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Spatial and Temporal Variability of Winter Rainfall in Nepal

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ABSTRACT

The study analyzed time-series rainfall data from 107 weather stations in Nepal between 1977 and 2018. Rainfall variability ranged from 10.66 mm in the dry winter of 2006 to 133.51 mm in the wet winter of 1989. There were notable dry periods, such as in 2008-9 and 2016-2018. The western region received more rainfall in the early decades, while the eastern Terai experienced drier conditions in recent decades. Decadal analysis revealed decreased winter rainfall across Nepal, with diverse patterns across regions. The composite analysis identified the dry and wet regions in large excess and large dry years. The central and eastern mountainous areas observed more rainfall, contrasting with the minimal rainfall in the lowlands of the eastern regions. These findings highlight changing climate dynamics, with regional variations in rainfall patterns across Nepal's western, central, and eastern (WCE) regions.

Keywords: Nepal, Spatial, Temporal, Variability, Winter rainfall

INTRODUCTION

Globally, monsoon is the vital source of water resources. The Asian monsoon circulation system, characterized by distinct wet and dry phases, monsoon undergoes significant variations in intra-seasonal, annual, and inter-annual timescales (Webster et al., 1998). During the wet phase, warm and moist winds are carried inland from the tropical oceans, bringing rainfall, while the dry phase involves cool, dry air transported from the continents (Yan *et al*., 2011). In addition to the monsoon, Western Disturbances, originating in the Mediterranean region, play an essential role in the winter rainfall patterns over the northern areas of the Indian subcontinent, including Nepal (Dimitri *et al*., 2007). These disturbances primarily affect the Karakoram and Hindu Kush regions of Pakistan, North India, and Nepal, contributing to snowfall in the high-altitude areas and occasional rainfall in the lowlands (Dimitri *et al*., 2007). Winter rainfall is important in South Asia because many people are dependent on agricultural practices. Large-scale circulation patterns drive the variability in the winter monsoon, the Siberian High, and the polar/Eurasian teleconnection, influencing storm occurrences and precipitation towards Nepal (Wang *et al*., 2013).

In Nepal's mountainous regions, winter precipitation contributes less, is crucial for groundwater recharge, irrigation, and agriculture. Major rivers of Nepal originate from the Himalayas. The river flow gives water for irrigation in low lowlands of Nepal and the Gangetic plains of India. However, the complex precipitation patterns in these complex mountain areas remain underexplored (Ichangi *et al*., 1987). Fluctuations in winter rainfall can lead to dry conditions that severely impact drinking water availability, agriculture, and the livelihoods of people in rural and Terai areas. Despite the importance of winter rainfall, comprehensive studies focusing on its spatial distribution and variability in Nepal remain limited.

Previous studies, such as those by Karki *et al*. (2016), and Sigdel and Ikeda (2012), have examined the inter-annual variability of winter precipitation and its links to ocean-atmospheric circulations. However, these studies have primarily focused on trends and the impacts of large-scale climate patterns, with fewer investigations into region-specific patterns, particularly during dry years. Shrestha et al. (2000) found weak correlations between winter rainfall and the Southern Oscillation Index (SOI) in Nepal. Despite these efforts, a comprehensive understanding of the spatial variability of winter rainfall, especially during major dry years, remains a significant research gap. Thus, one of the primary aims of this study is to quantify and map the winter rainfall received by Nepal over the past four decades, filling a critical gap in understanding climate patterns and their impacts on the region.

MATERIAL AND METHODS

Study Area

Nepal is a landlocked mountainous nation that borders China to the north and India to the south, east, and west. Its varied topography stretches from the lowland Terai (60 meters above sea level) in the south to the majestic Mount Everest (8848 meters) in the north. Nepal covers an area of 147,516 sq. km from east to west and 130–260 km from north to south. Monsoon-driven rainfall characterizes its climate, and rainfall variations are examined using 107 stations (Figure 1).

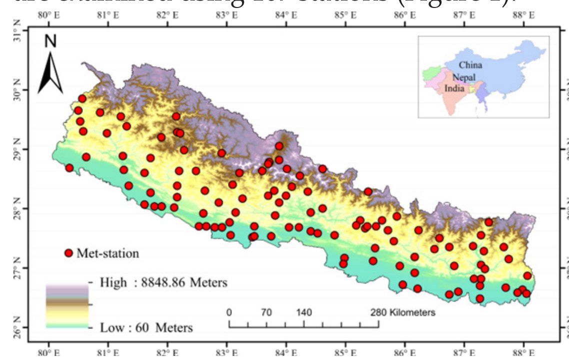

Figure 1: Spatial distributions of met-stations used in the present study over Nepal.

Data (methods of data collection)

This study used daily rainfall from 107 weather stations, provided by the Department of Hydrology and Meteorology, covering 1977–2018. Monthly and seasonal rainfall totals were derived by summing daily and monthly data (Bagale *et al*., 2023a). Stations with less than 5% missing records were prioritized, with most stations having missing data below 3%. For high-altitude stations with 5-10% missing data, a 30-year time series was used. The arithmetic mean method calculated averages, while missing rainfall was estimated using the Normal Ratio method (Bagale *et al*., 2023b). Winter rainfall distribution was visualized using the IDW technique (Patel *et al*., 2007).

RESULTS

Spatial variability of mean winter rainfall and December, January, and February months

Winter season, December, January, and February months' rainfall are depicted in (Figures 2a, b, c, and d), showing significant spatial variation. The western mountainous regions see more precipitation throughout the winter (Figure 2a), demonstrating the large spatial variations in winter precipitation throughout the nation. The western mountainous regions receive the highest precipitation, with the central and eastern highlands also experiencing notable rainfall. The far-western, central high mountains, and northeastern areas are identified as rainfall pockets, with over 100 mm of rainfall during winter. In contrast, lower eastern regions experience significantly less rainfall. The western lowlands and midlands receive more rainfall than the eastern areas. The far western, central, and northeastern regions are the heaviest rainfall zones, while the central and eastern lower lands are drier. Overall, the western region experiences the highest winter rainfall.

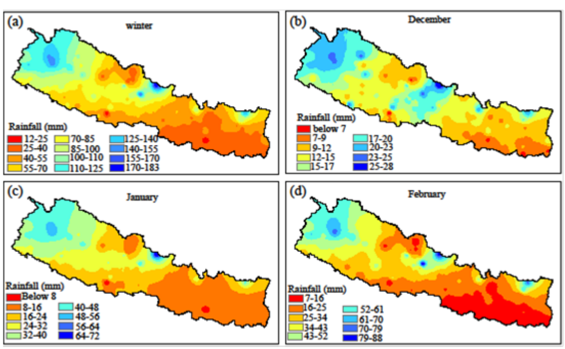

Figure 2: Spatial variability of rainfall for (a) winter, (b) December, (c) January, and (d) February months.

In December western Nepal received more precipitation than other areas. A similar pattern is indicated in January and February Figures (2c, d). In particular, the western region receives more rainfall than other areas, and December, January, and February months' rainfall generally increases with elevation.

Variability of winter rainfall

The average winter precipitation of Nepal was found 69.67 mm/season in the long-term climatology of the period 1977–2018. The rainfall variability varied from 10.66 mm/winter in the major dry year 2006 to 133.51 mm/winter in the major excess year 1989, clearly shown in Figure 5a. Winter rainfall has decreased frequently in the last two decades. In the years 1979, 2006, and 2009, the average winter rainfall recorded less than 18 mm/month (Figure 3). These episodes were observed in low rainfall in large areas over Nepal. Furthermore, the monthly variation of December, January, and February showed the rainfall amounts from 1977 to 2018 (Figure 4).

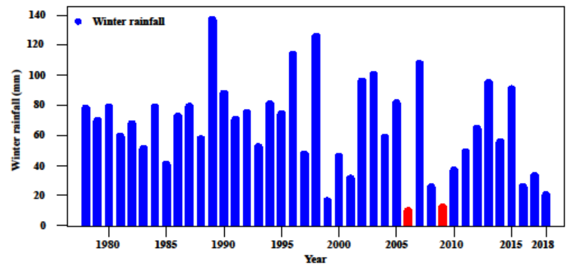

Figure 3: Temporal variability of winter rainfall, red color shows the lowest winter rainfall in 2006 and 2009.

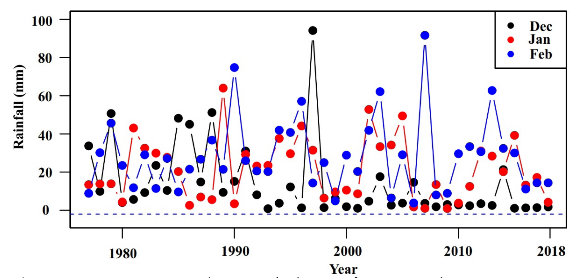

Figure 4: Temporal variability of December, January and February months' rainfall from 1977 to 2018.

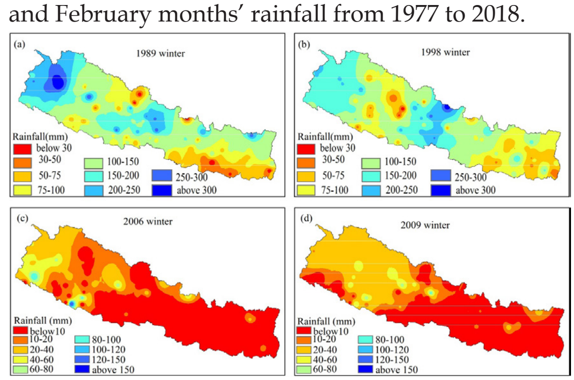

Figure 5: The extreme events for large excess years (a) 1989 and (b) 1998, for large deficit years (c) 2006 and (d) 2009

There was comparable geographical variability in rainfall during exceptional dry events in 2006 and 2009. The middle and eastern regions saw more damage during these occurrences than the western regions. These dry years were the worst in the previous forty-two years. The rainfall magnitudes of major dry years are interpolated in isohyetal maps, Figures 5c and 5d. Generally, winter rainfall decreased from west to east.

Decadal rainfall patterns in winter

The study investigated the fluctuations in Nepal's decadal winter rainfall patterns. In the winter, eastern Nepal's lowlands received minimal rainfall, while the western region recorded higher precipitation. Mountainous regions in the east and central areas exhibited heavier rainfall. Western Nepal received more precipitation than other areas (Figure 6a) in the first decade; a similar pattern is indicated in the second, third, and fourth decades (Figures 6b, c, d).

In the first decade, the far western region observed more rainfall than central and eastern Nepal. In this decade, the winter rainfall decreases gradually in WCE regions. The lowland of the eastern is more arid than other areas. Similarly, the second decade follows the same pattern; the rainfall decreases from western to eastern regions (Figure 6b). In the third decade, the rainfall amount decreases but the variability nature is the same. In the fourth decade, the eastern region is drier than in other decades.

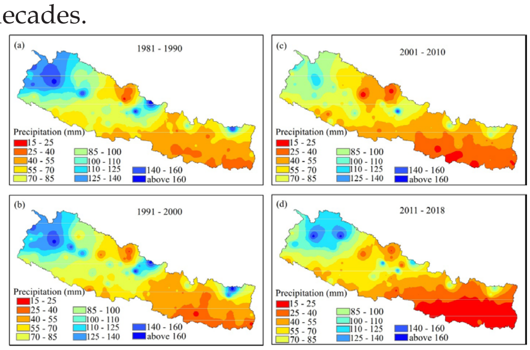

Figure 6: Spatial distribution of decadal precipitation (mm) for the winter season; from 1977 to 2018.

Overall, the western mountainous regions see more precipitation throughout the winter. Winter rainfall shows a marked spatial variation, with the highest rainfall observed in the high mountainous midlands of the central and eastern regions.

Table 1: Decadal Winter Rainfall for the Past Four Decades

Decades	Average winter rainfall
1981-1990	71.89
1991-2000	74.23
2001-2010	56.19
2011-2018	50.41

Composite wet and dry events for winter seasons

Over the past four decades, the three driest years (1999, 2006, and 2009), with average winter rainfall of less than 20 mm, were selected for composite deficit analysis. On the other hand, wetter years like 1989, 1998, and 1996 were selected for excess composite analysis. The western region generally experiences more rainfall than the CE regions, with some pockets of high rainfall in the central and northeast mountainous areas. The far-western region is the wettest, while the eastern lowlands receive the least. These patterns are illustrated in the isohyetal map 7, showing complex rainfall distribution across Nepal. Findings highlight that the eastern lowlands are the driest, while the northeast mountains and high regions of the central region are wetter, even in dry years.

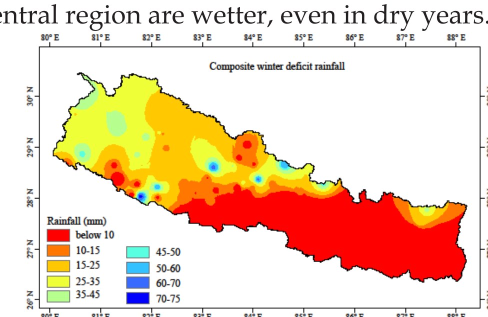

Figure 7: Spatial variability of composite winter dry years.

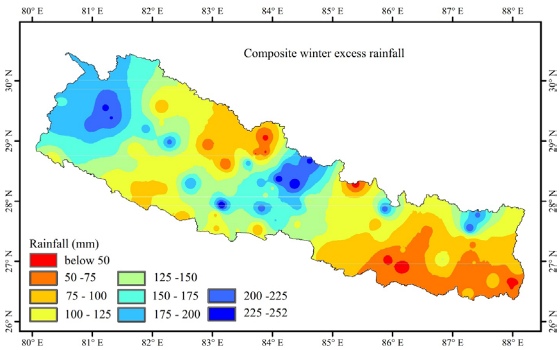

Figure 8: Spatial variability of composite winter dry years.

As can be seen in the isohyetal map (Figure 8), composite rainfall analysis determined the dry and wet zones over Nepal. Of all the regions of Nepal, the Far-Western region has the highest precipitation levels. It is drier in eastern Nepal's lower regions. In contrast to the plains of an eastern region, the northeast high mountain ranges had considerable rainfall. One noteworthy discovery is that elaborate heavy rainfall patterns were discovered in the complex mountain topography in the east and center. Average rainfall was higher in the western region than in the central and eastern regions.

DISCUSSION

The winter rainfall patterns in Nepal vary across western, central and eastern regions. The lower eastern regions are drier compared to the central and western regions, although the far western regions received heavier rainfall, which aligns with findings from Kanskar *et al.* (2004). From 1977 to 2018, the average winter rainfall in Nepal was 63.97 mm per winter. The study also identified notably dry years, particularly 2006 and 2009, which experienced significant rainfall deficits, a trend similar to findings by (Wang *et al.*, 2013; Dahal et al., 2015; Gaire *et al.*, 2024).

Dahal *et al.*, (2015) identified the worst drought episodes in 2006 and 2009 central regions of Nepal based on SPI indices for (1977-2010). Dahal *et al.*, (2021) observed the dry episodes based on SPI indices and noticed the dry seasons in eastern Nepal. The central and eastern region's reductions of rainfall in respective years are similar to the present study findings.

Wang *et al.* (2013) and Bagale *et al.* (2024) both highlighted that the winter droughts of 2005-2006 and 2008-2009 in Western Nepal were extreme, with these years receiving less than 50% of the average winter precipitation from November to February. This study similarly identified 2006 and 2009 as the driest winter seasons in the past four decades, with monthly rainfall averaging below 18 mm and each drought event.

Spatial analysis of rainfall in central and eastern Nepal shows a west-to-east decrease, with drier areas in the lower Terai region. Winter composite rainfall identifies dry and wet zones, essential for water management, irrigation, and agriculture. The findings align with Karki *et al.* (2015) and highlight how decreasing rainfall during dry years severely impacts mountain communities, leading to reduced food production and crop failure, which poses significant challenges for agriculture.

Dry periods severely impact agricultural production, as shown by studies (Wang *et al.*, 2013; Gentle and Maraseni, 2012). In Nepal, consecutive winter dry events (2008-2009, 2016-2018) have worsened living conditions for mountainous communities. Nepal's prosperity depends on agriculture, tourism, hydro-power, and related activities, highlighting the need for planners to consider extreme weather events in future planning.

CONCLUSION

This study examined the temporal and spatial variability of winter rainfall in Nepal from 1977 to 2018. Rainfall fluctuated between 10.66

mm in the dry year 2006 and 133.51 mm in the excess year 1989. The most extreme dry years were 2006 and 2009, while 1989 and 1998 saw the highest excess rainfall. These dry episodes affected large areas, with more stations reporting below-average rainfall. The eastern region experienced more frequent dry winters in recent years, particularly after 2000, compared to the central and western regions. Winter rainfall was consistently lower in the eastern region than in the others, with rainfall increasing with elevation across the WCE regions. The study highlighted intrinsic heavy rainfall patterns in the mountainous areas from west to east.

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