



Climate-Driven Spatio-Temporal Variability of Hydrological Processes in North Maharashtra: A Geospatial Approach

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Abstract:

Understanding climate-driven variability in hydrological processes is essential for sustainable water resource management in semi-arid regions. The present study examines the spatio-temporal variability of hydrological processes in North Maharashtra, India, using an integrated geospatial approach. Digital Elevation Model (DEM)-derived hydrological parameters, including flow direction and flow accumulation, were generated to characterize watershed morphology and drainage behavior. To capture climatic influences, 20 years annual average rainfall data were analyzed to assess long-term variability and its hydrological implications.

Spatial analysis reveals pronounced heterogeneity in topography-controlled runoff pathways, with higher flow accumulation zones concentrated along major river valleys and low-lying basins, while upland and plateau regions exhibit divergent drainage patterns. Temporal assessment of rainfall indicates significant inter-decadal variability, reflecting changing monsoon dynamics across the region. The integration of rainfall trends with DEM-based hydrological modeling highlights climate-induced shifts in runoff potential, drainage density, and watershed response characteristics.

The results demonstrate that climate variability, coupled with terrain attributes, plays a critical role in shaping hydrological processes in North Maharashtra. Areas experiencing increasing rainfall variability show heightened susceptibility to surface runoff concentration and hydrological extremes, whereas regions with declining or erratic rainfall display reduced flow continuity. This study underscores the effectiveness of geospatial techniques in capturing climate-hydrology interactions and provides valuable insights for watershed planning, flood risk assessment, and climate-resilient water management strategies in semi-arid regions.

Keywords: Climate variability; Hydrological processes; Spatio-temporal analysis; GIS; DEM; Rainfall variability; North Maharashtra

Introduction:

Climate variability has emerged as a critical factor influencing hydrological processes, particularly in monsoon-dominated and semi-arid regions of India. Changes in rainfall magnitude, intensity, and temporal distribution significantly alter runoff generation, drainage behavior, and water availability. North Maharashtra, characterized by diverse physiography ranging

from the Western Ghats to the Deccan Plateau, exhibits pronounced spatial contrasts in climate and hydrology. The region experiences strong orographic control on rainfall along the Western Ghats, while extensive rain-shadow zones remain highly vulnerable to water scarcity. Hydrological processes in such heterogeneous landscapes are governed by the combined influence of climate variability and terrain characteristics. Advances in

geospatial technology have enabled detailed assessment of these interactions through spatially explicit analysis. Digital Elevation Models (DEMs) provide critical insights into elevation, slope, and drainage networks that regulate surface runoff. Long-term rainfall datasets facilitate the evaluation of spatio-temporal climatic variability and monsoon dynamics. Despite several watershed-level studies in Maharashtra, comprehensive regional-scale assessments integrating climate and topographic controls remain limited. Understanding climate-driven hydrological variability is essential for sustainable watershed planning and water resource management. Such analyses are particularly relevant in the context of increasing climate extremes and monsoon uncertainty. The present study employs a geospatial approach to examine spatio-temporal variability in hydrological processes across North Maharashtra. By integrating DEM-derived hydrological parameters with long-term rainfall data, this research aims to provide actionable insights for climate-resilient water management in semi-arid regions.

Objectives:

1. To analyze the spatio-temporal variability of rainfall in North Maharashtra using long-term climatic data.
2. To delineate watershed characteristics and drainage networks using DEM-derived

hydrological parameters such as flow direction and flow accumulation.

3. To examine the influence of topography and rainfall variability on hydrological processes including runoff concentration and drainage behavior.
4. To identify hydrologically sensitive zones prone to runoff concentration and potential hydrological extremes for informed watershed management.

Study Area: North Maharashtra Region:

North Maharashtra is located in the north-western part of the state of Maharashtra, India, and broadly comprises Nashik, Dhule, Jalgaon, and Nandurbar districts. Geographically, the region extends between 19°00' N to 22°00' N latitude and 73°30' E to 76°30' E longitude. Physiographically, North Maharashtra exhibits marked diversity, encompassing: The Western Ghats escarpment and high rainfall zones in western Nashik, The Deccan plateau and basaltic uplands, The Tapi and Godavari river basins, characterized by undulating plains and alluvial valleys. Elevation ranges from about 100 m to over 1,600 m above mean sea level, exerting strong control over drainage development and runoff processes. The region is predominantly underlain by Deccan Trap basalt, influencing infiltration capacity and surface runoff behavior.

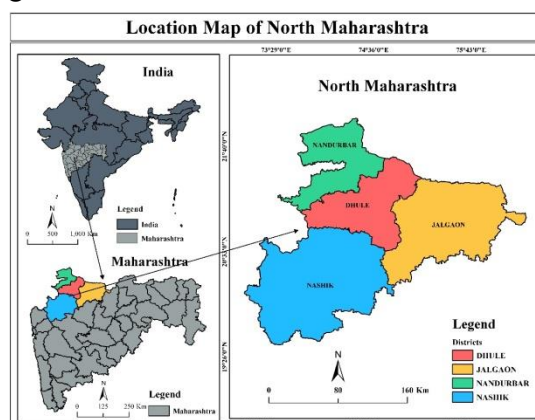


Fig.1.Location Map of Study Area

Climatically, North Maharashtra falls within semi-arid to sub-humid monsoonal regimes, receiving the majority of rainfall during the southwest monsoon (June–September). Annual rainfall varies spatially from less than 600 mm in eastern rain-shadow zones to over 3,000 mm in the Western Ghats, making the region highly sensitive to climatic variability. The region's dependence on rainfed agriculture and surface water resources makes it an ideal setting for investigating climate-driven spatio-temporal variability of hydrological processes.

Database and Methodology:

The present study utilizes multi-source geospatial and climatic datasets to analyze climate-driven hydrological variability in North Maharashtra. A 30 m resolution Digital Elevation Model (DEM) derived from SRTM/ASTER data was used to represent regional topography. Long-

term annual average rainfall data for a 20-year period (2005–2024) were employed to assess climatic variability. Administrative and drainage boundary layers were used to define the study extent and watershed limits. DEM preprocessing involved sink filling to eliminate spurious depressions and ensure hydrological correctness. All datasets were projected and resampled to a common spatial reference system for consistency. Flow direction was computed using the D8 algorithm, which assigns flow based on the steepest descent from each grid cell. Flow accumulation was subsequently derived to identify runoff concentration and drainage pathways. Rainfall variability was quantified through long-term mean computation and coefficient of variation analysis. The integrated geospatial framework enabled effective assessment of spatio-temporal hydrological processes and climate–terrain interactions.

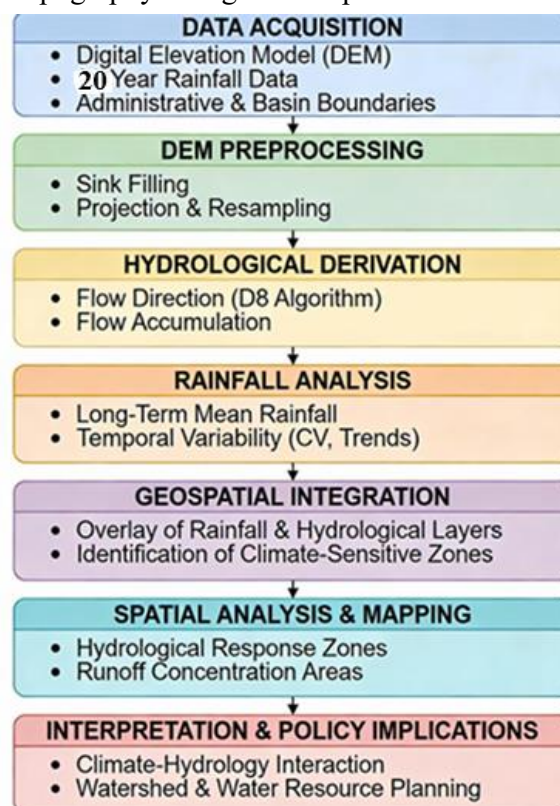


Fig.2. Methodology flow chart

1. Hydrological Derivation by Flow Direction:

Calculated using the D8 algorithm:

$$FD = \arg \max \left(\frac{z_c - z_n}{d_n} \right)$$

where

z_c = elevation of central cell

z_n = elevation of neighboring cell

d_n = distance to neighboring cell

2. Flow Accumulation:

$$FA_i = \sum_{j=1}^n f_j$$

where

FA_i = flow accumulation at cell i

f_j = contributing upstream cells

3. Rainfall Variability Analysis:

- Computation of long-term mean rainfall
- Temporal variability assessment using:

4. Coefficient of Variation (CV):

$$CV = \frac{\sigma}{\mu} \times 100$$

where

σ = standard deviation

μ = mean rainfall

Rainfall variability layers were spatially overlaid with DEM-derived flow accumulation maps to examine climate–hydrology interactions. This integration enabled identification of climate-sensitive hydrological zones exhibiting varying runoff responses. Areas of high rainfall variability coinciding with elevated flow accumulation were delineated as hydrologically vulnerable zones. Subsequently, spatial analysis techniques were applied to classify hydrological response zones across the study area. These zones reflect

differential terrain and climatic influences on hydrological behavior. Thematic maps were generated to visualize spatio-temporal patterns of hydrological processes. The mapping outputs provide a clear spatial understanding of climate-driven hydrological variability.

Results and Discussion:

Spatio-Temporal Rainfall Variability:

The average rainfall map (2005–2024), when interpreted alongside the location map of North Maharashtra, reveals pronounced spatio-temporal variability across the region. Inter-decadal analysis indicates that rainfall distribution is not uniform and reflects fluctuations associated with monsoon strength and frequency over time. The eastern districts, particularly Jalgaon and parts of Dhule, consistently record higher average rainfall values (around 800–910 mm), whereas the south-western and western parts of Nashik district exhibit comparatively lower rainfall (around 650–700 mm) in several pockets.

A strong spatial contrast between the Western Ghats and rain-shadow zones is evident. As shown in the location map, western Nashik lies closer to the Western Ghats escarpment, where orographic lifting enhances monsoonal precipitation. In contrast, the central and eastern parts of the region, located in the leeward rain-shadow zone, display reduced and more variable rainfall. This topography-controlled gradient highlights the dominant influence of relief on rainfall patterns in North Maharashtra.

The observed rainfall variability has important implications of monsoon behaviour, including uneven water availability and increased hydrological uncertainty. Areas experiencing higher rainfall variability are more susceptible to episodic intense rainfall events, while rain-shadow zones face frequent dry spells. Such spatio-temporal rainfall contrasts significantly

influence runoff generation, groundwater recharge, and overall hydrological processes,

underscoring the need for climate-responsive water resource planning in North Maharashtra.

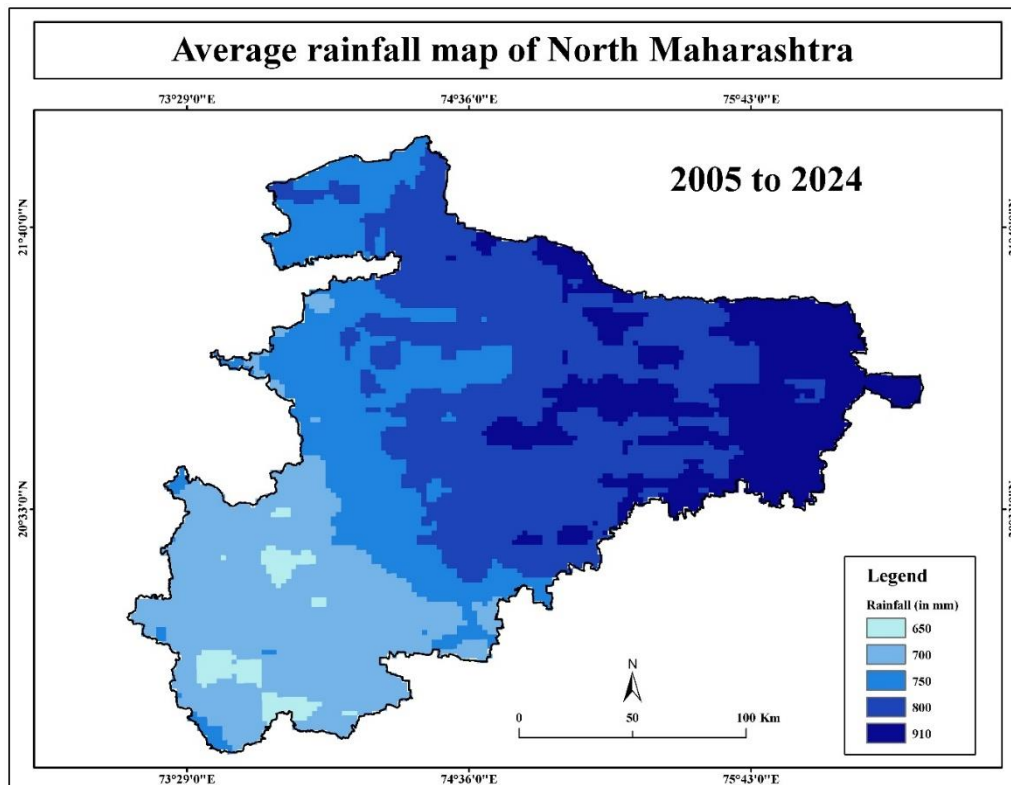


Fig.3.Average rainfall map of North Maharashtra

Topographic Control on Hydrological Processes:

The Digital Elevation Model (DEM) of North Maharashtra highlights strong topographic control over regional hydrological processes. Elevation across the region ranges from about 66 m to 1,569 m, reflecting the presence of the Western Ghats highlands, dissected plateaus, and low-lying river valleys. Higher elevation zones, particularly along the Western Ghats and adjoining uplands, are characterized by steep slopes that promote rapid surface runoff and well-defined drainage initiation. In contrast, the plateau and valley regions exhibit gentler slopes, allowing for slower runoff movement and greater water retention.

Slope variations derived from elevation significantly influence drainage density and channel orientation. Steep slopes in elevated terrains support dendritic and sub-dendritic

drainage patterns, while flatter plateau surfaces show relatively dispersed and elongated flow paths. The DEM also reveals that flow direction is predominantly controlled by regional relief, with water movement directed from the elevated western and south-western parts towards the lower eastern and north-eastern valleys.

A clear dominance of valley-controlled flow direction is observed in low-lying basins, where drainage converges along major river corridors. Conversely, plateau regions display more divergent flow patterns due to subtle elevation gradients. These observations confirm that elevation and slope act as primary physical controls on hydrological behavior in North Maharashtra, governing runoff pathways, drainage development, and watershed response characteristics.

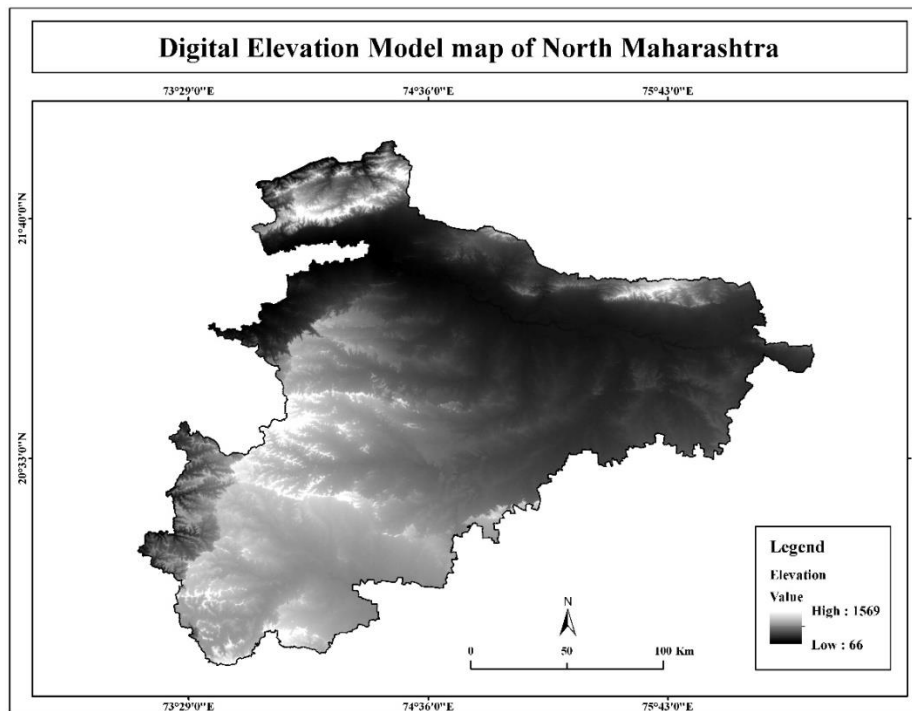


Fig.4.Digital elevation model of North Maharashtra

Flow Accumulation and Runoff Concentration Zones:

The flow accumulation analysis derived from the DEM provides critical insight into the spatial distribution of runoff concentration zones across North Maharashtra. Areas exhibiting high flow accumulation values represent locations where runoff from multiple upstream cells converges, forming well-defined drainage corridors. These high-flow accumulation corridors are prominently aligned along major river courses and tributary networks, indicating zones of sustained surface water movement.

A strong relationship is observed between flow accumulation patterns and river valleys, as low-lying basins naturally act as collectors of surface runoff. Valleys associated with major river systems such as the Godavari and Tapi basins show pronounced accumulation, reflecting their role as primary drainage pathways. In contrast, upland and plateau regions display lower accumulation values, characterized by dispersed flow and limited runoff convergence.

The concentration of runoff in low-elevation basins highlights areas that are more susceptible to flooding, erosion, and sediment transport, particularly during intense monsoonal rainfall events. These runoff concentration zones play a crucial role in regulating downstream hydrological response and water availability. Overall, the flow accumulation map effectively delineates hydrologically significant corridors and basins, underscoring the influence of terrain-controlled drainage on runoff processes in North Maharashtra.

Climate–Hydrology Interaction:

The interaction between climatic variability and hydrological processes in North Maharashtra is strongly reflected in the spatial relationship between rainfall patterns and runoff pathways. Areas experiencing higher rainfall variability exhibit pronounced changes in runoff generation, with intense rainfall events producing

rapid surface flow along pre-defined drainage channels identified through flow direction and flow accumulation analysis. In contrast, regions with relatively stable or lower rainfall show reduced runoff continuity and fragmented flow pathways.

Climatic fluctuations, particularly variations in monsoon onset, intensity, and duration, have led to shifts in hydrological response across the region. Increased rainfall variability enhances runoff concentration in low-lying basins and river valleys, amplifying the risk of flooding and soil erosion. Conversely, prolonged dry spells and erratic rainfall patterns reduce surface runoff and limit groundwater recharge in plateau and rain-shadow areas. These findings indicate that rainfall variability, when coupled with topographic controls, significantly alters hydrological behavior, emphasizing the sensitivity of regional water systems to climate-driven changes in North Maharashtra.

Implications for Watershed Management:

The integration of rainfall variability, topography, and flow accumulation highlights distinct flood-prone and water-scarce zones across North Maharashtra. Areas characterized by high flow accumulation in low-lying river valleys and basins are more susceptible to flooding during intense monsoonal events, while plateau and rain-shadow regions experience chronic water scarcity due to low and erratic rainfall. This spatial contrast underscores the need for location-specific watershed interventions.

The study provides a scientific basis for climate-resilient watershed planning strategies, emphasizing the prioritization of flood moderation measures such as channel stabilization and floodplain management in high-runoff zones. In water-deficient areas, strategies including rainwater harvesting, groundwater recharge structures, and soil–water conservation

measures are essential to enhance water availability and reduce vulnerability to climatic fluctuations.

Given that North Maharashtra largely falls within a semi-arid climatic regime, the findings are highly relevant for regional water management planning. The geospatial identification of hydrologically sensitive zones can support informed decision-making for sustainable watershed development, climate adaptation, and long-term water security in semi-arid landscapes.

Conclusion:

This study investigated the climate-driven spatio-temporal variability of hydrological processes in North Maharashtra using an integrated geospatial framework. By combining DEM-derived hydrological parameters (flow direction and flow accumulation) with 30-year rainfall data, the research successfully captured the interaction between climatic variability and terrain-controlled hydrological response.

The findings of the present study are largely consistent with regional and national hydrological studies that highlight the combined influence of rainfall variability and topography on hydrological processes in semi-arid and monsoon-dominated regions of India. Earlier studies conducted in the Deccan Plateau and Western Ghats regions have similarly reported strong orographic control on rainfall distribution and terrain-driven runoff concentration. The observed patterns of higher runoff and flow accumulation along river valleys and low-lying basins in North Maharashtra align well with these established hydrological frameworks.

The added value of spatio-temporal geospatial integration in this study lies in its ability to simultaneously capture climatic variability and terrain-controlled hydrological response at a regional scale. Unlike many earlier

studies that focused either on rainfall trends or watershed morphometry independently, the present approach integrates long-term rainfall data with DEM-derived hydrological parameters. This integrated geospatial framework enables a more comprehensive understanding of climate–hydrology interactions, offering improved spatial clarity and practical applicability for watershed management and climate adaptation planning in semi-arid regions.

The findings reveal substantial spatial heterogeneity in rainfall distribution, strongly influenced by physiography, particularly the Western Ghats escarpment and rain-shadow zones. Temporal analysis indicates marked inter-decadal variability in rainfall patterns, reflecting shifts in monsoon behavior. DEM-based hydrological modeling highlights that topography plays a decisive role in runoff concentration, drainage development, and watershed response, while rainfall variability acts as a critical climatic driver modulating these processes.

The integration of climatic and topographic datasets demonstrates that areas with higher rainfall variability and favourable terrain conditions exhibit increased susceptibility to runoff concentration and hydrological extremes, whereas regions with declining or erratic rainfall show fragmented hydrological connectivity. Overall, the study confirms that climate variability, when coupled with geomorphological controls, significantly alters hydrological dynamics in semi-arid and sub-humid regions like North Maharashtra.

The geospatial approach adopted in this study proves effective for regional-scale hydrological assessment and provides a robust scientific basis for climate-sensitive water resource planning.

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