

Spatio-Temporal Dynamics and Variability of Rainfall in North-Western Rajasthan, India (1991–2024)

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Article Citation:

Arshdeep Singh¹, Apperdeep Kaur², "Spatio-Temporal Dynamics and Variability of Rainfall in North-Western Rajasthan, India (1991–2024)", International Journal of Recent Trends in Multidisciplinary Research, September-October 2026, Vol 6(05), 221-228.



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Abstract: In this research, the spatial and temporal distribution of annual rainfall in North-Western Rajasthan is studied between 1991 and 2024 based on the Climate Hazards InfraRed Precipitation with Station (CHIRPS) v2.0 rainfall data and GIS technology. Annual rainfall data was analyzed through QGIS and Microsoft Excel was used for tabulating and plotting of statistical graphics. Spatial distribution of rainfall maps of years 1991 and 2024, rainfall change map, and temporal graph of rainfall were created. It was found that there exists a clear west to east rainfall gradient with relatively less rainfall in western and northwestern areas and relatively high rainfall in eastern and southeastern parts. Mean annual rainfall increased from 72.52 mm in 1991 to 250.39 mm in 2024. Maximum rainfall value and standard deviation of rainfall were relatively more in 2024 and had increased from 426.25 mm and 90.81 mm in 1991 to 1,110.12 mm and 282.40 mm, respectively. Change in rainfall value was more than 599 mm in certain parts of eastern and southeastern areas. This research gives an explicit analysis of rainfall variability in the arid and semi-arid regions of North-Western Rajasthan and emphasizes the differences in rainfall between its western and eastern regions.

Keywords: CHIRPS v2.0, GIS, North-Western Rajasthan, Rainfall, and Spatial Analysis.

1. Introduction

Rainfall is one of the key factors in the hydrological cycle and holds tremendous significance in the fields of agriculture, water supply, groundwater recharge, ecosystems, and socio-economic processes. There are variations in the distribution of rainfall in terms of space and time, especially in the arid and semi-arid regions with limited water sources. Variations in rainfall can affect soil moisture, agricultural productivity, drought periods, and water availability in the region. This makes it imperative to understand variations in rainfall (Das et al., 2020).

India exhibits great variability in rainfall, largely due to the Indian summer monsoon. The southwest monsoon accounts for the major share of rainfall in most parts of India. However, there are marked differences in the intensity and distribution of the rainfall pattern across

Different regions and years. These differences cause variations in water availability and agricultural conditions. Research studies conducted on Indian monsoon rainfall have found significant variation in rainfall spatially and temporally (Mazumdar, 1998). These variations are of utmost importance in the regions where agriculture and water sources rely on precipitation.

Rajasthan state is one of the most vulnerable states to climatic change in India, considering that huge areas of the state lie in arid and semi-arid climatic zones. It is interesting to note that there is variability in rainfall in the state wherein the further away the state gets from its southeast and east, the lesser will be the rainfall in the arid west side of the state. There are also high levels of variability in the rainfall pattern in Rajasthan. Previous studies have found variable southwest monsoon rainfall characteristics in Rajasthan (Ali et al., 2005). High levels of variability in rainfall in Rajasthan, including mean and extreme rainfall in different cities of Rajasthan, have also been reported (Pingale et al., 2014). Recently, significant variability in precipitation in Rajasthan, showing increasing and decreasing trends in precipitation, have also been reported (Porwal & Choudhary, 2023).

North Western Rajasthan is one of the areas located in Thar Desert and is one of the most arid regions in India. The area is characterized by low precipitation, high temperatures, sandy soils and limited water supply. In other words, the variability of

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rainfall becomes especially significant for rain fed agricultural production, irrigation requirements, aquifers replenishment, drought probability and water resources management in the region. It was found that there are some changes in monsoonal precipitation in northwestern India, including the increase in some parts of the region (Singh et al., 2022; Joseph et al., 2024). Therefore, rainfall variability may have some impact on crop productivity and water resources sustainability. In this context, the spatial analysis of rainfall is necessary due to the peculiarities of climate and environment in the region.

It is important to have adequate spatial coverage when assessing the amount of rainfall in large, climatically diverse regions. While rain gauge data offer accurate measurements at point locations, their spatial distribution can be constrained where there are sparse rain gauges. Satellite-based gridded rainfall data sets thus offer valuable data for regional rainfall assessments. CHIRPSv2.0 (Climate Hazards InfraRed Precipitation with Station) offers precipitation data sets for the past 35 years at a spatial resolution of 0.05°, which is appropriate for regional rainfall assessment (Funk et al., 2015).

Earlier studies have been conducted on rainfall variability and trends in various parts of Rajasthan and northwestern India. For instance, some recent studies have analyzed rainfall variability and trends in the Parbati River Basin of Rajasthan through non-parametric methods of statistical analysis (Agrawal et al., 2024). The different locations, data sets, time frames, and techniques adopted by these studies suggest the requirement of a region-specific study. Specifically, an analysis of annual rainfall patterns in northwestern Rajasthan in the form of a spatial analysis using a common gridded rainfall dataset for the years 1991 to 2024 will be highly beneficial.

Considering the above discussion, the current research focuses on examining the spatial and temporal variability of annual rainfall in North-Western Rajasthan from 1991–2024 through the use of CHIRPS v2.0 rainfall data and geographical information system techniques. The objectives of the study are to investigate the spatial pattern of annual rainfall in 1991 and 2024, to analyze the spatial variability between these two years and to measure temporal variability through selected years (1991, 1996, 2001, 2006, 2011, 2016, 2021, and 2024).

2. Study Area

The state of Rajasthan lies in the north-western part of India and occupies about 342,239 km² of land, thus being the largest state of India geographically. Rajasthan lies roughly between 23°03'N–30°11'N and 69°28'E–78°16'E. Various geographical and climatic features are present in the state, such as the Thar Desert in the western and north-western areas and the Aravalli Mountains which span the whole state. The western regions are mostly arid while the eastern and south-eastern regions experience relatively more wet weather conditions. Rainfall is very irregular both in space and time, with the arid western regions getting significantly less rainfall compared to the eastern and south-eastern regions. Such geographic and climatic differences make an important environment for the analysis of rainfall variability in the state (Kharol et al., 2013; Monir & Sarker, 2024).

The current research will be done in North-Western Rajasthan, which includes the following districts: Bikaner, Churu, Hanumangarh, Sri Ganganagar, Jaisalmer, Barmer, Jodhpur, Nagaur, Sikar, Jhunjhunu, Phalodi, Balotra, and Didwana-Kuchaman. For the purposes of the current research, North-Western Rajasthan can be defined as the region that features mainly arid and semi-arid lands stretching from highly arid deserts in the western part to relatively less arid lands in the northern and eastern parts. The region is characterized by sandy planes and aeolian dunes, highly varying and low amounts of precipitation, high evaporation rate, and different availability of water. Due to this, there are huge differences in moisture availability and agricultural potential in this region. Thus, precipitation is one of the most climatic factors influencing the development of agriculture in North-Western Rajasthan. Such environmental gradient is a suitable environment for analyzing annual rainfall distribution (Singh & Kumar, 2015).

The climate of the study area is mainly arid to semi-arid and has high summer temperatures, low relative humidity, high rates of evaporation, and sporadic rainfall. The rainfall pattern is highly seasonal and is mainly received during the southwest monsoon period, causing high spatial and temporal variability in precipitation. Water availability is the limiting factor due to low rainfall and high rate of evaporation. Irrigation in relation to the Indira Gandhi Canal in the northern parts of the area, such as the district of Sri Ganganagar, has changed the face of agriculture. There is an interesting spatial difference between the desert environments that are rain-fed in the western and central areas of the study area and the agriculturally productive regions in the north (Mehta et al., 2025).

The soils and land forms of North-Western Rajasthan also exhibit features of their arid environment. Windblown sand and sandy soils occupy large parts of the area whereas alluvial soil is found in certain regions of the northern plains. The poor water holding capacity of the coarse soils, combined with high rates of evaporation and low amounts of precipitation poses several limitations for agricultural activities and water table recharge. Studies carried out in the north-western part of Rajasthan have emphasized the significance of rainfall for groundwater recharge and have revealed that there are considerable variations in groundwater availability due to the influence of climate, topography and subsoil features (Chaudhary & Satheeshkumar, 2018). The agriculture systems in the region rely on the availability of rainfall, groundwater, and irrigation, water being an important determinant in the maintenance of crop production (Rathore et al., 2014).

The presence of strong climatic gradients, variability in rainfall, large areas of arid regions, variation in irrigated agriculture and rainfed agriculture, and scarcity of water sources renders North Western Rajasthan a suitable area to conduct rainfall studies. These attributes form the basis on which the spatial and temporal analysis of rainfall for the years 1991–2024 can be conducted using CHIRPS v2.0 rainfall data and GIS methods.

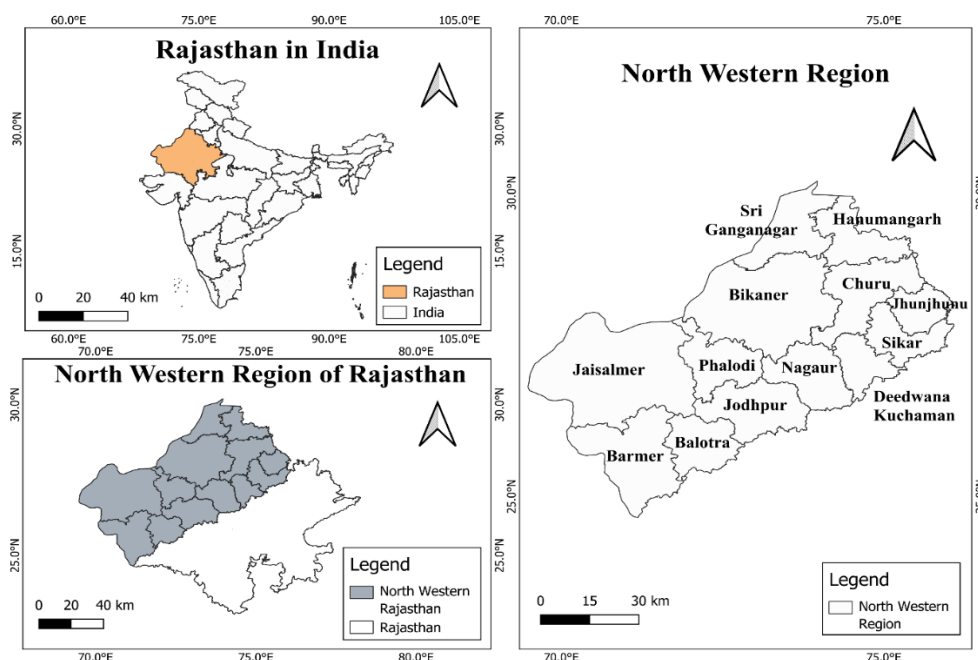


Figure 1.1 Location of the Study Area: Rajasthan, the North western region and its constituent Districts

Source- Survey of India, 2025 and prepared by QGIS

3. Objective

1. To analyse the spatial distribution of annual rainfall in North-Western Rajasthan during 1991-2024.
2. To assess the spatial change in annual rainfall between 1991 and 2024.
3. To examine the temporal variability of annual rainfall using selected years from 1991-2024.

4. Data And Methodology

This research makes use of CHIRPS v2.0 annual rainfall dataset in GeoTIFF format in the selected years between 1991-2024 to assess the spatial and temporal variability of rainfall in North-Western Rajasthan. The rainfall datasets have been processed using QGIS, while MS Excel is used for statistical tabulation and graphical presentation. The spatial boundaries of the study area have been prepared using spatial boundary datasets taken from the Survey of India. The rainfall datasets have been processed based on the extent of the study area such that the analysis reflects the defined North-Western Rajasthan.

The rainfall raster datasets have been processed and clipped to the spatial boundary of the study area using QGIS. Annual rainfall distribution maps have been prepared for the years 1991 and 2024 to evaluate the spatial distribution and geographical variations of rainfall in the region. For evaluating the spatial changes of rainfall in 1991 and 2024, raster calculation has been done by using the formula, 'Rainfall Change = Rainfall in 2024 - Rainfall in 1991'. The positive values reflect the increment of rainfall and vice versa. The generated raster of rainfall change has been classified to appropriate intervals and mapped.

The temporal variability was performed by using certain years which were 1991, 1996, 2001, 2006, 2011, 2016, 2021, and 2024. The selected years were generally considered at five-year intervals, except for 2024, which was included as the most recent year available for the study. For each of the above years, the mean annual rainfall, maximum rainfall, and standard deviation were calculated from the rainfall data in the raster file of the study area. Mean annual rainfall data were shown in a line graph, whereas maximum rainfall and standard deviation were shown in table form to depict variability among the selected years.

5. Results And Discussion

The results and discussion section explains the spatio-temporal analysis for the Northwest Rajasthan. Sub-sections A and B provide yearly analysis of rainfall distribution for the year 1991 and 2024, respectively.

A. Spatial Distribution of Annual Rainfall in 1991:

The rainfall distribution pattern during 1991 of North-Western Rajasthan shows significant geographical variation in the sense that there is an increasing trend of rainfall in the eastward and south-eastwards of the region under study as compared to the westward and south-westward of the region. The classification of rainfall distribution was done into six classes: ≤ 71 mm, 71-142 mm, 142-213 mm, 213-284 mm, 284-355 mm and >355 mm.

The minimum rainfall category of less than or equal to 71 mm is predominantly found in the far-western part of the study region, specifically within Jaisalmer district. The second class of rainfall having an annual rainfall of 71 to 142 mm is mainly located in the western and south-western regions of the study area, comprising some parts of Jaisalmer and Barmer districts. They are the most arid areas within the study area in the year 1991.

The middle regions of the study area are marked by rainfall of 142 to 213 mm and 213 to 284 mm. The two classes are

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mainly distributed in some parts of Bikaner, Jodhpur, Nagaur and adjacent regions, representing the transitional belt between the dry western regions and the relatively moist eastern regions.

The high rainfall zones of 284–355 mm and greater than 355 mm have been predominantly found near the eastern and south-eastern peripheries of the study region, especially in certain sections of the districts of Churu and Nagaur. The maximum value of annual rainfall of 426.25 mm was recorded in this eastern and south-eastern part that is relatively wetter, while the minimum values of annual rainfall have been found mostly in the western desert area. In general, the rainfall distribution pattern of 1991 is quite spatially varied, with an increase in the value of annual rainfall in west-east and south-east directions in the North-Western Rajasthan region.

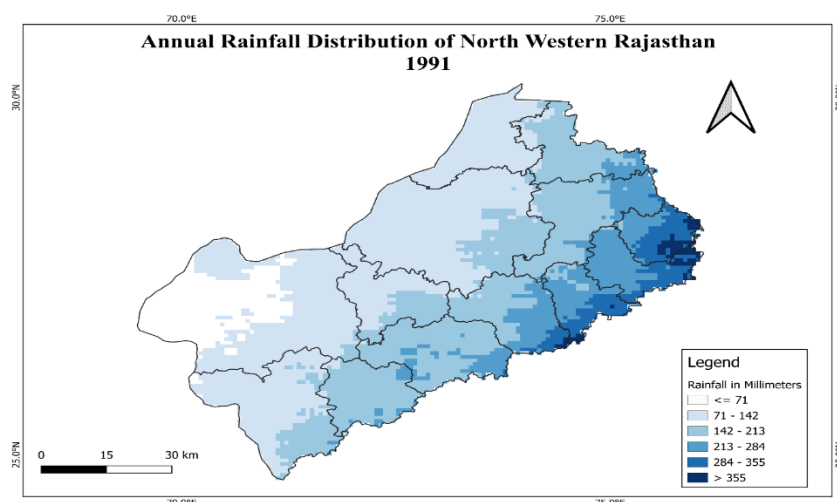


Figure 1.2 Spatial Distribution of Annual Rainfall in North Western Rajasthan 1991.

B. Spatial Distribution of Annual Rainfall in 2024:

North-Western Rajasthan rainfall distribution pattern in 2024 shows significant spatial variation, which is mostly increasing with the increase in the distance from the western and north-western parts to the east and south-eastern parts. Rainfall distribution has been divided into six different categories such as ≤ 185 mm, 185–370 mm, 370–555 mm, 555–740 mm, 740–925 mm and > 925 mm. This spatial distribution of rainfall distribution can be attributed to the prevailing climate of aridity and semi-aridity.

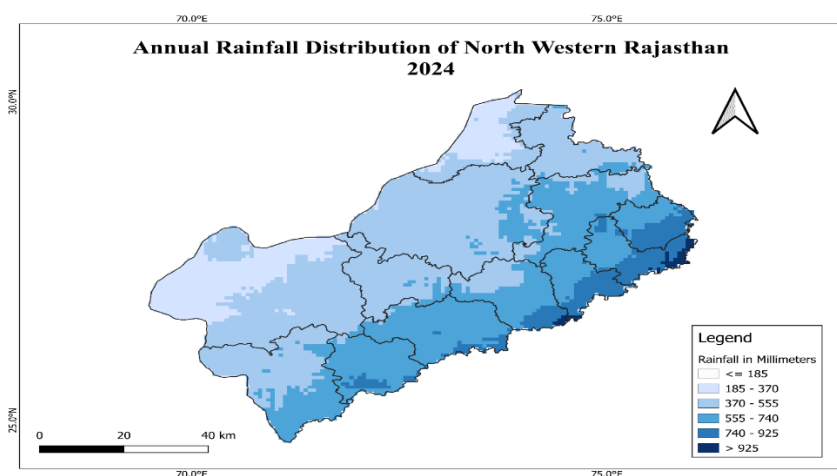


Figure 1.3 Spatial Distribution of Annual Rainfall in North Western Rajasthan 2024.

Source - CHIRPS v2.0 rainfall data (GeoTIFF), processed and mapped by using QGIS.

Lower rainfall distribution categories (≤ 185 mm and 185–370 mm) have been mostly found in the western and north-western parts of the study area like Jaisalmer and Barmer. Some parts of Bikaner district are also experiencing low rainfall. These districts form the relatively dry part of the study area. Rainfall gradually increases moving towards the middle parts of the study area.

The moderate rainfall zones (370 to 555 mm and 555 to 740 mm) are primarily found in the central and eastern areas of the study area. These zones are prevalent in districts like Bikaner, Jodhpur, Nagaur, Churu, Sikar, and Jhunjhunu, but their distribution pattern differs from one district to another. It is a transitional zone that lies between the dry west of the study area and the wetter east and south-east of the study area.

The higher rainfall zones (740–925 mm and > 925 mm) are primarily located towards the eastern and south-eastern regions of the study area, especially within the eastern regions of Sikar, Jhunjhunu, and neighbouring districts falling within the study area. The maximum value of annual rainfall is 1,110.12 mm, which lies in this zone of higher rainfall. In general, the distribution

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of rainfall for the year 2024 shows an obvious increase in rainfall from west to east and south-east direction. The western regions receive relatively less rainfall while the eastern and south-eastern regions receive relatively more rainfall.

C. Spatial change of Annual Rainfall in North Western Rajasthan between 1991 and 2024:

Rainfall changes across North-Western Rajasthan for the years 1991-2024 was determined through comparison of annual rainfall map for the years 1991 and 2024. The formula for determining rainfall change was as follows:

$$\text{Annual Rainfall change (mm)} = \text{Annual Rainfall in 2024} - \text{Annual Rainfall in 1991}$$

Positive values depict an increase in rainfall while negative values denote a decrease in rainfall. The resultant difference map was classified into Six rainfall-change classes for analysis purposes.

The lower rainfall changes classes, namely ≤ 125 mm and 125-250mm are found predominantly in the extreme northern part of the study area, especially in Sri Ganganagar, some regions of Hanumangarh. The western and north-western parts, comprising major areas in Bikaner and western Jaisalmer, are predominantly represented by the 250-375 mm rainfall change classes, which suggest an increase in rainfall to a moderate level. On the other hand, the central part of the study area, especially parts of Churu, Nagaur, and Jodhpur, shows the transition from the 250-375 mm rainfall change classes to 375-500mm. This indicates a relatively large increase in annual rainfall. The southern and south-eastern parts, especially parts of Sikar, Jhunjhunu, and southern Nagaur, exhibit higher rainfall change classes, namely 375-500mm and 500-625mm and above.

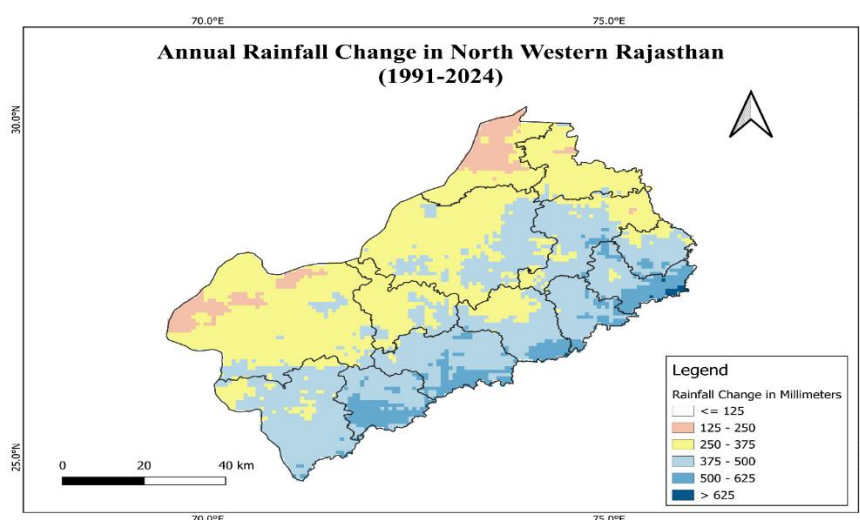


Figure1.4 Spatial Changes of Annual rainfall in North Western Rajasthan Between 1991 and 2024

Source - CHIRPS v2.0 rainfall data (GeoTIFF), processed and mapped by using QGIS.

The regions that experience the greatest changes in rainfall (>625 mm) are the eastern, southeastern and southern sectors of the study area, especially parts of Sikar, Jhunjhunu, Nagaur and Jodhpur. In general, the distribution pattern suggests that the changes in rainfall occur in a general pattern of northwest to southeast, where there are relatively lesser changes in rainfall in the arid western districts, like Bikaner and Jaisalmer, with gradually increasing changes in rainfall as we move from west towards east and southeast in the study area. Further evidence for this trend can be provided by the comparison of the annual rainfall maps, as it is evident from the results that the maximum annual rainfall increased from 426.25 mm in 1991 to 1,110.12 mm in 2024, a total increase of 683.87 mm. This way, from the analysis of rainfall changes, it can be seen that the change in annual rainfall is mainly positive throughout the period 1991 to 2024 in the region of North-Western Rajasthan.

D. Mean Annual Rainfall Pattern of Selected years between 1991-2024

Years	Mean Annual Rainfall (mm)	Maximum Annual Rainfall(mm)	Standard Deviation
1991	72.52	426.25	90.81
1996	177.19	1001.49	216.2
2001	143.92	740.5	170.76
2006	149.8	895.5	191.71
2011	199.68	771.67	228.96
2016	182.3	872.03	211.99
2021	163.44	939.5	199.55
2024	250.388	1110.12	282.4

Table1-: Mean Annual Rainfall, Maximum Rainfall and Standard Deviation in North-Western Rajasthan for Selected Years, 1991–2024.

The annual mean rainfall demonstrates high variability on an annual basis in North-Western Rajasthan over the chosen years from 1991 to 2024, with the overall positive trend. In particular, mean annual rainfall rose from 72.52 mm in 1991 up to 177.19 mm in 1996; then fell to 143.92 mm in 2001. Subsequently, it increased to 149.80 mm in 2006 and 199.68 mm in 2011. It then declined in 2016 (182.30 mm) and 2021 (163.44 mm); and then rose considerably to 250.39 mm in 2024, which is the highest mean annual rainfall in the selected years. Therefore, the temporal trend demonstrates high year-by-year variability, whereas the fitted trend line demonstrates the overall positive tendency of the mean annual rainfall.

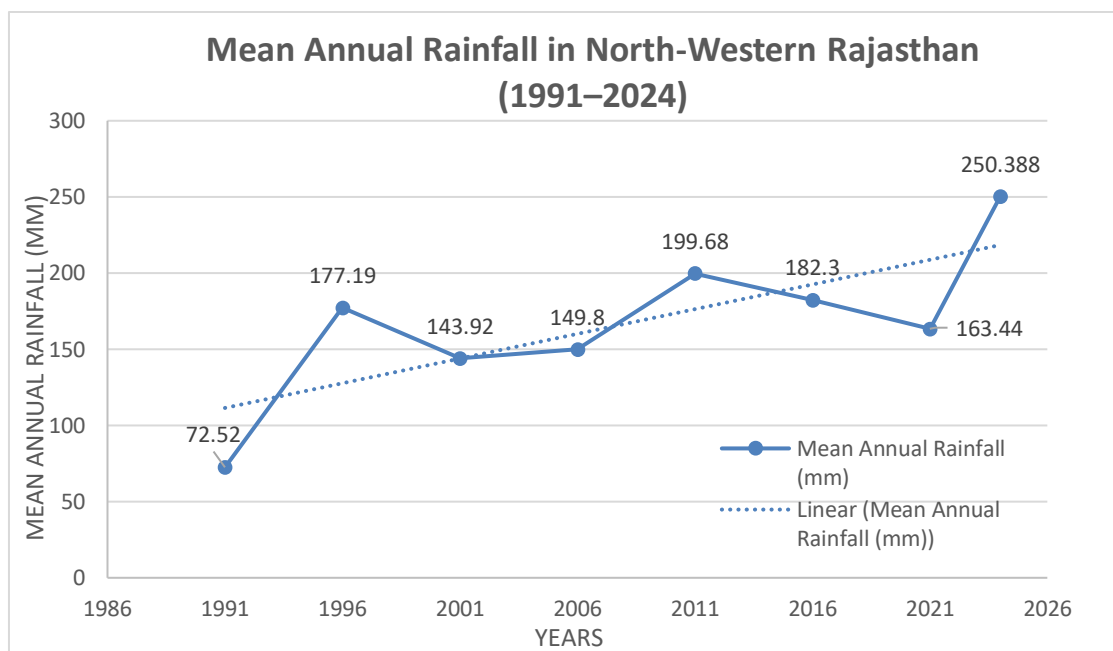


Figure1.5:- Temporal Changes of Mean Annual Rainfall in North Western Rajasthan (selected years).

Source - CHIRPS v2.0 rainfall data (GeoTIFF), processed by using QGIS and made by excel.

Statistical evidences supporting the above observations have been shown in Figure 1.6. From Figure 1.6, it can be seen that the standard deviation of rainfall was minimum in 1991 (90.81 mm) and maximum in 2024 (282.40 mm). This means that there is increase in the spatial variability of rainfall. Moreover, the maximum rainfall, as indicated in Table 1, has increased from 426.25 mm in 1991 to 1,110.12 mm in 2024. The statistical variations are thus confirmed by the spatial variations of the rainfall distributions.

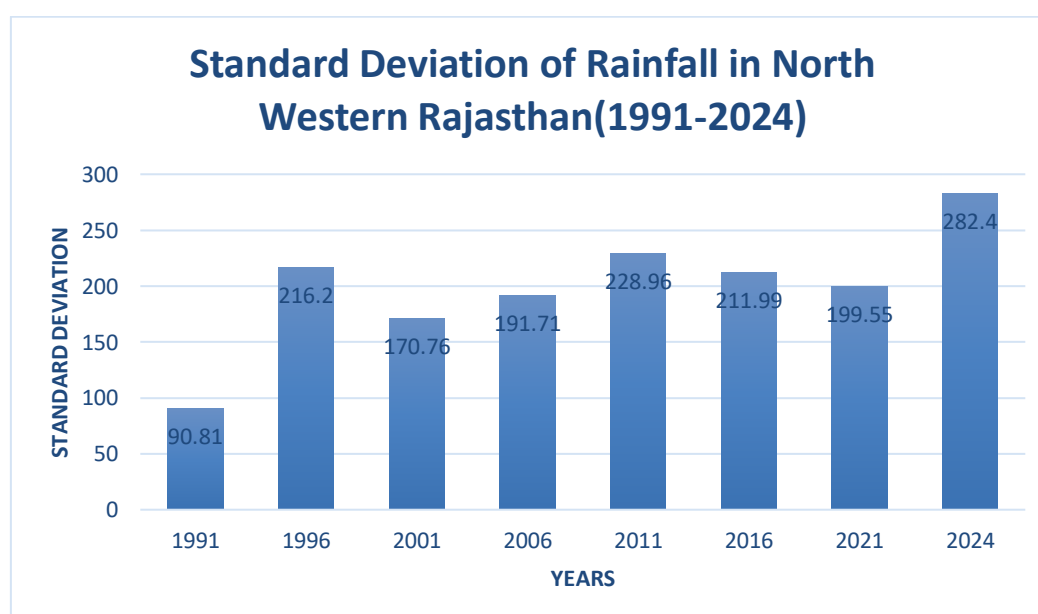


Figure1.6:- Standard Deviation of Annual Rainfall in North Western Region

Source - CHIRPS v2.0 rainfall data (GeoTIFF), processed by using QGIS and made by excel.

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It is worth mentioning that there is a significant variability in annual rainfall on North-Western Rajasthan from 1991 to 2024 years in space and time. There is a clear gradient in terms of the geographical location, which is characterized by less annual rainfall in the west and north-west and gradually increasing values in the east and south-east. Annual mean rainfall ranged from 72.52 mm in 1991 to 250.39 mm in 2024 despite noticeable yearly deviations.

Supporting statistics confirm a spatial variability in terms of rainfall. Namely, the maximum annual rainfall value ranged from 426.25 mm in 1991 to 1,110.12 mm in 2024; at the same time, standard deviation in terms of rainfall ranged from 90.81 mm in 1991 to 282.40 mm in 2024, suggesting a greater spatial variability of rainfall in 2024. The rainfall-change analysis demonstrates the increase exceeding 599 mm in the eastern and southeastern regions. It is possible to conclude that rainfall changes did not occur evenly in North-Western Rajasthan. However, the differences in the two years should be considered rainfall changes and not the trend, as there is no statistical confirmation of the significance of the trend.

There are several consequences of the variability in the amount of rainfall that have implications for regional planning and water resource management. The western and northwestern regions that are relatively drier need to pay more attention to the development of drought-resistant agriculture, irrigation systems, rainwater harvesting, and replenishment of groundwater resources. On the other hand, the eastern and southeastern regions can benefit from rainwater storage and drainage systems. Future research on rainfall variability should include seasonally adjusted rainfall data, indices for extreme rainfall and drought, groundwater conditions, and climate projections to give an overall assessment of rain pattern and its effect on water resources and agricultural planning.

E. Limitations

There are some limitations of the current study which must be considered in the interpretation of findings. Firstly, the temporal analysis is done for selected years (1991, 1996, 2001, 2006, 2011, 2016, 2021, and 2024) instead of annual continuous record for the entire period from 1991 to 2024. Hence, the overall rising trend in mean annual rainfall during the selected years cannot be considered as a statistically significant trend. Secondly, the spatial change analysis is conducted by considering a comparative analysis between 1991 and 2024 years; hence, the result will depict the change between these two specific years instead of a continuous trend in time. Thirdly, CHIRPS v2.0 gridded rainfall data is used for analysis, and there may be variations between gridded rainfall estimate and rain-gauge observation. Lastly, the study has focused on annual rainfall only, without considering seasonal variability, extreme precipitation event, and drought index. Further studies including continuous annual records, trend analysis tests, station-wise validation, and seasonal as well as extreme rainfall parameters may help to give a better idea about rainfall variability in North Western Rajasthan.

6. Conclusion

The study reveals significant spatial and temporal variations of annual rainfall in North-Western Rajasthan from 1991 to 2024. There appears to be a clear west-east rainfall gradient, which is characterized by lower rainfall levels in western and north-western areas, whereas the eastern and south-eastern areas experience relatively higher rainfall. There is an increasing trend of mean annual rainfall, which went from 72.52 mm in 1991 to 250.39 mm in 2024, and the maximum rainfall value that rose from 426.25 mm to 1,110.12 mm. It should be noted that standard deviation increased from 90.81 mm to 282.40 mm indicating spatial variability in rainfall in 2024. In the context of rainfall change analysis, there were more than 599 mm increases in the eastern and south-eastern parts. Overall, the obtained data reveals significant spatial heterogeneity and inter-annual variations in the rainfall of North-Western Rajasthan. The above findings indicate the necessity of location-based approaches in the management of agriculture and water resources, especially drought-proofing and water efficiency in the relatively drier west regions.

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Currently, I am a Assistant Professor in the Department of Geography, Punjabi University Patiala. I am done my Ph.D. on intensification of agricultural activities on groundwater resources. Along with that I teach Geomorphology, Climatology, Human Impact on Environment. I am supervising candidates on their respective topics of urbanization, urban sprawl, land use land cover, and groundwater potential zone identification.