Spatial and Temporal Variability of Rainfall in the Western Region of Nepal

Amrit Gaire[1], Damodar Bagale[1*], Prabin Acharya[1], and Ram Hari Acharya[2]

[1]*Central Department of Hydrology and Meteorology, Tribhuvan University, Kathmandu, Nepal*
[2]*Department of Meteorology, Trichandra Multiple Campus, Tribhuvan University, Kathmandu, Nepal*

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ABSTRACT

The temporal and spatial variability of seasonal, annual, and decadal rainfall over 44 years in western Nepal was investigated using rainfall data from 36 meteorological stations in various physiographic regions. Missing data were addressed using the normal ratio method, and significant trends in annual rainfall were assessed through the Man-Kendall test. Western Nepal receives about 79.7% of annual rainfall during the monsoon, followed by 10.7% during the pre-monsoon, 3.3% during the post-monsoon, and 6.3% during the winter. The analysis revealed distinct seasonal excess and deficit episodes, with the highest monsoon rainfall recorded in 2000 and the lowest in 1979. During the study period, there is a large temporal variability of seasonal and annual rainfall. The central part of western Nepal receives heavy rainfall in monsoon seasons than other parts. In winter seasons more rainfall is received in the Northwest part and decreases towards the central and eastern parts of western Nepal. The midlands of western Nepal received higher annual rainfall than the other regions. The present study identified that the seasonal rainfall has been decreasing patterns in the Western region of Nepal for the past four decades.

Keywords: Seasonal rainfall, Spatial, Temporal, Variability and Western Nepal

1. Introduction

Rainfall is a crucial climatic factor that affects water availability across different regions and times (De Luıs et al., 2000). Addressing the challenges posed by climate variability involves understanding, identifying, and quantifying rainfall and its trends (Bagale et al., 2023a). South Asian countries are significantly influenced by the Indian summer monsoon, which is driven by seasonal heating in the Tibetan Plateau and changes in temperature and pressure gradients (Flohn, 1957; Webster et al., 1998). India has frequently encountered extreme rainfall events in recent decades (Krishnamurthy and Goswami, 2000; Bhalme and Jadhav, 1984). The monsoon displays considerable variability, often affected by the El Niño Southern Oscillation (ENSO) (Bhalme and Jadhav, 1984). Similarly, Bangladesh has experienced a decreasing trend in monsoon rainfall in recent decades (Ahasan et al., 2010). Overall, monsoon rainfall in South Asia has generally decreased over the last few decades (Kumar et al., 2013).

Previous researchers have explored the variability of rainfall in Nepal (Bagale et al., 2023a; Shrestha et al., 2012; Dhital and Kayastha, 2013; Baidya et al., 2008; Bohlinger et al., 2017). About 80% of rainfall from June to September comes from the southwest Indian monsoon. Additionally, moisture is brought in by southeastern winds from the Bay of Bengal and sometimes the Arabian Sea (Bagale et al., 2023b; Ichiyanagi et al., 2007). In winter, rainfall is mainly influenced by westerly winds from the Mediterranean Sea and Siberia (Sigdel and Ikeda, 2012). These circulation patterns affect different regions of Nepal unevenly, with central and eastern regions experiencing greater summer rainfall due to southeasterly influences, while western Nepal receives more winter rainfall from westerly sources (Ichiyanagi et al., 2007; Kansakar et al., 2004). However, there has been limited research specifically focusing on rainfall patterns in Western Nepal (Wang et al., 2013). Western Nepal generally receives lower annual rainfall but experiences higher amounts during the winter season compared to other parts of Nepal (Ichiyanagi et al., 2007; Kansakar et al., 2004; Shrestha, 2000). Given Nepal's reliance on agriculture, where rainfall serves as the primary source of both surface and groundwater, variations in precipitation significantly impact crop yields across agricultural regions (Revadekar and Preethi, 2012). The study aims to provide insights into water availability and address local water scarcity issues in Western Nepal. This study represents the first attempt to comprehensively analyze long-term climatic data (1977 to 2020) to quantify monthly and seasonal rainfall variability in western Nepal.

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*Corresponding author: Damodar Bagale, damu.bagale@gmail.com

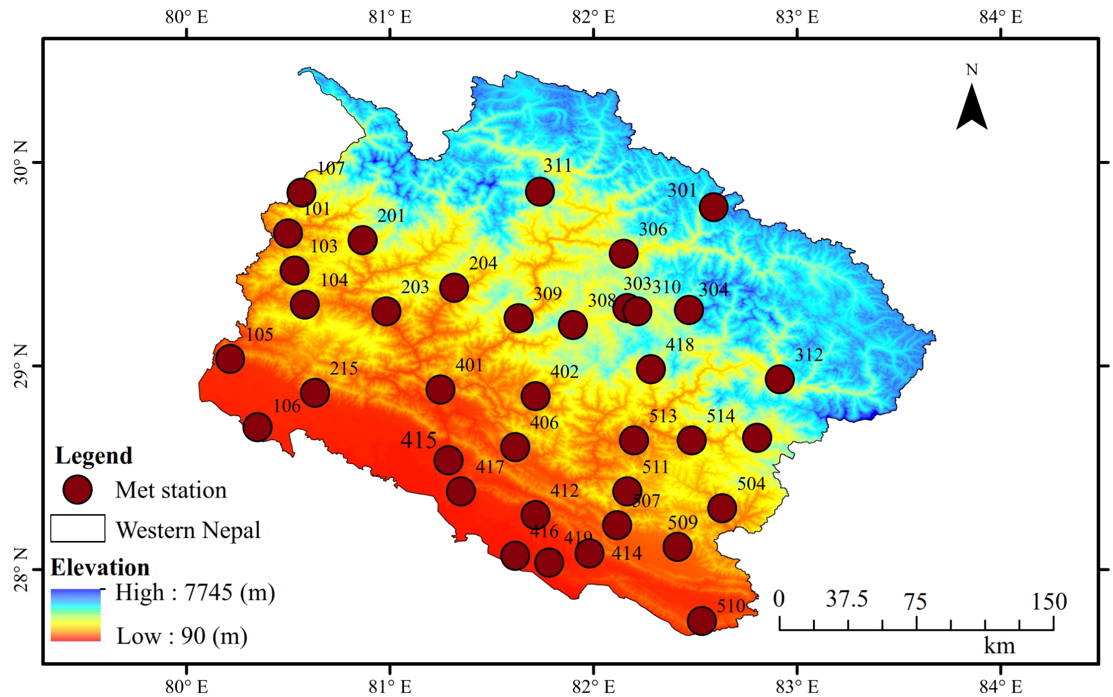


Figure 1. Location map of western Nepal, along with rainfall stations.

The primary objective is to investigate how rainfall varies in Western Nepal over time and space. Specifically, we aim to (i) identify annuals with seasonal rainfall surpluses and deficits, and (ii) examine rainfall indicating decreasing or increasing rainfall patterns in Western Nepal.

2. Study Area

Western Nepal stretches from 27º 68' to 30º 48' N latitude and 80º 05' to 83º 68' E longitude, with elevations ranging from about 90 m in the southern Terai plains to 7,746 m in the north (Fig. 1). The region experiences four main seasons. The monsoon season lasts from June to September, characterized by cloudy days and frequent rain. In contrast, winter months are dry with clear skies and little rainfall. The Post-monsoon season includes October and November, during which Nepal experiences occasional thunderstorms similar to those in the pre-monsoon.

3. Data and Methods

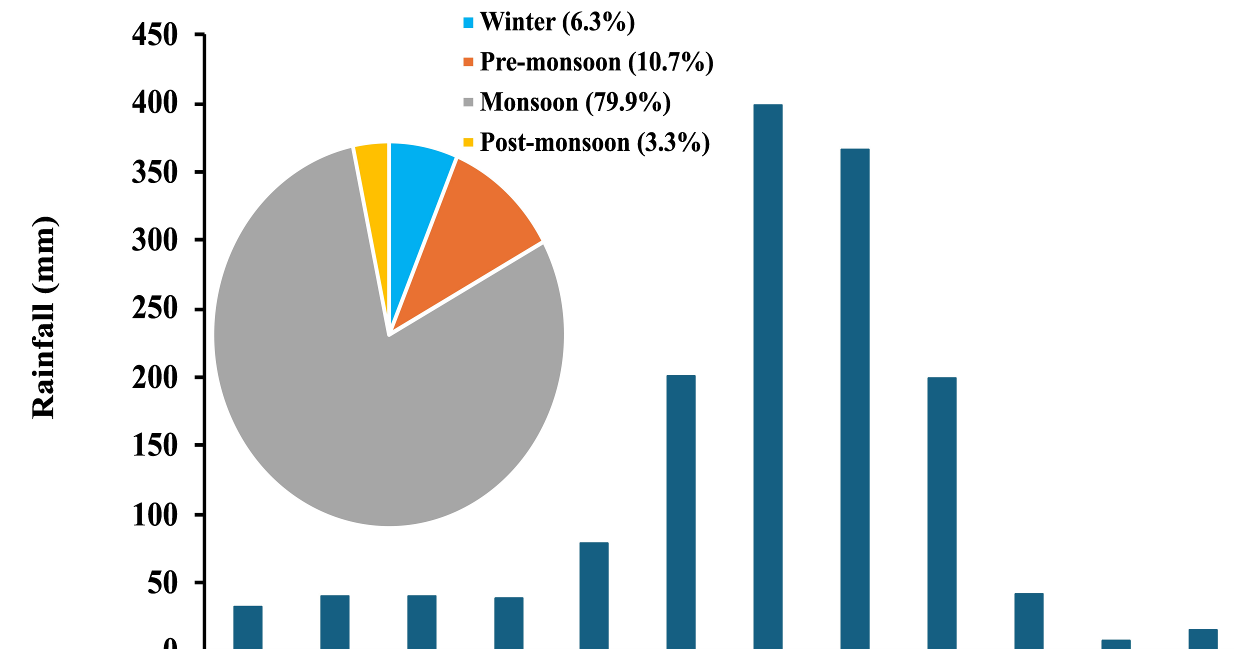
Daily rainfall data for 44 years (1977–2020) was collected by the Department of Hydrology and Meteorology (DHM) of Nepal. The stations are chosen according to the availability of the maximal data length and a uniform spatial distribution. The daily rainfall data was added up to get the monthly total rainfall numbers. Similarly, monthly total rainfall data from January to December were added to determine the annual total rainfall statistics. The total annual rainfalls at stations were calculated after completing the missing data. The average annual, seasonal, and monthly rainfall was determined using the arithmetic mean. The four seasons are defined as pre-monsoon (March to May), monsoon (June to September), post-monsoon (October and November), and winter (December to February).

We used the Normal Ratio method to estimate missing rainfall values in the dataset from nearby weather stations (Bagale et al., 2023b). To evaluate significant increases and decreases in the rainfall data, we applied the Man-Kendall (MK) test to assess trends over time (Kendall, 1975; Mann, 1945). The MK test is commonly used by researchers to identify trends in climate data worldwide and additionally, detailed descriptions of this trend detection method can be found in studies (Dhital and Kayastha, 2013; Taxak et al., 2014; Shrestha et al., 2019; Dhital et al., 2023; Bagale et al., 2024; Karki et al., 2017).

4. Results

4.1. Rainfall Statistics

The monthly rainfall variation of western Nepal is clearly shown in (Fig. 2), July received the maximum rainfall, whereas November had the lowest. The monthly pattern of rainfall is similar from January to April, from May to July the rainfall pattern rises to a peak level and falls to November, as indicated in (Fig. 2). It is indicated that the monsoon season deals with the highest mean seasonal rainfall, whereas the lowest mean value of the post-monsoon.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall(mm)	33.01	40.38	39.85	39.32	78.43	200.85	398.68	366.18	199.27	41.78	7.56	16.21

Figure 2. Average monthly rainfall (mm) and seasonal rainfall (%) in Western Nepal.

The western region of seasonal variability is shown in (Fig. 2).

Approximately 79.7% of the annual rainfall contributes to the monsoon season across western Nepal followed by pre-monsoon 10.7%, post-monsoon 3.3%, and winter 6.3%.

4.2. Spatial Variability of Seasonal Rainfall

Winter rainfall in western Nepal varies significantly, ranging from less than 40 mm to over 150 mm (Fig. 3a). Rainfall increases from the southwest to the northwest, peaking in the central area, then decreases again. The western and northwestern parts receive the most winter rainfall, while the eastern, southeastern, and northeastern areas experience less. The eastern lowlands see the lowest winter rainfall, showing a clear gradient from west to east and north to south, as illustrated in Fig. 3a.

Pre-monsoon rainfall ranges widely in location, from less than 50 mm to more than 240 mm (Fig. 3b). The northern and central parts of the region see low pre-monsoon rainfall. In western Nepal, the monsoon rainfall varies greatly in space, from 255 mm to over 1990 mm (Fig. 3c). Low levels of monsoon rainfall are observed in the region's north-central area. The monsoon pocket locations are clearly shown in (Fig. 3c).

Post-monsoon rainfall varies greatly across the area, with amounts ranging from under 25 mm to over 85 mm (see Fig. 3d). The southeastern and northeastern parts of the region experience more post-monsoon rainfall. The lower eastern part receives the highest post-monsoon rainfall, while the northeast part receives the least.

4.3. Spatial Variability of Annual Rainfall and Its Trends

The average annual rainfall in the western region of Nepal is 1,437.21 mm. There are areas of high rainfall, particularly in the higher elevations of the far western part, with two main pockets: one in the northwestern region and another in the eastern region. The northeastern area has the lowest rainfall, and lower amounts are also found in the central and northeastern parts. Fig. 4 clearly shows the variability of annual rainfall across the region.

Fig. 5 illustrates the annual rainfall trends from 38 stations. Among them, 27 stations showed a decreasing trend, while 4 stations showed an increasing trend. Additionally, three stations had a significant decrease, one station had a significant increase, and one station showed no change. However, the MK test identified that the annual rainfall has been decreasing by about 0.5 mm/annum during the study period from 1977 to 2020.

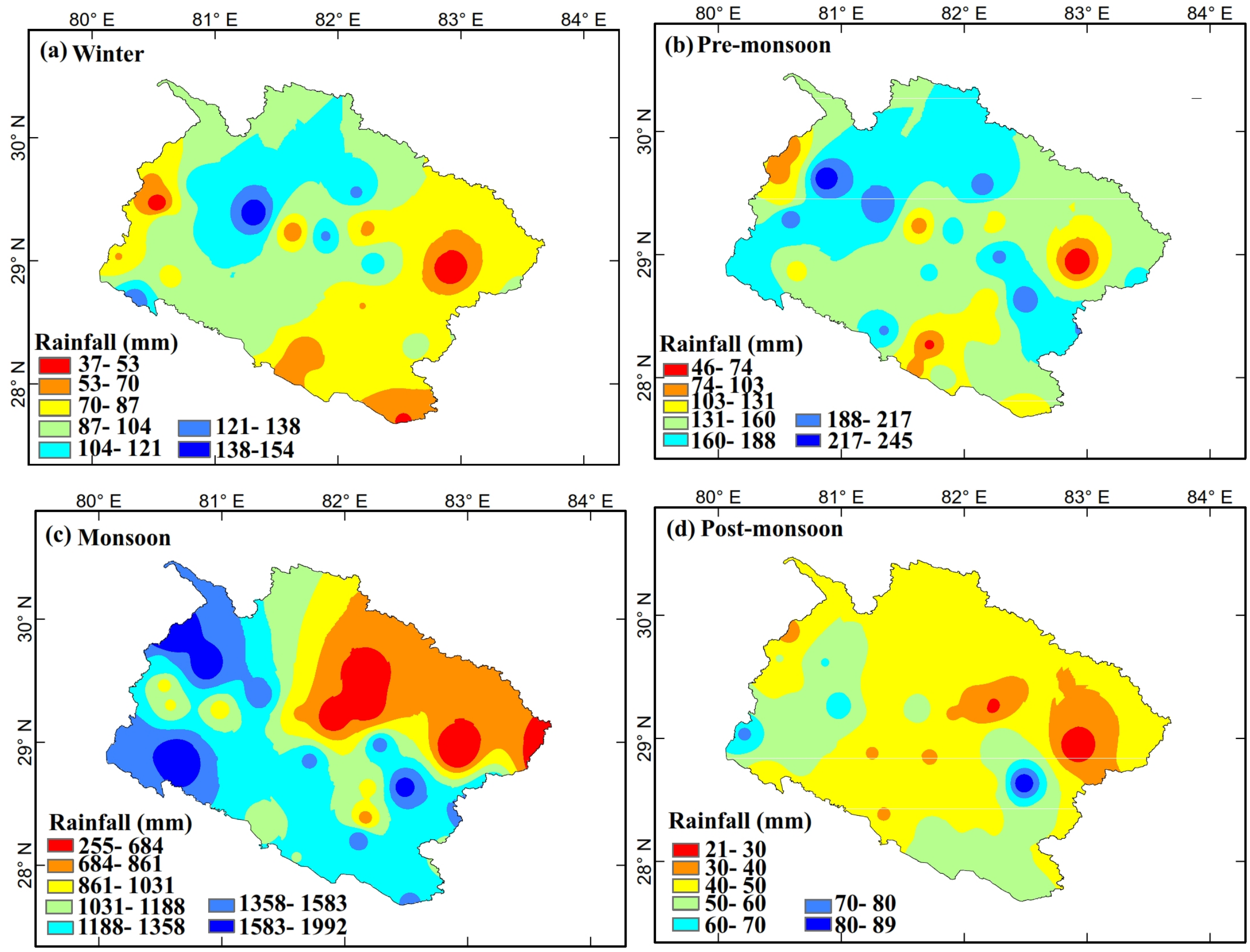


Figure 3. In the western part of Nepal, the mean seasonal rainfall during (a) winter, (b) pre-monsoon, (c) monsoon, and (d) post-monsoon is distributed spatially (1977-2020).

4.4. Temporal Analysis of Seasonal and Annual Rainfall and Its Anomaly

The temporal analysis of seasonal and annual rainfall and its anomaly over western Nepal was carried out for 44 years (1977–2020). The year's anomaly is positive (>0), whereas some episodes experience a negative (<0). The positive values observed represent rainy or surplus episodes, and the negative values represent dry or deficit episodes.

4.5. Winter Rainfall and Its Anomaly

The winter rainfall in western Nepal varies greatly over time. The average minimum rainfall was 28.11 mm of rainfall in 2006. Winter rainfall is highest in 2020 with a rain amount of 167.30 mm, followed by 2019 with 163.68 mm. The mean value of winter rainfall for the western region is 87.30 mm. Fig. 6a shows the decreasing winter rainfall pattern in western Nepal.

The temporal variability of rainfall anomalies is clearly shown in Fig. 6b. The positive anomaly represents the wet seasons and the negative for dry seasons. In the winter season, the positive anomaly is high in 2020, which is followed by 2019, whereas the negative is in 2006, which is followed by 2009 (Fig. 6b).

4.6. Pre-monsoon Rainfall and Its Anomaly

The pre-monsoon rainfall of the western region showed a large year-to-year variation as shown in Fig. 7a. Pre-monsoon rainfall was highest in 1982, with an amount of 246.85 mm, which was followed by 234 mm in 1990. The lowest pre-monsoon rainfall was received in 1996 which is 92.21 mm, which is followed by 2003 with rainfall of 103.7 mm. The mean value of pre-monsoon rainfall is 151.09 mm. Fig. 7a clearly shows the decreasing rainfall pattern in Western Nepal.

The variability of rainfall anomalies is shown in Fig. 7b. In pre-monsoon season, the positive anomaly was high in

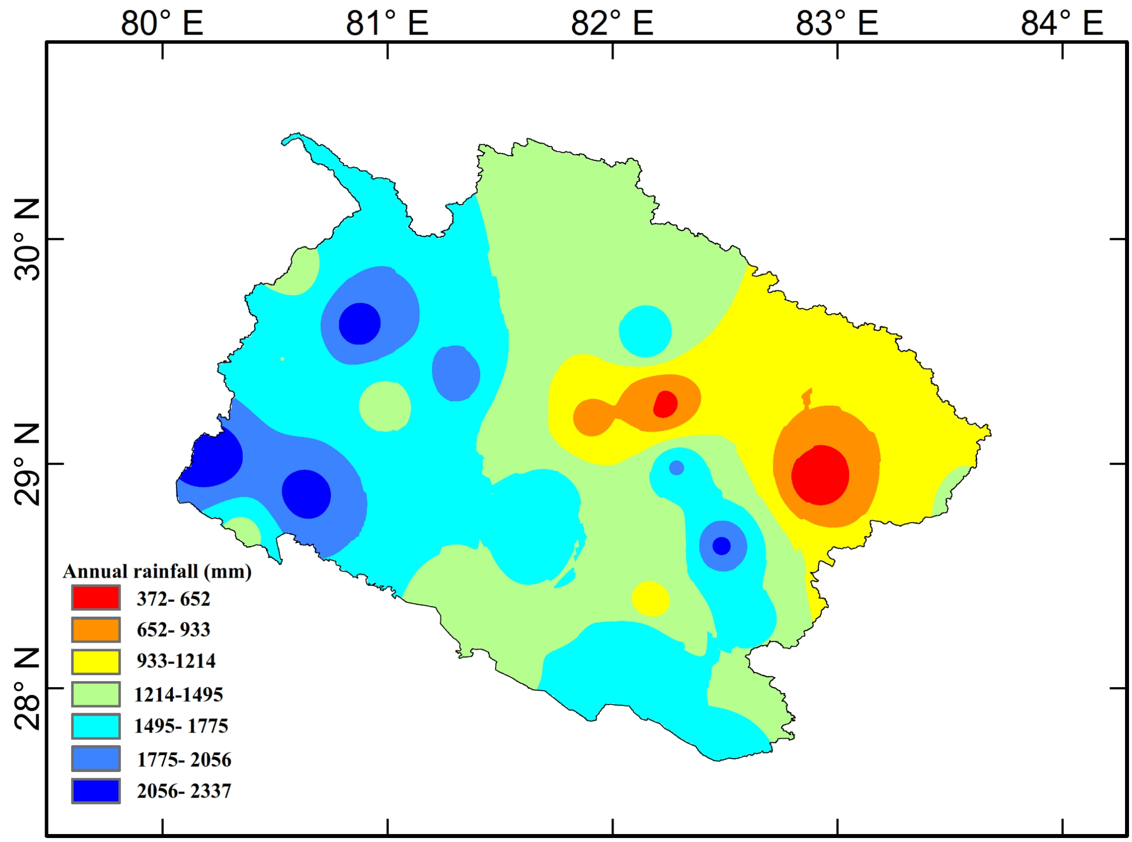


Figure 4. The mean seasonal rainfall is distributed spatially (1977-2020) in the western part of Nepal.

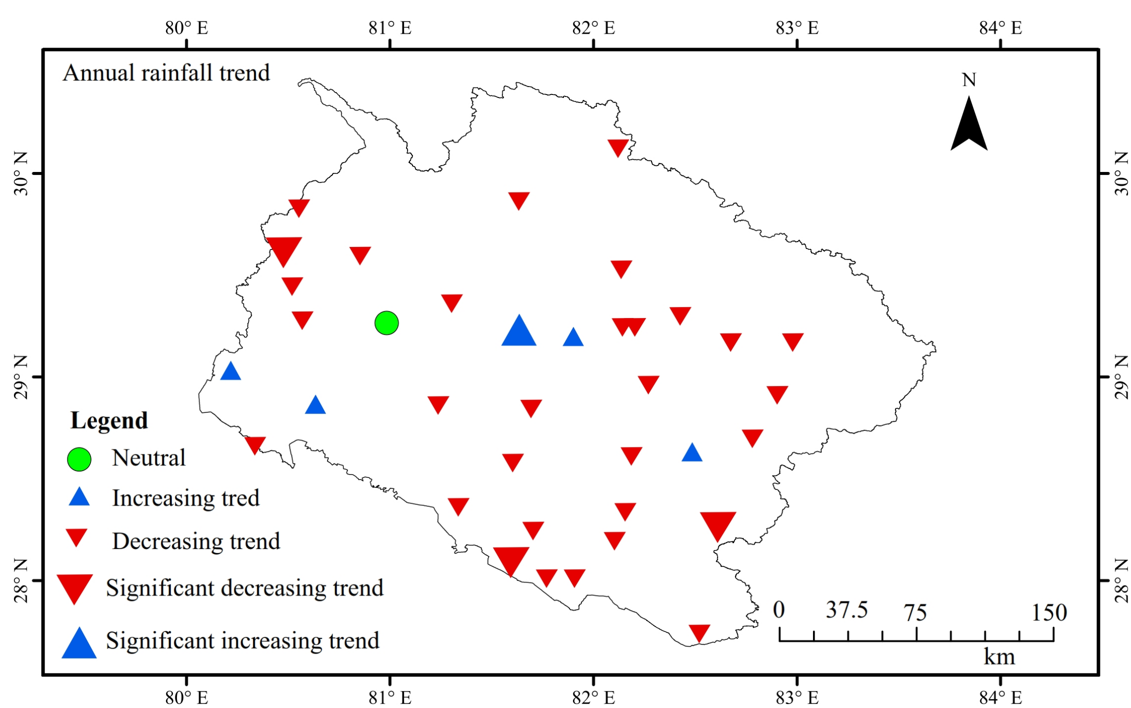


Figure 5. Spatial variability of annual rainfall trends over the western region of Nepal.

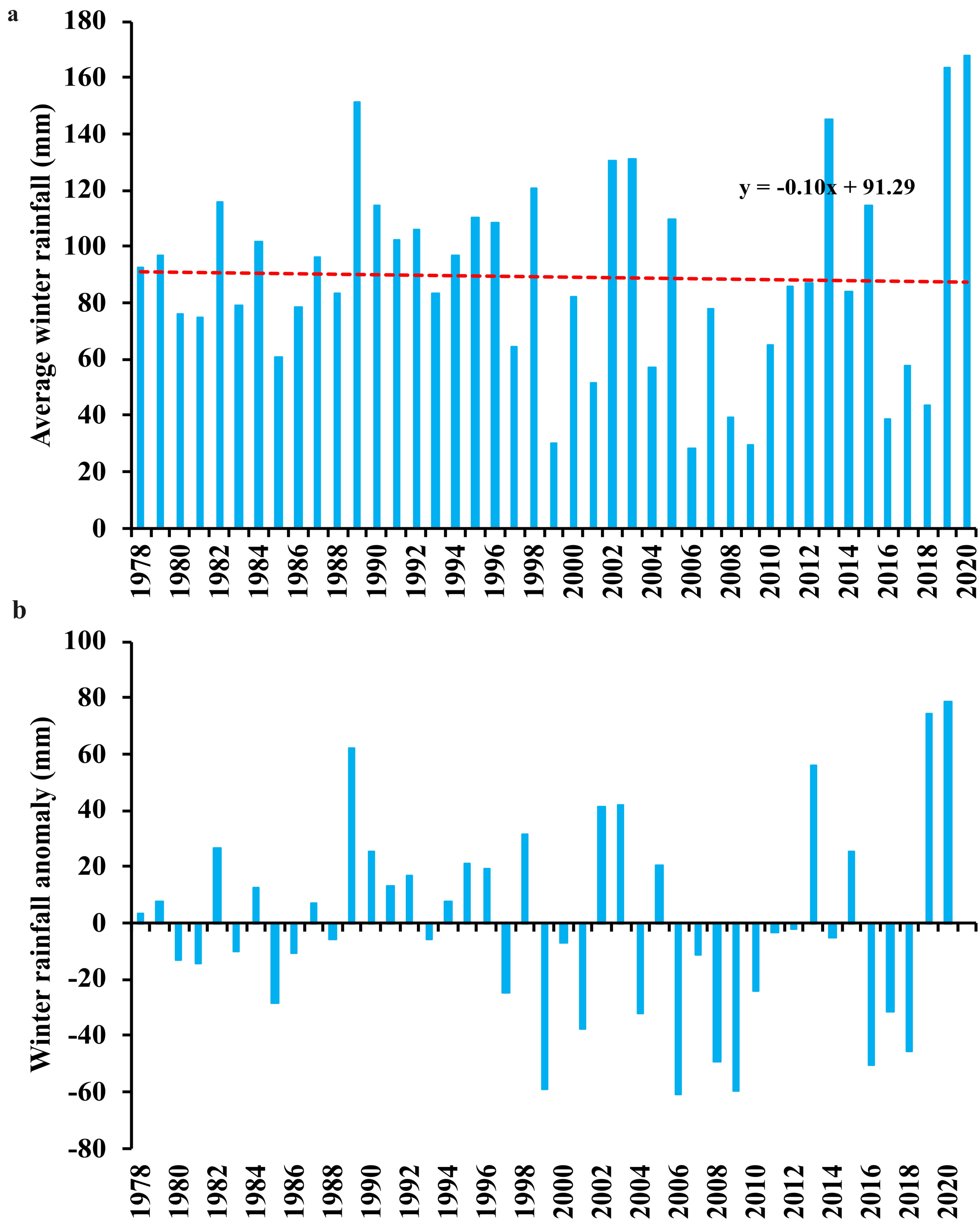


Figure 6. Temporal variability of (a) average winter rainfall and (b) anomaly in western Nepal.

1982, which was followed by 2020 and 1990, whereas the negative anomaly was high in 1996, which was followed by 2010.

4.7. Monsoon Rainfall and Its Anomaly

The variability of monsoon rainfall is clearly shown in Fig. 8a. During the study period, the rainfall ranged from

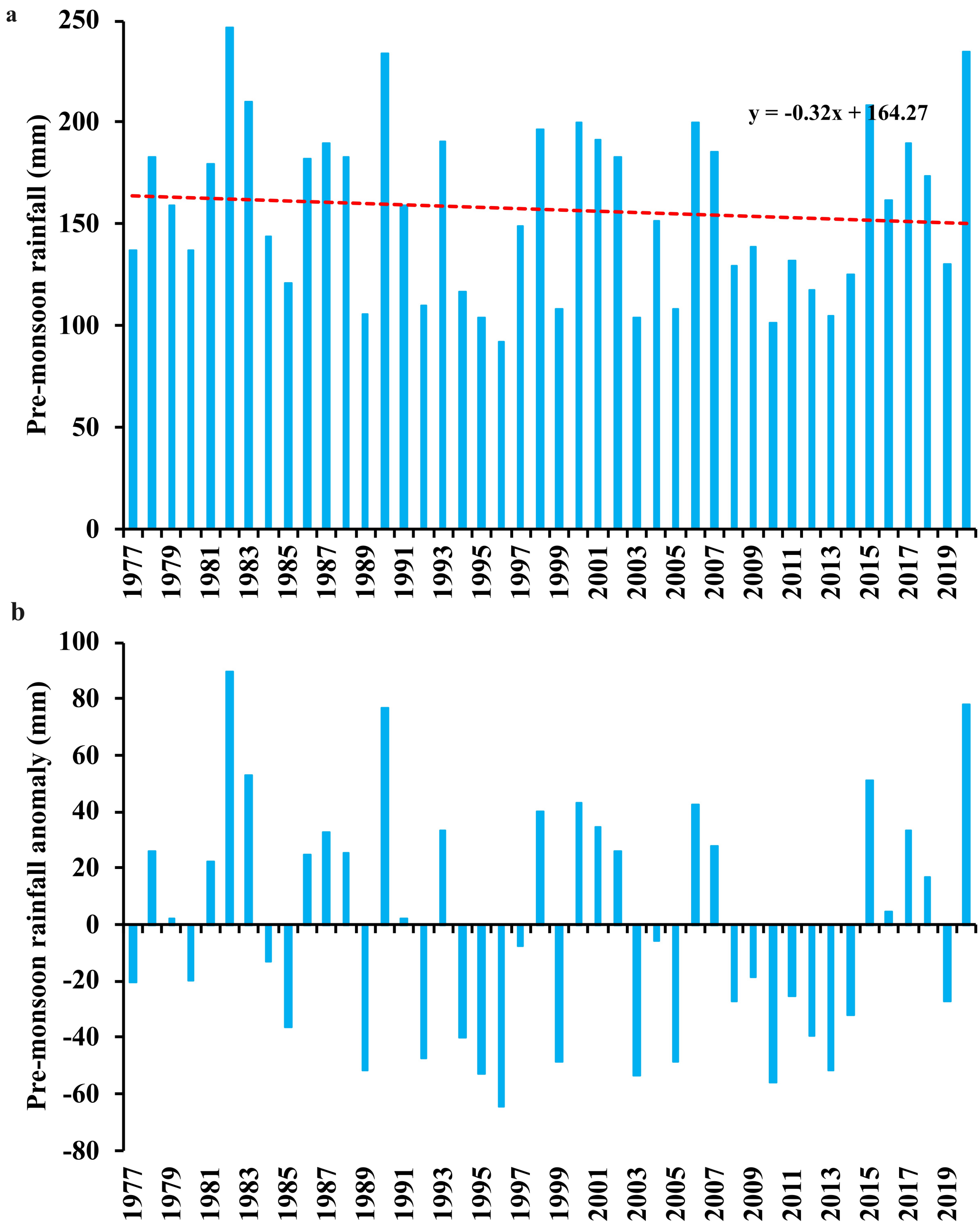


Figure 7. Temporal variability of (a) average pre-monsoon rainfall and (b) anomaly in western Nepal.

1438.46 mm in the year 2000 to 886.92 mm in the year 1979. The average monsoon rainfall is 1137.70 mm from 1977 to 2020. Monsoon rainfall shows a decreasing pattern in western Nepal (Fig. 8a).

Fig. 8b provides a clear picture of the temporal variability of monsoon rainfall anomalies. In the monsoon season, the positive anomaly was high in 2000, which was followed by 1998. In contrast, the negative anomaly was high in 1979, which was followed by 2004 and 1977 (Fig. 8b).

4.8. Post-monsoon Rainfall and Its Anomaly

There is significant year-to-year variation in post-monsoon rainfall, as shown in Fig. 9a. The highest recorded post-monsoon rainfall was 172.30 mm in 2009, followed by 166.78 mm in 1985. The mean value of post-monsoon

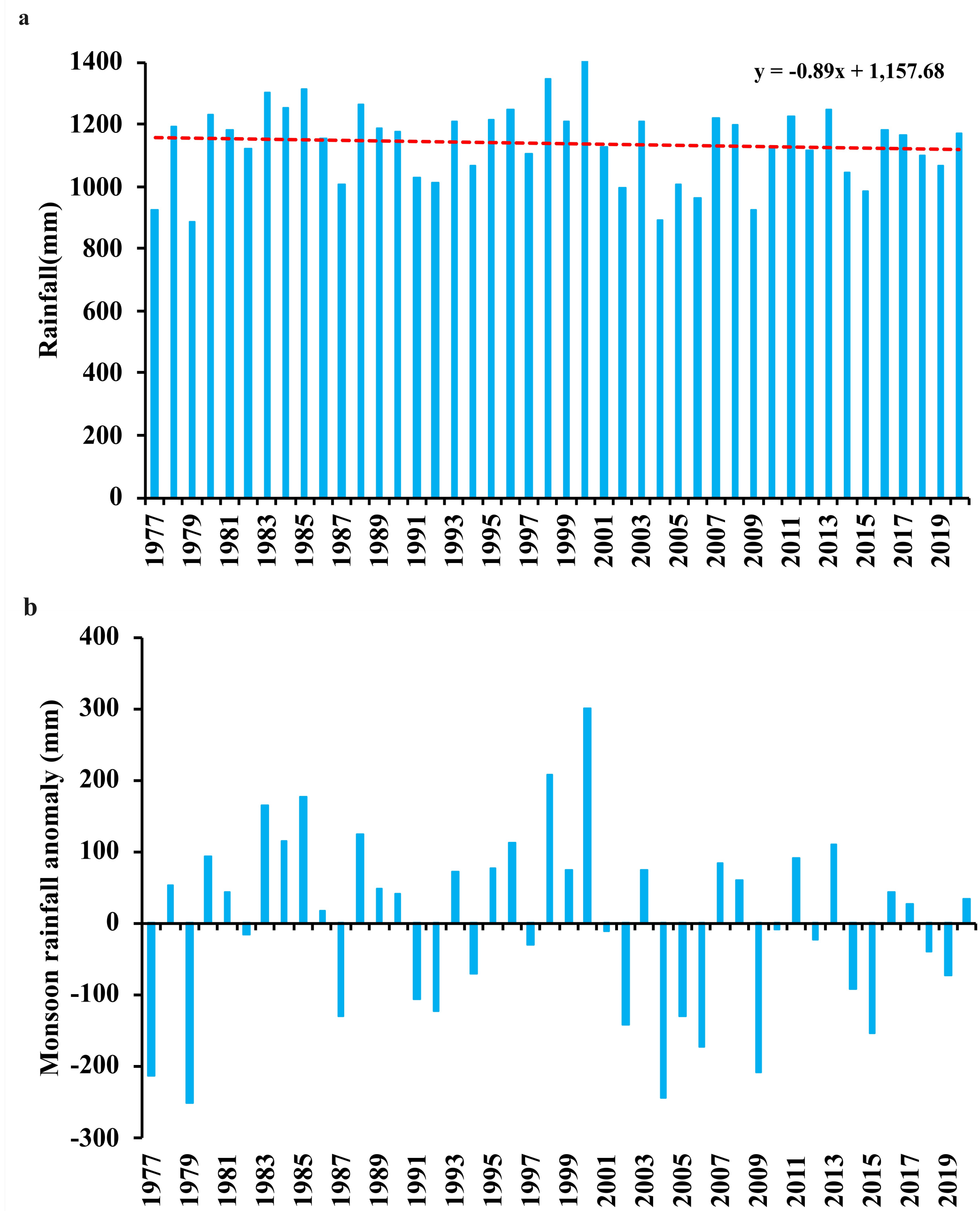


Figure 8. Temporal variability of (a) average monsoon rainfall and (b) anomaly in the western region of Nepal.

rain is 47.93 mm. The post-monsoon rainfall shows the decreasing rainfall patterns in western Nepal.

The variability of post-monsoon rainfall anomalies is depicted in Fig. 9b. In the post-monsoon season, the positive anomaly is high in 2009, which is followed by 1985, whereas the negative is in 2020, which is followed by 1994.

4.9. Annual Rainfall and Its Anomaly

There is a large annual rainfall variation in western Nepal. In the annual average, the occurrence of 24 years with a positive anomaly and 19 years with a negative anomaly indicates a dry condition. It is observed that the consecutive three years of 2004, 2005, and 2006 dealt with a similar low pattern of rainfall of about 1250 mm as a deficit year. The average rainfall of western Nepal is 1432.04 mm during the

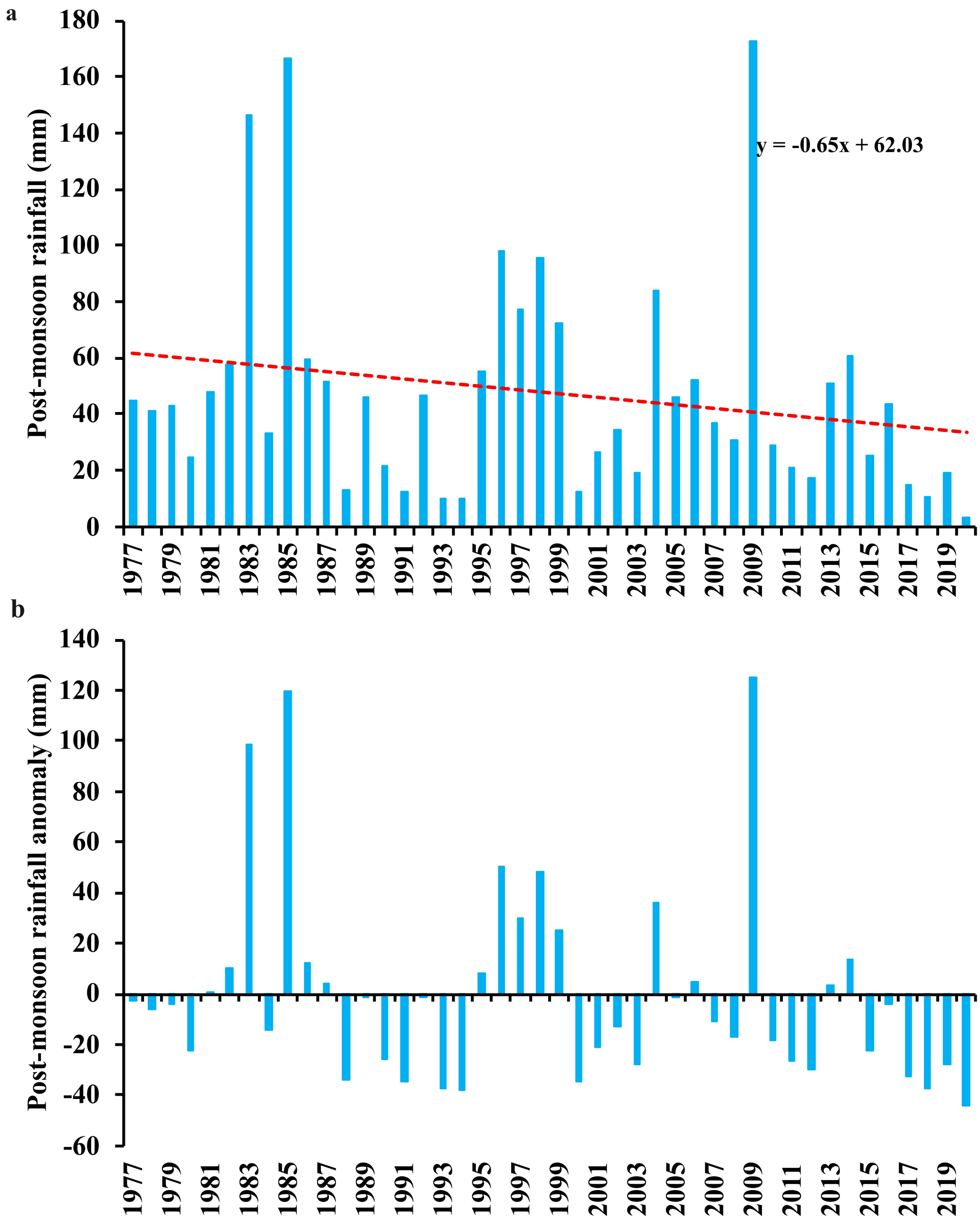


Figure 9. Temporal variability of (a) average Post-Monsoon rainfall and (b) anomaly in the western region of Nepal.

study periods (1977-2020). The annual rainfall shows the decreasing rainfall patterns in western Nepal (Fig. 10a).

The temporal variability of annual rainfall anomalies is clearly shown in Fig. 10b. The annual anomaly of the western region of Nepal is shown in Fig. 10b. It shows that 1977 experienced the maximum negative value of anomaly, followed by 1979 and 2004, whereas the maximum positive value was experienced in 1983, which was followed by 1985 and 2000. Positive/negative values show the wet/dry episodes.

4.10. Decadal Seasonal and Annual Rainfall Patterns in Western Nepal

This study quantifies decadal rainfall patterns, including seasonal and annual totals. The decadal patterns are clearly shown in Figs. 11(a, b, c, d, and e) and Table 1. From

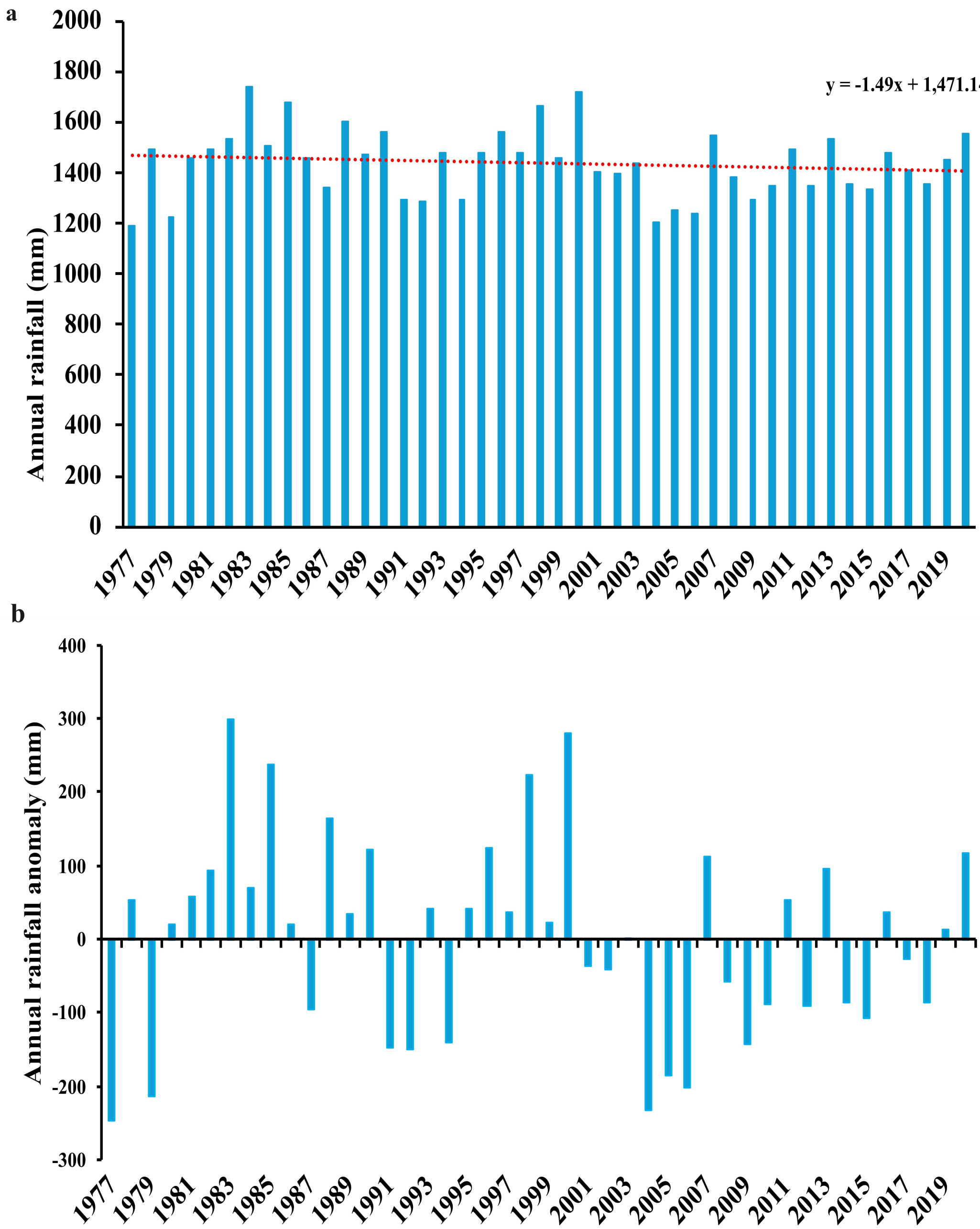


Figure 10. (a) Average annual rainfall in the western region of Nepal, (b) Annual anomaly of the western region of Nepal.

1981 to 1990, the average annual rainfall was 1,537.77 mm. Table 1 also includes details on pre-monsoon, monsoon, post-monsoon, and winter rainfall, along with other decadal seasonal and annual rainfall data.

It is found that annual average rainfall has been increasing in the 80s and 90s, whereas a decreasing trend has been seen in the last two decades.

5. Discussion

Monthly rainfall data from 1977 to 2020 showed a strong increase starting in May, peaking in July due to the monsoon. Western Nepal receives about 79.7% of its rainfall during the monsoon, followed by 10.7% during the pre-monsoon, 3.3% during the post-monsoon, and 6.3% during the winter of the annual rainfall. These findings align

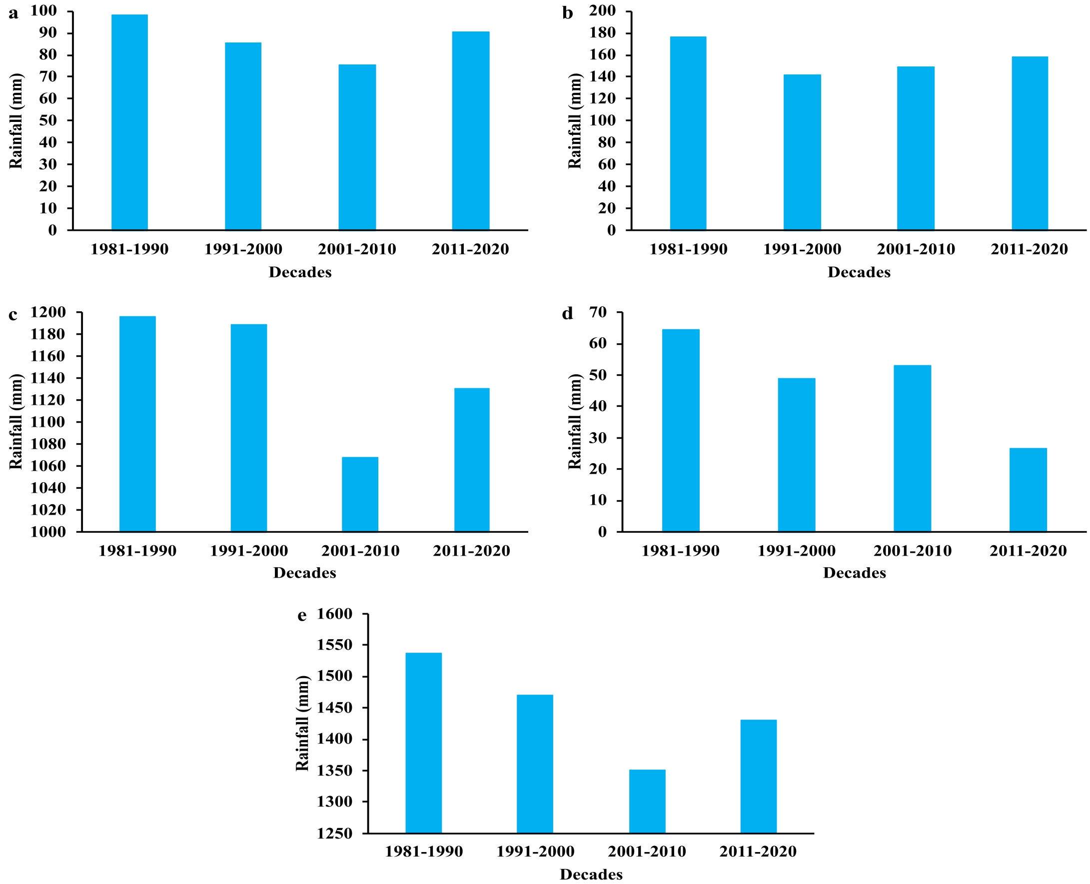


Figure 11. Decadal rainfall variability of winter, pre-monsoon, monsoon, post-monsoon, and annual.

Table 1. Decadal distribution of seasonal and annual rainfall in mm.

Year	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
1981-1990	98.33	176.49	1195.94	64.52	1537.77
1991-2000	85.32	142.12	1188.90	49.02	1470.49
2001-2010	75.49	149.16	1067.44	53.10	1350.59
2011-2020	90.61	157.76	1130.35	26.65	1429.87

with earlier studies (Bagale et al., 2023a; Ichiyanagi et al., 2007).

The trend analysis of the standardized precipitation index generated from the time series rainfall data of 1977 to 2018 over Nepal identified that the seasonal and annual rainfall has been decreasing in Nepal (Bagale et al., 2021, 2024). The annual rainfall trends of western Nepal indicated the decreasing trends of rainfall have resembled with above-mentioned previous studies.

Rainfall anomaly analysis is a technique used to identify and assess deviations in rainfall patterns. This is useful for understanding the temporal variability and changes in rainfall characteristics. The present study's results align with (Bagale et al., 2023a; Shrestha, 2000). The severe dry events of winter (2006 and 2009) and monsoon (1979 and 2004) in western Nepal are in line with (Bagale et al., 2023a; Wang et al., 2013). Similarly, the findings of the winter and monsoon wet years are in line with above mention previous researchers' findings.

There is a large spatial variability of rainfall in western Nepal; the far western region is wetter than the other regions. These results are in line with earlier studies (Kafle, 2014). There is significant variability of temporal and spatial seasonal rainfall in western Nepal. The results are supported by Bagale et al. (2023a). After 2000, western Nepal experienced three consecutive dry years 2004, 2005, and

2006. The time series rainfall datasets analysis indicates that the country's average monsoon rainfall decreased in Bangladesh from 1961 to 2010 (Ahasan et al., 2010). The present study has identified that during the study periods 1977 to 2020, the rainfall decreased in Western Nepal. The results of this study indicate that rainfall has significantly decreased since 1990. This decline may be linked to the southwest Indian monsoon system, which has also been decreasing in recent decades (Kumar et al., 2013; Varikoden et al., 2015). Similar findings by Kumar et al. (2013) show that monsoon rainfall in South Asia has declined over the past few decades.

Over the past four decades, decadal seasonal rainfall patterns have decreased in western Nepal. Similar results were found by Ahasan et al. (2010) in Bangladesh, Sein et al. (2015) in Myanmar, and Varikoden et al. (2015) in India, supporting the findings of this study. The decrease in monsoon rainfall in this region may be linked to the frequent El Niño Southern Oscillation (Bagale et al., 2021; Varikoden et al., 2015).

6. Conclusion

This study analyzed rainfall data from 36 meteorological stations between 1971 and 2020 to explore the variability of monthly, seasonal, and decadal rainfall in western Nepal. July is the wettest month and November is the driest. Monsoon seasons get almost 79.7% of annual rainfall, with the remaining distributed among pre-monsoon, post-monsoon, and winter. There is significant spatial variability, with northern areas generally receiving less monsoon rainfall than the lower and middle regions, which see more overall rainfall. Since 2000, dry events have increased, and seasonal rainfall patterns are decreasing. Monsoon rainfall varied substantially with a minimum of 886.92 mm in 1979 and a maximum of 1,438.46 mm in 2000. Winter rainfall ranged from 28.10 mm in 2006 to 167.30 mm in 2020. The average winter and monsoon rainfall is 87.30 mm and 1137.70 mm respectively from 1977 to 2020. MK test showed that many of the stations of the western region of Nepal show decreasing trends of annual rainfall indicating that the dry events are increasing. The annual rainfall has been decreasing by nearly 0.5 mm/annum. Furthermore, the decadal study indicates that rainfall has decreased in recent decades.

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