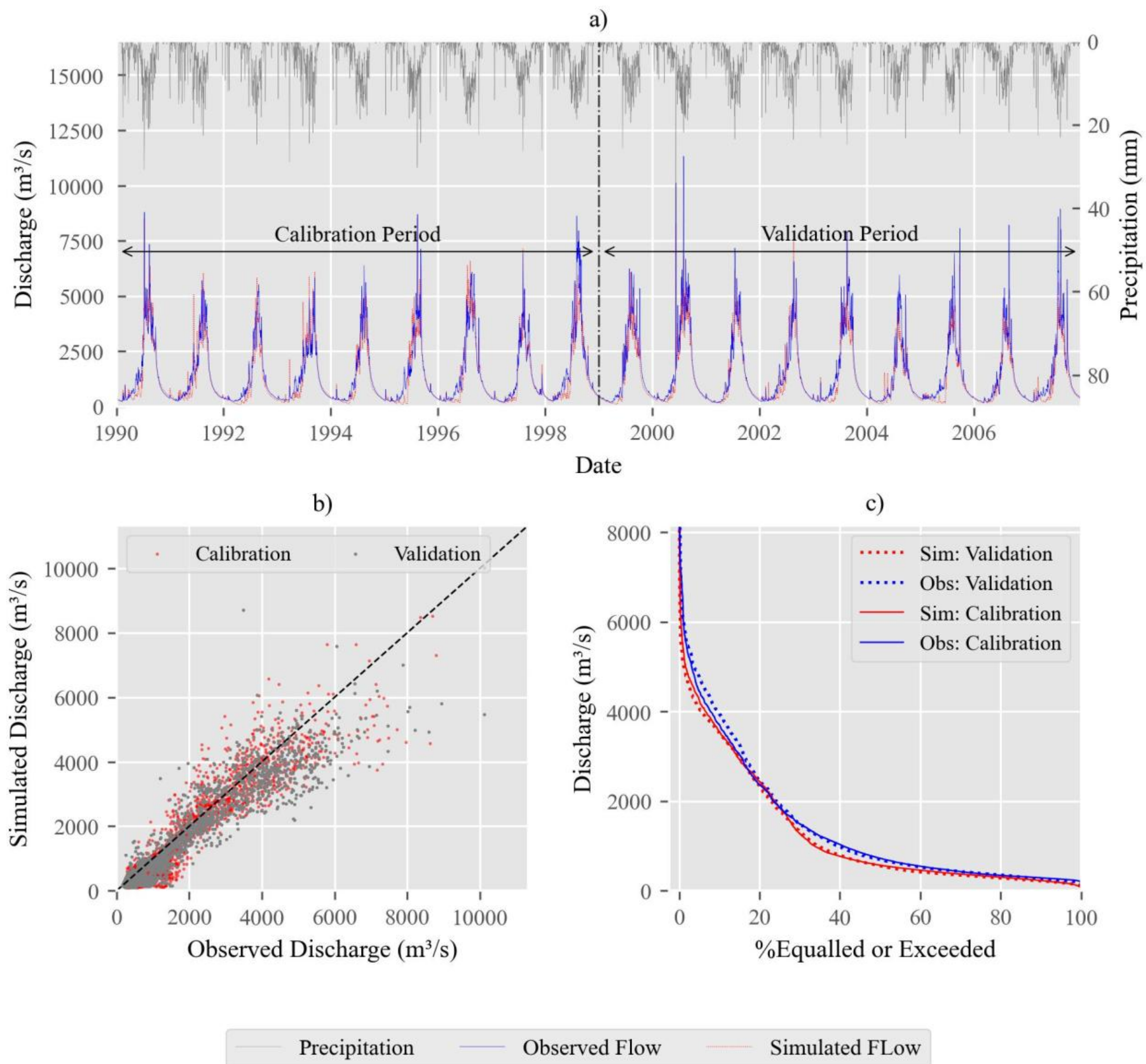


Figure 8-17 Model performance for Karnali River Basin at Chisapani

a) Observed and simulated daily hydrograph, b) Flow duration curves and c) Scatter plot of daily flows

8.3.6 Water Balance Components of Karnali Basin

The annual average values of water balance components for the baseline period (1980–2019) are presented in **Figure 8-18**. The average annual precipitation is estimated at 1,203 mm, with 433 mm (36% of annual precipitation) lost as evapotranspiration and 744 mm (62% of annual precipitation) contributing to the water yield.

The basin's overland flow is estimated at 189 mm, which accounts for 25% of the total water yield. Lateral and groundwater flows constitute 555 mm, representing 75% of the total water yield. A small portion of water is lost as deep percolation storage in the basin. The spatial distribution of these water balance components is illustrated in **Figure 8-19**.

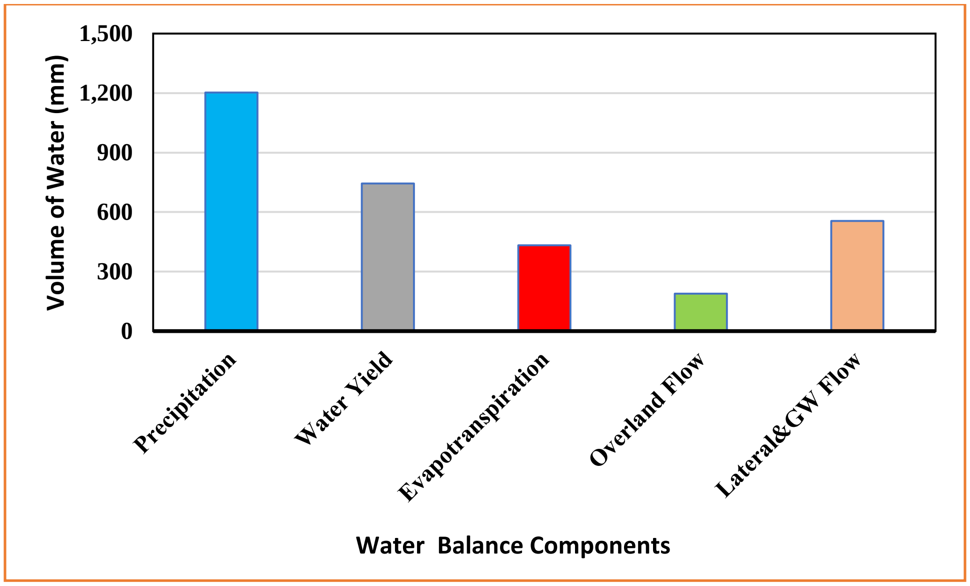


Figure 8-18 Water balance components of Karnali Basin

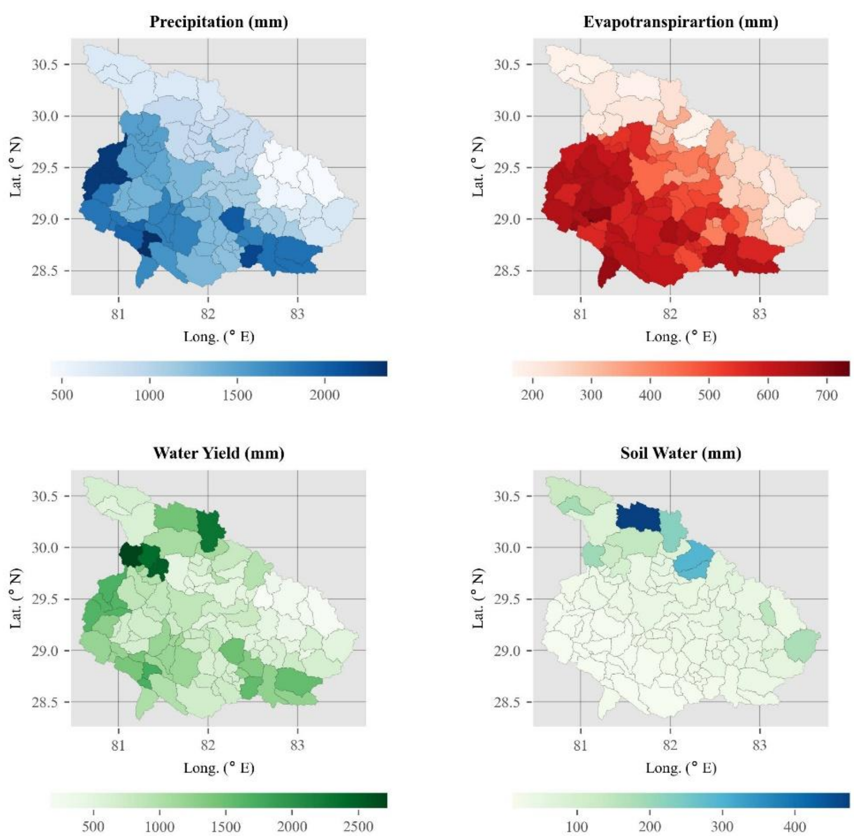


Figure 8-19 Spatial distribution of these components water balance components in Karnali Basin

8.3.7 Model Performance for Chamelia River Basin

The calibration and validation of the SWAT model for Chamelia River at Nyalbadi (St. 120). The model's performance was evaluated on a daily time scale using performance indicators: NSE, PBIAS, R^2, and KGE as in for other basins. The values of these indicators fall under a very good range (**Table 8-6**). This indicates that the model developed for the Chamelia basin performs quite well. It can be seen from the visual evaluation of the hydrograph depicting the simulated and observed discharge, FDC, and scatter plots given in **Figure 8-20**.

Table 8-6 Model performance for Chamelia Basin

Time Step	Period	NSE	PBIAS (%)	R^2	KGE
Daily	Calibration	0.80	-10.92	0.87	0.82
	Validation	0.84	10.18	0.86	0.81

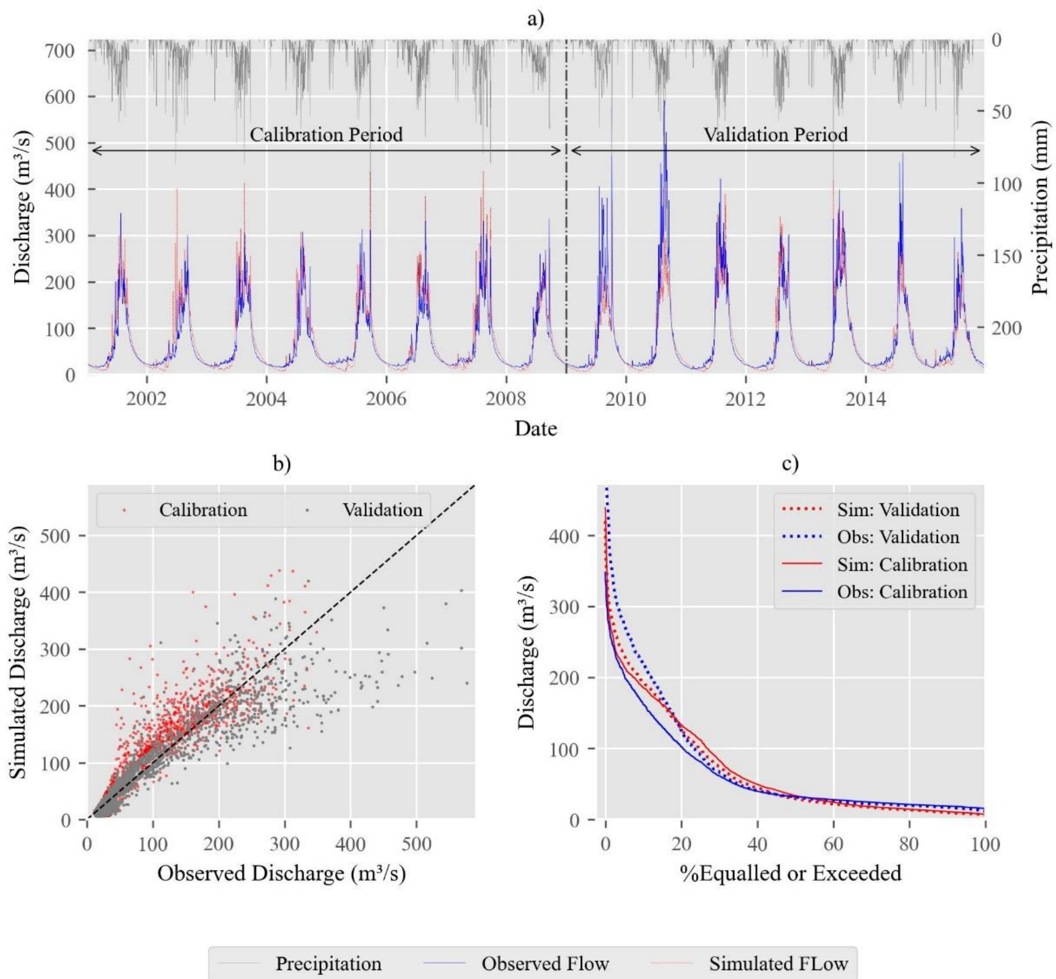


Figure 8-20 Model performance for Chamelia River

a) Observed and simulated daily hydrograph, b) Flow duration curves and c) Scatter plot of daily flows

8.3.8 Water Balance Components of Chamelia Basin

The annual average values of water balance components for the baseline period (1999–2015) are presented in **Figure 8-21**. The average annual precipitation is estimated at 2,129 mm. Evapotranspiration accounts for 681 mm (34% of the total precipitation), the remaining part to the water yield. The overland flow is estimated at 225 mm, which constitutes 16% of the total water yield, while base flow (lateral and groundwater flows combined) is estimated at 1,210 mm, accounting for 84% of the total water yield. The spatial distribution of these water balance components across the basin is illustrated in **Figure 8-22**.

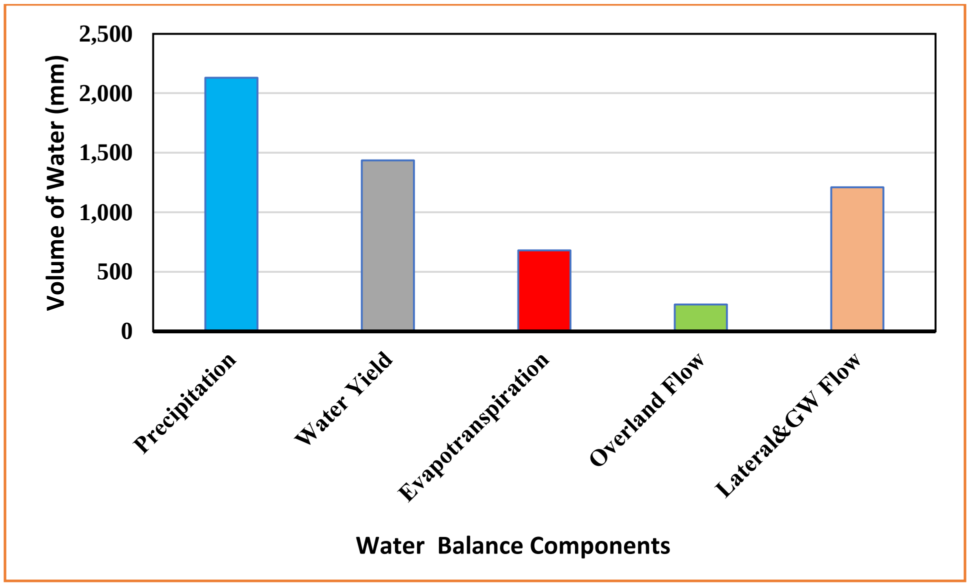


Figure 8-21 Water balance components of Chamelia River

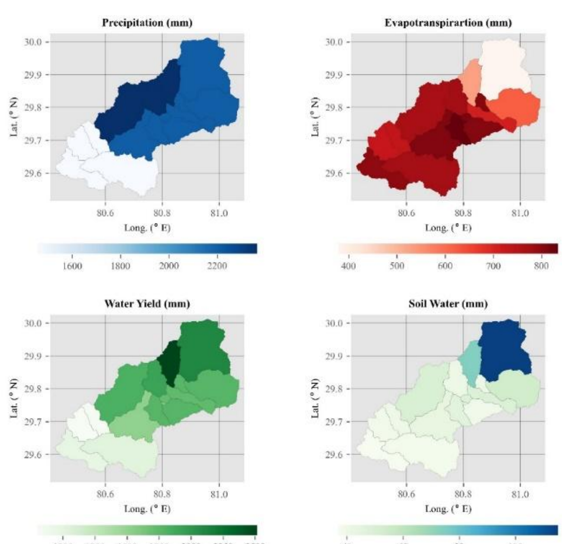


Figure 8-22 Spatial distribution of various water balance components in Chamelia basin

8.3.9 Model Performance for Kankai River Basin

The model underwent a manual calibration process using observed discharge data at hydrological St. 795 Mainachuli of Kankai River. During the calibration and validation process, four key performance metrics were assessed to evaluate the model's accuracy. The statistical performance indicator values are provided in **Table 8-7**. The performance indicators reveal that the SWAT model did not capture the hydro-dynamic phenomena of this basin as effectively as it did in other basins. This discrepancy is further illustrated by the plots of simulated and observed hydrographs, scatter diagrams, and the flow duration curve (FDC) shown in **Figure 8-23**. It indicates that there are some issues with hydro-climatic data of the basin.

Table 8-7 Model performance indicators for Kanaki River Basin

Time Step	Period	NSE	PBIAS	R^2	KGE
Daily	Calibration	0.45	-14.64	0.53	0.32
	Validation	0.41	-38.44	0.58	0.31

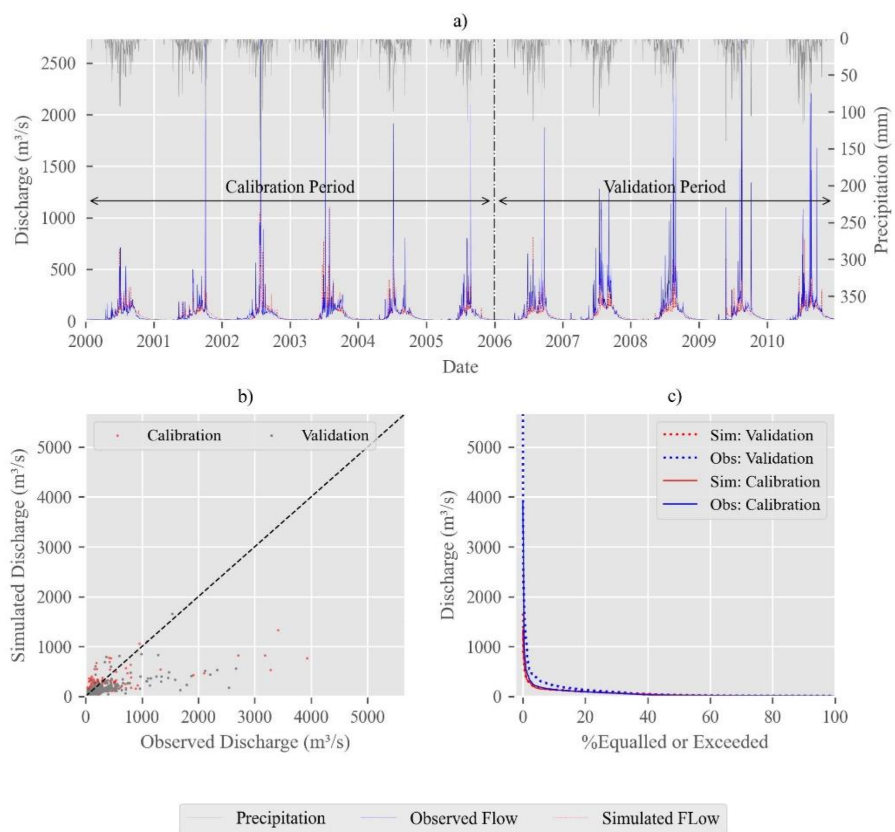


Figure 8-23 Performance of the model for Kankai river

8.3.10 Model Performance for Bagmati River Basin

Calibration and validation of the SWAT model for the Bagmati River Basin at Padheredovan was done. The NSE value obtained from statistical analysis exceeded 0.7, which falls within an appropriate range. Similarly, the R^2 and KGE values were both greater than 0.5, indicating they are within the permissible range. A negative PBIAS value suggests that the model overestimated flow during the calibration period, while a higher positive PBIAS during the validation period indicates a greater underestimation of flow. The performance metrics, as presented in **Table 8-8** are within an acceptable range, indicating satisfactory model performance. For visual inspection, the hydrograph, FDC, and scatter plot for this station are shown in **Figure 8-24**. Both the hydrograph pattern and FDC are well-reproduced at station 589, though there is a slight overestimation of long-term average flows. Based on these results, the model's overall performance was deemed acceptable for further use.

Table 8-8 Model performance indicators for Bagmati River Basin

Time Step	Period	NSE	PBIAS	R^2	KGE
Daily	Calibration	0.75	-2.27	0.77	0.62
	Validation	0.53	27.13	0.68	0.45

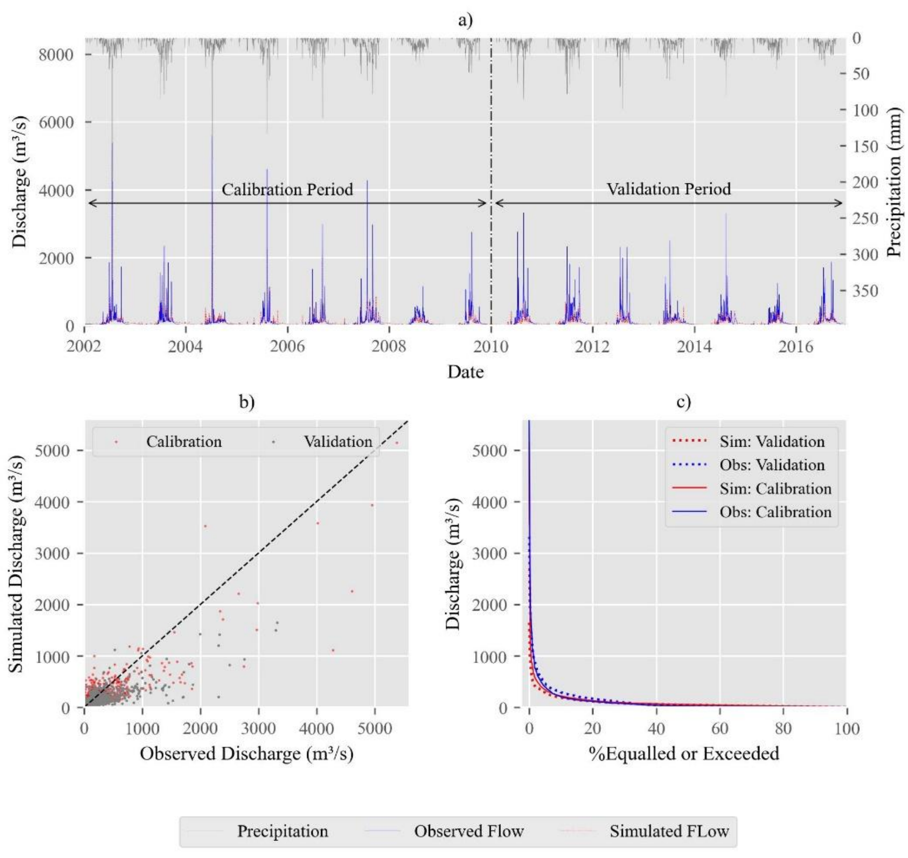


Figure 8-24 Performance of the model for Bagmati Basin

8.3.11 Water Balance Components of Bagmati Basin

The annual average values of water balance components for the baseline period (1980–2017) were estimated. The average annual precipitation is 1,797 mm, with water yield estimated at 1,130 mm (63% of the total precipitation) and evapotranspiration at 667 mm (37% of the total precipitation). The water yield consists of 921.27 mm of base flow (the combined total of groundwater and lateral flows) and 208.44 mm of overland flow (**Figure 8-25**). The spatial distribution of various components of water balance is shown in **Figure 8-26**.

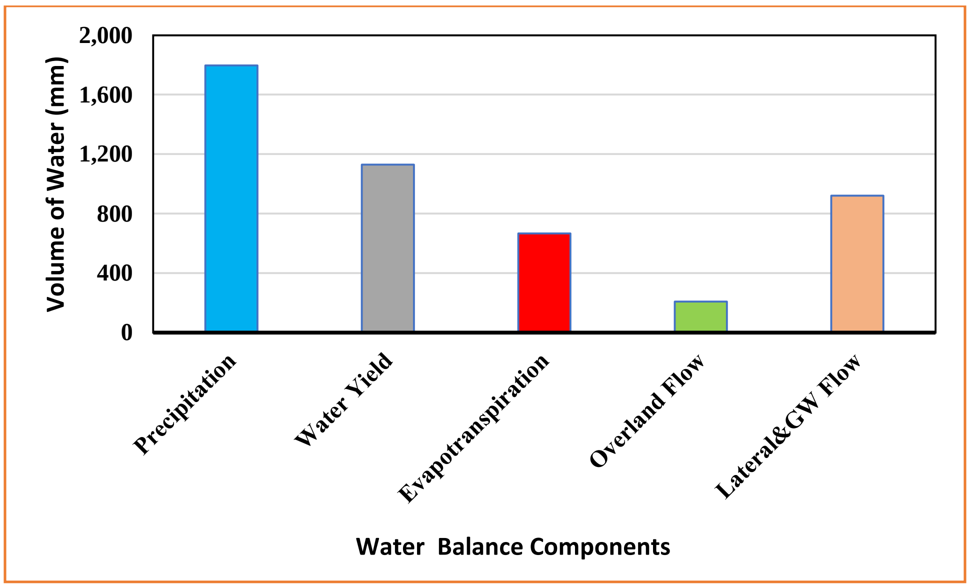


Figure 8-25 Water balance components of Bagmati Basin

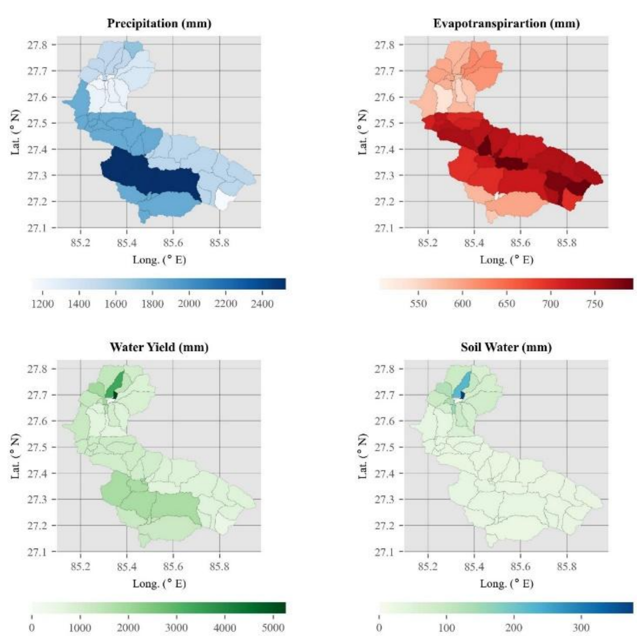


Figure 8-26 Spatial distribution of various components of water balance in Bagmati Basin

8.3.12 Model Performance for West Rapti River Basin

The SWAT model for the West Rapti Basin was calibrated and validated using discharge data from hydrological stations St. 330 (Nayagaun), St. 350 (Bagasoti), and St. 375 (Kusum). To assess the model's performance statistically, the performance parameters NSE, PBIAS, R^2, and KGE were calculated for each station. The results are presented in **Table 8-9**. For station 330, the NSE value exceeded 0.7 during calibration, and for all stations, the NSE exceeded 0.5 during both calibration and validation periods, which is considered adequate. The negative PBIAS values indicate an overestimation of flow, while the PBIAS values for stations 330 and 350 are within the permissible range (i.e., less than 25).

The R^2 value for station 330 was very good during both calibration and validation, making it suitable for modeling purposes. For the other stations, the R^2 values exceeded the 0.5 threshold, which is considered appropriate. The KGE values for stations 330 and 350 were both above 0.5. Based on these performance parameters, the developed model for the West Rapti Basin can be considered satisfactory for flow simulation.

In addition to the statistical evaluation, the model's performance was also visually assessed. A hydrograph, scatter plot, and flow duration curve (FDC) were plotted in **Figure 8-27**, showing simulated and observed discharge on a daily basis for both the calibration and validation periods. The model estimates both high and low flows reasonably well.

Table 8-9 Model performance for West Rapti River Basin

Station no.	**Time Step**	**Period**	**NSE**	**PBIAS**	**R^2**	**KGE**
330	Daily	Calibration	0.71	-13.48	0.72	0.59
		Validation	0.65	-21.29	0.78	0.69
350		Calibration	0.62	-2.75	0.63	0.52
		Validation	0.70	-3.10	0.70	0.63
375		Calibration	0.54	-25.70	0.56	0.36
		Validation	0.60	-25.65	0.62	0.36

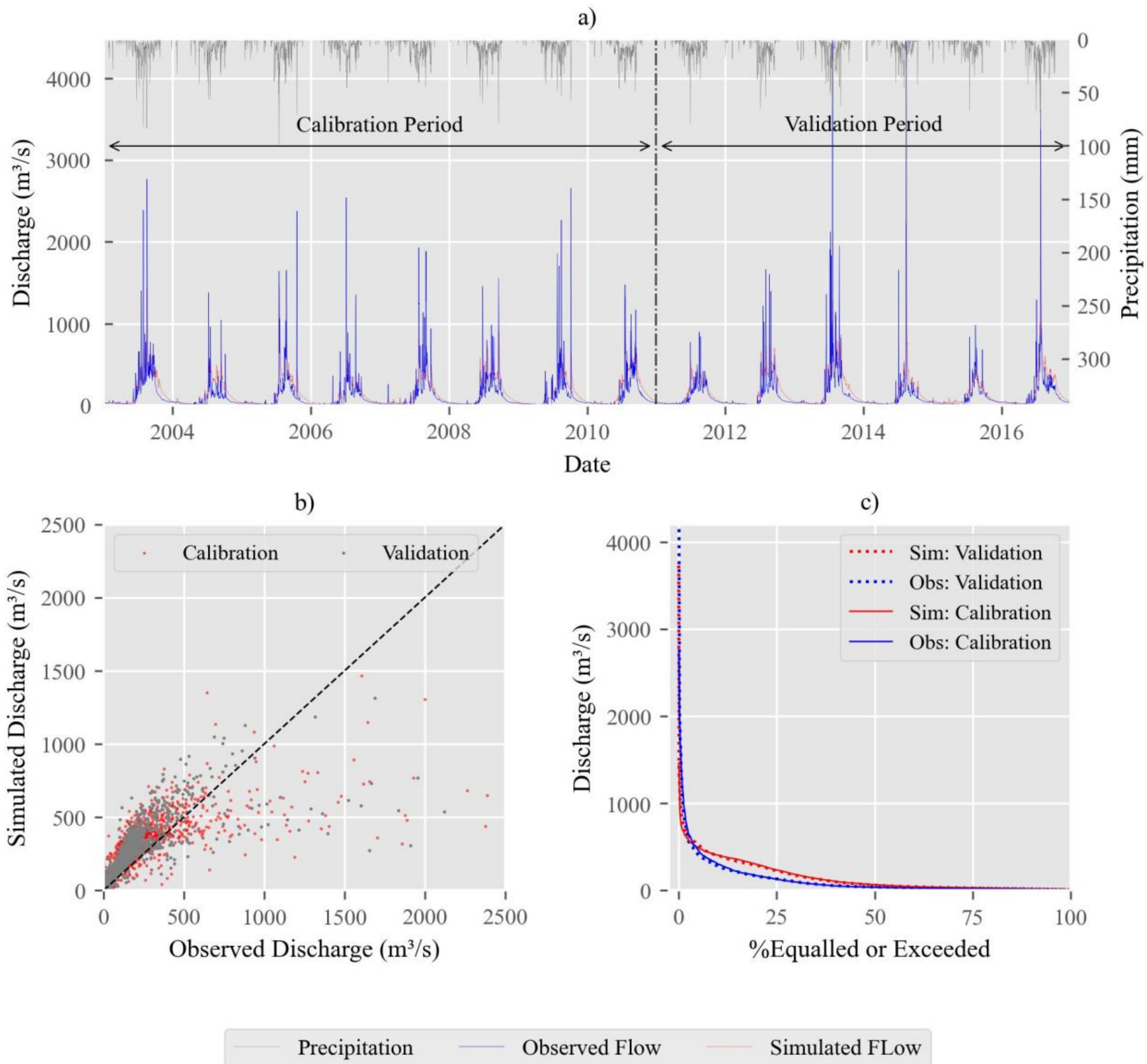


Figure 8-27 Model performance for West Rapti Basin

8.3.13 Water Balance Components of West Rapti Basin

The average values of water balance components for the baseline period (1980–2019) were estimated, and shown in **Figure 8-28**. The average annual precipitation is 2,035 mm. Evapotranspiration accounts for 615 mm, which is 30% of the total precipitation. The remaining 1,409 mm, or 69% of the precipitation, constitutes the water yield. The water yield consists of 19% overland flow, equivalent to 274 mm, and 81% base flow, equivalent to 1,135 mm. The base flow includes both lateral flow and groundwater flow. The spatial distribution of the various water balance components is shown in **Figure 8-29**.

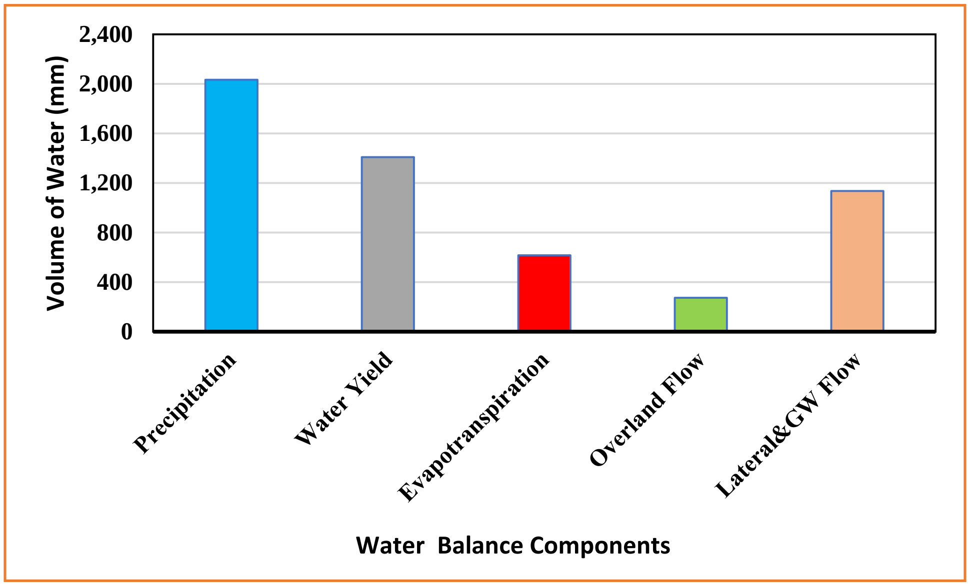


Figure 8-28 Water balance of West Rapti Basin

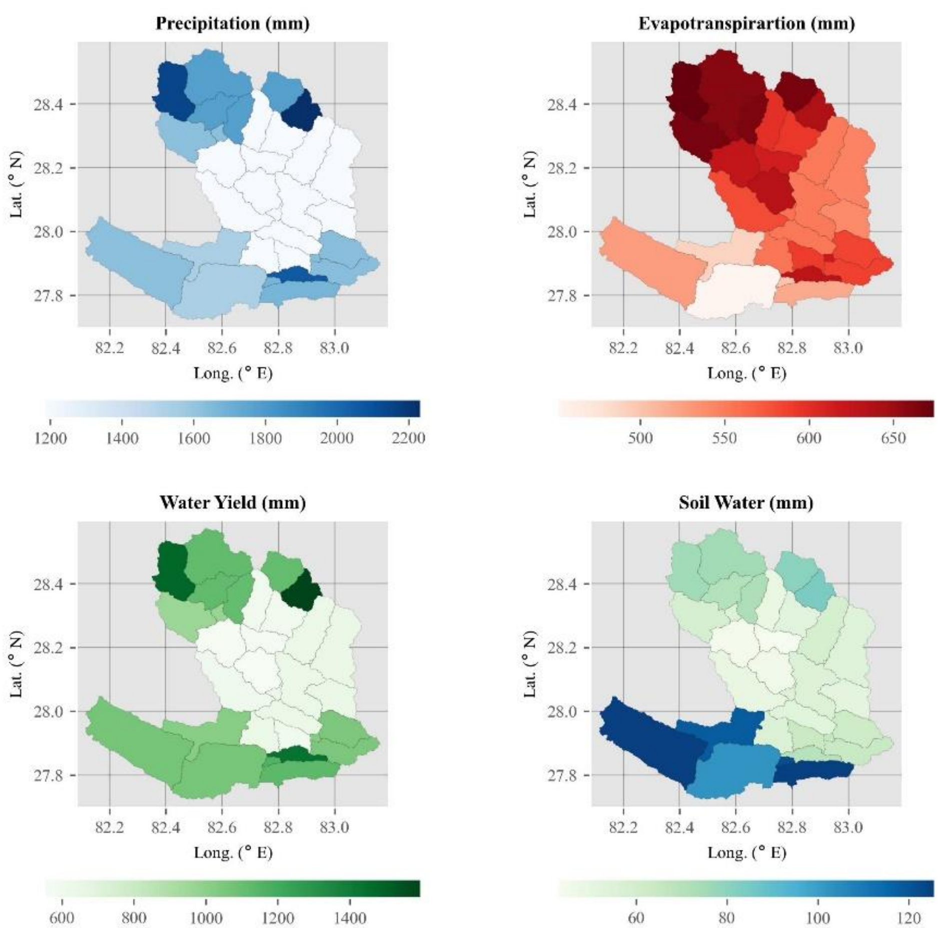


Figure 8-29 Spatial distribution of various components of water balance of West Rapti Basin

8.3.14 Model Performance for Babai River Basin

Hydrological station 289.95 at Chepang was used to calibrate and validate the SWAT model for the Babai River Basin. The performance metrics obtained are provided in **Table 8-10**. The primary focus was to achieve a Nash-Sutcliffe Efficiency (NSE) value within an acceptable range. The NSE was closer to 50% during the validation phase and slightly above 50% during the calibration period.

The PBIAS value of -19.72 during the calibration period indicates an overestimation of flow. However, since a PBIAS value under 25 is considered acceptable, this is within range. The R^2 value during calibration exceeds 0.5, which is considered adequate, although during the validation period, it drops below 0.5. The KGE value remained consistently below 0.5 for both the calibration and validation periods.

The lower observed discharge values in the Babai River Basin affected the SWAT model's efficiency. This may be due to the fact that observed discharge values in the basin are relatively low. The overestimation of runoff by the model, likely resulting from a lower runoff-to-precipitation ratio, contributed to the reduced efficiency of the SWAT model.

The hydrograph, FDC, and scatter plot comparing daily observed and simulated flows are shown in (**Figure 8-30**). The simulated hydrographs accurately reflect observed daily flows and match the precipitation pattern. The FDC is also well reproduced. Overall, the model is considered satisfactory.

Table 8-10 Model performance indicator for Babai River at Chepang

Time Step	Period	NSE	PBIAS	R^2	KGE
Daily	Calibration	0.51	-19.72	0.54	0.44
	Validation	0.45	5.89	0.45	0.35

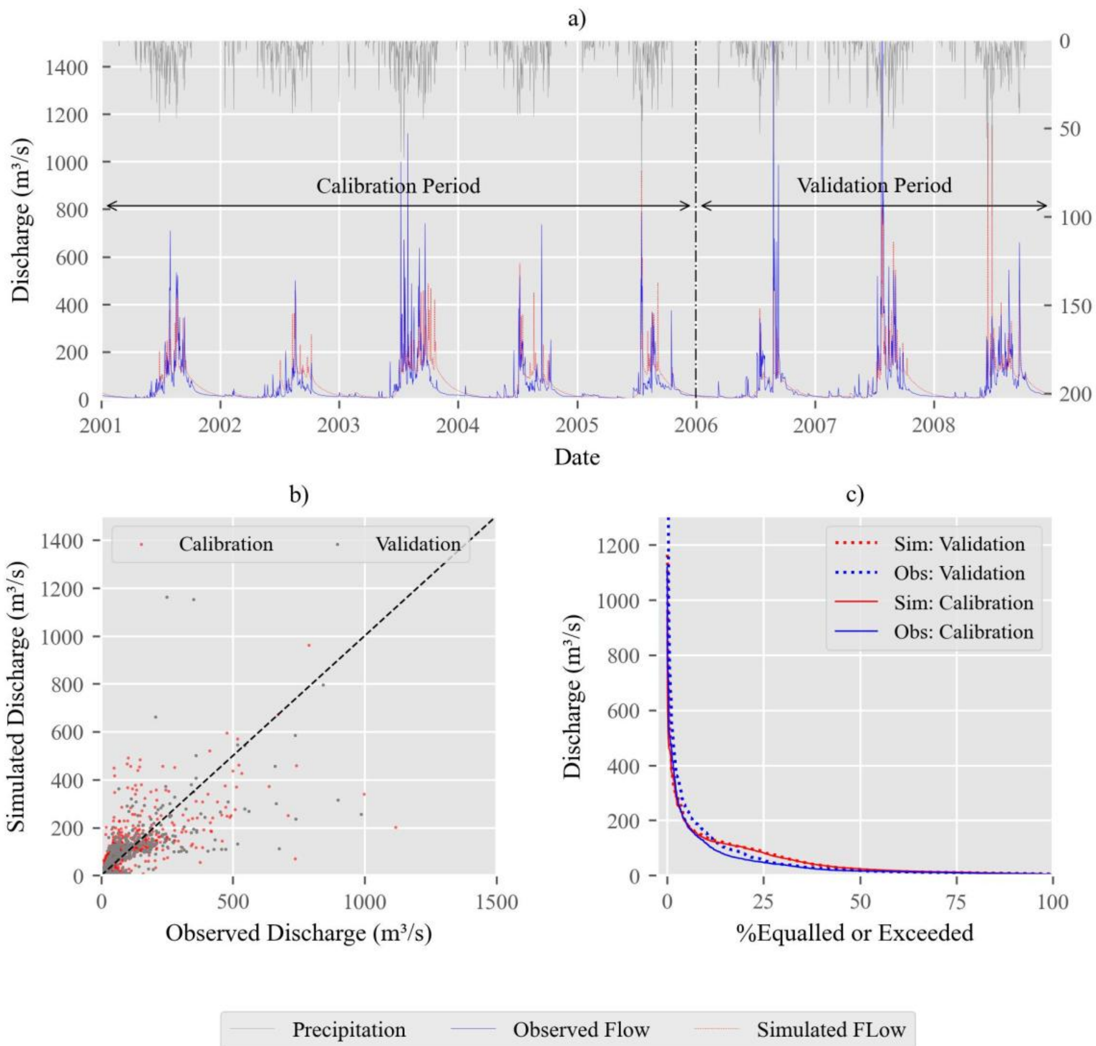


Figure 8-30 Model performance at Chepang of Babai River

8.3.15 Water Balance Components of Babai Basin

The annual average values of water balance components of Babai River at Chepang of the baseline period (1980-2019) are shown in . The annual average precipitation of the basin is 1,466 mm, with a water yield of 765 mm, which constitutes 52% of the total precipitation. Base flow (lateral and groundwater flows) accounts for 70% of the total water yield, while overland flow makes up the remaining 30%. The average annual evapotranspiration is 701 mm. The spatial distribution of the various components of the water balance is shown in **Figure 8-32**.

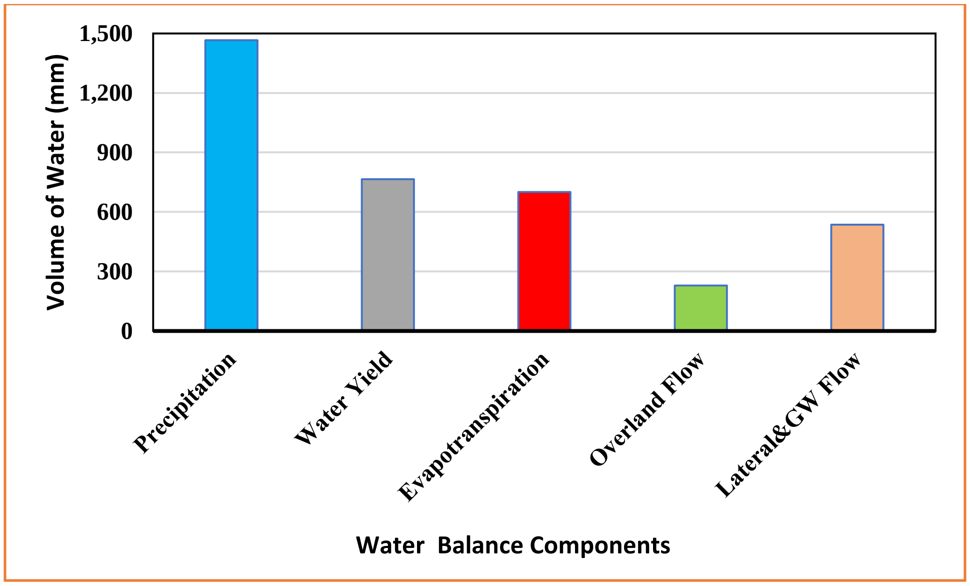


Figure 8-31 Water Balance of Babai River Basin

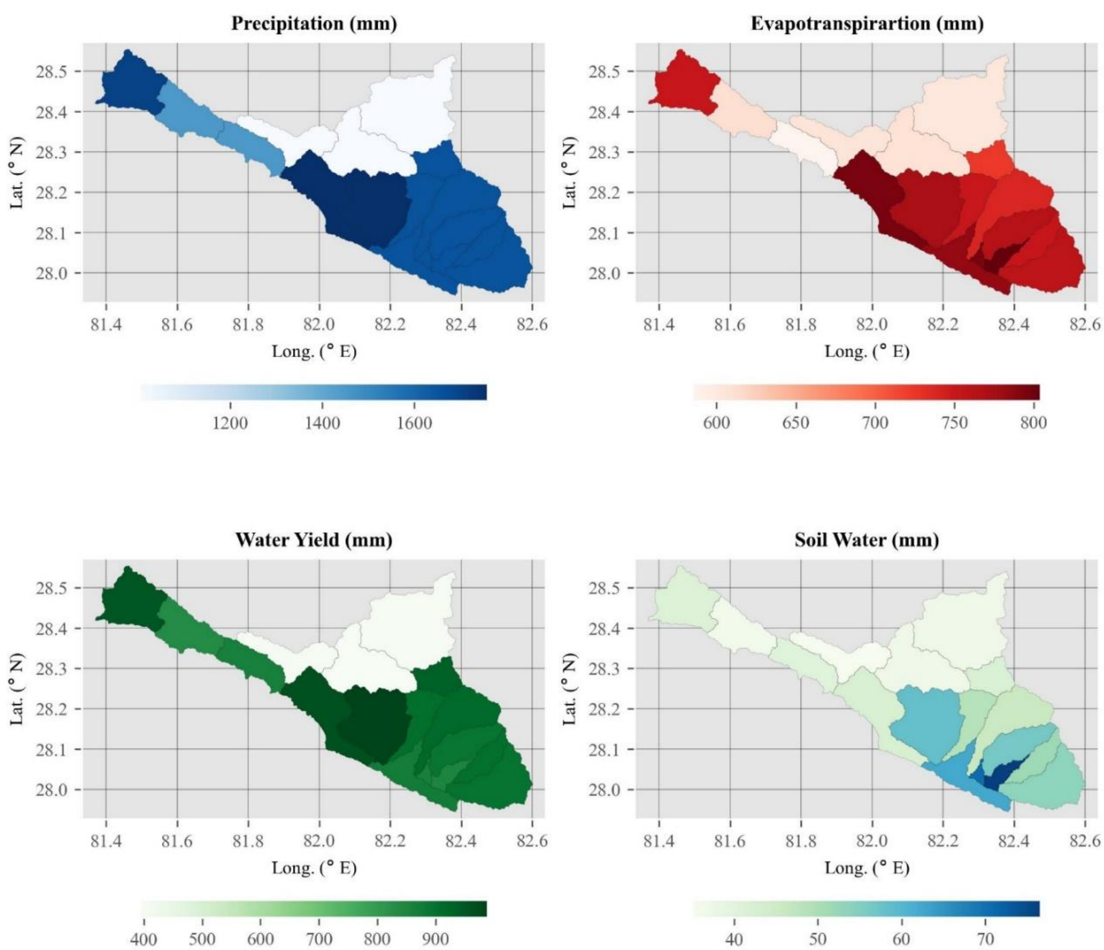


Figure 8-32 Spatial distribution of components of water balance in Babai Basin

8.3.16 Model Performance for Kamala River Basin

The Kamala River Basin does not have a hydrological station, making it impossible to calibrate and validate the SWAT model for this basin. However, the hydrology of the Kamala River Basin is likely similar to that of nearby basins. The Kankai River Basin, located close to the Kamala River Basin, was used as a reference. To run the SWAT model for the Kamala River Basin, the parameter values from the calibration and validation of the Kankai River Basin SWAT model were applied. The simulation period for the SWAT model was 43 years, from 1980 to 2023, with a 2-year warming period. After running the model, the hydrology of the Kamala River Basin was observed and utilized for further analysis.

8.3.17 Water Balance Components of Kamala Basin

The volume of water balance components of Kamala Basin is shown **Figure 8-33**. The average annual precipitation is 1,522 mm. After accounting for all water movements, the net water yield is 934.71 mm, which constitutes approximately 61% of the total precipitation. Of this, base flow accounts for 80%, or about 748 mm, while overland flow contributes the remaining 20%, approximately 186 mm. Evapotranspiration, the water lost to the atmosphere, totals around 588 mm annually, or about 39% of the total precipitation.

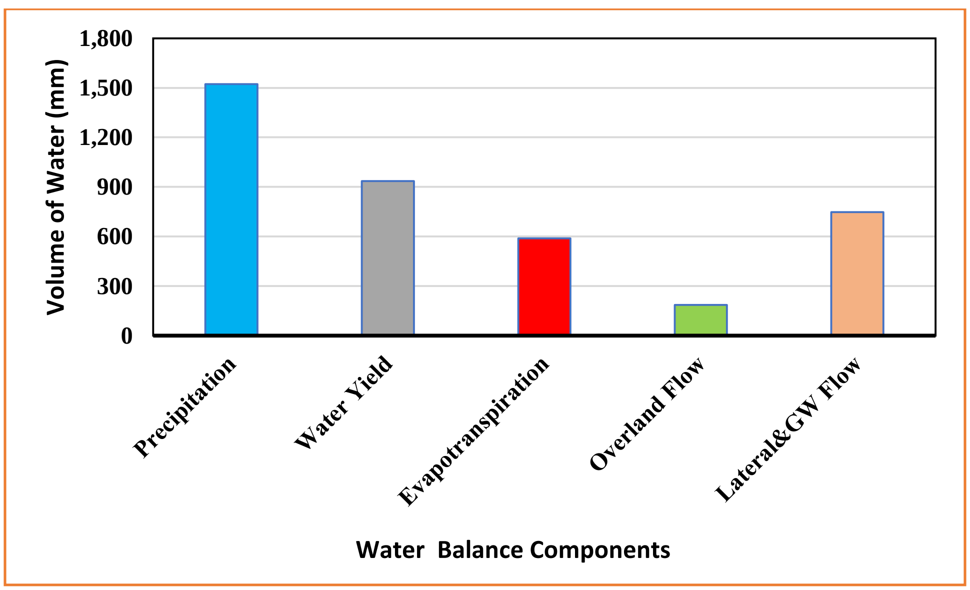


Figure 8-33 Water Balance of Kamala River Basin

CHAPTER 9: ASSESSMENT OF IMPACT OF CLIMATE CHANGE

9.1 General Background

Climate change (CC) refers to long-term shifts in temperatures and weather patterns, primarily caused by human activities, especially the burning of fossil fuels like coal, oil, and gas. These activities release greenhouse gases such as carbon dioxide, methane, and nitrous oxide into the atmosphere, trapping heat and causing the Earth's temperature to rise. This phenomenon leads to a variety of effects, including more frequent extreme weather events (like floods, droughts, and hurricanes), rising sea levels, melting ice caps, and disruptions to ecosystems and biodiversity. While natural processes can also drive climate variations (e.g., volcanic eruptions, solar cycles), current changes are occurring at an unprecedented rate, driven mostly by human activity.

Precipitation, temperature and flow are the main hydro-climatic variables to be assessed as the impact of CC. Other effects are the consequences of the changes in these variables. The following steps were employed to assess the impact of CC in these variables are:

Step 1: Selection of Suitable GCMs/RCMs

i. Downloading climate data (precipitation & temperature) from the pool of Climate Models.

ii. Calculate the statistical performance parameters (NSE, KGE, PBIAS etc.) from the baseline observed climate data with climate model output and compare the parameters.

iii. Select 3 best GCMs/RCMs from the pool of models.

Step 2: Bias correction of climate data both historical and future ones.

Step 3: Carrying out hydrological simulation using calibrated and validated hydrological model (developed in **Chapter 8)** and get flow data of both historical and future period

Step 4: Extracting the required hydro-climatic data of interest.

Step 5: Performing climate change impact assessment

Absolute change in any hydroclimatic variable (X) due to the impact of climate change is assessed using **Equation (9-1)**.

$$\Delta X = X_{future} - X_{baseline} \quad (9\text{-}1)$$

Where,

X_{future}= Future variable X (precipitation/temperature/flow)

$X_{baseline}$= Baseline variable X (precipitation/temperature/flow)

The percentage change in the given variable is calculated using **Equation (9-2)**.

$$\Delta X\% = \frac{X_{future} - X_{baseline}}{X_{baseline}} \% \quad (9\text{-}2)$$

Generally, temperature change is expressed in absolute term and precipitation and flow are expressed in relative term.

9.2 Climate Models Selection and Bias Correction

The climate model runs from the CMIP6 era were retrieved from the World Climate Research Programme (WCRP) repository, which may be found at: **https://esgf-node.llnl.gov/search/CMIP6/**. The climate models selected for this study, along with their other details, have been listed in **Table 9-1**. These models have been selected based on the literature reviews for South Asia, such as: Almazroui et al. (2020), Mishra et al., (2020).

Table 9-1 Climate model outputs for future projection

SN	GCM	Spatial Resolution (Lat. X Lon.)	Historical Period	Research Center
1	ACCESS-CM2	1.25º X 1.875º	1980-2014	Australian Community Climate and Earth System simulator
2	ACCESS-ESM1-5	1.5º X 1.875º		Australian Community Climate and Earth System simulator
3	BCC-CSM2-MR	1.1215º X 1.125º		Beijing Climate Center
4	CanESM5	2.8125º X 2.8125º		Canadian Center for Climate Modeling and Analysis
5	EC-Earth3-Veg	0.7018º X0.7031º		European Community Earth
6	INM.INM-CM4-8	1.5º X 2º		Institute of Numerical Mathematics
7	INM-CM5-0	1.5º X 2º		Institute of Numerical Mathematics
8	IPSL-CM6A-LR	2.50º X 1.27º		Institute Pierre-Simon Laplace Climate Modelling Centre
9	MIROC6	1.4 º X 1.4º		Model for Interdisciplinary Research on Climate
10	MPI-ESM1-2-LR	1.5° X 1.5°		Max Planck Institute for Meteorology
11	MRI-ESM2-0	1.1215º X 1.125º		Meteorological Research Institute
12	NESM3	1.88° X 1.88°		Nanjing University of Information Science and Technology
13	NorESM2-LM	0.9424º X 1.25º		Norwegian Climate Center
14	NorESM2-MM	1º X 1º		Norwegian Climate Center
15	CNRM-CM6-1	0.50 X 0.50		Centre National de Recherches Météorologiques
16	CNRM-ESM2-1	1.41° X 1.40°		Centre National de Recherches Météorologiques
17	EC-Earth3	0.7018º X 0.7031º		European Community Earth
18	GFDL-ESM4	1.25° X 1.00°		Geophysical Fluid Dynamics Laboratory
19	KACE-1-0-G	1.88º X 1.25º		National Institute of Meteorological Sciences, Republic of Korea
20	MPI_ESM1-2-HR	0.9351º X 0.9375º		Max Planck Institute for Meteorology

The model outputs were downloaded at a day resolution for the climatic variables: maximum temperature, minimum temperature, and precipitation for the historical period (1980-2014), and time series for the future period (2015-2055) for SSP2-4.5 and SSP5-8.5 scenarios. After the raw series of these outputs were compared with the observed series, only the three best GCMs were selected for the ensembling. The performance evaluations were based on the rating ranges (as given by Moraisi et al., 2007) given in **Table 9-2**.

Table 9-2 Performance ratings for the selection of GCMs

Model Performance	R^2	NSE	RSR	PBIAS	Rating
Very Good	0.75<D ≤1.00	0.75<N≤1.00	0.00<R≤0.50	P≤ ±10	5
Good	0.65<D ≤0.75	0.65<N≤0.75	0.50<R≤0.60	±10<P≤ ±15	4
Satisfactory	0.50<D ≤0.65	0.50<N≤0.65	0.60<R≤0.70	±15<P≤ ±25	3
Unsatisfactory	0.40<D ≤0.50	0.40<N≤0.50	0.70<R≤0.80	±25<P≤ ±35	2
Poor	D≤0.40	N≤0.40	R>0.80	P≥ ±35	1

These climate model outputs are based on relatively coarse resolution and may have biases owing to uncertainty in them in comparison to observed climatic records. Since these "raw" outputs cannot be used directly at the catchment scale, we handle those using bias-correcting approaches, and for this study, we use the "quantile mapping" approach to minimize such biases. This method has been used in several cases in Nepal such as Chapagain et al., (2021) and Dhaubanjar et al., (2020) for Western Nepal, Lamichhane & Shakya (2019) in Kathmandu Valley, etc.

The term 'quantile' refers to the inverse cumulative distribution function. The cumulative distribution function of the historical model outputs is contrasted to that of the observed series in the quantile mapping approach and subsequently modified to correspond to the observed cumulative distribution function (Camici et al., 2014). This concept is mathematically represented by **Equation (9-3).**

$$P_{GCM}{}_{k,QM}^{baseline} = F^{-1}{}_{P_{OBS}{}_k^{baseline}}\left[F_{P_{GCM}{}_k^{baseline}}\left(P_{GCM}{}_k^{baseline}\right)\right] \quad ,k = 1,2 \,.... \qquad (9\text{-}3)$$

Here, the term P refers to the climatic variable under investigation, F refers to the cumulative distribution function (*cdf*) and F^{-1} is its corresponding quantile form. Also, $P_{GCM}{}_k^{baseline}$ indicates the cumulative distribution function of the GCM outputs in the baseline (historical) period for the month k, and similar definitions can be established for other variables as well. The ratio R_k can be computed based on the *cdf*s of the observations and the baseline GCM series, as given in **Equation (9-4)**.

$$R_k[\, F_{P_{GCM}{}_k^{future}}\left(P_{GCM}{}_k^{future}\right)] = \frac{F^{-1}{}_{P_{OBS}{}_k^{baseline}}\left[F_{P_{GCM}{}_k^{future}}\left(P_{GCM}{}_k^{future}\right)\right]}{F^{-1}{}_{P_{GCM}{}_k^{baseline}}\left[F_{P_{GCM}{}_k^{future}}\left(P_{GCM}{}_k^{future}\right)\right]} \qquad (9\text{-}4)$$

The above ratio is then used to transform the future GCM series as given by **Equation (9-5)**.

$$P_{GCM}{}_{k,QM}^{fut} = (P_{GCM}{}_k^{fut}.\, R_k) \quad ,k = 1,2 \,.... \qquad (9\text{-}5)$$

i. Types of Quantile Mapping Algorithms

Within the quantile mapping approach, there are three general forms of transformations: Distribution-Derived Transformation, Parametric Transformation, and Non-Parametric Transformation (Gudmundsson et al., 2012; Gudmundsson, 2016; Enayati et al., 2021).

- **Distribution Derived Transformation:**

Under this method, a theoretical *cdf* can be utilized to determine the parameters and derive quantile functions for the observed and simulated series. This derived transfer function enables the transformation of the modeled data distribution to align with the distribution of the observed time series (Gudmundsson L., 2016). Notably, this method is specifically suitable for rainfall variables only. Within the method, the distributions such as Bernoulli-Gamma, Bernoulli-exponential, Bernoulli-Weibull and Bernoulli-Lognormal are included and in this study, these distributions have also been explored for the transformation of the modeled precipitation series of different climate models.

- **Parametric Transformation:**

The idea regarding this approach is to conform the parametric transformation to the quantile-quantile association of the observed/recorded and the modeled series, and then utilize the transformation on the modeled series to make it in line with the distribution of the observed dataset (Gudmundsson et al., 2012). The initial and crucial phase is to compute the empirical cumulative distribution functions of the observed and modeled series, after which a series of transformation functions may be employed to link the *cdf*s of the observed and modeled series.

Under this study, the transformation functions: Linear ($P_0 = a + b * P_m$), Scale ($P_o = b * P_m$), Power ($P_o = aP_m^c$) and Exponential tendency to asymptote ($P_0 = (a + b * P_m)(1 - \exp(-P_m/\tau))$) has been considered for the quantile mapping approach. Here, P_0 and P_m are the cdfs of the observed and modeled series and the parameters a, b, c, and τ are to be estimated to define the transformation function.

- **Non-Parametric Transformation:**

The non-parametric transform approach is based on applying an adjustment matrix to the CDFs of observed and modeled data sets and then interpolating between the two quantiles (Bong et al., 2018). This approach comprises techniques such as smoothing spline, empirical quantile methods, robust empirical quantile methods, and others. For such transformation methods, the quantile-quantile relation of the observed and the modeled series is defined for the regularly spaced quantiles, and are used for the transformation purpose. In case of values outside the quantile ranges, the interpolation such as linear, tri-cubic spline, etc., can be used to estimate the approximation.

For this study, the above mentioned non-parametric transformation methods have been used under the quantile mapping methods (

Table 9-3).

Table 9-3 Statistical transformation functions for quantile mapping method

Type of Transformations	
Distribution Derived Transformation**	Bernoulli-Exponential Distribution
	Bernoulli-Gamma Distribution
	Bernoulli-Weibull Distribution
	Bernoulli-Log-normal Distribution
Parametric Transformation	Power
	Linear
	Exponential tendency to asymptote
	Scale
Non-Parametric Transformation	Smoothing Spline
	Robust Empirical quantiles: Linear
	Robust Empirical quantiles: Tri-Cubic
	Empirical quantiles: Linear
	Empirical quantiles: Tri-Cubic

** Only for precipitation

ii. Selection of Suitable Quantile Mapping Method

The historical raw precipitation series of each GCMs are bias-corrected using the thirteen quantile mapping methods while the model simulated raw temperature series are bias-corrected using the nine methods for each of the climate model outputs. In order to select the best-performing methods out of such cluster of quantile mapping methods, the performance metrics such as R^2, NSE, PBIAS and RSR are computed for each method. The values of such metrics are then transmuted to their corresponding rating in the scale of 1 to 8 based on **Table 9-4**, as per the performance ratings given in Moriasi, et al., (2007).

Table 9-4 Performance ratings for the selection of bias correction method

Model Performance	R^2	**NSE**	**RSR**	**PBIAS**	**Rating**
Very Good	0.85<D≤1.00	0.85<N≤1.00	0.00<R≤0.25	P≤ ±5	8
	0.75<D≤0.85	0.75<N≤0.85	0.25<R≤0.50	±5<P≤ ±10	7
Good	0.70<D≤0.75	0.70<N≤0.75	0.50<R≤0.55	±10<P≤±12.5	6
	0.65<D≤0.70	0.65<N≤0.70	0.55<R≤0.60	±12.5<P≤±15	5
Satisfactory	0.57<D≤0.65	0.57<N≤0.65	0.60<R≤0.65	±15<P≤ ±20	4
	0.50<D≤0.57	0.50<N≤0.57	0.65<R≤0.70	±20<P≤ ±255	3
Unsatisfactory	0.40<D≤0.50	0.40<N≤0.50	0.70<R≤0.80	±25<P≤ ±35	2
Poor	D≤0.40	N≤0.40	R>0.80	P≥ ±35	1

After the selection of the best-performing quantile mapping method based on the overall average rating of all stations, the future series (for both SSP245 and SSP585 scenarios) are transformed using the same approach for the climatic stations.

9.3 Selected GCMs for Precipitation and Temperature

Top three GCMs selected for each basin using the method discussed above is shown in **Figure 9-1**. In **Table 9-5, Table 9-6 and Table 9-7** top three selected GCMs for precipitation, maximum temperature, and minimum temperature are provided respectively for each basin; along with the suitable quantile mapping method used for the bias correction and the optimum function. Bias correction was performed for each of the chosen GCMs using the 'qmap' package in the R environment. Based on the optimal bias correction method in the historical period, the same method was also applied for the future series to produce the future projections for both SSP245 and SSP585 scenarios.

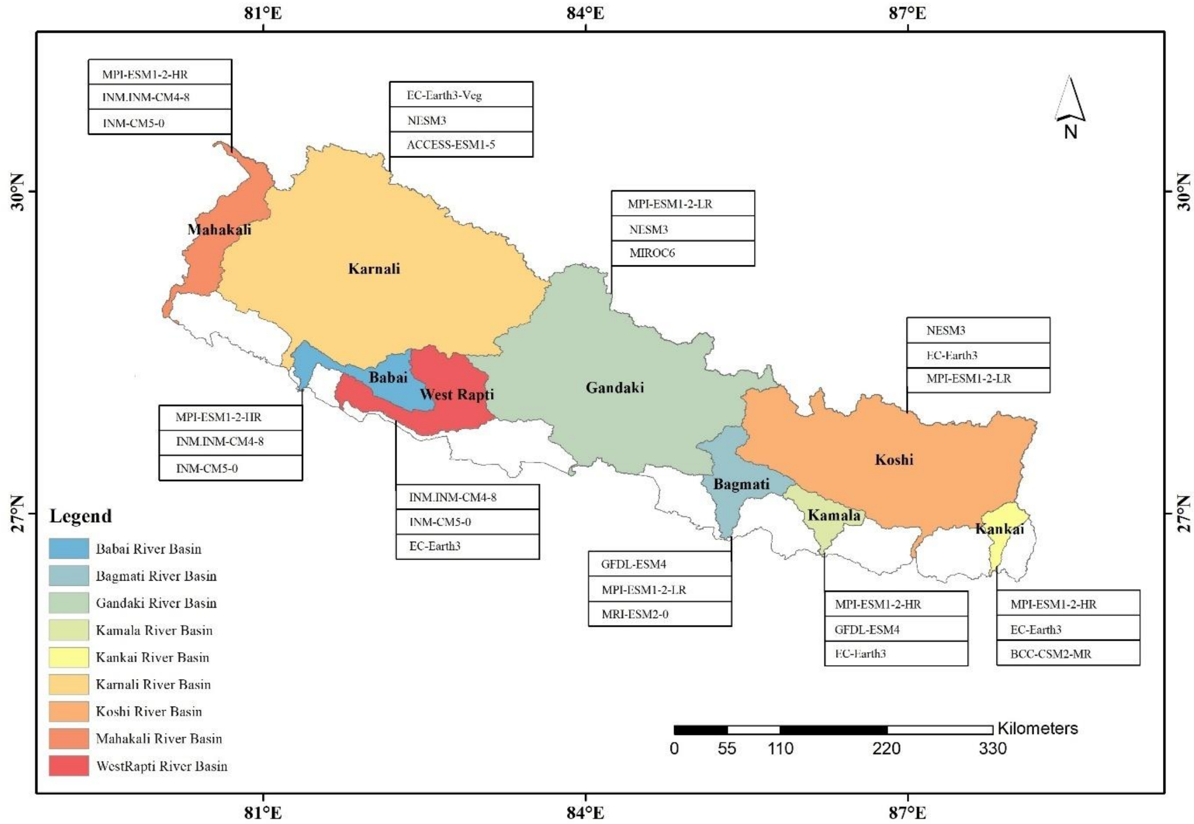


Figure 9-1 Top three GCMs selected for major river basins

Table 9-5 Selected GCMs for precipitation

SN	Basin	GCM	Type of Q-map	Function
1	Koshi	NESM3	Distribution	Bernoulli-Gamma
		MPI-ESM1-2-LR	Distribution	Bernoulli-Gamma
		EC-Earth3	Distribution	Bernoulli-Weibull
2	Gandaki	MIROC6	Distribution	Bernoulli-Weibull
		MPI-ESM1-2-LR	Distribution	Bernoulli-Gamma
		NESM3	Distribution	Bernoulli-Gamma
3	Karnali	ACCESS-ESM1-5	Distribution	Bernoulli-Weibull
		EC-Earth3-Veg	Distribution	Bernoulli-Gamma
		NESM3	Distribution	Bernoulli-Gamma
4	Chamelia	MPI_ESM1-2-HR	Distribution	Bernoulli-Weibull
		INM.INM-CM4-8	Distribution	Bernoulli-Weibull
		INM-CM5-0	Distribution	Bernoulli-Weibull
5	Kankai	BCC-CSM2-MR	Parametric	Power
		EC-Earth3	Distribution	Bernoulli-Weibull
		MPI_ESM1-2-HR	Distribution	Bernoulli-Gamma
6	Kamala	EC-Earth3	Non-parametric	Tri-cubic
		GFDL-ESM4	Parametric	Power
		MPI_ESM1-2-HR	Parametric	Linear
7	Bagmati	MPI-ESM1-2-LR	Distribution	Bernoulli-Gamma
		MRI-ESM2-0	Distribution	Bernoulli-Weibull
		GFDL-ESM4	Parametric	Power
8	West Rapti	EC-Earth3	Distribution	Bernoulli-Gamma
		INM.INM-CM4-8	Non-parametric	Tri-cubic
		INM-CM5-0	Non-parametric	Tri-cubic
9	Babai	INM.INM-CM4-8	Non-parametric	Tri-cubic
		INM-CM5-0	Parametric	Linear
		MPI_ESM1-2-HR	Distribution	Bernoulli-Gamma

Table 9-6 Selected GCMs for maximum temperature

	Basin	GCM	Type of Q-map	Function
1	Koshi	NESM3	Parametric	Exponential tendency to asymptote
		MPI-ESM1-2-LR	Non-parametric	Smoothing Spline
		EC-Earth3	Non-parametric	Smoothing Spline
2	Gandaki	MIROC6	Non-parametric	Smoothing Spline
		MPI-ESM1-2-LR	Non-parametric	Smoothing Spline
		NESM3	Non-parametric	Linear
3	Karnali	ACCESS-ESM1-5	Non-parametric	Smoothing Spline
		EC-Earth3-Veg	Non-parametric	Smoothing Spline
		NESM3	Non-parametric	Smoothing Spline
4	Chamelia	MPI_ESM1-2-HR	Non-parametric	Linear
		INM.INM-CM4-8	Non-parametric	Linear
		INM-CM5-0	Non-parametric	Linear (Robust)
5	Kankai	BCC-CSM2-MR	Non-parametric	Smoothing Spline
		EC-Earth3	Non-parametric	Smoothing Spline
		MPI_ESM1-2-HR	Non-parametric	Smoothing Spline
6	Kamala	EC-Earth3	Non-parametric	Smoothing Spline
		GFDL-ESM4	Non-parametric	Smoothing Spline
		MPI_ESM1-2-HR	Non-parametric	Smoothing Spline
7	Bagmati	MPI-ESM1-2-LR	Non-parametric	Linear (Robust)
		MRI-ESM2-0	Non-parametric	Smoothing Spline
		GFDL-ESM4	Non-parametric	Smoothing Spline
8	West Rapti	EC-Earth3	Non-parametric	Linear (Robust)
		INM.INM-CM4-8	Non-parametric	Linear (Robust)
		INM-CM5-0	Non-parametric	Linear (Robust)
9	Babai	INM.INM-CM4-8	Non-parametric	Smoothing Spline
		INM-CM5-0	Non-parametric	Smoothing Spline
		MPI_ESM1-2-HR	Non-parametric	Smoothing Spline

Table 9-7 Selected GCMs for minimum temperature

SN	Basin	GCM	Type of Q-map	Function
1	Koshi	NESM3	Non-parametric	Linear
		MPI-ESM1-2-LR	Non-parametric	Linear
		EC-Earth3	Non-parametric	Linear
2	Gandaki	MIROC6	Non-parametric	Smoothing Spline
		MPI-ESM1-2-LR	Non-parametric	Linear
		NESM3	Non-parametric	Smoothing Spline
3	Karnali	ACCESS-ESM1-5	Non-parametric	Linear (Robust)
		EC-Earth3-Veg	Non-parametric	Smoothing Spline
		NESM3	Non-parametric	Linear
4	Mahakali	MPI_ESM1-2-HR	Non-parametric	Linear
		INM.INM-CM4-8	Non-parametric	Linear
		INM-CM5-0	Non-parametric	Linear
5	Kankai	BCC-CSM2-MR	Non-parametric	Linear
		EC-Earth3	Non-parametric	Linear
		MPI_ESM1-2-HR	Non-parametric	Linear
6	Kamala	EC-Earth3	Non-parametric	Linear
		GFDL-ESM4	Non-parametric	Linear
		MPI_ESM1-2-HR	Non-parametric	Linear
7	Bagmati	MPI-ESM1-2-LR	Non-parametric	Linear (Robust)
		MRI-ESM2-0	Non-parametric	Smoothing Spline
		GFDL-ESM4	Non-parametric	Linear
8	West Rapti	EC-Earth3	Non-parametric	Linear
		INM.INM-CM4-8	Non-parametric	Linear
		INM-CM5-0	Non-parametric	Linear
9	Babai	INM.INM-CM4-8	Non-parametric	Smoothing Spline
		INM-CM5-0	Non-parametric	Linear
		MPI_ESM1-2-HR	Non-parametric	Smoothing Spline

9.4 Impact of Climate Change on Precipitation

Two scenarios (SSP245 and SSP585) were considered in this study to assess the potential impact of climate change on precipitation. The long-term annual average of bias-corrected precipitation data for the historical period, referred to as the baseline (1985–2014: 30 years), and the future period (2025–2054: 30 years) were compared on a basin-wise basis for this purpose.

Table 9-8 shows the percentage changes in precipitation due to climate change for nine major basins, based on the top three selected GCMs. The overall ensemble average change in precipitation for Nepal appears to be modest, with an increase of 3% under SSP245 and 6% under SSP585. Station-wise impacts of climate change on precipitation are provided in **Appendix (Table E-1)**.

Table 9-8 Impact on climate change on precipitation

Unit: %

SN	Basin	SSP245				SSP585			
1	**Koshi**	EC-Earth3	MPI-ESM1-2-LR	NESM3	MME	EC-Earth3	MPI-ESM1-2-LR	NESM3	MME
		8.29	-5.52	-2.70	0.02	11.32	-8.15	-5.15	-0.65
2	**Gandaki**	MIROC6	MPI-ESM1-2-LR	NESM3	MME	MIROC6	MPI-ESM1-2-LR	NESM3	MME
		-4.88	-0.47	0.86	-1.51	-0.05	-1.96	0.74	-0.42
3	**Karnali**	ACCESS-ESM1-5	EC-Earth3-Veg	NESM3	MME	ACCESS-ESM1-5	EC-Earth3-Veg	NESM3	MME
		3.54	4.59	1.41	3.41	3.90	6.47	-0.66	3.54
4	**Chamelia**	INM-CM5-0	INM.INM-CM4-8	MPI_ESM1-2-HR	MME	INM-CM5-0	INM.INM-CM4-8	MPI_ESM1-2-HR	MME
		5.87	5.76	-0.04	3.79	13.00	9.44	0.70	7.60
5	**Kankai**	BCC-CSM2-MR	EC-Earth3	MPI_ESM1-2-HR	MME	BCC-CSM2-MR	EC-Earth3	MPI_ESM1-2-HR	MME
		3.84	9.96	3.20	5.49	6.24	12.45	1.88	6.81
6	**Kamala**	EC-Earth3	GFDL-ESM4	MPI_ESM1-2-HR	MME	EC-Earth3	GFDL-ESM4	MPI_ESM1-2-HR	MME
		6.61	-4.89	7.54	3.17	9.27	2.38	11.40	7.67
7	**Bagmati**	GFDL-ESM4	MPI-ESM1-2-LR	MRI-ESM2-0	MME	GFDL-ESM4	MPI-ESM1-2-LR	MRI-ESM2-0	MME
		-3.23	-3.16	2.96	-1.17	0.30	-5.22	6.24	0.41
8	**West Rapi**	EC-Earth3	INM-CM5-0	INM.INM-CM4-8	MME	EC-Earth3	INM-CM5-0	INM.INM-CM4-8	MME
		14.85	-2.59	19.90	10.65	16.67	13.08	25.01	18.14
9	**Babai**	INM-CM5-0	INM.INM-CM4-8	MPI_ESM1-2-HR	MME	INM-CM5-0	INM.INM-CM4-8	MPI_ESM1-2-HR	MME
		-5.47	18.34	0.42	4.33	8.17	25.77	-3.43	10.15

Note: MME – Multi Model Ensemble

1. Koshi Basin

Among the three models considered in this study, two predict a decrease in precipitation, while one predicts an increase in the Koshi Basin for both SSP245 and SSP585. The ensemble change under SSP245 is nearly zero (0.02%), and under SSP585, it is also minimal (-0.65%). However, the uncertainty is significant in both scenarios, with varying changes observed among rain gauge stations (**Figure 9-2**).

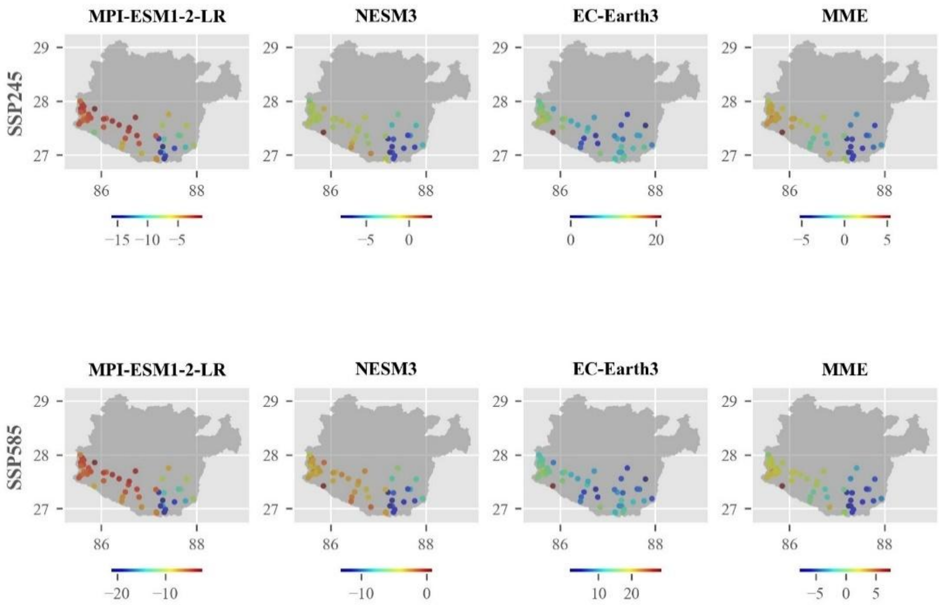


Figure 9-2 Impact of climate change on precipitation in Koshi Basin

2. Gandaki Basin

The predictions of precipitation by three climate models under both climate scenarios (SSP245 and SSP585) in the Gandaki Basin do not indicate a significant increase or decrease on an annual scale. Similar to the Koshi Basin, two models predict a decrease in precipitation, while one model predicts an increase. The average change is -1.5% for SSP245 and -0.4% for SSP585. The percentage change at each rain gauge station is illustrated in **Figure 9-3**.

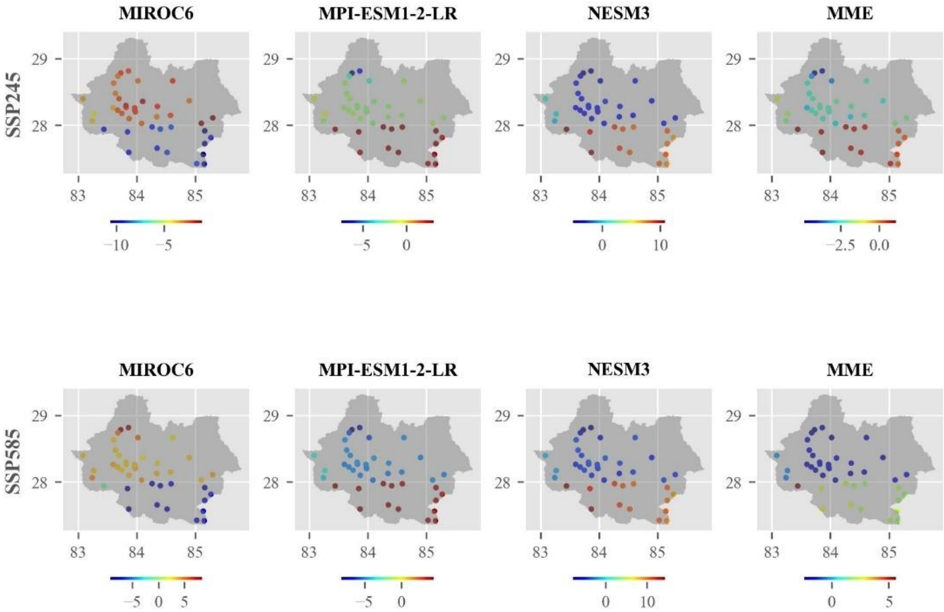


Figure 9-3 Impact of climate change on precipitation in Gandaki Basin

3. Karnali Basin

Based on the precipitation predictions from three GCMs, the long-term average change in precipitation from baseline values is 3.4% under SSP245 and 3.5% under SSP585 for the Karnali Basin. Except for one model (NESM3) under SSP585, all other models predict an increase in precipitation in this basin. This suggests a likelihood of increased future precipitation in the basin on an annual scale. Station-wise changes are provided in **Figure 9-4**.

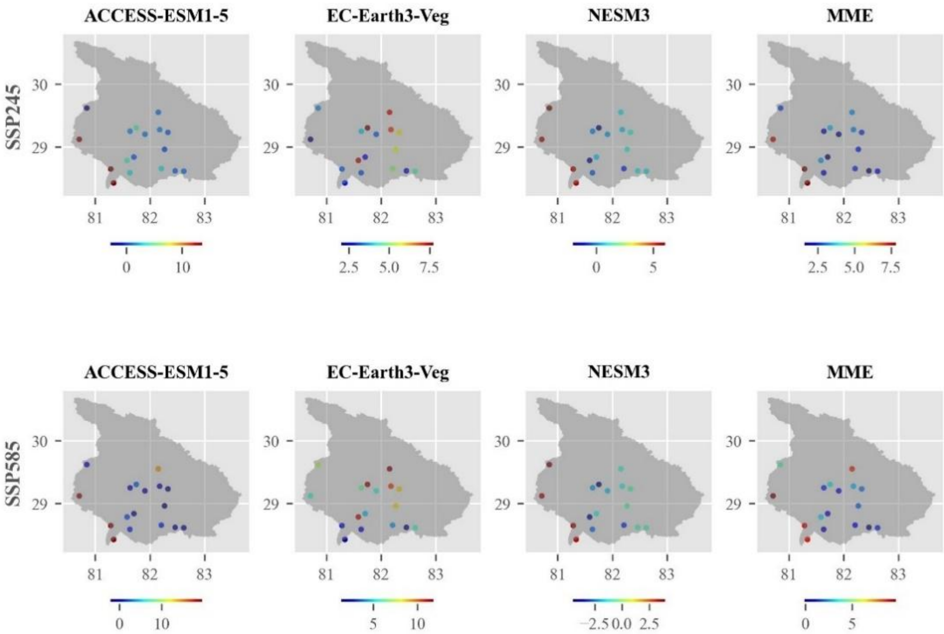


Figure 9-4 Impact of climate change on precipitation in Karnali Basin

4. Chamelia Basin

Except for one GCM under SSP245 (MPI-ESM1-2-HR), which predicts a decrease in average precipitation in the Chamelia Basin, the other two models under SSP245 and all three models under SSP585 predict an increase in precipitation for this basin. The ensemble averages are 3.8% and 7.6% for the SSP245 and SSP585 scenarios, respectively. Station-wise probable changes in precipitation are shown in **Figure 9-5**.

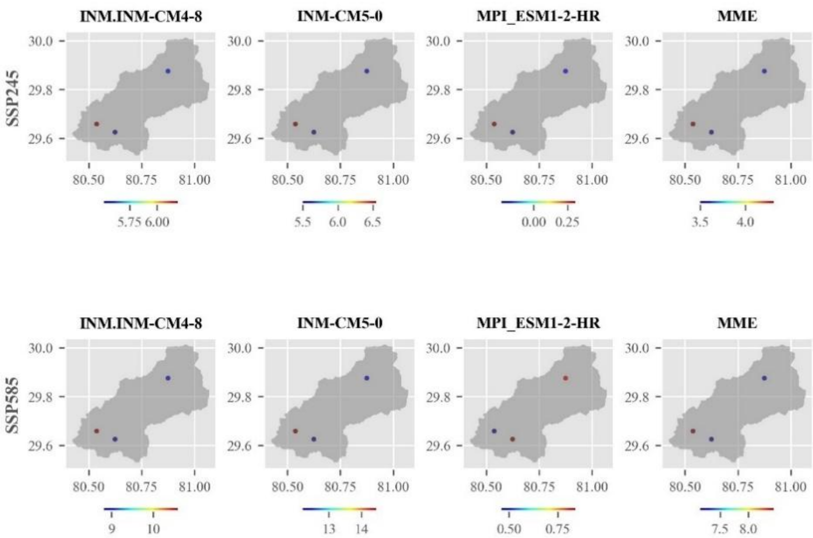


Figure 9-5 Impact of climate change in precipitation in Chamelia Basin

5. Kankai Basin

All models under both scenarios predict an increase in precipitation in the Kankai Basin. The ensemble average change is 5.5% under the SSP245 scenario and 6.8% under the SSP585 scenario. Station-wise changes are shown in **Figure 9-6**.

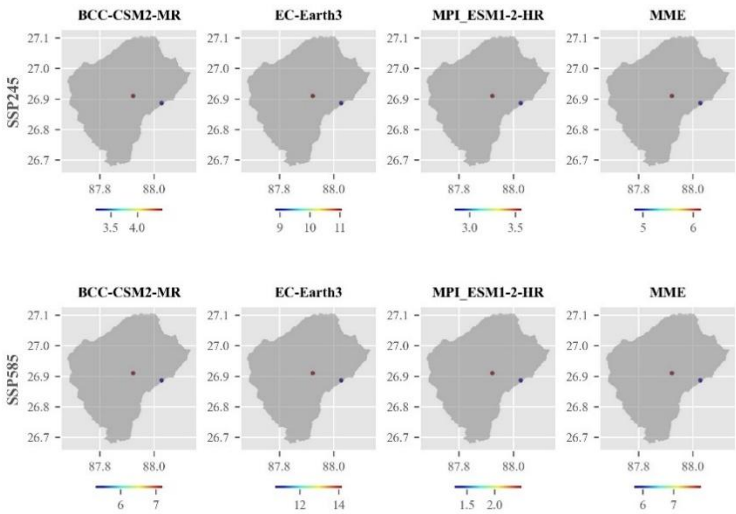


Figure 9-6 Impact of climate change in precipitation in Kankai Basin

6. Kamala Basin

The prediction of future precipitation by all models under both scenarios, except for the GFDL-ESM4 model under the SSP245 case, indicates an increase in the Kamala Basin. The ensemble average changes are 3.2% and 7.7% under SSP245 and SSP585, respectively. Station-wise changes are shown in **Figure 9-7**.

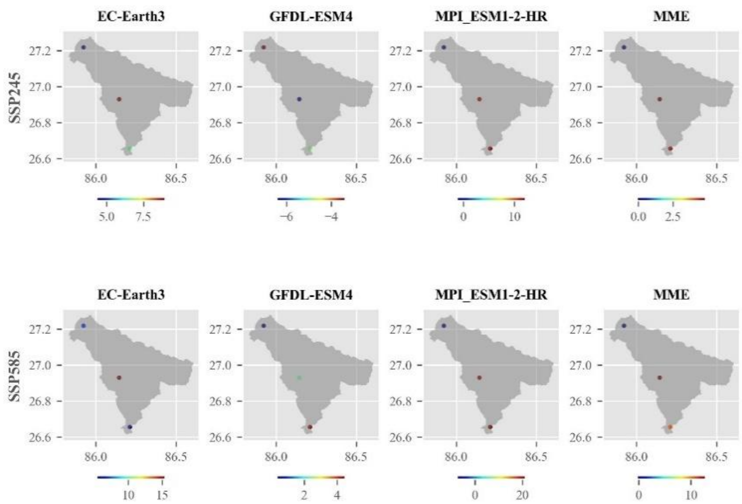


Figure 9-7 Impact of climate change in precipitation in Kamala Basin

7. Bagmati Basin

The predicted changes in precipitation from the baseline in the Bagmati Basin are as follows: under SSP245, two models predict a decrease, while under SSP585, two models predict an increase. The overall average changes are -1.2% and +0.4% under SSP245 and SSP585, respectively. Station-wise changes are shown in **Figure 9-8**.

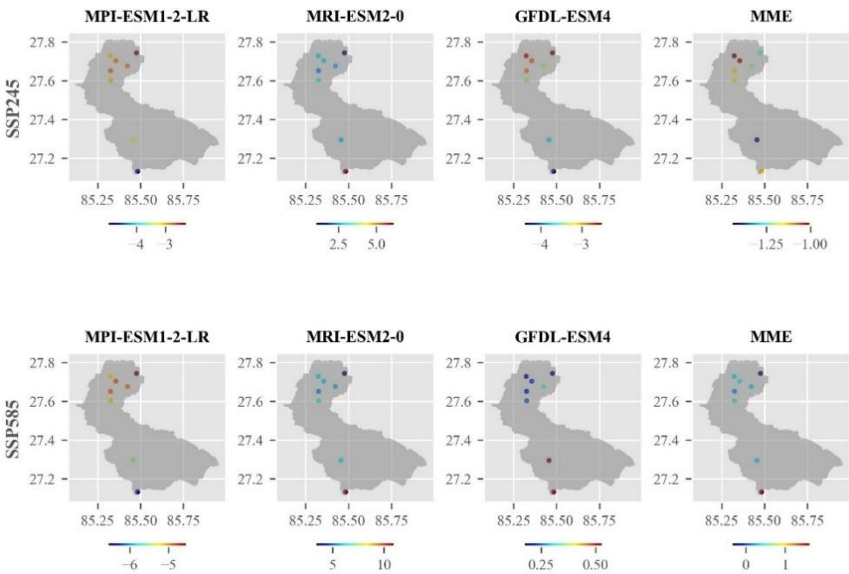


Figure 9-8 Impact of climate change in precipitation in Bagmati Basin

8. West Rapti Basin

The average changes in predicted future precipitation in the West Rapti Basin are 10.7% and 18.1% under the SSP245 and SSP585 scenarios, respectively. All predictions are positive except for one model (INM-CM5-0) under SSP245. Station-wise changes are depicted in **Figure 9-9**.

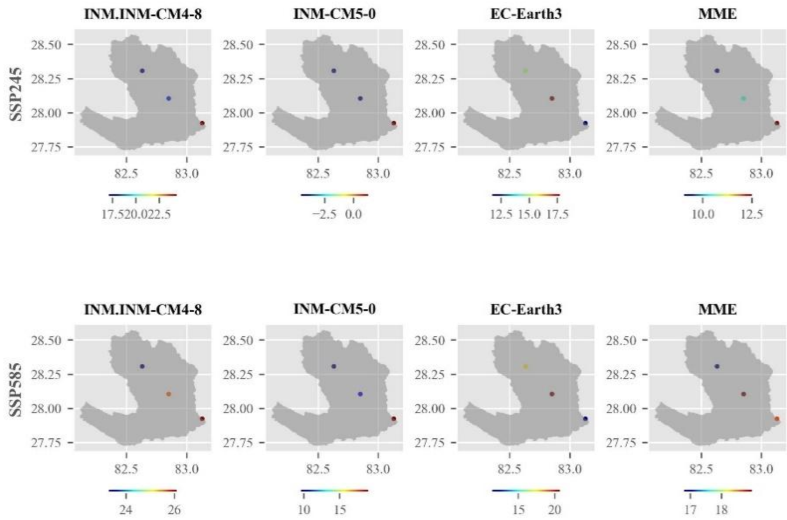


Figure 9-9 Impact of climate change in precipitation in West Rapti Basin

9. Babai Basin

One model in both scenarios predicts a decrease in future precipitation compared to the baseline. The ensemble averages are 4.3% and 10.2% under SSP245 and SSP585, respectively. Station-wise changes in future precipitation with respect to the baseline are shown in **Figure 9-10**.

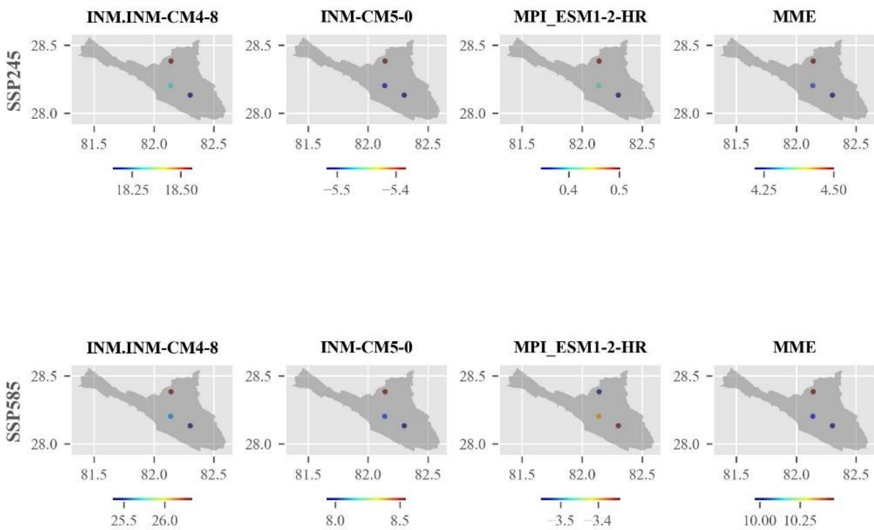


Figure 9-10 Impact of climate change in precipitation in Babai Basin

9.5 Impact of Climate Change on Temperature

Impacts of climate change in maximum and minimum temperatures are given in **Table 9-9** and **Table 9-10** respectively. The predicted future temperatures, both maximum and minimum, under both the SSP245 and SSP585 scenarios in all nine basins are higher than the baseline values.

The overall average increase in maximum temperature across the country is 0.71°C under the SSP245 scenario and 0.84°C under the SSP585 scenario. However, the degree of change varies across different basins and between the two scenarios. Under SSP245, the highest increase is predicted for the Karnali Basin, i.e., 0.98°C, and the lowest increase is predicted for the Kankai and Kamala Basins, i.e., 0.5°C among the nine basins. Interestingly, under the SSP585 scenario as well, the highest increase is predicted for the Karnali Basin, with a temperature value of 1.23°C, and the lowest increase is predicted for the Kamala Basin, with 0.49°C.

In the case of minimum temperature, the country-level average increase is 0.96°C under the SSP245 scenario and 1.15°C under the SSP585 scenario. These values are slightly higher than those for the increase in maximum temperature. Similar to maximum temperature, the rate of increase in minimum temperature is predicted to be the highest for the Karnali Basin (1.15°C under SSP245 and 1.41°C under SSP585) and the lowest for the Kamala Basin (0.76°C under SSP245 and 0.83°C under SSP585).

In both the maximum and minimum temperature cases, the rate of increase is higher under SSP585 than under SSP245.

Table 9-9 Impact of climate change in maximum temperature

Unit: °C

SN	Basin	SSP245				SSP585			
1	**Koshi**	EC-Earth3	MPI-ESM1-2-LR	NESM3	MME	EC-Earth3	MPI-ESM1-2-LR	NESM3	MME
		0.84	0.55	0.71	0.70	1.05	0.56	0.96	0.85
2	**Gandaki**	MIROC6	MPI-ESM1-2-LR	NESM3	MME	MIROC6	MPI-ESM1-2-LR	NESM3	MME
		0.84	0.64	1.13	0.87	0.96	0.71	1.40	1.02
3	**Karnali**	ACCESS-ESM1-5	EC-Earth3-Veg	NESM3	MME	ACCESS-ESM1-5	EC-Earth3-Veg	NESM3	MME
		1.27	0.60	1.05	0.98	1.54	0.79	1.35	1.23
4	**Chamelia**	INM-CM5-0	INM.INM-CM4-8	MPI_ESM1-2-HR	MME	INM-CM5-0	INM.INM-CM4-8	MPI_ESM1-2-HR	MME
		0.78	0.87	0.66	0.77	1.03	0.97	0.74	0.91
5	**Kankai**	BCC-CSM2-MR	EC-Earth3	MPI_ESM1-2-HR	MME	BCC-CSM2-MR	EC-Earth3	MPI_ESM1-2-HR	MME
		0.55	0.65	0.32	0.51	0.62	0.92	0.22	0.59
6	**Kamala**	EC-Earth3	GFDL-ESM4	MPI_ESM1-2-HR	MME	EC-Earth3	GFDL-ESM4	MPI_ESM1-2-HR	MME
		0.60	0.47	0.49	0.52	0.76	0.35	0.36	0.49
7	**Bagmati**	GFDL-ESM4	MPI-ESM1-2-LR	MRI-ESM2-0	MME	GFDL-ESM4	MPI-ESM1-2-LR	MRI-ESM2-0	MME
		0.58	0.53	0.82	0.65	0.57	0.53	1.00	0.70
8	**West Rapi**	EC-Earth3	INM-CM5-0	INM.INM-CM4-8	MME	EC-Earth3	INM-CM5-0	INM.INM-CM4-8	MME
		0.65	0.83	0.80	0.76	0.69	1.09	1.00	0.93
9	**Babai**	INM-CM5-0	INM.INM-CM4-8	MPI_ESM1-2-HR	MME	INM-CM5-0	INM.INM-CM4-8	MPI_ESM1-2-HR	MME
		0.63	0.66	0.67	0.65	0.88	0.84	0.67	0.80

Table 9-10 Impact of climate change in minimum temperature

Unit: °C

SN	Basin	SSP245				SSP585			
1	**Koshi**	EC-Earth3	MPI-ESM1-2-LR	NESM3	MME	EC-Earth3	MPI-ESM1-2-LR	NESM3	MME
		1.19	0.64	1.00	0.94	1.45	0.72	1.28	1.15
2	**Gandaki**	MIROC6	MPI-ESM1-2-LR	NESM3	MME	MIROC6	MPI-ESM1-2-LR	NESM3	MME
		1.14	0.79	1.24	1.06	1.25	0.87	1.52	1.21
3	**Karnali**	ACCESS-ESM1-5	EC-Earth3-Veg	NESM3	MME	ACCESS-ESM1-5	EC-Earth3-Veg	NESM3	MME
		1.37	0.93	1.16	1.15	1.59	1.21	1.43	1.41
4	**Chamelia**	INM-CM5-0	INM.INM-CM4-8	MPI_ESM1-2-HR	MME	INM-CM5-0	INM.INM-CM4-8	MPI_ESM1-2-HR	MME
		0.96	1.06	0.84	0.95	1.34	1.25	1.07	1.22
5	**Kankai**	BCC-CSM2-MR	EC-Earth3	MPI_ESM1-2-HR	MME	BCC-CSM2-MR	EC-Earth3	MPI_ESM1-2-HR	MME
		0.84	1.10	0.54	0.82	0.97	1.33	0.55	0.95
6	**Kamala**	EC-Earth3	GFDL-ESM4	MPI_ESM1-2-HR	MME	EC-Earth3	GFDL-ESM4	MPI_ESM1-2-HR	MME
		0.99	0.65	0.63	0.76	1.22	0.66	0.62	0.83
7	**Bagmati**	GFDL-ESM4	MPI-ESM1-2-LR	MRI-ESM2-0	MME	GFDL-ESM4	MPI-ESM1-2-LR	MRI-ESM2-0	MME
		0.81	0.73	1.26	0.94	1.00	0.82	1.55	1.12
8	**West Rapi**	EC-Earth3	INM-CM5-0	INM.INM-CM4-8	MME	EC-Earth3	INM-CM5-0	INM.INM-CM4-8	MME
		0.96	0.94	1.10	1.00	1.19	1.31	1.33	1.27
9	**Babai**	INM-CM5-0	INM.INM-CM4-8	MPI_ESM1-2-HR	MME	INM-CM5-0	INM.INM-CM4-8	MPI_ESM1-2-HR	MME
		0.98	1.11	0.85	0.98	1.37	1.34	0.96	1.22

9.6 Climate Change Impact High and Low Flows

Flow simulations of all nine basins were carried out using ensembled precipitation, maximum and minimum temperatures using calibrated hydrological model, discussed in **Chapter 8**, for each basin for both historical (1980-2014) and future periods (2025-2054). Top five highest and bottom five lowest flows under both climate scenarios (SSP245 and SSP 585) were extracted from for each basin outlet. They are compared with respective historical top five highest and bottom five lowest flows to assess the impact of climate change on high and low flows. To reduce the uncertainty, average change of all the top five and bottom five flows were also calculated and compared them with the respective historical averages for all basins.

9.6.1 Climate Change Impact on High and Low Flows of Class A Rivers

The impact of climate change in percentage of top five high flows of Class A River Basins is given in **Table 9-11** (for SSP245) and **Table 9-12** (for SSP585). Similarly, bottom five low flows of these basins are given in **Table 9-13** (for SSP245) and **Table 9-14** (SSP585).

Table 9-11 Impact of CC on top five high flows of Class A River Basins under SSP245

Rank	River Basins: SSP 245						
	Koshi				Gandaki		
	Historic	Future	Change (%)		Historic	Future	Change (%)
Highest	7603	7818	2.8		9602	8728	-9.1
2nd Highest	7456	7638	2.4		9186	8686	-5.4
3rd Highest	7104	7556	6.4		8655	8298	-4.1
4th Highest	6788	7429	9.4		8337	8234	-1.2
5th Highest	6763	7403	9.5		8313	8118	-2.3
Average	**7143**	**7569**	**6.0**		**8819**	**8413**	**-4.6**
Rank	River Basins: SSP 245						
	Karnali				Chamelia		
	Historic	Future	Change (%)		Historic	Future	Change (%)
Highest	9251	8797	-4.9		323	373	15.5
2nd Highest	8092	6298	-22.2		313	352	12.5
3rd Highest	7658	5903	-22.9		305	335	9.6
4th Highest	7255	4657	-35.8		303	334	10.4
5th Highest	7197	4656	-35.3		303	330	9.0
Average	**7891**	**6062**	**-23.2**		**309**	**345**	**11.5**

The overall average of predicted future flows is approximately 6% and 12% higher than the baseline flows in the Koshi and Chamelia Basins, respectively, under scenario SSP245 (**Table 9-11**). All top five future flows exceed the corresponding baseline flows in these basins, suggesting that future high flows are expected to surpass baseline values. However, in the Gandaki and Karnali Basins, high flows are anticipated to be lower than baseline levels for the same scenario. On average, future flows in the Gandaki Basin are predicted to be 5% smaller than the baseline, while in the Karnali Basin, they are expected to be nearly 20% smaller.

Under scenario SSP585, future flows are projected to exceed baseline values by about 16% in Chamelia Basin whearas in the Karnali Basin, where flows are expected to decrease by nearly 20% compared to baseline values (**Table 9-12**). The two western basins, Karnali and Chamelia, follow similar patterns under both scenarios, with SSP585 showing slightly greater magnitudes than SSP245.

In contrast, the Koshi and Gandaki Basins exhibit opposite trends under SSP585 compared to SSP245. Future flows in the Koshi Basin are expected to be lower than baseline values under SSP585, while in the Gandaki Basin, they are projected to increase. However, the highest future flow in the Gandaki Basin remains lower than the baseline value, consistent with the SSP245 scenario.

Table 9-12 Impact of CC on top five high flows of Class A River Basins under SSP585

Rank	River Basins: SSP 585							
	Koshi				Gandaki		
	Historic	Future	Change (%)		Historic	Future	Change (%)
Highest	7603	7327	-3.6		9602	9477	-1.3
2nd Highest	7456	7067	-5.2		9186	9431	2.7
3rd Highest	7104	7027	-1.1		8655	9203	6.3
4th Highest	6788	6972	2.7		8337	8988	7.8
5th Highest	6763	6955	2.8		8313	8940	7.5
Average	**7143**	**7070**	**-1.0**		**8819**	**9208**	**4.4**
Rank	River Basins: SSP 585						
	Karnali				Chamelia		
	Historic	Future	Change (%)		Historic	Future	Change (%)
Highest	9251	7721	-16.5		323	379	17.5
2nd Highest	8092	6435	-20.5		313	375	19.8
3rd Highest	7658	6266	-18.2		305	355	16.4
4th Highest	7255	5922	-18.4		303	342	12.9
5th Highest	7197	5827	-19.0		303	337	11.2
Average	**7891**	**6434**	**-18.5**		**309**	**358**	**15.6**

Under the SSP245 scenario, low flows in the Koshi and Karnali Basins are expected to exceed baseline values by approximately 25% and 90%, respectively (**Table 9-13**). In contrast, low flows are anticipated to decrease by about 40% in the Gandaki Basin and 10% in the Chamelia Basin under the same scenario.

For the SSP585 scenario, low flows are projected to be higher than baseline values in the Koshi (20%), Karnali (50%), and Chamelia (20%) Basins (**Table 9-14**). However, in the Gandaki Basin, low flows are expected to decrease by approximately 50%.

Table 9-13 Impact of CC on bottom five low flows of Class A Basins under SSP245

Rank	River Basins: SSP 245						
	Koshi				Gandaki		
	Historic	Future	Change (%)		Historic	Future	Change (%)
Lowest	90	115	28.3		94	55	-41.8
2nd Lowest	94	116	22.8		96	56	-42.1
3rd Lowest	95	116	22.6		97	57	-41.0
4th Lowest	95	120	25.3		98	60	-38.9
5th Lowest	97	120	23.5		98	61	-37.3
Average	**94**	**117**	**24.5**		**97**	**58**	**-40.2**

Rank	River Basins: SSP 245						
	Karnali				Chamelia		
	Historic	Future	Change (%)		Historic	Future	Change (%)
Lowest	102	193	89.9		4.9	4.6	-6.4
2nd Lowest	104	195	86.8		4.9	4.6	-7.8
3rd Lowest	105	195	86.0		5.0	4.6	-8.3
4th Lowest	106	195	84.5		5.1	4.6	-9.9
5th Lowest	108	197	82.3		5.2	4.6	-10.3
Average	**105**	**195**	**85.9**		**5.0**	**4.6**	**-8.6**

Table 9-14 Impact of CC on bottom five low flows of Class A Basins under SSP585

Rank	River Basins: SSP 585						
	Koshi				Gandaki		
	Historic	Future	Change (%)		Historic	Future	Change (%)
Lowest	90	109	22.0		94	46	-50.6
2nd Lowest	94	111	17.9		96	49	-49.6
3rd Lowest	95	113	19.3		97	49	-49.0
4th Lowest	95	114	19.6		98	50	-48.5
5th Lowest	97	114	17.4		98	51	-48.2
Average	**94**	**112**	**19.2**		**97**	**49**	**-49.2**

Rank	River Basins: SSP 585						
	Karnali				Chamelia		
	Historic	Future	Change (%)		Historic	Future	Change (%)
Lowest	102	151	48.5		4.9	5.7	17.7
2nd Lowest	104	154	47.5		4.9	5.8	17.9
3rd Lowest	105	156	48.9		5.0	6.0	18.6
4th Lowest	106	157	48.6		5.1	6.1	18.1
5th Lowest	108	160	47.8		5.2	6.2	19.3
Average	**105**	**155**	**48.3**		**5.0**	**5.9**	**18.3**

9.6.2 Climate Change Impact on High and Low Flows of Class B Rivers

The impact of climate change in percentage of top five high flows of Class B River Basins is given in **Table 9-15** (for SSP245) and **Table 9-16** (for SSP585). Similarly, bottom five low flows of these basins are given in **Table 9-17** (for SSP245) and **Table 9-18** (SSP585).

Under the SSP245 scenario, high flows in all Class B River Basins, except the Kankai Basin, are expected to exceed baseline values (**Table 9-15**). The projected increases are approximately 9% in the Kamala Basin, 12% in the Bagmati Basin, 13% in the West Rapti Basin, and 9% in the Babai Basin. In contrast, the Kankai Basin is expected to see a decrease of about 5%. These percentages represent the average of the top five flows. However, mixed results are observed among the top five flows in most basins under this scenario, except for the Kankai and Bagmati Basins.

Table 9-15 Impact of CC on top five high flows of Class B River Basins under SSP245

Rank	River Basins: SSP 245						
	Kankai				Kamala		
	Historic	Future	Change (%)		Historic	Future	Change (%)
Highest	755	737	-2.4		1868	2970	59.0
2nd Highest	634	699	10.3		1763	1656	-6.1
3rd Highest	581	527	-9.3		1660	1569	-5.5
4th Highest	565	487	-13.8		1649	1542	-6.5
5th Highest	537	469	-12.7		1485	1463	-1.5
Average	**614**	**584**	**-5.0**		**1685**	**1840**	**9.2**
Rank	River Basins: SSP 245						
	Bagmati				West Rapti		
	Historic	Future	Change (%)		Historic	Future	Change (%)
Highest	1498	1684	12.4		1572	2324	47.8
2nd Highest	1483	1671	12.7		1477	1631	10.4
3rd Highest	1330	1541	15.9		1458	1534	5.2
4th Highest	1320	1528	15.8		1402	1376	-1.9
5th Highest	1317	1355	2.9		1395	1358	-2.7
Average	**1390**	**1556**	**12.0**		**1461**	**1645**	**12.6**
Rank	River Basin: SSP 245						
	Babai						
	Historic	Future	Change (%)				
Highest	1198	1762	47.1				
2nd Highest	1029	918	-10.8				
3rd Highest	869.2	883.5	1.6				
4th Highest	838.7	791.2	-5.7				
5th Highest	760.6	744.4	-2.1				
Average	**939**	**1020**	**8.6**				

Under the SSP585 scenario, future high flows are expected to decrease relative to baseline values in the Kankai, Bagmati, and Babai River Basins by approximately 14%, 12%, and 7%, respectively (**Table 9-16**). In contrast, the Kamala and West Rapti Basins are projected to experience increases in high flows compared to baseline values. The probable increases are about 60% in the Kamala Basin and 25% in the West Rapti Basin.

Table 9-16 Impact of CC on top five high flows of Class B River Basins under SSP585

Rank	River Basins: SSP 585					
	Kankai			Kamala		
	Historic	Future	Change (%)	Historic	Future	Change (%)
Highest	755	662	-12.4	1868	3672	96.6
2nd Highest	634	535	-15.6	1763	3118	76.9
3rd Highest	581	494	-14.9	1660	2429	46.3
4th Highest	565	483	-14.6	1649	2205	33.7
5th Highest	537	481	-10.4	1485	2127	43.2
Average	**614**	**531**	**-13.6**	**1685**	**2710**	**60.8**

Rank	River Basins: SSP 585					
	Bagmati			West Rapti		
	Historic	Future	Change (%)	Historic	Future	Change (%)
Highest	1498	1325	-11.5	1572	2592	64.9
2nd Highest	1483	1282	-13.6	1477	1789	21.1
3rd Highest	1330	1213	-8.8	1458	1737	19.1
4th Highest	1320	1172	-11.2	1402	1483	5.8
5th Highest	1317	1159	-12.0	1395	1472	5.5
Average	**1390**	**1230**	**-11.5**	**1461**	**1815**	**24.2**

Rank	River Basin: SSP 585		
	Babai		
	Historic	Future	Change (%)
Highest	1198	1011	-15.6
2nd Highest	1029	923.9	-10.2
3rd Highest	869.2	847.6	-2.5
4th Highest	838.7	824	-1.8
5th Highest	760.6	774.4	1.8
Average	**939**	**876**	**-6.7**

The bottom low flows of Class B River Basins, as presented in **Table 9-17**, indicate that all basins except the Bagmati Basin are likely to experience higher flows in the future compared to baseline values under the SSP245 scenario. The projected increases are approximately 44% in the Kankai Basin, 109% in the Kamala Basin, 11% in the West Rapti Basin, and 10% in the Babai Basin. In the Bagmati Basin, the decrease is minimal, at around 1%.

Table 9-17 Impact of CC on bottom five low flows of Class B River Basins under SSP245

Rank	River Basins: SSP 245					
	Kankai			Kamala		
	Historic	Future	Change (%)	Historic	Future	Change (%)
Lowest	4.3	6.2	43.7	0.92	2.07	124.7
2nd Lowest	4.4	6.3	43.6	0.95	2.08	118.7
3rd Lowest	4.5	6.4	43.4	1.01	2.09	106.0
4th Lowest	4.5	6.5	45.1	1.04	2.09	101.0
5th Lowest	4.5	6.6	45.4	1.07	2.12	98.0
Average	**4.4**	**6.4**	**44.3**	**1.00**	**2.09**	**109.1**

Rank	River Basins: SSP 245					
	Bagmati			West Rapti		
	Historic	Future	Change (%)	Historic	Future	Change (%)
Lowest	5.2	5.1	-3.6	8.8	9.7	10.4
2nd Lowest	5.3	5.3	-0.3	8.8	9.7	10.5
3rd Lowest	5.3	5.3	0.4	8.8	9.8	11.2
4th Lowest	5.4	5.4	-1.2	8.8	9.8	11.3
5th Lowest	5.5	5.4	-1.2	8.8	9.9	12.7
Average	**5.4**	**5.3**	**-1.2**	**8.8**	**9.8**	**11.2**

Rank	River Basin SSP 245		
	Babai		
	Historic	Future	Change (%)
Lowest	1.8	1.9	8.9
2nd Lowest	1.8	2.0	10.1
3rd Lowest	1.8	2.0	10.4
4th Lowest	1.8	2.0	11.1
5th Lowest	1.9	2.1	11.8
Average	**1.8**	**2.0**	**10.5**

Under the SSP585 scenario, future low flows are expected to increase in the Kankai and Kamala Basins by approximately 24% and 128%, respectively. In contrast, low flows are projected to decrease in the other three basins: by about 5% in the Bagmati Basin, 26% in the West Rapti Basin, and 21% in the Babai Basin (**Table 9-18**).

Table 9-18 Impact of CC on bottom five low flows of Class B River Basins under SSP585

Rank	River Basins: SSP 585					
	Kankai			Kamala		
	Historic	Future	Change (%)	Historic	Future	Change (%)
Lowest	4.3	5.5	26.2	0.92	2.18	136.9
2nd Lowest	4.4	5.5	25.3	0.95	2.27	138.7
3rd Lowest	4.5	5.5	23.7	1.01	2.29	126.0
4th Lowest	4.5	5.5	23.4	1.04	2.32	123.2
5th Lowest	4.5	5.5	22.2	1.07	2.32	116.8
Average	**4.4**	**5.5**	**24.1**	**1.00**	**2.28**	**127.9**

Rank	River Basins: SSP 585					
	Bagmati			West Rapti		
	Historic	Future	Change (%)	Historic	Future	Change (%)
Lowest	5.2	5.0	-3.8	8.8	6.4	-26.4
2nd Lowest	5.3	5.1	-3.9	8.8	6.5	-26.3
3rd Lowest	5.3	5.1	-4.4	8.8	6.5	-26.0
4th Lowest	5.4	5.1	-5.7	8.8	6.5	-25.8
5th Lowest	5.5	5.1	-6.8	8.8	6.6	-25.0
Average	**5.4**	**5.1**	**-4.9**	**8.8**	**6.5**	**-25.9**

Rank	River Basin SSP 585		
	Babai		
	Historic	Future	Change (%)
Lowest	1.8	1.4	-22.1
2nd Lowest	1.8	1.4	-21.0
3rd Lowest	1.8	1.4	-20.6
4th Lowest	1.8	1.5	-19.9
5th Lowest	1.9	1.5	-19.2
Average	**1.8**	**1.4**	**-20.5**

9.7 Climate Change Impact on Drought

The analysis of drought characteristics presented in **Chapter 7** revealed that all the drought indices and parameters considered in this study, across all time scales, showed comparable values. To assess the impact of climate change on drought, changes in drought parameters, i.e., total drought duration, drought severity, and drought intensity (defined as severity per unit of drought duration) were calculated in the Koshi, Gandaki, and Karnali River Basins; taking historic and future flow series of these basins for both scenarios (SSP245 and SSP585). These parameters represent the hydrological drought (Standardized Streamflow Index, SSI-12) which is given in **Table 9-19**.

The results presented in this table show mixed trends for the drought parameters due to the impact of climate change. Future drought duration is expected to increase for the Karnali Basin under both scenarios (15% under SSP245 and 2% under SSP585). However, it may decrease by 13% under SSP245 for the Koshi Basin, while it may increase by 2% under SSP585. In the Gandaki Basin, the results are the opposite: drought duration increases by 9% under SSP245 and decreases by 2% under SSP585, compared to baseline values.

Similar mixed trends are observed for drought severity and drought intensity as well. Drought severity is expected to decrease in the Koshi Basin and increase in the Karnali Basin under both climate scenarios. In the Gandaki Basin, it is expected to increase under SSP245 and decrease under SSP585. However, drought intensity is decreasing for the Karnali Basin compared to baseline values. For the other two basins, the trends are mixed.

Table 9-19 Climate change impact on drought parameters

Total Drought Duration					
Basin	Baseline	SSP245	SSP585	% Change (SSP245)	% Change (SSP585)
Koshi	62	54	63	-13	2
Gandaki	74	81	66	9	-11
Karnali	61	70	62	15	2
Drought Severity					
Basin	Baseline	SSP245	SSP585	% Change-SSP245	% Change-SSP585
Koshi	78	72	77	-7	-1
Gandaki	91	95	81	5	-10
Karnali	77	84	78	9	1
Drought Intensity					
Basin	Baseline	SSP245	SSP585	% Change-SSP245	% Change-SSP585
Koshi	1.25	1.34	1.22	6.7	-2.4
Gandaki	1.23	1.17	1.23	-4.5	0.4
Karnali	1.26	1.20	1.26	-5.0	-0.5

CHAPTER 10: FLOOD AND DROUGHT RISK MANAGEMENT

10.1 General

Flood and drought risks pose significant challenges to all water resource-related works. The planning and development of hydropower, irrigation, water supply, or agricultural command area projects require a thorough understanding of flood and drought dynamics to implement proactive measures for minimizing their adverse impacts.

Knowledge of flood magnitude, especially with consideration of the impacts of climate change, is essential for designing hydropower spillways, constructing embankments to protect agricultural lands near rivers, or determining the size of intake structures for irrigation projects. Similarly, understanding drought conditions is crucial for estimating the probability of reduced energy production in hydropower projects or assessing irrigation needs for agriculture.

This chapter provides a summary of the possible causes of flood and drought hazards in Nepal, followed by a discussion of risk management approaches to mitigate these disasters. Measures for minimizing flood and drought risks are also briefly described.

10.2 Flood Hazard Risk Management

10.2.1 Causes of Flood Hazard in Nepal

The causes of flood hazards in Nepal can be generalized as follows:

A. Natural Causes

1. Heavy rainfall

Heavy rainfall, especially during the monsoon season, can cause rivers to overflow, resulting in widespread flooding.

2. Fragile geology

The rising of the riverbed, caused by soil erosion in the upstream catchment and bank cutting—particularly at river bends in plain regions—leads to flooding in adjacent areas. Flooding may also result from Landslide Dam Outburst Floods (LDOFs) and river shifting.

3. Topography

Catchment areas with long and steep slopes tend to produce floods of higher magnitude. Additionally, areas located downhill are at greater risk of flooding. A change in the river gradient from steep to flat leads to: (i) the deposition of sediments, causing the riverbed level to rise, and (ii) an increase in flow depth. These factors collectively exacerbate the risk of flooding.

4. River shifting

Due to the fragile geology of river and stream banks, along with periodic aggradation and degradation of the channel, river shifting—especially in plain regions—has become a recurrent phenomenon, significantly increasing flood risk.

5. Climate change

Climate change may alter precipitation patterns, leading to greater volume and higher intensity, which in turn increases the risk of flooding. Additionally, the occurrence of Glacial Lake Outburst Floods (GLOFs) may rise due to the impacts of climate change.

B. Manmade Causes

1. Deforestation and unstainable agricultural practices

Deforestation and agricultural practices that do not follow proper soil and water management principles in the catchment have led to increased runoff and soil erosion, further exacerbating the risk of flooding.

2. Haphazard road construction and improper sediment disposal

The disposal of soils and sediments from haphazard road construction, especially in the hilly regions of the country, into the river system has increased the sediment load, raised the riverbed level, and elevated the flow stage, resulting in flooding downstream.

3. Unplanned urbanization and encroachment of floodplains

Unplanned urbanization, including the blockage of natural drainage and inadequate drainage systems in terms of both quantity and size, along with the encroachment of floodplains (both in urban and rural areas), has amplified flood risks and increased the likelihood of flooding.

4. Lack or improper flood mitigation measures

Most flood-prone areas lack effective flood protection measures (e.g., embankments, flood retention ponds/reservoirs) and bank protection measures (e.g., revetments, gabions). Where such measures exist, they are often implemented as patchwork solutions, typically at sections of rivers or streams where overflows occurred in response to previous floods. Additionally, in many locations, these measures involve narrowing the river width.

5. Inadequate awareness, early warning systems, and flood preparedness

Inadequate awareness, early warning systems, and preparedness measures leave communities vulnerable during flood events.

10.2.2 Flood Hazard Risk Management Steps, Approach and Activities

1. Steps of flood hazard risk management

The main steps of flood risk management are:

i. Flood planning mitigation measures (preparedness, before disaster).
ii. Response measures (during a disaster).
iii. Recovery (after disaster)

2. Approaches for flood hazard risk mitigation

In flood management, there are two primary approaches for flood hazard mitigation and protection: structural and non-structural.

i. **Structural measures** involve infrastructure development, such as levees or dams, that modify river flow. The basic principles include flood storage, diversion, and confinement.

ii. **Non-structural measures** include various mitigation strategies that do not modify river flow. These measures encompass education, reporting, warning and forecasting, risk assessment, emergency services, land use planning, flood insurance, building codes, health and social measures, and public participation.

3. Activities of flood risk management

Flood hazard risk management (includes structural and non-structural measures) needs a complete ordered set of activities before and after the hazard as given below and presented in **Figure 10-1**.

(a) Pre-flood activities

The pre-flood activities include the following:

i. Distinguish vulnerable areas
ii. Disaster planning to find discharge paths, public service, and infrastructure supplies for emergency actions
iii. Construction of flood-related infrastructure (physical structure and forecasting system)
iv. Land-use planning and preventing unsuitable development in the flood plains
v. Awareness among the people exposed to flood

(b) During the event activities

The during-the-flood activities include the following:

i. Flood forecasting and warning: It involves the provision of real-time information to responders and the public alike, media warnings, use of sirens, mobile phone and internet alert messages
ii. Rescue operation

(c) Post-flood activities

The post-flood activities include the following:

i. Injuries relief

ii. Reconstruction of damaged places

iii. Recovery of the environment and the economy

iv. Review of the flood management measures to advance the planning for future hazards

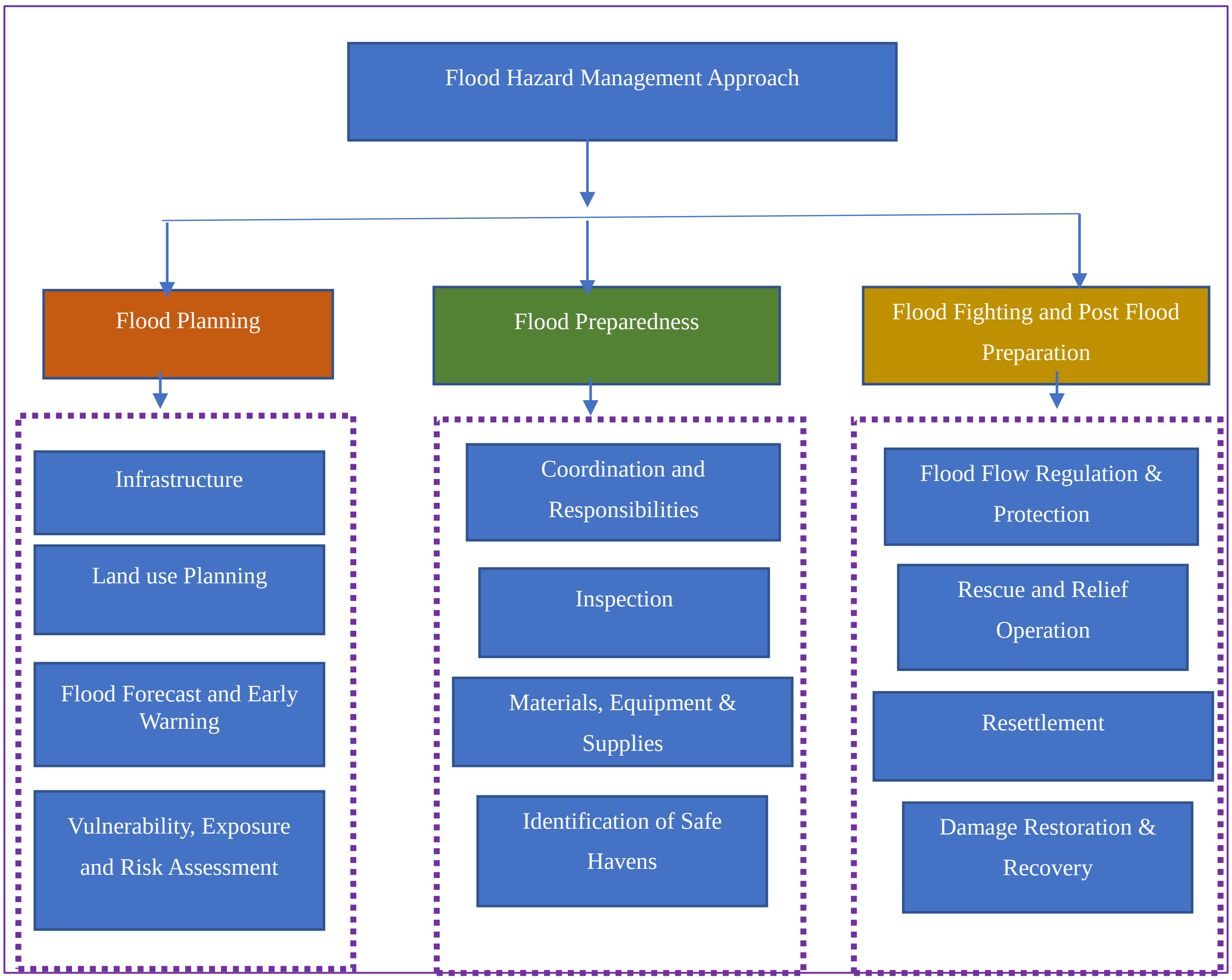


Figure 10-1 Flood hazard management activities

10.2.3 Short-Term Measures for Minimizing Flood Hazard Risk

The aim of short-term measures is to reduce the immediate risk of flooding and its impacts in the study areas. Below are some short-term flood hazard minimization measures:

1. **Sandbag barriers:** Sandbag barriers can be deployed to protect critical locations from rising waters during the monsoon. They can reinforce existing structures or create temporary walls in areas without structures. Ensure an adequate supply of sandbags before the monsoon season.
2. **Portable flood barriers:** Barriers made of durable materials, such as metal or PVC, can be quickly assembled and installed. These barriers are interconnectable to form a continuous barrier. Ensure an adequate supply before the monsoon season.
3. **Gabion walls/spurs:** Gabion walls and spurs should be constructed as necessary at critical locations based on the site's requirements.
4. **Remove obstructions from the drainage system:** Clear any obstructions to river/stream flow, such as large boulders or trees, before the monsoon begins.
5. **Emergency evacuation shelters:** Establish emergency evacuation shelters and ensure residents in flood-prone areas are informed, providing them with a clear plan of action in the event of flooding.
6. **Rapid response teams:** Deploy rapid response teams in flood-prone areas to assist residents with evacuation and provide emergency shelter and support.
7. **Pre-positioned emergency supplies:** Strategically place emergency supplies, such as food, water, and medical supplies, in flood-prone areas to ensure residents have access to basic necessities during flooding.
8. **Restrict waste disposal in the flow system:** Restrict the disposal of domestic or industrial waste, as well as soil and sediments generated during road or construction activities, into rivers/streams.

These short-term measures can help reduce the immediate risk of flooding. However, it's important to note that they are not a substitute for medium-term flood hazard mitigation or long-term flood risk management strategies.

10.2.4 Medium-Term Flood Hazard Risk Mitigation Measures

While it’s not always possible to prevent floods, there are ways to mitigate risks at the local level. Here are some methods to consider:

1. **Build flood barriers:** Construct barriers, such as embankments, to confine floods with a 100-year return period in rivers/streams.
2. **Construct flood storage:** Build flood ponds or reservoirs wherever possible to store excess floodwater.

3. **Construct bank protection and flow diversion structures:** Install revetments to protect riverbanks from scouring and sloughing, and use spurs to divert floodwaters from areas prone to flood impact.
4. **Retrofitting buildings:** Retrofit existing buildings with flood-resistant materials and features to minimize damage during floods. Encourage the use of flood-resistant materials for new constructions, with RCC buildings being ideal.
5. **Build animal sheds, permanent warehouses, and flood-proof shelters:** Construct safe animal sheds, warehouses with flood-resistant rooms, and RCC shelter houses in flood-prone areas to protect people, animals, and important assets, ensuring basic living facilities during floods.
6. **Maintain the drainage system:** Keep rivers and streams clear of obstructions to allow for smooth water flow.
7. **Restrict the disposal of waste in the flow system:** Prevent the disposal of domestic/industrial waste, soil, and sediments from construction activities into rivers/streams.
8. **Develop early warning systems:** Install flood sensors, alarms, or other early warning systems to alert residents of potential flooding, allowing them to take precautions.
9. **Floodplain zoning:** Implement zoning (e.g., Zone Z_0, Z_1, Z_2, Z_3, Z_4) to limit development in flood-prone areas.
10. **Implement land use plans strictly:** Ensure local governments enforce land use and floodplain management policies, following the zoning guidelines (Z_o to Z_4).
11. **Create green infrastructure:** Promote planting trees, constructing rain gardens, and establishing forest ponds, flood ponds, and reservoirs wherever possible.
12. **Educate residents:** Provide education on flood preparedness and response, including emergency planning and supply stocking, to reduce property damage and loss of life.
13. **Develop community flood response plans:** Create community-wide flood response plans to ensure clear actions are taken during floods, minimizing confusion and potential injuries.

10.3 Drought Risk Management

10.3.1 Causes of Drought

A. Natural Causes of Drought

1) Changes in ocean temperatures

El Niño refers to a large-scale ocean-atmosphere climate interaction associated with episodic warming of sea surface temperatures (SST) across the central and east-central Equatorial Pacific. La Niña, the opposite of El Niño, is characterized by cooler-than-average ocean temperatures in the Pacific Ocean. El Niño conditions often coincide with a period of weak monsoons and rising temperatures in this region, which significantly increases the likelihood of droughts during El Niño events. Depending on the event's strength, it can cause changes in precipitation patterns in Nepal and other parts of Asia (OnlineKhabar, 2023). Droughts have been recorded during both El Niño and non-El Niño years in Nepal (Bagale, 2021). However, while El Niño previously had a strong association with droughts in this region, this relationship has weakened in recent years (Pandey et al., 2019). As an agriculture-dependent country, Nepal must understand the El Niño phenomenon and take appropriate measures to mitigate its effects.

2) Low rainfall

The The primary cause of drought is insufficient or lack of rainfall. When a region or area experiences an extended period without adequate rainfall, a water deficiency occurs, and that area is considered to be in a state of drought.

B. Man-made Causes

The following are the main causes of drought (Natural Energy Hub, 2023; Eltohami, 2016):

1. **Deforestation**

   The removal of forests can disrupt local weather patterns and reduce the amount of moisture released into the atmosphere. This decrease in available moisture can contribute to drought conditions.

2. **Urbanization**

   The expansion of cities and urban areas increases water demand while reducing natural vegetation that aids in moisture retention and groundwater recharge. This can result in localized urban droughts.

3. **Groundwater depletion**

   Over-extraction of groundwater for various uses, such as irrigation, industrial activities, and drinking water, can lower water tables and ultimately lead to drought conditions.

4. **High water demand**

   Intensive agriculture, growing industrialization, and high population growth can outstrip available water supplies, leading to drought conditions.

5. **Climate change**

   Climate change is altering precipitation patterns and raising temperatures in certain regions, contributing to more frequent, severe, and prolonged droughts.

6. **Poor water management**

   Inefficient water management practices can worsen drought conditions by failing to optimize water usage and conservation efforts.

10.3.2 Drought Risk Management Measures

Pre-drought and post-drought measures are the two main components of drought risk management as presented in **Figure 10-2**. Preparedness and mitigation measures fall under pre-drought risk management, while reaction, response, and recovery are part of post-drought risk management. Drought mitigation and preparedness refer to proactive actions aimed at reducing potential vulnerabilities in society, the economy, and the environment (Ndayiragije and Li, 2022). In contrast, response and recovery involve actions taken in reaction to drought events, with the goal of helping affected populations cope with the impacts of drought and restoring pre-drought living conditions in the affected region.

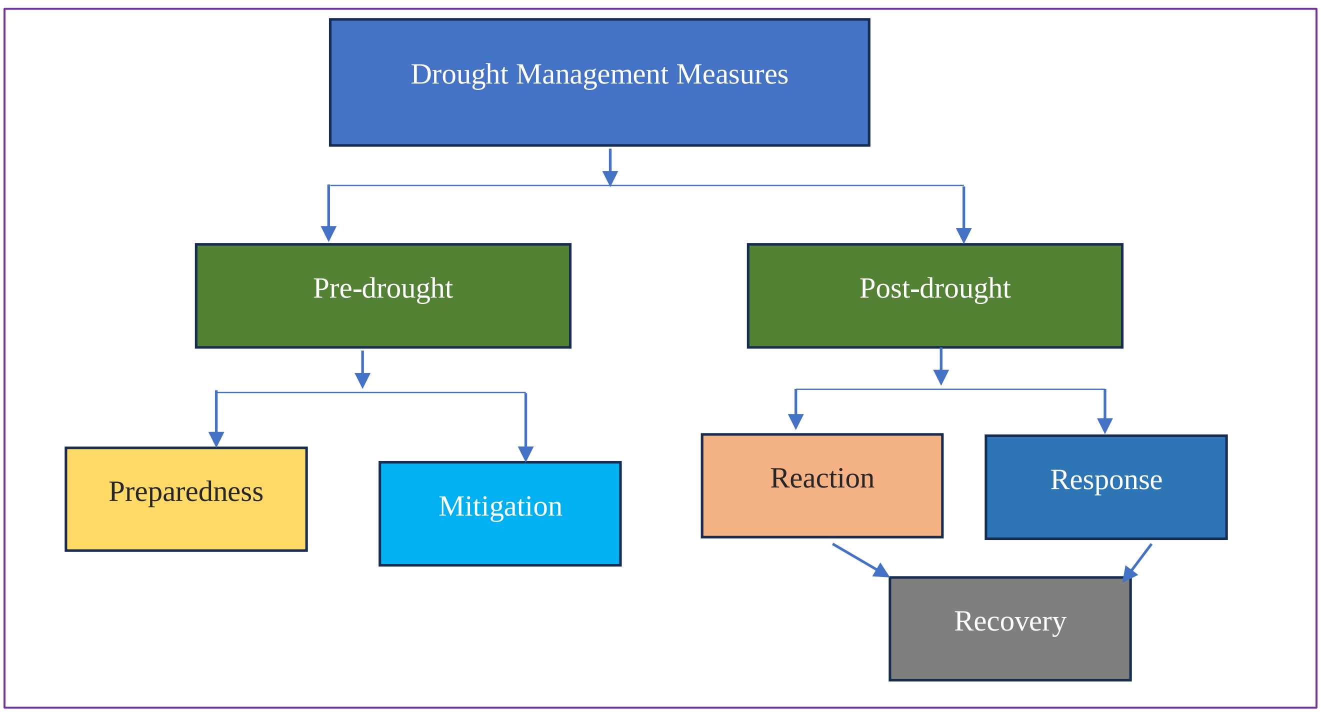


Figure 10-2 Drought management measures

1. **Drought preparedness**

Drought preparedness refers to the policies, plans, and actions taken before a drought occurs to help people cope, predict, and forewarn of approaching drought conditions. It ensures a coordinated and effective response in the event of a drought (Ndayiragije and Li, 2022). Key elements include:

- **Development of Early Warning and Forecast Systems**: Establishing climate change early warning systems and integrating drought indicator tools to provide reliable information to regional or national decision-makers.
- **Hazard Organizations**: Creating organizations that will oversee and ensure a coordinated, effective response during drought incidents.
- **Agricultural Planning**: Promoting the cultivation of drought-resistant crops and seasonal crops that are more resilient to water deficits.
- **Enhancement of Coping Capacity**: While these measures won't eliminate the risk of droughts, they will significantly enhance the ability to cope with drought conditions.

2. **Mitigation strategies**

Drought mitigation strategies aim to reduce the negative effects of drought. They include:

- **Efficient Water Resource Management**: This includes practices like water recycling and reuse.
- **Water-Saving Irrigation Technologies**: Implementing irrigation methods like micro and drip irrigation to conserve water.
- **Construction of Water Storage Infrastructure**: Building reservoirs and dams with scientifically-based management policies for water supply.
- **Avoiding Deforestation**: Minimizing deforestation as it contributes to environmental degradation.
- **Groundwater Recharge**: Implementing infiltration galleries to recharge groundwater supplies.
- **Preserving Natural Ecosystems**: Avoiding wildfires and preserving natural parks and wetlands to maintain ecological balance.

Mitigation strategies can help reduce the impact of drought when it occurs.

3. **Reaction and response**

The reaction to drought involves taking immediate actions to minimize harm to human and animal life when a drought strikes. Key actions include:

- **Emergency Assistance**: Immediate intervention to preserve life and provide the basic needs of drought victims. Response actions are typically carried out by governments, provinces, or local communities.
- **Provision of Basic Needs**: Supplying food and clean drinking water to the most vulnerable populations.
- **Financial Assistance**: Providing monthly allowances to low-income individuals affected by drought.
- **Food Price Control**: Lowering the prices of food and animal feed to make essential resources more accessible

10.3.3 Flood vs Drought Risk Management

While evidence points to droughts as an increasing problem, floods have garnered more attention from policymakers and academics. This is likely due to the more visible consequences of floods, which are rapid, high-impact events that destroy physical infrastructure, damage homes, and disrupt livelihoods. As a result, floods often trigger swift policy responses through domestic relief systems, supported by international relief agencies (Botzen et al., 2019). In contrast, droughts are spatially diffuse, with a slow onset that makes them harder to detect. Due to their gradual emergence and lower visibility, policy responses to drought tend to be less pronounced (Damania et al., 2017). However, droughts, which are long-term and silent crises, can have a much greater global economic impact than other disasters (Zaveri, 2023).

CHAPTER 11: CONCLUSION AND RECOMMENDATIONS

11.1 Conclusions

Owing to its unique physical, geological, and climatic characteristics, Nepal is highly prone to both floods and droughts. This study analyzed climate, flood, and drought conditions in Nepal, primarily based on data collected from the Department of Hydrology and Meteorology. Four major issues were identified with Nepal's hydro-meteorological data: (1) scarcity of climate data in the northern part of the country, (2) an almost total lack of hydrological data in the flood-prone southern region, (3) poor quality of data from most measurement stations, characterized by numerous missing values and erroneous observations, and (4) coarse temporal resolution of the observed data. After screening the hydro-climatic data, the analysis considered daily rainfall data from 179 stations, daily maximum and minimum temperature data from 67 stations, and flow data from 44 stations for high flow and 41 stations for low flow.

A very high spatial variation in rainfall was observed within the country, ranging from less than 300 mm to over 5,500 mm annually. Nearly 80% of the annual rainfall occurs during the monsoon season, with almost half of it concentrated in just two months—July and August. The monsoon typically begins in June, with an average onset date of June 13. Monsoon withdrawal usually occurs in September or October. Notably, during the 1980s and 1990s, withdrawal predominantly took place in September, whereas in recent years, it has shifted to October. However, no specific temporal trend in annual rainfall was observed across Nepal.

Temperature variation across the country is also substantial, ranging from below -10 °C during winter in the mountainous regions to over 45 °C during summer in the Terai region. The lowest and highest monthly temperatures are recorded in January and May-June, respectively. Both maximum and minimum temperatures showed a significant increasing trend during the analysis period, indicating that the country is experiencing continuous warming.

Approximately 5% of the years in Nepal were characterized by extreme climatic conditions (Hot-Dry, Cold-Dry, Hot-Wet, or Cold-Wet). The Southern Oscillation Index and Niño 3.4 Sea Surface Temperature Anomalies showed a strong correlation with the Percentage Departure of Nepal Rainfall. Empirical Orthogonal Function (EOF) analysis revealed that, during winter, 58.04% of the variance is explained by Mode 1, highlighting its dominance, whereas, during summer, the variance is more distributed, with Mode 1 explaining only 21.72%.

Monthly variation in the flows of Nepalese rivers is quite significant, with approximately 75% of the annual flow occurring during the monsoon season. Around 80% of these flood flows occur in just two months, July and August. In contrast, nearly all instantaneous low flows occur during the non-monsoon seasons.

Floods with return periods ranging from 2 to 10,000 years were estimated using instantaneous flood records from selected hydrological stations. The analysis revealed that 13 past instantaneous maximum flood (IMF) events exceeded the 100-year return period. Similarly, 25 and 49 events were estimated to surpass the 50-year and 25-year return periods, respectively. No discernible temporal trend was observed in the river flows of Nepal.

A power relationship was established between instantaneous flood magnitude and catchment area for Class A Rivers of Nepal. Additionally, a linear relationship was found between IMF and one-day annual maximum floods, where the IMF of Class A rivers is approximately 16% higher than the annual daily maximum floods. Incessant precipitation was found to be the primary factor contributing to floods. However, the blockage of river flow by barriers upstream of gauging stations and subsequent breaching was also identified as a significant contributing factor to IMFs.

On average, approximately 115 flood incidents occur annually in Nepal over the past 44 years. Four districts in the Terai region—Sarlahi, Morang, Rautahat, and Jhapa—each recorded more than 200 flood disasters. Glacial Lake Outburst Floods (GLOFs) and Landslide Dam Outburst Floods (LDOFs) have caused substantial loss of life and property downstream due to the sudden release of large volumes of water.

A flood inventory was developed for Nepal based on IMFs and one-day annual maximum floods. Field visits confirmed that the local population's experience with the country’s hydro-climatic conditions aligns with the observed data.

The drought parameters—frequency, severity, and intensity—calculated using the SPI and RDI indices are almost identical across all months. However, parameters calculated using the SPEI index show slight variations. The probability of meteorological drought occurrence in Nepal is approximately 15-18%.

Drought intensity (DITDD) values remain consistent across all time scales (1-, 2-, 3-, 4-, and 12-months) and indices (SPI, SPEI, RDI, SMI, SSI), averaging around -1.41. This value indicates that droughts in Nepal are generally of moderate intensity. The probability of moderate drought occurrence (12%) is nearly three times higher than that of severe droughts (4%). Extreme droughts are rare in Nepal, accounting for only 1% of all recorded drought events historically. The maximum recorded consecutive drought duration in the country is approximately 11 months.

Local communities attribute decreased precipitation and increased temperatures as the primary causes of drought in Nepal. Nearly two-thirds of respondents reported experiencing drought annually. The most severe impacts of drought perceived by the locals were on agriculture and drinking water supplies.

Separate Soil and Water Assessment Tool (SWAT) hydrological models were developed for the nine major river basins of Nepal to assess their hydrological processes. The models were calibrated and validated using available historical hydro-climatic data for each basin. The model performance was found to be better for Class A River Basins compared to Class B River Basins. However, the SWAT model shows limitations in accurately simulating high flows.

The effects of climate change on precipitation, temperature, extreme flows (top and bottom five), and droughts were evaluated by comparing future long-term averages (2025–2054) to baseline values (1985–2014). The assessment considered two scenarios, SSP245 and SSP585.

On average, changes in precipitation for Nepal are projected to be moderate, with an increase of 3% (range: -1.5% to +10.7%) under SSP245 and 6% (range: -0.7% to +18.1%) under SSP585. Both maximum and minimum temperatures are expected to rise across all basins, though at varying rates. The projected countrywide average increase in maximum temperature is 0.71°C under SSP245 and 0.84°C under SSP585. Similarly, the average increase in minimum temperature is estimated at 0.96°C under SSP245 and 1.15°C under SSP585.

In Class A River Basins, the largest increase in future high flows (average of the top five flows) under SSP245 is anticipated in the Chamelia Basin (+12%), while the largest decrease is forecasted in the Karnali Basin (-23%). Under SSP585, these changes are projected to be +16% for Chamelia and -19% for Karnali. For Class B River Basins, the maximum increase in high flows under SSP245 is expected to be +13% in the West Rapti Basin, while the maximum decrease is -5% in the Kankai Basin. Under SSP585, the highest increase is projected in the Kamala Basin (+61%), with the greatest decrease again occurring in the Kankai Basin (-14%).

Changes in low flows (average of the bottom five flows) compared to baseline values in Class A River Basins are expected to range from -40% (Gandaki) to +90% (Karnali) under SSP245, and from -49% (Gandaki) to +48% (Karnali) under SSP585. In Class B River Basins, the expected changes range from -1% (Bagmati) to +109% (Kamala) under SSP245 and from -26% (Babai) to +128% (Kamala) under SSP585.

Hydrological drought, parameters revealed mixed trends across both climate scenarios.

The legal instruments in Nepal are sufficiently robust to address flood and drought risks, although they pose challenges for water resource development projects. The planning and implementation of hydropower, irrigation, water supply, and agricultural command area projects demand a comprehensive understanding of floods and droughts. Such knowledge is crucial for minimizing adverse impacts through proactive and informed measures.

11.2 Recommendations

11.2.1 Technical Recommendations

The following technical recommendations are provided based on the findings of this study:

1. Installation of Hydroclimatic Data Acquisition Systems

The availability of fine-resolution hydroclimatic data of good quality and at appropriate locations is essential to minimize data-related uncertainties in hydroclimatic analysis for water resource projects (e.g., hydropower, irrigation, water supply, and agriculture). There is a notable lack of climate data in the northern regions and flow data in the Terai. It is recommended to install sufficient data acquisition systems following established standards, particularly in these regions. Additionally, flow gauging stations should be established near the Chinese border on rivers originating from China. These data can serve as boundary conditions for hydrological modeling and ensure accurate flow analysis within Nepal. Real-time data acquisition is especially recommended for better precision.

2. Integrated Approach for Hydrological/Flood Prediction

The study highlights the close relationship between river hydrology and precipitation in Nepal, with heavy rainfall being a primary cause of river flooding. Other contributing factors include LDOFs and GLOFs upstream of gauging stations, as well as land use changes at the local and basin levels. It is recommended to adopt an integrated approach for hydrological and flood prediction studies, incorporating climatological, hydro-geological, and land use/land cover changes for a comprehensive analysis.

3. Customization of Hydrological Models for Flood Estimation

Current hydrological models, such as SWAT, calibrated and validated with long-term daily climate and flow data, are insufficient for capturing high flows. To improve flood prediction accuracy, the use of fine-resolution hydroclimatic data (e.g., hourly data) is strongly recommended.

4. Purpose-Specific Drought Analysis

Understanding water availability during critical periods is crucial for planning. For example, lean period flows for hydropower projects, rainfall in June for seedbed preparation, and precipitation in June and July for rainfed paddy cultivation are key factors. It is recommended to conduct purpose-specific drought studies tailored to specific needs rather than relying solely on generic indices and parameters from rain gauge stations.

5. **Bottom-Up Approach for Climate Change Impact Assessment**

   The traditional top-down approach for assessing climate change impacts on river hydrology often involves bias-correction and downscaling techniques, which introduce significant uncertainties. To reduce these uncertainties, particularly regarding changes in precipitation and temperature, a bottom-up approach is recommended. This method is more efficient and focuses on local-level climate variables and their direct impacts

11.2.2 General Policy Recommendation

Based on the literature review and analysis conducted in this study, the following general policy recommendations for managing floods, droughts, and climate risks in Nepal are proposed:

1. **Adopt Proactive Approaches**

Policies, acts, plans, and guidelines for addressing floods, droughts, and other climate-related disasters should emphasize proactive rather than reactive approaches.

2. **Develop Comprehensive Guidelines**
   Specific guidelines for managing floods, including GLOFs and LDOFs, as well as drought and climate risk management, need to be developed.

3. **Invest in Resilient Infrastructure and Institutions**
   The nation should prioritize investments to address flood and drought vulnerabilities by upgrading institutional frameworks and building resilient infrastructure to support a drought- and flood-resilient economy.

4. **Prioritize Research and Development (R&D)**
   R&D in this area should be elevated as a high priority at the policy level.

5. **Integrate Risk Management in Development Plans**
   Flood and drought risk management must be incorporated into development plans and projects related to water resources, such as hydropower, irrigation, and agricultural command area development.

6. **Establish Disaster Insurance Policies**
   Comprehensive insurance policies should cover not only flood, drought, and climate-related disasters but also other types of disasters.

7. **Enhance Preparedness for Climate Change**

   As climate change is expected to increase the severity of floods and droughts, immediate emphasis should be placed on preparedness measures to reduce vulnerabilities in society, the economy, and the environment.

8. **Prioritize Drought Management**

   Drought management should receive priority on par with flood and other disaster management efforts. Developing, implementing, and integrating drought early warning systems can significantly mitigate its impacts on society and the country.

9. **Focus on Policy Implementation**

   In addition to formulating robust disaster management policies, equal attention must be given to their effective implementation.

11.2.3 Specific Policy Recommendation

A. Policy Interventions in Hydropower Development Planning

Addressing flood-related challenges in hydropower development planning requires targeted policy interventions to minimize risks and ensure sustainable development. Likewise, addressing drought-related issues through policy interventions is essential to maintain hydropower as a reliable energy source, even during periods of water scarcity.

The following are key policy interventions that can be implemented for sustainable development planning at the basin level:

Flood Related Policy Intervention

1. **Basin Level Integrated Water Resources Management**
   i. **Policy**: Implement (IWRM) principles that integrate flood management with hydropower planning, considering the entire watershed.
   ii. **Intervention**: Develop a framework for coordinated management of water resources at river basin level, balancing hydropower generation, flood control, water supply for irrigation and domestic use, and ecosystem needs etc.
2. **Flood Risk Assessment**
   i. **Policy**: Require mandatory flood risk assessments as a part of hydropower project planning.
   ii. **Intervention**: Apply advance hydrological modeling technique to assess probable floods, considering climate change scenarios too, at the intake and powerhouse site of the hydropower project.

3. **Hydropower Design Standards**

   i. **Policy**: Introduce mandatory design standards that ensure hydropower infrastructure that can withstand extreme flood events, considering climate change impacts.

   ii. **Intervention**: Prepare guidelines to enforce higher floodwater storage capacities, flood-proofing, and resilient hydraulic and structural design for dams, spillways, powerhouses, and other critical infrastructure.

4. **Climate Change Adaptation Policies**

   i. **Policy**: Incorporate climate change adaptation into hydropower policies, ensuring that projects are designed to cope with increasing flood variability due to climate change.

   ii. **Intervention**: Develop adaptive management plans (e.g., secondary and emergency spillways) that account for increased frequency and intensity of floods due to climate change, ensuring that hydropower infrastructure remains flexible and responsive to changing flood patterns.

5. **Early Warning Systems and Emergency Preparedness**

   i. **Policy**: Integrate early warning systems (EWS) and emergency preparedness protocols into hydropower development policies.

   ii. **Intervention**: Mandate hydropower operators to invest in automated flood forecasting and early warning systems, ensuring real-time data sharing with downstream communities and disaster management agencies.

Drought Related Policy Interventions

1. **Design Storage Hydropower Project**

   i. **Policy**: Encourage the development of storage hydropower projects.

   ii. **Intervention**: Implement policies that prioritize projects with water storage solutions, i.e., storing water when there are high flows in the monsoon season which can be used for hydropower generation during low flow seasons.

2. **Water Availability Assessment and Monitoring**

   i. **Policy**: Make water availability assessments mandatory for hydropower projects, with continuous monitoring.

   ii. **Intervention**: Need hydropower projects to incorporate real-time water monitoring systems that track river flow rates and predict water availability based on seasonal and long-term climate changes.

3. **Reservoir Management and Operation Guidelines**

   i. **Policy**: Introduce reservoir operation guidelines that optimize water storage and usage during periods of drought.

   ii. **Intervention**: Develop operating rules for reservoirs to prioritize water conservation, ensuring that sufficient water is retained during periods of excess flow to buffer against future drought conditions.

4. **Climate-Responsive Hydropower Planning**

   i. **Policy**: Require hydropower planning processes to account for climate change projections, particularly regarding changing rainfall patterns and increased drought frequency.

   ii. **Intervention**: Integrate climate change models into hydropower feasibility studies, ensuring that new projects are designed with the flexibility to cope with reduced water availability and prolonged drought periods.

5. **Environmental Flow Requirements**

   i. **Policy**: Enforce strict environmental flow requirements to ensure that downstream ecosystems receive adequate water during droughts, even if it limits hydropower production.

   ii. **Intervention**: Set minimum flow levels based on downstream minimum water requirements that must be maintained in rivers to protect downstream socio-economic activities, aquatic life and water quality, regardless of hydropower generation demands during drought periods.

B. Policy Interventions in Irrigation and Agricultural Development Planning

The primary purpose of irrigation for agricultural land is to enhance agricultural production and productivity. Policy interventions in irrigation and agricultural development planning can be effectively addressed under a single heading.

Integrating flood management strategies is essential for ensuring the sustainability of irrigation systems and maintaining agricultural productivity. Similarly, policy interventions in irrigation development planning to address drought-related challenges are` crucial for ensuring water security and sustaining agricultural productivity. The key policy interventions for irrigation development planning in the context of flood and drought challenges are outlined below:

Flood Related Policy Intervention

1. **Basin Level Integrated Water Resources Management Approach**

   i. **Policy**: Apply Integrated Water Resources Management principles into irrigation and agricultural planning to balance water use for agriculture and flood control as well as other sectors at the basin level.

ii. **Intervention**: Develop strategies that coordinate irrigation with flood management, including multipurpose water storage systems and policies that prioritize both agricultural water needs and flood protection measures.

2. Flood-Resilient Irrigation Infrastructure

i. **Policy**: Prepare guidelines for flood-resilient irrigation infrastructure that can withstand heavy rainfall and high-water levels.

ii. **Intervention**: Indorse the construction of flood-proof canals, drainage systems, and embankments to prevent waterlogging and damage during floods. Use flexible irrigation systems like sprinkler or drip irrigation as far as possible, which can be adjusted during flood events to minimize damage.

3. Build Water Storage Systems

i. **Policy**: Encourage the development of water storage infrastructure (e.g., reservoirs, forest and agricultural ponds) that can help regulate excess water during flood events.

ii. **Intervention**: Promote multi-purpose water storage facilities that can store excess water during floods and release it gradually for irrigation during dry periods. This reduces both flood risks and water scarcity, improving agricultural resilience.

4. Floodplain Zoning for Irrigation Development

i. **Policy**: Implement floodplain zoning policies to regulate irrigation projects in high-risk areas.

ii. **Intervention**: Restrict large-scale irrigation development in flood-prone zones, or design systems in these areas to be flood-adaptive.

5. Climate Change Adaptation in Irrigation Planning

i. **Policy**: Incorporate climate change adaptation strategies into irrigation and agricultural planning to address the increasing frequency and intensity of floods.

ii. **Intervention**: Employ climate models to predict future flood risks and guide the design of irrigation systems that are resilient to changing precipitation patterns.

6. Sustainable Land Use and Catchment Management

i. **Policy**: Incorporate sustainable land use and catchment management practices that mitigate flood risks while supporting irrigation and agriculture practices.

ii. **Intervention**: Promote soil and water conservation techniques, such as terracing, contour plowing, and reforestation, in irrigation development areas. Implement catchment management practices that reduce runoff, improve water infiltration, and prevent downstream flooding in agricultural zones.

Drought Related Policy Intervention

1. **Water Use Efficiency and Conservation**
   i. **Policy**: Promote policies that enhance water use efficiency in irrigation systems.
   ii. **Intervention**: Encourage the adoption of efficient irrigation technologies, such as drip and sprinkler irrigation systems, which minimize water loss and maximize productivity.

2. **Drought-Resilient Crop Varieties**
   i. **Policy**: Promote the use of drought-resistant crop varieties in drought-prone regions.
   ii. **Intervention**: Encourage and provide incentives for farmers to plant drought resilient crop varieties. This reduces the pressure on water resources while maintaining agricultural output during periods of drought.

3. **Water Storage Infrastructure**
   i. **Policy**: Develop policies that encourage investment in water storage infrastructure to capture and store water during periods of abundance for use during drought.
   ii. **Intervention**: Promote the construction of small-scale reservoirs, water harvesting systems

4. **Drought Early Warning Systems**
   i. **Policy**: Establish drought early warning systems to provide timely information and guide proactive responses in irrigation management.
   ii. **Intervention**: Develop real-time drought monitoring and forecasting tools that provide data on water availability, soil moisture, and climatic conditions. Equip farmers and irrigation managers with actionable information to adjust irrigation practices ahead of severe drought conditions.

5. **Agroforestry and Soil Moisture Conservation**
   i. **Policy**: Support agroforestry and soil moisture conservation practices to enhance drought resilience in irrigated agriculture.
   ii. **Intervention**: Encourage the adoption of agroforestry systems, which improve soil structure and water retention, and reduce the need for irrigation. Promote mulching, cover cropping, and conservation tillage practices that help maintain soil moisture and reduce evaporation during drought periods.

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