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Spatial and Temporal Variation in Precipitation Across Ganga River Basin: Analysis Using Multiple Software's

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Abstract
Climate change is reshaping hydrological systems worldwide, with river basins among the most vulnerable to its effects. The Ganga River Basin (GRB), one of the world's largest and most densely populated basins, is particularly sensitive to these changes. As a critical freshwater source for agriculture, domestic use, and ecological sustenance, the GRB plays a central role in India's environmental and socio-economic stability. Long-term precipitation trends in the GRB show vast spatial and temporal changes. While some regions, particularly in the lower basin, show increasing rainfall, others demonstrate declining trends or greater interannual fluctuations. This study utilizes high-resolution climate data from the Climatologies at High Resolution for the Earth's Land Surface Areas (CHELSA) version 2.1 dataset, covering the period 1979 to 2018. CHELSA provides free access to high-resolution climate data for research and application. Change in precipitation is visible after year 2000 in GRB with maximum change is visible in monsoon season in GRB where it decline in western part of the basin on the other hand there is increase in eastern part of the basin in same period, while there is slight increase in pre-monsoon precipitation in most part of the GRB. The yearly mean is not that change but there is change in seasonal mean with increasing variability during recent years. With the enhancement in the software technologies it is now become a good tool to study this type of climate change in depth and can contribute great knowing the fact how it will going to shape or impact our future generation. Artificial intelligence can do the process of analysing and predicting the extreme events due to climate change with the help of weather forecasting model very well in future as of the AI is still developing.

Keywords: GRB, climate change, tools, artificial intelligence

Introduction

Climate change is reshaping hydrological systems worldwide, with river basins among the most vulnerable to its effects. The Ganga River Basin (GRB), one of the world's largest and most densely populated basins, is particularly sensitive to these changes. As a critical freshwater source for agriculture, domestic use, and ecological sustenance, the GRB plays a central role in India's environmental and socio-economic stability. Recent decades have witnessed growing concern over the basin's climatic shifts, particularly in relation to precipitation shifts, extreme weather events, and long-term water security. The GRB's unique topographical diversity and influence on regional climate dynamics have long attracted researchers aiming to understand its hydrometeorological behaviour and anticipate future shifts under climate change.

The Ganga River Basin stretches from the glacier-fed Himalayan foothills to the flat Indo-Gangetic plains, creating distinct climatic zones. Steep, snow-fed terrains in the upper basin contrast with fertile, densely populated floodplains below. Such geographical diversity leads to varied climate behaviours and makes precipitation patterns harder to predict across the basin.

Freshwater resources are under great threat due to the increasing demands of a rising population and the adverse effects of human intervention. Rising temperatures, glacial retreat, and erratic monsoon behaviours severely affect streamflow variability, groundwater sustainability, and ecosystem health. All these alterations in climate only increase the frequency and intensity of natural disasters like floods, droughts, landslides, and heat waves, disrupting both natural and human life cycles (U. K. Singh & Kumar, 2018). With over 600 million people residing in the GRB, the consequences of climate change are profound (Khandu et al., 2017). The majority of the population depends on rain-fed agriculture, making them highly vulnerable to precipitation variations. Differences in rainfall timing and intensity affect crop cycles, food security, and rural livelihoods. Urban populations, too, are increasingly burdened by water shortages, strained infrastructure, and heightened risks to public health (Misra, 2011). Therefore, the socio-economic vitality of the basin is intricately dependent on the stability of its climate systems (Hasan et al., 2022).

Long-term precipitation trends in the GRB show vast spatial and temporal changes. While some regions, particularly in the lower basin, show increasing rainfall, others demonstrate declining trends or greater interannual fluctuations. Seasonal shifts, such as delayed monsoon onset or shortened rainy periods, have also been observed. These changes make it challenging for water management and agricultural planning across the whole basin (Yaduvanshi & Ranade, 2015). Climate change is a key driver of these precipitation shifts. Studies indicate that rising temperatures and changing atmospheric circulation are influencing monsoonal variations, leading to more extreme rainfall events (Sharma et al., 2021). These differences in patterns underline the need for localized climate readings.

Studying climate change in the GRB is important for science and policy-making. The basin's complex water systems, ecological importance, and socio-economic dependence make it a key area for climate research. Understanding how climate factors interact with physical features, land use, and human activities can help improve water management, reduce disaster risks, and develop sustainable strategies. This research contributes to a more resilient future for one of the world's most climate-sensitive river basins. With the enhancement in the software technologies it is now become a good tool to study these type of climate change in depth and can contribute great knowing the fact how it will going to shape or impact our future generation.

Study Area

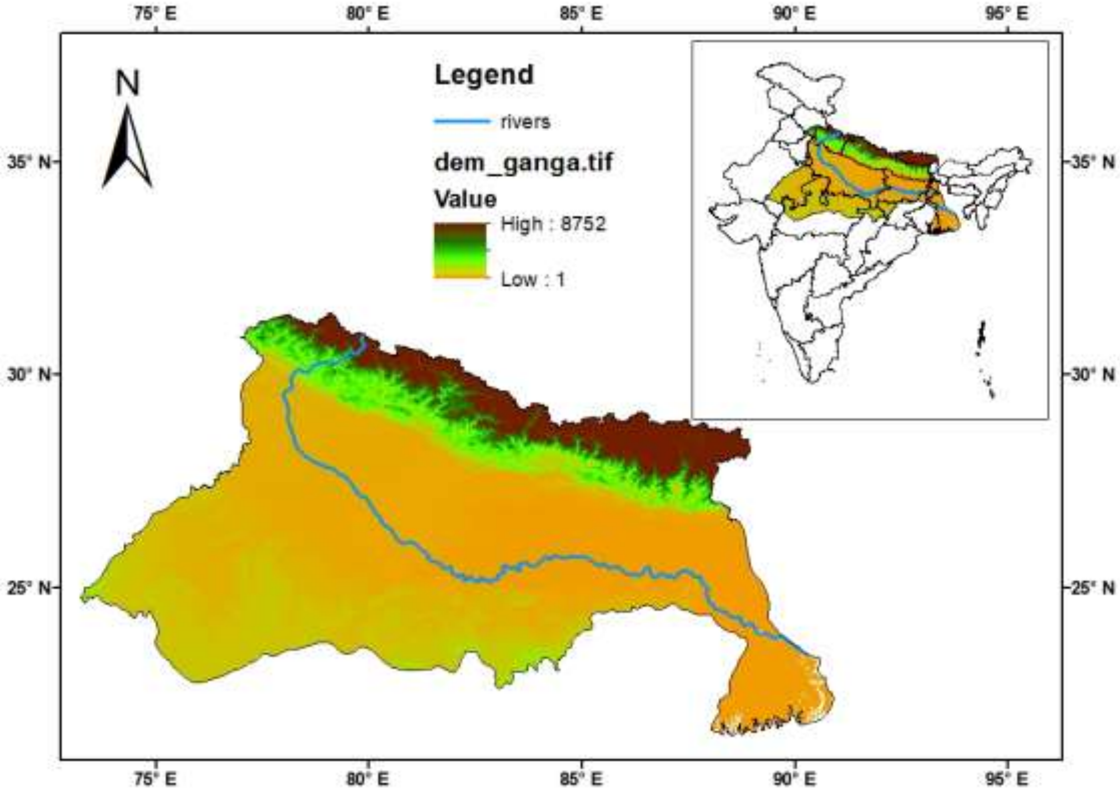

Fig. 1 The map depicts the study area, which is the Ganga River Basin, along with its digital elevation model (DEM). The Ganga River is marked in blue, illustrating its course across different terrain, ranging from mountainous regions to low-lying plains.

This study looks at the Ganga River Basin (GRB), a major river system that crosses India, Nepal, and Bangladesh. The basin covers a total area of around 1,086,000 km², of which 861,452 km² lies within India. The basin stretches across a wide range of landscapes, from glacier-fed mountains in the north to fertile, flat plains in the centre and low-lying deltas in the south.

Within this unique terrain, the research emphasizes a comparison between the plains of the Indo-Gangetic belt and the hills of the Himalayan foothills to examine variations in precipitation and climate patterns. Different elevations, land cover, and water processes in these regions affect how they experience climate change.

The Indo-Gangetic belt, which includes low-lying, fertile floodplains and intensive agriculture, often experiences prolonged monsoon rains, flooding, and seasonal waterlogging(Ojha et al., 2020; Rattan et al., 2021). These locations are highly responsive to even minor shifts in monsoon intensity and timing due to their flat topography and dense population(Pant et al., 2023). On the other hand, the Himalayan foothills, with their steep hills, dense forests, and snow-fed river systems, are more prone to short-duration, extreme rainfall events, which can trigger flash floods, landslides, and glacial lake outbursts (Sabin et al., 2020). Elevation plays a key role in balancing temperature and precipitation patterns, determining rainfall distribution, and seasonal snow runoff.

The Ganga River, another important element of the GRB, flows over 2,525 km from the Gangotri Glacier to the Bay of Bengal, linking the Himalayan foothills with the Indo-Gangetic plains. It serves as a critical

component of the basin's water system, driven by changes in rainfall and terrain along its course. As climate change shifts precipitation patterns, it's becoming increasingly important to study how the river behaves across different regions (Jain & Singh, 2020).
Differences in terrain across the basin shape unique patterns of water flow, land use, and climate vulnerability. Analysing these contrasting landscapes reveals how climate change doesn't affect all parts of the basin equally, allowing room for improvements in decision-making for climate responses that match local conditions.

Data and Methodology
This study utilizes high-resolution climate data from the Climatologies at High Resolution for the Earth's Land Surface Areas (CHELSA) version 2.1 dataset, covering the period 1979 to 2018. CHELSA provides free access to high-resolution climate data for research and application. This includes monthly precipitation estimates at a high resolution of ~1 km (30 arc-seconds), generated through orographic modelling and machine learning-based downscaling of the global atmospheric reanalysis (ERA5). The dataset is well-suited for a statistical downscaling approach, incorporating factors like wind fields, exposure, and boundary layer height to improve precipitation estimates, especially where elevation variability influences rainfall distribution(Schneider et al., 2013).
First and foremost, all values were arranged in a monthly, seasonal, and yearly order. After this, the values were extracted into images, using GIS software, with GRB as its study area. Since the extracted values contained values in large units, it was then converted into millimeters. These were next arranged by season, month, and year. Following these are the mean precipitation calculations for the spatial and temporal study of the precipitation trends in the Ganga River Basin.

1. Spatial
Climate means were computed for 1979–1999 (earlier), 2000–2018 (later), and 1979–2018 (40-year average). Seasonal shifts were evaluated using later-minus-earlier anomaly maps to capture changes in rainfall intensity and spatial coverage. The year 2000 is widely used as a reference in 1980–2020 change assessments (Saini et al., 2023; M. Yadav et al., 2024).Seasons for the Ganga River Basin (GRB) were defined as: Winter (Dec–Feb), pre-monsoon (Mar–May), monsoon (Jun–Sep), and post -monsoon (Oct–Nov).All computations, spatial analyses, figures, and visualizations were performed in GIS and using R ,Python packages. The GRB boundary was delineated using publicly available shapefiles to ensure consistent spatial extent.The GRB shows a reordering of seasonal precipitation: monsoon rainfall is dominant, winter precipitation exhibits moderate gains, and post-monsoon rainfall remains scattered and minimal, indicating evolving hydroclimatic behavior with early-season rainfall increasingly influencing basin hydrology (A. Singh & Jain, 2022)
2. Temporal
To examine long-term precipitation characteristics of the Ganga River Basin (GRB), we used the GIS Cell Calculator to compute temporal mean precipitation for 1980–2019 at monthly, seasonal (Winter: Dec–Feb; pre-monsoon: Mar–May; monsoon: Jun–Sep; post-monsoon: Oct–Nov), and annual scales, generating monthly mean rasters (January–December), seasonal mean rasters , and annual mean rasters; zonal statistics were then applied to these rasters across hydrological zones to derive summary tables (mean, sum, standard deviation), with means organized by month, season, and year, providing a clear

framework to assess spatial–temporal rainfall patterns for water resource planning in the GRB (Surinaidu et al., 2020).

Results

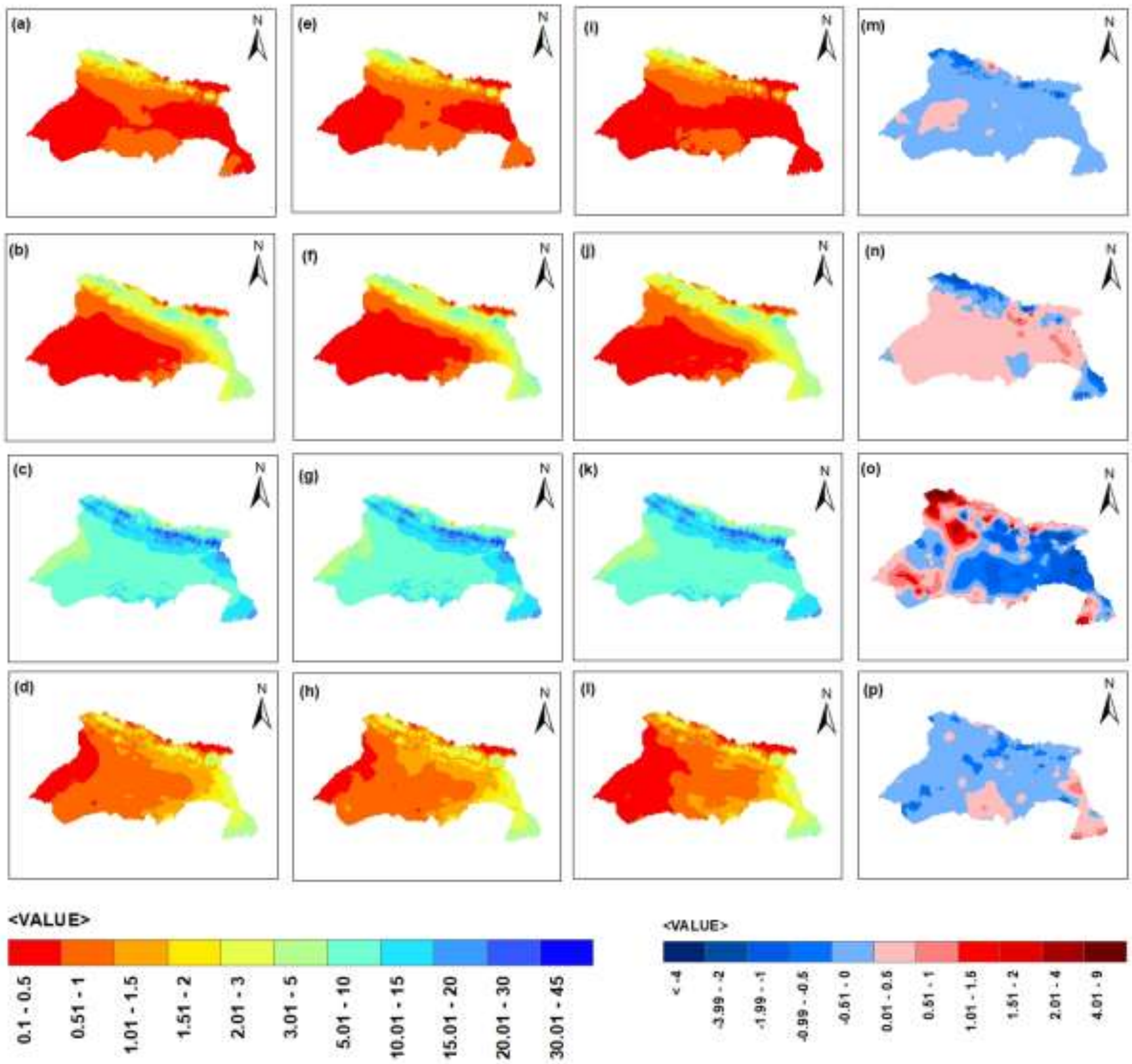

Fig 2 Mean calculation of precipitation trends(mm/d) of GRB using CHELSA observation. The first panel shows the precipitation mean during (a) winter, (b) monsoon, (c) monsoon, and (d) post-monsoon seasons from 1979 to 1999. In the second panel (e-h), the figures are the same as those in (a-d), but for the period from 2000 to 2018. The third panel (i-l) is the same as (a-d), but from 1979 to 2018, displaying the mean for all 40 years. The last panel involves the calculation of the means of later minus earlier periods, where (m-p) has the same seasonal order as (a-d).

The research studies the rainfall patterns within the GRB from 1979 to 2018, based on the study area map presented. Every unique landscape of the GRB has varying elevation, which significantly influences rainfall spread around its region. Given below are the results of the spatial mean precipitation trends displaying seasonal comparisons, along with the anomaly maps of each season in different periods, and temporal mean precipitation trends, with monthly, yearly, and seasonal comparisons to understand how area and time affect rainfall and how these factors play a role in GRB's climate behaviour.

1. Spatial

(1) Seasonal Mean Precipitation (1979–1999 vs. 2000–2018)

In the earlier period (1979–1999), winter precipitation is minimal across most of the basin, especially in the low-elevation southern plains, where larger areas are depicted in red (0.1-0.5) (Fig 2(a)). The later period (2000–2018) shows a slight intensification in the central areas, along with increasing changes in the elevated zones (2.01 to 10) (Fig 2(e)). These changes indicate more frequent western disturbances impacting higher terrains, especially along the Himalayan margins, suggesting a growing role of winter rainfall in elevated zones (Fig 2 (i)) (Madhura et al., 2015; M. Yadav et al., 2024).

Pre-monsoon rainfall remains spatially sparse across both time periods. Mostly covered by red and orange tones (<1), precipitation is largely confined to the elevated zones, with no significant expansion or intensification observed in the later years. This season continues to offer minimal contribution to the total annual mean rainfall (Fig 2(b),(f),(e)).

The monsoon season, being the most intense and spatially widespread in both periods, displays extreme rainfall throughout the basin. In 1979–1999, substantial precipitation is evident across the Himalayan foothills and central basin (shaded in blue, >5.01) as in Fig 2(c). In the later period (2000–2018), these high precipitation zones extend farther in the south and east, covering broader areas with deepening blue shades. This suggests an immense rise in hydrological activities and evolving water system dynamics, presenting pre-monsoon rainfall as the largest annual rainfall contributor to the GRB (Fig 2(g),(k)(Swarnkar et al., 2021).

Post - monsoon rainfall, in the earlier period, exhibits higher values (green to light blue, 2.01-5), mainly in southeastern basin regions. However, by 2000–2018, the map reflects a slight drop in the rainfall patterns in the region, with fewer regions having high precipitation values. An increase in the shift toward yellow-green tones suggests that this season has lesser spatial consistency, possibly due to altered circulation patterns or land-use changes.

(2) Long-Term Mean Seasonal Precipitation Patterns (1979–2018)

The spatial distribution of 40-year mean precipitation across the Ganga River Basin reveals a strong link between elevation and rainfall intensity. Elevated northern areas along the Himalayan foothills and highlands display deep blue shades (30.1-45), especially in the monsoon season. The hilly regions also receive the most rainfall during other seasons. This suggests that the region's topography greatly shapes its rainfall patterns, with higher terrains lifting moist air, causing it to condense and fall as rain (Duckstein et al., 1973), particularly during the stormy monsoon and post - monsoon periods.

In contrast, southern plains and central low-elevation terrains show a clear transition through green, yellow, and orange tones, with rainfall intensities ranging from 3.01 to 10, and in some areas falling as low as 0.5 to 2, specifically in the western GRB. These values indicate a weaker moisture content and reduced precipitation activities.

Notably, moderately high precipitation zones (10.01–20) appear in the eastern GRB, where proximity to the Bay of Bengal likely supports higher storm activity (Chanda et al., 2018). The gradients changing from blue in the north to red-orange in the south show how terrain and atmospheric differences can substantially affect precipitation in those areas. Factors like altitude, storm paths, and wind patterns interact to produce such long-term precipitation figures, which are key to understanding the seasonal changes and anomalies analysed in later sections.

(3) Net Change in Mean Seasonal Precipitation (2000–2018 minus 1979–1999)

The later minus earlier anomaly maps are crucial because they help quantify and visualize how precipitation patterns have changed over time, not just what the current distribution looks like. While mean precipitation maps show where and how much it rains on average, anomaly maps capture the direction and magnitude of change, informing about the evolving climate variations across GRB.

Seasonal Precipitation Change Across the Ganga River Basin (1980–2019)

1. Winter precipitation change

The pocket in Himalayan foothills exhibit increased rainfall (0.51–2 mm/day), likely due to enhanced western disturbances and orographic uplift. Meanwhile, the northeastern and eastern regions show decreasing trends (0 to –1.99 mm/day), likely from dry, cold air masses. The central basin reveals a mixed pattern of minor gains and losses, reflecting variable influences of topography and weather systems. Western and southern zones exhibit widespread decline (–0.5 to –2 mm/day) (Fig 2.(m)), suggesting reduced influence of winter storm systems. Overall, the basin shows a mean decline in winter precipitation (Parajuli et al., 2021).

2. Pre-monsoon Precipitation change

Pre-monsoon rainfall increases are noted in the eastern and northeastern GRB, with red gradients indicating gains up to +4 mm/day (Fig 2.(n)), The central corridor shows patchy variability, with both minor gains and declines. Western and southern regions experience weaker anomalies, with light pink and blue shades, pointing to neutral or slight increases. Despite regional differences, the overall trend shows a basin-wide rise in pre-monsoon precipitation, particularly in the east (V. Kumar & Jain, 2011; P. Singh et al., 2008; Mal et al., 2022).

3. Monsoon precipitation change

The Himalayan foothills and southeast basin show strong increases (+1.01 to >4 mm/day), likely driven by enhanced storm activity and Bay of Bengal influence (Bharti et al., 2016). The central and western GRB display mixed trends, with scattered increases and declines due to shifting monsoonal and geographic factors(Fig 2.(o)),. The southern plains mostly exhibit declines (0 to –1.99 mm/day). This season presents the most inconsistent patterns, marked by clear north-south contrasts (C. Kumar et al., 2021).

4. Post-monsoon precipitation change

The northern and southeastern regions show minor gains, while the central and western GRB experience significant declines (up to –3 mm/day). Flat terrain, weakening monsoonal winds, and rising temperatures contribute to reduced rainfall consistency(Fig 2.(p)),. The post-monsoon season overall reflects a declining trend, with negative anomalies especially in southwestern and central regions (Bera, 2017).

2.Temporal Mean

Monthly mean

The bar graph illustrates monthly precipitation trends across the Ganga River Basin over a 40-year period, displaying a distinct seasonal hydrological pattern.

January through May remain comparatively dry, with slight fluctuations in mean precipitation values (approx. 0.5–2 mm), indicating low hydrological activity and dry continental conditions. A visible shift occurs in June, where precipitation rises (approx. 6 mm), marking the onset of intensified moisture and the transition into the pre-monsoon phase.

Precipitation peaks during July (approx. 12 mm) and August (approx. 11.5 mm), driven by the large-scale moisture transport from the Bay of Bengal and a few other sources. September (approx. 7 mm) sustains considerable rainfall before giving way to a prominent decline. While October (approx. 2 mm) still holds residual monsoonal influence, November and December face a notable decline (< 0.5 mm), falling to dry-season levels, similar to January values.

Overall, this graph affirms the dominance of the monsoon window (June–September) in shaping the basin's hydrological cycle, with rainfall increasing between May and July and significantly decreasing in the post-monsoon season (October-November). These patterns prove the critical importance of monsoon timing and stability for the basin locally (KOTHYARI et al., 1997; Rai et al., 2021).

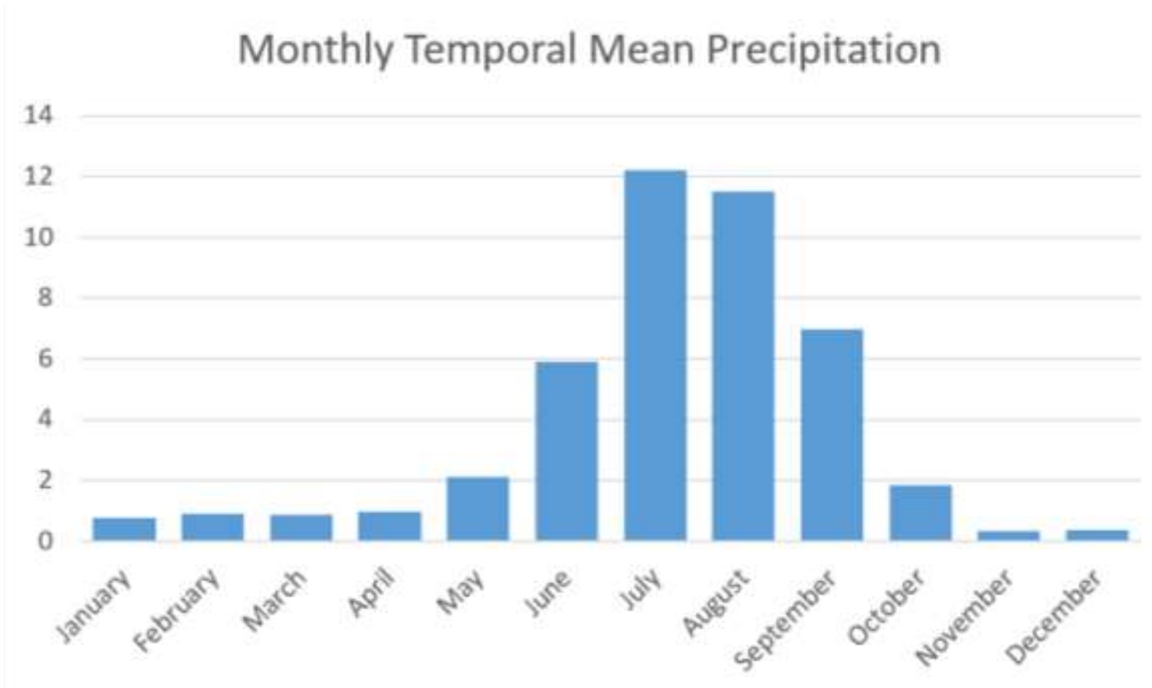

Fig 3 Monthly Temporal Mean Precipitation (1979-2018): Bar graph showing distinct precipitation shifts in months across the GRB. Each month's values represented are the mean of each month in all 40 years.

Seasonal and Yearly mean

The combined graph illustrates the precipitation across yearly and seasonal scales, offering a comparative view of long-term hydroclimatic patterns in the Ganga River Basin. The yearly mean precipitation shows a relatively narrow range (approx. 3 mm to 4.5 mm), with gentle fluctuations and no definitive upward or downward trend. This stability suggests that while short-term variations occur, the basin's overall annual rainfall remains resilient over time with minimal yearly mean increase (Fig 4.).

In contrast, the differing magnitudes and seasonal variability are clear in the graph and present the seasonal trends in the GRB. Winter and pre-monsoon precipitation remain consistently low (rarely exceeding 2 mm), highlighting their minor role in shaping overall precipitation totals. The monsoon season (June–September) dominates the graph with substantially higher values (approx. 6.7 mm to 11 mm), validating its status as the basin's primary rainfall contributor. The post-monsoon phase (October–November), plotted alongside (approx. < 3 mm), shows only occasional peaks in years like 1985, 1986, and 2014 (Fig 4.).

Together, the graph underscores the strong seasonal asymmetry in GRB precipitation, with most rainfall occurring during the monsoon period, while the other seasons fluctuate within low to moderate mean rainfall. This visualization not only supports zonal statistics findings but also emphasizes the importance of focusing on climate resilience and hydrological planning on the dominant monsoon patterns as well as submissive precipitation patterns during other seasons (Singha et al., 2024).

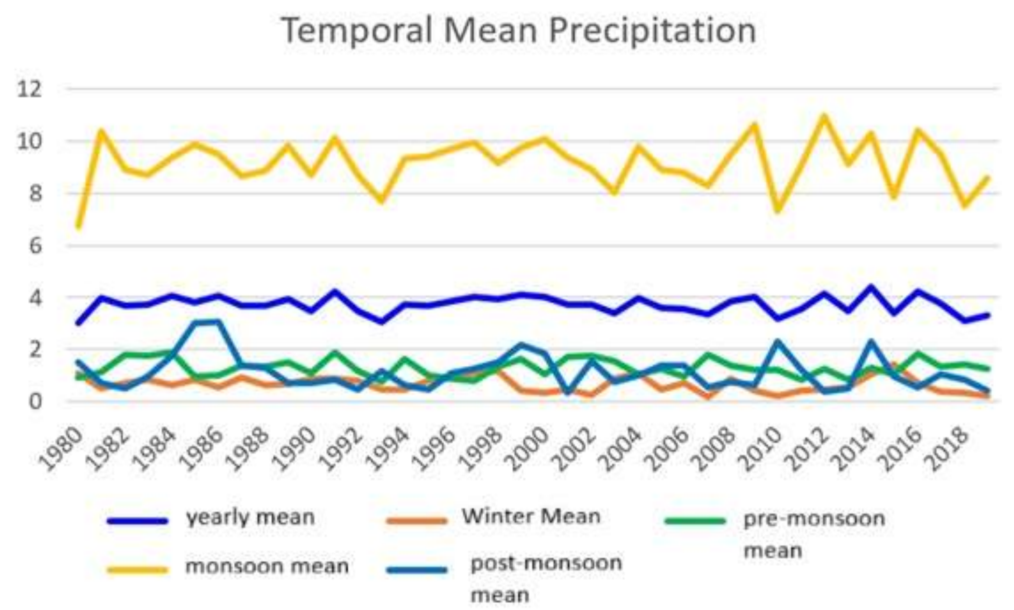

Fig 4 Seasonal Precipitation Trends and Annual Precipitation Variability (1979–2018): Line graph depicting seasonal variability each year, and year-to-year fluctuations in total rainfall, revealing long-term trends and anomalies across the Ganga River Basin.

Conclusions

Change in precipitation is visible after year 2000 in GRB with maximum change is visible in monsoon season in GRB where it decline in western part of the basin on the other hand there is increase in eastern part of the basin in same period, while there is slight increase in pre-monsoon precipitation in most part of the GRB. The yearly mean is not that change but there is change in seasonal mean with increasing variability during recent years. In this study different software is used for analysis as the development is very good for research but with the passing time the AI (artificial Intelligence) collaboration in the tools helpful in studying climate change will of great help. This will help in reducing processing time, improving results, making images more interactive and helping the science. With the enhancement in the software technologies it is now become a good tool to study this type of climate change in depth and can contribute great knowing the fact how it will going to shape or impact our future generation. Artificial intelligence can do the process of analysing and predicting the extreme events due to climate change with the help of weather forecasting model very well in future as of the AI is still developing.

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