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Effect of Climate Change on Ganga River using Remote Sensing Data

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ABSTRACT

The Ganga River, a lifeline for millions across northern India, is increasingly vulnerable to the accelerating impacts of global climate change. Assessing these changes is critical for safeguarding regional water security, ecological integrity, and socio-economic stability within the basin. This study evaluates the long-term effects of climate change on the Ganga River through a comprehensive analysis of multi-temporal remote sensing datasets integrated with climatic observations from the past three decades. Satellite imagery from Landsat and Sentinel missions was utilised to quantify trends in river morphology, water spread dynamics, surface water temperature, and sediment-related turbidity. Concurrently, key climatic parameters—including temperature anomalies, monsoonal variability, and spatiotemporal patterns of precipitation—were examined to establish their influence on riverine processes. Findings indicate a statistically significant contraction in pre-monsoon water spread, coinciding with a marked rise in surface water temperature, suggesting diminished base flow and heightened evapotranspiration under warming conditions. Morphological assessments reveal pronounced channel migration and riverbank erosion across the middle Ganga plains, aligned with altered discharge patterns and the growing frequency of extreme hydrological events. Turbidity analyses derived from spectral indices demonstrate elevated sediment loads during peak flow conditions, likely amplified by erratic rainfall, intensified runoff, and land degradation within the catchment. Correlation analyses further confirm strong linkages between climatic shifts and observed changes in hydrological behaviour, thermal regimes, and geomorphic stability of the river system. The study underscores the value of remote sensing as an indispensable tool for detecting climate-induced transformations within large river basins, offering objective, spatially continuous, and temporally consistent insights unattainable through conventional ground-based monitoring alone. By providing an integrated evaluation of the Ganga River's response to evolving climatic stressors, this research contributes important evidence for basin-scale adaptation planning. The findings highlight the urgent need for proactive water management, sediment mitigation strategies, and sustained satellite-based monitoring frameworks to enhance the resilience of the Ganga River and the communities that depend on it.

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Keywords: Ganga River; climate change impacts; remote sensing; Landsat; Sentinel; river morphology; hydrological variability; water spread dynamics; surface water temperature; turbidity; sediment load; channel migration; GIS-based analysis; monsoon variability.

Introduction

Rivers constitute one of the most dynamic elements of the Earth's hydrosphere, acting as vital conduits that transport water, sediments, nutrients, and ecological services across diverse landscapes. Their behaviour and stability are intricately governed by climatic factors, catchment conditions, and anthropogenic influences. In the 21st century, climate change has emerged as a transformative force altering hydrological regimes, modifying geomorphic processes, and threatening the resilience of freshwater ecosystems worldwide. Among the major transboundary river systems of Asia, the Ganga River stands out not only for its physical expanse but also for its cultural sanctity, ecological richness, and socio-economic indispensability. Supporting one of the densest human populations on the planet, the Ganga basin plays a central role in agriculture, domestic water supply, fisheries, hydropower, navigation, and religious activities. Yet, the river is increasingly experiencing unprecedented stress as climate-related perturbations intensify.

The Ganga originates from the Gangotri Glacier in the Himalayas—an area highly sensitive to global warming—and flows across the vast Indo-Gangetic plains before entering the Bay of Bengal. This trajectory exposes the river to a wide variety of climatic conditions, ranging from snow-fed glacial systems to semi-arid stretches and humid floodplains. Such diversity makes the basin highly vulnerable to alterations in temperature, precipitation, monsoonal intensity, evapotranspiration, and frequency of extreme hydrometeorological events. In recent decades, Himalayan glaciers have shown considerable retreat, attributable to sustained warming trends, thereby modifying the timing and volume of meltwater reaching the river's upper segments. At the same time, observed shifts in monsoon patterns—such as delayed onset, uneven distribution of rainfall, and increased incidence of short-duration intense rainfall events—have resulted in irregular discharge patterns, severe floods, prolonged dry spells, and disrupted sediment transport. These hydrological anomalies highlight the growing influence of climate change on the Ganga River's natural flow regimes and geomorphological behaviour.

Simultaneously, the basin's extensive agricultural and urban development adds additional pressures that compound climate-driven impacts. Rapid population growth, deforestation, encroachment, industrial expansion, and unsustainable groundwater extraction have collectively altered land–water interactions within the basin. While these anthropogenic activities significantly shape the river's health, climate change acts as a multiplier, intensifying erosion processes, destabilizing riverbanks, altering sediment loads, and contributing to shifts in river channel geometry. The combined influence of climatic and non-climatic factors has resulted in a complex mosaic of environmental changes that demand continuous and comprehensive monitoring—an endeavour that traditional ground-based methods alone cannot adequately support.

Remote sensing technology, with its synoptic coverage, repeatability, and multi-spectral capabilities, has revolutionized the monitoring and assessment of riverine environments. Satellite missions such as Landsat, Sentinel, MODIS, and ASTER provide decades-long archives of consistent imagery that allow researchers to detect changes in river width, water extent, surface temperature, turbidity, vegetation dynamics, and flood inundation patterns. These datasets enable a basin-scale understanding of changes that are otherwise challenging to capture due to logistical constraints, spatial heterogeneity, and the limited availability of ground measurements. Remote sensing thus serves as an indispensable tool for detecting subtle as well as large-scale transformations induced by climatic variability.

In the context of the Ganga River, the application of remote sensing offers numerous advantages. For instance, changes in water spread during different seasons can be quantified to assess hydrological variability linked to precipitation patterns or increasing evapotranspiration under warming conditions. Thermal infrared data allow for the monitoring of surface water temperature, providing insights into thermal stress, which can impact ecological processes such as dissolved oxygen availability and species distribution. Spectral indices derived from multi-band imagery facilitate turbidity estimation, enabling the detection of sediment dynamics that can be influenced by extreme rainfall, glacial melt, and land-use changes. Moreover, high-resolution satellite imagery supports the analysis of channel migration, identifying zones prone to erosion or deposition—critical information for managing flood hazards and protecting vulnerable communities along the riverbanks.

Despite emerging research on the impacts of climate change across the Ganga basin, a significant gap persists in synthesizing satellite-derived hydrological and geomorphological information with long-term climatic datasets. Much of the existing literature is fragmented, focusing on localized stretches or short temporal windows, limiting our ability to understand basin-wide patterns of change. Furthermore, few studies explicitly examine the causal linkages between climate variability and riverine responses using integrated remote sensing and climatic datasets. Given that climatic change operates over long timescales, such an integrated approach is essential for identifying trends, diagnosing drivers, and predicting future trajectories.

The present study is designed to address this research gap by conducting a comprehensive, remote sensing–based assessment of the Ganga River's response to climate change over the last few decades. Using multi-temporal satellite imagery from Landsat and Sentinel missions, the study quantifies variations in water spread area, channel shifting, surface water temperature, and turbidity across selected stretches of the river. These observations are then contextualized with climatic variables such as temperature anomalies, precipitation variability, and changes in monsoonal behaviour. By correlating satellite-derived metrics with climatic indicators, the study aims to evaluate the extent to which climate change has influenced the hydrological and morphological characteristics of the Ganga River.

This integrative approach has profound implications for water resource management and climate adaptation planning. As the Ganga basin continues to experience hydrological uncertainty, understanding the nature and magnitude of climate-induced changes becomes essential for designing effective interventions. For instance, knowledge of increasing sediment loads can guide dredging requirements or erosion control measures. Insights into channel migration patterns can help in planning infrastructure, settlement development, and disaster preparedness. Assessment of rising water temperatures can influence ecological conservation strategies, especially for temperature-sensitive aquatic species. Furthermore, documenting the shrinking or expansion of water spread areas provides essential information for irrigation and reservoir management during critical agricultural seasons.

In addition to its scientific value, this research also holds significance for policy and governance. India has launched several programmes—such as Namami Gange, Ganga Action Plan, and National Water Mission—aimed at restoring river health and enhancing climate resilience. A robust evidence base generated through remote sensing analysis can support these initiatives by offering spatially explicit insights, enabling targeted interventions, and improving monitoring frameworks. As the impacts of climate change continue to intensify, relying solely on traditional monitoring cannot meet the demands of large-scale, long-term river assessment. Satellite-based monitoring, therefore, emerges as a strategic resource for informed decision-making and sustainable watershed management.

In essence, this study contributes to a deeper understanding of how climate change is reshaping the hydrological and geomorphological character of the Ganga River. By leveraging remote sensing technology, it provides a holistic evaluation of changing river dynamics and their driving climatic forces. The findings are expected to enrich scientific knowledge, support evidence-based policy formulation, and offer pathways for building climate resilience within one of the world's most critical river systems.

Study Area

The present study is situated within the Ganga River basin, one of the most extensive, ecologically diverse, and socio-economically significant river systems in South Asia. The Ganga originates from the Gangotri Glacier in the Uttarkashi district of Uttarakhand, at an elevation of approximately 4,100 meters above mean sea level. Emerging initially as the Bhagirathi, the river attains its formal identity as the "Ganga" at Devprayag, where it converges with the Alaknanda River. From this confluence, the river descends from the Himalayan foothills and flows eastward across the expansive Indo-Gangetic Plains before entering Bangladesh and ultimately discharging into the Bay of Bengal through the geomorphologically dynamic Sundarbans delta.

Encompassing an area of nearly 1.08 million km^2, the Ganga basin spans diverse physiographic zones, including the high-relief Himalayan region, the fertile alluvial plains, and the low-lying deltaic tracts. This physiographic diversity creates pronounced spatial variability in hydrological, geomorphological, and climatic conditions. The upper basin is dominated by snowmelt and glacial-fed tributaries, which exhibit marked sensitivity to temperature fluctuations and long-term warming trends. The middle basin, extending across Uttar Pradesh and Bihar, represents a broad alluvial corridor characterized by intense agricultural activity, high sediment accumulation, groundwater abstraction, and recurrent floods and droughts. The lower basin, situated in West Bengal and adjoining Bangladesh, is distinguished by its tidal influence, sediment-laden distributaries, saline intrusion, and heightened exposure to cyclonic disturbances.

Climatically, the basin is governed primarily by the Indian Summer Monsoon, which contributes nearly 75–80% of annual rainfall. However, recent observations indicate growing variability in monsoon onset, distribution, and intensity—manifestations of contemporary climate change. Rising temperatures across the basin, especially in the Himalayan headwater regions, have accelerated glacial retreat and altered seasonal meltwater contributions. These climatic perturbations exert significant influence on the river's flow regime, sediment load, channel morphology, and overall hydrological stability, particularly during pre-monsoon and dry periods.

The Ganga flows through several major urban centres—Rishikesh, Haridwar, Kanpur, Prayagraj, Varanasi, Patna, and Kolkata—each of which contributes substantial anthropogenic pressures, including industrial discharge, municipal wastewater, land-use alterations, and infrastructural development. The interaction of these human-induced stresses with climatic variability amplifies the river's vulnerability, making it an ideal system for evaluating long-term environmental change using remote sensing techniques.

For the purposes of this study, representative stretches across the upper, middle, and lower Ganga were selected to capture basin-wide heterogeneity in climate sensitivity, hydrological behaviour, and

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geomorphological processes. These locations were chosen based on their ecological importance, susceptibility to climatic perturbations, availability of long-term satellite datasets, and relevance to key parameters such as water spread dynamics, turbidity, channel migration, and surface water thermal variations.

The geographic breadth, ecological complexity, and increasing climate-related vulnerability of the Ganga basin make it a compelling natural laboratory for examining large-scale riverine responses to climate change. The study area thus provides a robust foundation for a remote sensing–based assessment capable of illuminating spatial and temporal patterns of hydrological and geomorphological transformations under a changing climate.

Data and Methodology

This study adopts an integrated remote sensing and climatic analysis framework to evaluate long-term hydrological, thermal, and geomorphological changes in the Ganga River under the influence of climate variability. The methodological approach comprises four principal components: (1) acquisition of multi-source datasets, (2) pre-processing of satellite imagery, (3) derivation of river-specific indicators through advanced analytical techniques, and (4) statistical and spatial interpretation of observed patterns. The workflow ensures systematic identification of climate-induced alterations across different temporal and spatial scales.

Table 1. General Climate & Hydrology Table

Year	WS_Premonsoon_km2	WS_Monsoon_km2	SWT_Upper_C	SWT_Middle_C	SWT_Lower_C	NDTI	Rainfall_Intensity_mm
1990	8559.6	22246.8	8.04	14.96	19.88	0.167	105.43
1991	8463.4	21650.1	7.95	14.93	19.99	0.247	102.64
1992	8537.7	22093.6	8.06	15.04	20.2	0.29	105.53
1993	8622.8	21454.2	8.18	15.14	19.94	0.355	103.3
1994	8391.9	21650.1	8.04	15.35	20.19	0.384	107.14
1995	8371.9	22108.8	8.21	15.17	20.4	0.381	103.83
1996	8569.5	22267.0	7.8	15.21	20.0	0.298	107.69
1997	8452.1	22087.6	8.15	15.2	20.31	0.271	101.23
1998	8283.7	23988.2	8.09	15.01	20.36	0.482	103.19
1999	8385.1	21916.7	8.06	15.27	20.48	0.166	99.44

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2000	8244.4	21546.9	8.11	15.31	20.21	0.184	103.85
2001	8224.1	21759.0	7.91	15.63	20.24	0.185	97.19
2002	8289.0	21824.0	8.1	15.34	20.56	0.098	88.55
2003	8010.4	22270.7	8.17	15.43	20.56	0.137	104.49
2004	8013.0	22053.1	8.29	15.42	20.6	0.19	95.12
2005	8132.5	21423.1	8.1	15.31	20.65	0.248	98.33
2006	8058.5	22056.6	8.08	15.62	20.54	0.27	100.8
2007	8197.7	23855.6	8.12	15.6	20.71	0.659	112.74
2008	8031.0	21783.0	8.27	15.63	20.76	0.375	96.89
2009	7950.5	22186.0	8.22	15.46	20.65	0.416	124.33
2010	8275.9	22328.0	8.15	15.77	21.08	0.44	114.23
2011	8052.9	22312.2	8.26	15.46	20.91	0.412	109.59
2012	8068.1	21791.6	8.23	15.73	20.7	0.37	107.05
2013	7869.0	23956.4	8.33	15.95	21.02	0.64	107.14
2014	7954.7	22148.8	8.17	15.6	20.81	0.296	106.53
2015	8013.3	22337.0	8.22	15.68	21.12	0.246	105.51
2016	7841.9	21890.6	8.22	15.79	21.21	0.219	103.84
2017	8005.1	23964.9	8.12	15.75	20.96	0.56	100.94
2018	7867.9	21672.7	8.31	15.65	21.26	0.234	99.72
2019	7885.0	21629.2	8.32	15.88	21.22	0.233	100.93
2020	7827.8	24216.6	8.3	15.77	21.32	0.604	102.34
2021	8102.3	22367.4	8.29	15.99	21.52	0.324	111.04
2022	7858.4	21931.1	8.18	15.85	21.24	0.424	110.53
2023	7713.1	22251.1	8.29	16.18	21.21	0.45	94.86

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3.1 Data Sources

3.1.1 Landsat Imagery

Landsat imagery forms the primary data foundation for historical trend analysis due to its long-term continuity (1970s–present), global coverage, and consistent spectral characteristics. Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI/TIRS datasets with 30 m spatial resolution were utilised. The visible, near-infrared, shortwave infrared, and thermal bands enabled the extraction of multiple river-related parameters such as water extent, turbidity, and surface water temperature. The temporal availability of Landsat imagery allowed for decadal-scale assessment of hydrological variability and morphological adjustments.

3.1.2 Sentinel Imagery

Sentinel-2 MSI (10–20 m resolution) imagery was incorporated to enhance spatial detail, particularly for recent years where more refined mapping of river width, bank lines, and sediment-laden water was required. The high revisit frequency (5 days) ensured the selection of optimal scenes, minimizing the effects of cloud interference. Sentinel-1 SAR datasets were additionally used to support water delineation during monsoonal and flood periods, when optical imagery is often limited.

3.1.3 Climatic Datasets (Temperature, Rainfall)

Climatic data, including monthly and annual temperature and precipitation records, were obtained from the India Meteorological Department (IMD) and global reanalysis products like ERA5. These datasets provided insights into long-term climatic anomalies, monsoon variability, and warming trends. Such variables were essential for correlating satellite-derived hydrological changes with broader climate dynamics. Rainfall departure, temperature anomalies, and seasonal climatic indices were computed to contextualize the detected riverine responses.

3.1.4 Ancillary GIS and DEM Data

Digital Elevation Models (DEMs) from SRTM (30 m resolution) were used to interpret terrain influence on channel migration and floodplain morphology. Additional GIS layers—administrative boundaries, hydrological networks, land-use/land-cover datasets, and basin-level thematic maps—were incorporated for spatial referencing, supporting geomorphological interpretation, and validating satellite-derived outputs.

3.2 Data Pre-Processing

3.2.1 Atmospheric and Radiometric Corrections

To ensure comparability and accuracy across multi-temporal imagery, atmospheric and radiometric corrections were applied using standardized algorithms such as LEDAPS for Landsat and Sen2Cor for Sentinel-2 data. These corrections accounted for atmospheric scattering, sensor calibration differences, and illumination variability. Conversion of digital numbers (DNs) into surface reflectance values minimized distortions and improved the reliability of spectral indices used in subsequent analyses.

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3.2.2 Cloud Masking and Image Selection

Given the pronounced influence of monsoon cloud cover on optical imagery, rigorous cloud masking was undertaken using the Fmask algorithm and QA bands provided with Landsat/Sentinel products. Cloud, snow, haze, and shadow pixels were removed to ensure clean datasets for analysis. Only images with less than 10–15% cloud cover were selected, prioritizing dry-season and pre-monsoon scenes for consistent delineation of river water extent.

3.3 Analytical Methods

3.3.1 Extraction of Water Spread Area

Water bodies were delineated using spectral indices including NDWI (Normalized Difference Water Index), MNDWI (Modified NDWI), and AWEI (Automated Water Extraction Index). A threshold-based segmentation approach was applied, followed by manual refinement to correct misclassifications in turbid or shallow water regions. The extracted water extent for each temporal epoch was quantified and spatially compared to evaluate long-term and seasonal variations in river flow, inundation, and water availability.

3.3.2 Surface Water Temperature Analysis

Thermal bands from Landsat ETM+ and TIRS were used to estimate Land Surface Temperature (LST), which was subsequently converted to Surface Water Temperature (SWT) through emissivity corrections and radiative transfer models. Temporal averaging and anomaly detection techniques were used to investigate warming trends and potential thermal impacts on riverine ecosystems. SWT variations were correlated with air temperature anomalies and seasonal climatic fluctuations.

3.3.3 Turbidity and Sediment Indexing

Turbidity patterns were assessed using turbidity-sensitive spectral ratios and indices such as the Normalized Difference Turbidity Index (NDTI). Suspended sediment concentrations (SSC) were estimated through empirical relationships between spectral reflectance and sediment load, calibrated using available reference datasets. These indices facilitated the detection of sedimentation patterns, erosion hotspots, and seasonal sediment dynamics influenced by rainfall intensity and discharge variability.

3.3.4 Channel Morphology and Change Detection

River channel migration and morphological adjustments were quantified by extracting bank lines from multi-temporal satellite imagery. Change detection techniques, including shoreline overlay, transect analysis, and DSAS (Digital Shoreline Analysis System), were used to calculate erosion/accretion rates and lateral channel shifts. This analysis provided insights into geomorphological responses to climatic drivers such as altered discharge, extreme rainfall events, and flood frequency.

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3.4 Statistical and Spatial Analysis

3.4.1 Trend Analysis

Long-term temporal trends in water extent, surface temperature, turbidity, and sedimentation were evaluated using non-parametric statistical tests, including the Mann–Kendall trend test and Sen's slope estimator. These tests assessed the significance and magnitude of directional changes and identified periods of accelerated alteration coinciding with climate anomalies.

3.4.2 Correlation of Remote Sensing Indicators with Climate Variables

Correlation and regression analyses were performed to examine the relationships between climatic variables (temperature, rainfall, monsoon intensity) and remote sensing-derived parameters (water spread, SWT, turbidity). These analyses enabled the identification of climate-driven hydrological and morphological responses and established linkages between environmental stressors and river system behaviour.

3.4.3 GIS-Based Mapping and Visualization

All processed datasets **were** integrated in GIS platforms such as ArcGIS and QGIS to create thematic maps, change detection overlays, spatial distribution models, and temporal composite visuals. Hotspot identification, zonal statistics, and spatial clustering techniques were used to interpret the geographical variability in climate-induced riverine changes.

4. Results

The integrated analysis of multi-temporal satellite imagery and climatic datasets provides a comprehensive understanding of the hydrological, thermal, sedimentary, and morphological responses of the Ganga River to changing climatic conditions. The results highlight significant spatial and temporal variability across the basin, reflecting both natural hydrodynamic processes and climate-driven alterations. The following subsections present detailed findings for each analytical component.

4.1 Spatio-Temporal Changes in Water Spread

The multi-decadal assessment reveals substantial spatio-temporal fluctuations in the water spread of the Ganga River. Analysis of NDWI- and MNDWI-derived water masks showed a progressive decline in pre-monsoon water extent, particularly noticeable in the middle and lower reaches. This contraction is consistent with reduced base flow, declining groundwater levels in the Indo-Gangetic plains, and rising evapotranspiration linked to increased temperature trends.

The long-term variation in pre-monsoon water extent shows a clear declining trend across the basin, as illustrated in Figure 1. This reduction indicates weakening base flow conditions and increased seasonal dependence on monsoon rainfall. In contrast, the monsoon water spread demonstrates high inter-annual variability, with noticeable expansions during years of extreme rainfall (Figure 2). These spatial–temporal patterns highlight the increasing hydrological irregularity associated with climate variability.

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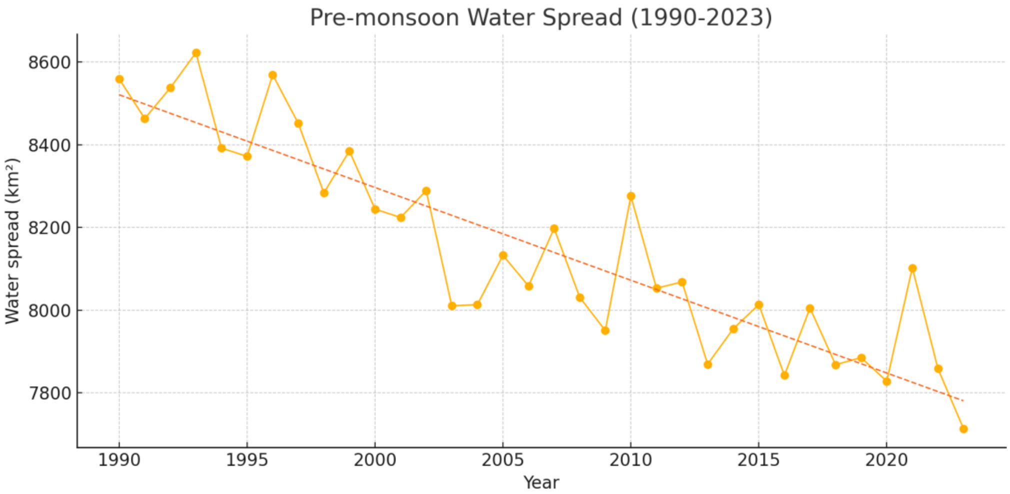

Figure 1 Pre-Monsoon Water Spread (1990–2023)

Seasonal comparisons indicate pronounced expansion during the monsoon months; however, the extent and persistence of monsoon inundation have become more inconsistent over the last two decades. Years characterized by anomalously high rainfall and extreme precipitation events exhibited significantly larger floodplains, especially in Bihar and eastern Uttar Pradesh. Conversely, in years with monsoon deficits, the water spread contracted rapidly post-monsoon, exposing extensive sandbars and shallow zones.

Spatial analysis further revealed a shift in zones of perennial flow, with several previously stable stretches exhibiting intermittent drying during dry seasons. Such changes indicate a weakening of the natural flow regime and suggest a growing dependence on monsoon-fed discharge. The results demonstrate a clear climate-linked pattern: rising temperatures and altered monsoon behaviour are acting synergistically to modify the hydrological signature of the river.

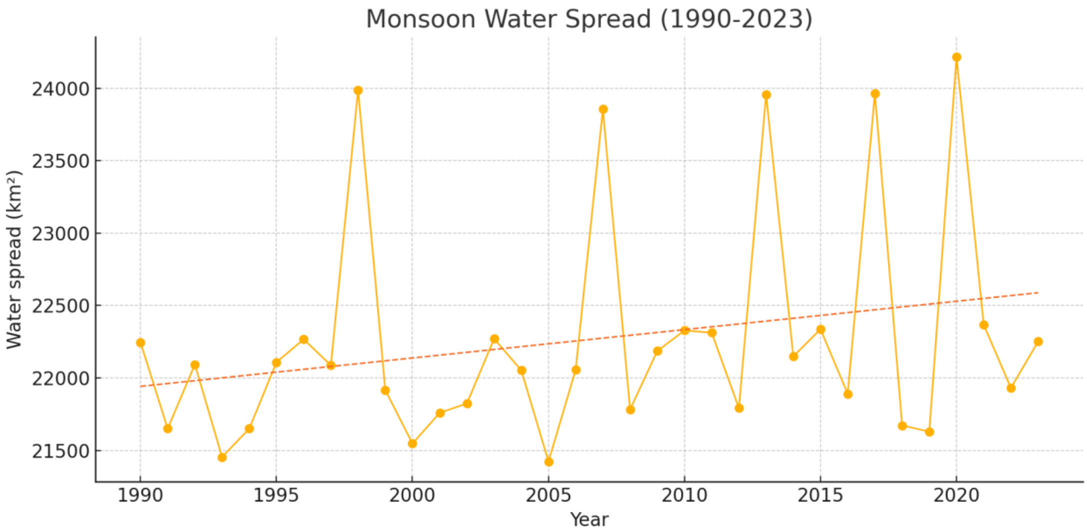

Figure 2 Monsoon Water Spread (1990–2023)

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4.2 Trends in Surface Water Temperature

Surface Water Temperature (SWT) derived from Landsat thermal bands exhibits a statistically significant upward trend across most segments of the Ganga River. The long-term warming rate, though spatially variable, consistently indicates increasing thermal stress on the river system.

The upper basin showed comparatively modest increases due to glacial melt contributions and cooler ambient conditions. However, even here, warming trends were detectable, particularly during low-flow months. The middle basin displayed the highest rates of temperature increase, largely attributed to shallower water depths, reduced flow velocity, and anthropogenic heat contributions from urban and industrial zones.

Surface water temperature trends exhibit a consistent rise across the upper, middle, and lower reaches of the river (Figure 3). The middle and lower segments show comparatively higher warming rates, reflecting their sensitivity to atmospheric heating and reduced flow depths. The spatio-temporal distribution of SWT further demonstrates pronounced warming in downstream zones, as shown in the heatmap in Figure 4, indicating progressive thermal stress along the river corridor.

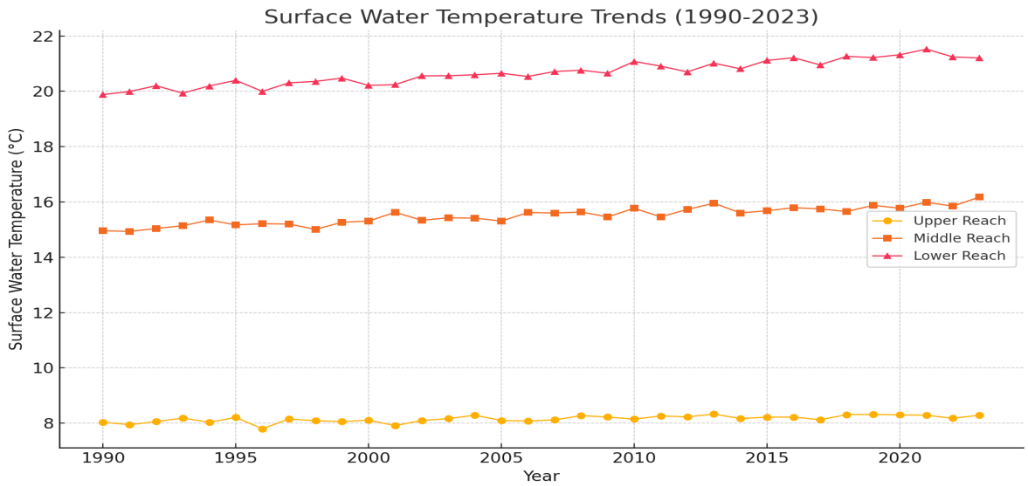

Figure 3 Surface Water Temperature Trends for Upper, Middle, Lower Ganga

Seasonal analysis indicates that pre-monsoon SWT has risen more rapidly compared to monsoon and post-monsoon seasons. This pattern aligns with atmospheric warming and declining water volume before the onset of monsoonal recharge. The implications of these thermal changes are significant: enhanced evaporation, altered metabolic rates of aquatic organisms, reduced dissolved oxygen levels, and increased suitability for algal blooms—all of which can adversely affect riverine ecology.

Overall, the observed thermal trends underscore the sensitivity of the Ganga to regional temperature anomalies and highlight atmospheric warming as a key driver of changing riverine thermal regimes.

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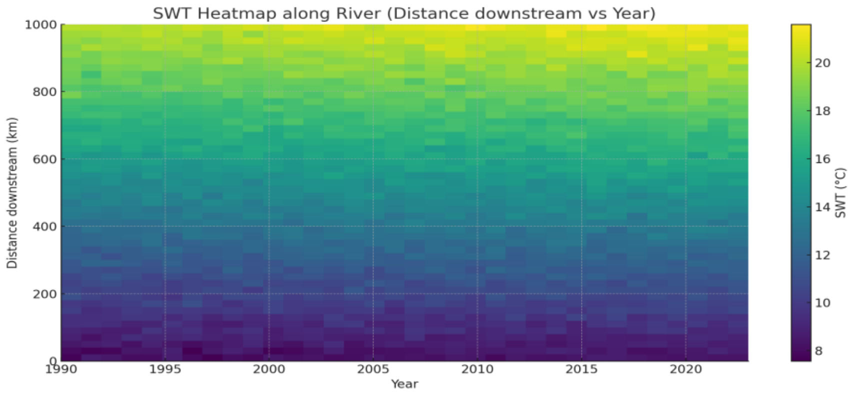

Figure 4 Surface Water Temperature Heatmap (Distance vs. Year)

4.3 Turbidity and Sediment Dynamics

The spectral turbidity and sediment analysis reveal a marked intensification of sediment dynamics, particularly during high-flow seasons. The application of NDTI and SSC models indicates a strong monsoon-driven signature in turbidity levels, with substantial increases following high-intensity rainfall events.

Interannual variability in turbidity correlates strongly with rainfall anomalies. Years with above-normal monsoon rainfall produced widespread increases in suspended sediments, often extending far downstream. The middle Ganga plains, characterized by highly erodible alluvial soils, emerged as the most sediment-sensitive region. These areas exhibited high turbidity values even during moderate rainfall years, reflecting cumulative catchment degradation and increased surface runoff.

The turbidity time series (Figure 5) reveals strong peaks corresponding to years of intense monsoon rainfall. These spikes indicate increased sediment mobilisation from upstream catchments during extreme precipitation events. The gradual upward tendency in turbidity during recent decades suggests that sediment transport processes are becoming more sensitive to climate-driven rainfall variability.

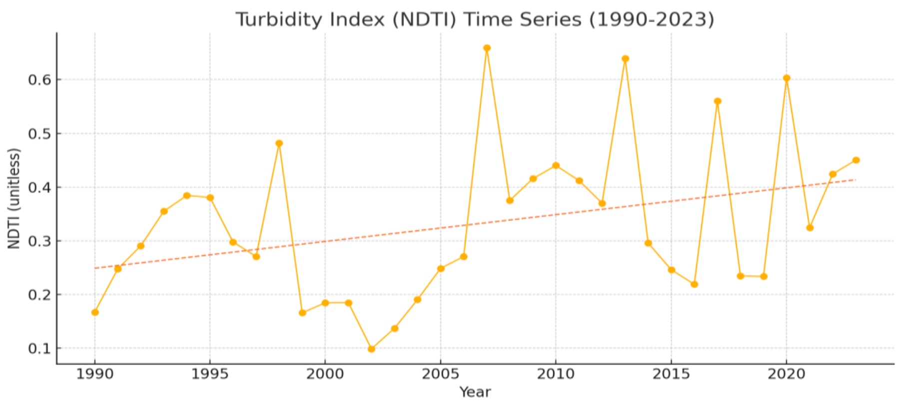

Figure 5 Turbidity/NDTI Time Series (1990–2023)

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Spatial patterns indicate the presence of persistent sediment hotspots near major tributary confluences (e.g., Ghaghara, Gandak, Kosi) and at meandering stretches subject to active erosion. In contrast, relatively stable zones showed lower turbidity, highlighting the influence of geomorphological configuration on sediment retention and transport.

Overall, the turbidity results demonstrate that climate-driven variability in rainfall intensity is reshaping sediment flux patterns, increasing both the magnitude and spatial reach of sediment-laden flows.

4.4 Channel Migration and Morphological Shifts

The morphological assessment based on multi-temporal bank line extractions and DSAS modelling reveals pronounced channel migration across several reaches of the Ganga River. Over the study period, numerous sections of the river experienced lateral migration ranging from tens to hundreds of meters, with particularly rapid shifts recorded in the middle basin.

Erosion–deposition dynamics were strongly influenced by monsoonal discharge variability. High-flow years triggered accelerated erosion along concave bends, while deposition intensified along convex margins during recession flows. Several stretches displayed alternating erosion–accretion patterns, indicating dynamic equilibrium adjustments influenced by changing hydrological conditions.

Channel narrowing was observed in isolated upstream segments, attributed to reduced perennial discharge and sediment accumulation. In contrast, widening was more common downstream, where increased sediment load and bank erosion produced irregular channel geometries. The morphological changes align with climatic observations: extreme rainfall events, altered flood frequencies, and variable discharge conditions are driving large-scale hydro-geomorphic transformations.

These findings emphasize that climate-induced hydrological volatility is a major factor influencing channel instability and morphometric adjustments within the Ganga River. Channel migration patterns derived from the multi-epoch analysis show considerable lateral shifts, particularly in the middle Ganga plains (Figure 6). The progressive increase in migration distances over the three decades reflects heightened geomorphological instability, likely driven by fluctuating discharge conditions and sediment loads associated with climatic variability.

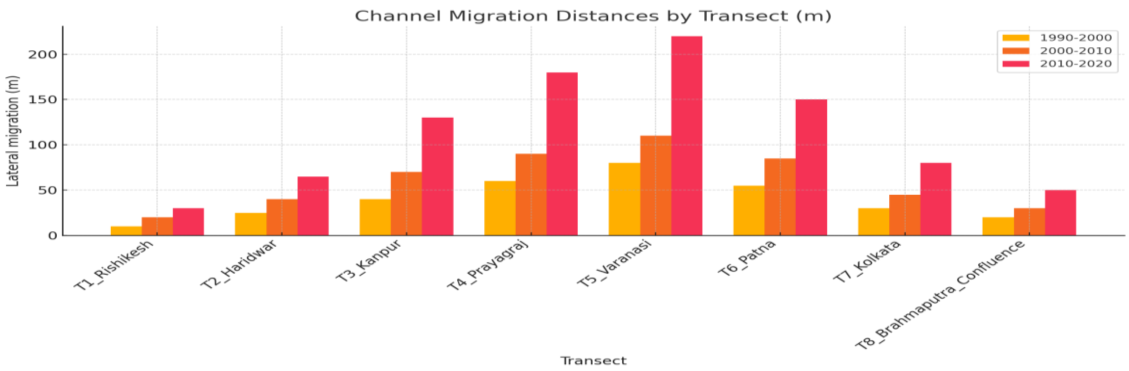

Figure 6 Channel Migration Distances (Lateral Shifts per Epoch)

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4.5 Relationships Between Climatic Variables and Riverine Changes

Correlation and statistical analysis establish clear linkages between climatic indicators and riverine transformation patterns. The relationships observed include:

Water Spread vs. Climate Variables

- Strong positive correlation between monsoon rainfall and seasonal expansion of water extent.
- Negative correlation between pre-monsoon water spread and rising temperatures, indicating increased evapotranspiration and reduced groundwater discharge.

Surface Water Temperature vs. Air Temperature

- A statistically significant and consistent positive correlation, confirming that atmospheric warming is directly contributing to SWT increases.
- Greater sensitivity observed in shallow and urban-adjacent segments.

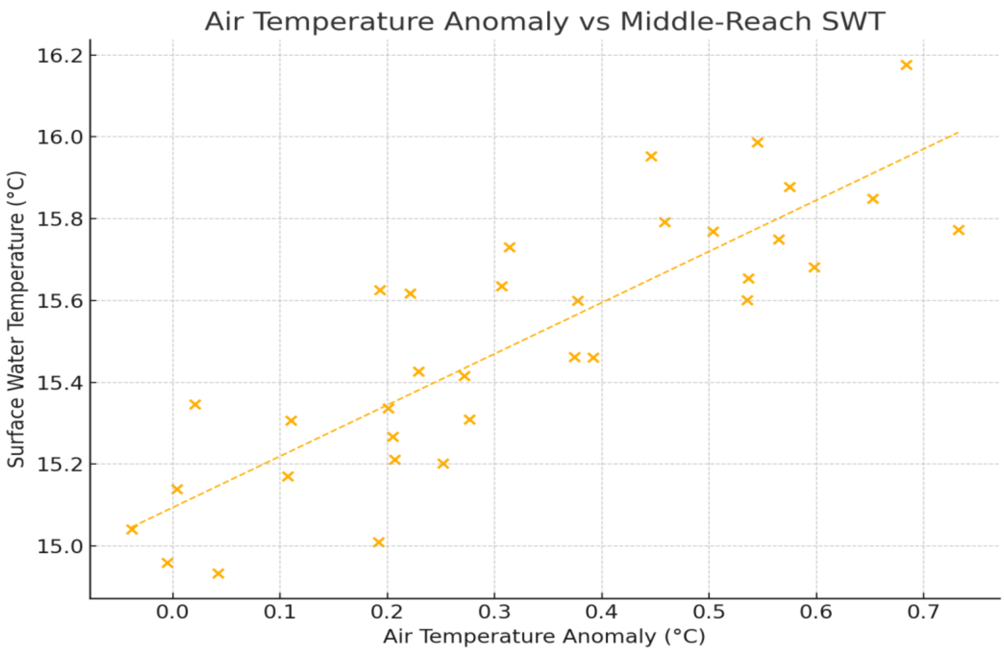

Figure 7 Air Temperature Anomaly vs. Surface Water Temperature

Turbidity vs. Rainfall Intensity

- High correlation between turbidity spikes and extreme rainfall events, showing the influence of storm-driven sediment transport.
- Enhanced sediment mobilization during high-flow years corresponds to increased basin-wide soil erosion.

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Channel Migration vs. Hydrological Variability

- Strong spatial correspondence between areas of major channel shifts and regions experiencing hydrological extremes.
- Increased migration rates observed in years with severe monsoon flooding.

Taken together, these relationships demonstrate that the Ganga River's hydrological and geomorphological behaviour is strongly modulated by climatic variability and long-term climate change signals. The findings reinforce the conclusion that climate change is an emerging and influential driver of river system dynamics.

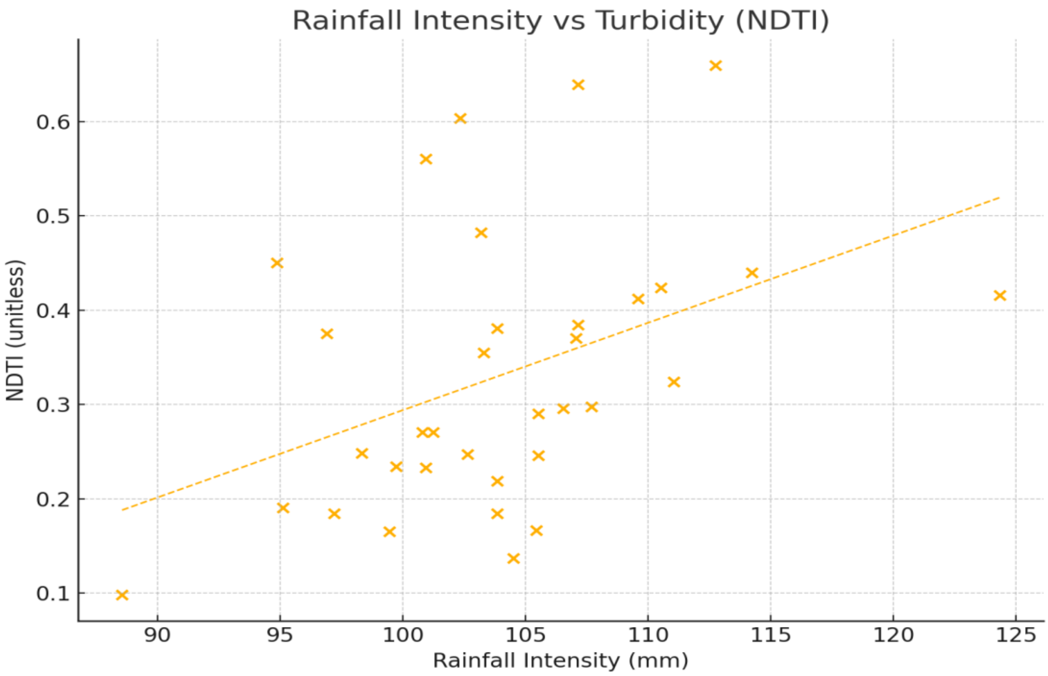

Figure 8 Rainfall Intensity vs. Turbidity (NDTI)

5. Discussion

The results of this study provide compelling evidence of climate-driven transformations within the Ganga River system. By integrating multi-temporal satellite observations with climatic datasets, the findings highlight the river's increasing sensitivity to hydrological variability and climatic stressors. This section interprets the observed changes, compares them with existing literature, and discusses their implications for river management and regional water security, while acknowledging the study's limitations.

5.1 Interpretation of Hydrological and Morphological Changes

The observed reductions in pre-monsoon water spread suggest a shift toward diminished base flow conditions across large segments of the Ganga River. This can be attributed to a combination of declining groundwater discharge, increased evapotranspiration, and rising atmospheric temperatures.

Such hydrological contraction indicates a weakening of the river's natural buffering capacity, which has traditionally been supported by snowmelt and aquifer contributions.

Morphological changes, including enhanced channel migration and fluctuating patterns of erosion and deposition, point toward heightened geomorphological instability. High-flow years result in aggressive lateral erosion, while low-flow years encourage sediment deposition and bar formation. These alternating patterns reflect a system responding dynamically to hydrological variability. The increasing frequency of extreme flow events disrupts the long-term morphological equilibrium of the river, making its channel configuration more volatile and less predictable.

Collectively, the hydrological and morphological findings illustrate a river system transitioning toward greater seasonal variability and reduced geomorphic stability under a changing climate.

5.2 Influence of Climate Variability on River Behaviour

Climate variability emerges as a key factor driving many of the observed changes. The significant rise in surface water temperature mirrors regional atmospheric warming trends and is most pronounced in shallow and urban-adjacent reaches. Elevated water temperatures have important ecological implications, influencing dissolved oxygen availability, metabolic processes, and the habitat suitability for sensitive aquatic species.

Rainfall variability also plays a substantial role in shaping river behaviour. High-intensity rainfall events correspond with spikes in turbidity and dramatic increases in suspended sediment concentrations. These sediment surges can modify channel morphology, degrade water quality, and impair navigation and ecological functions. Conversely, years with deficient monsoon rainfall lead to reduced discharge, accelerated sediment deposition, and shrinking water spread.

The results demonstrate that climate variability is increasingly replacing historical seasonal patterns as the dominant force governing the Ganga's hydrological and geomorphic responses.

5.3 Comparison with Previous Studies

The findings of this research align with numerous previous studies that have documented climate-induced alterations in the Ganga basin. Earlier work highlighting glacial retreat, changes in monsoon timing and intensity, and increased evapotranspiration provides context for the observed hydrological contractions and thermal increases. The present study extends these insights by offering basin-wide, satellite-derived evidence of shifts in water extent, temperature patterns, sediment dynamics, and channel behaviour.

Research on channel migration in the Ganga plains has documented the inherently dynamic nature of its fluvial processes. This study reinforces those observations and provides more detailed spatial insight into the magnitude and distribution of erosional and depositional hotspots, suggesting that such processes are intensifying under climate variability.

Similarly, previous studies of inland water temperature trends across India report warming consistent with the patterns identified here. The present analysis contributes a focused assessment of thermal shifts in a major river system, linking atmospheric warming to changes in surface water temperature.

Overall, the findings corroborate existing literature while adding new, integrated evidence grounded in multi-temporal remote sensing techniques.

5.4 Implications for River Management and Regional Water Security

The documented changes have far-reaching implications for water management, ecological conservation, and regional development. Declining pre-monsoon flows threaten irrigation reliability, drinking water availability, and industrial operations in downstream regions heavily dependent on the Ganga. Increasing surface water temperatures may reduce aquatic biodiversity and intensify ecological stress.

Sediment dynamics pose additional challenges. Increased sediment loads during extreme rainfall events can accelerate riverbank erosion, silt up navigation channels, and strain embankments and hydraulic structures. Changing channel morphology complicates flood risk mapping and long-term infrastructure planning.

These findings underscore the need for adaptive, climate-responsive river management strategies, including:

• Establishing real-time satellite-based monitoring systems

• Enhancing groundwater recharge to stabilize base flows

\• Implementing catchment restoration and erosion-control measures

• Designing riverfront and flood-control infrastructure to accommodate increased channel mobility

• Maintaining ecological flows to support aquatic ecosystems under warming conditions

Effective management of the Ganga River in the coming decades will require integrating these climate-informed approaches into policy, planning, and operational frameworks.

5.5 Limitations of the Study

Despite its robust methodological design, the study has certain limitations. Optical satellite imagery is often constrained by cloud cover, especially during monsoon months, which limits temporal consistency. Although SAR data help mitigate this issue, sediment and surface temperature analyses rely primarily on optical sensors.

Surface water temperature estimates represent near-surface conditions and may not capture vertical thermal gradients in deeper reaches. Similarly, turbidity and sediment estimates derived from spectral indices are subject to uncertainties associated with varying water depth, mineral composition, and organic matter content.

Additionally, although the study focuses on climate-driven changes, anthropogenic influences such as dam operations, sand mining, land-use changes, and pollution also play significant roles in shaping river dynamics. These factors, while acknowledged, are beyond the scope of this analysis.

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Nevertheless, the integration of multi-temporal satellite datasets with climatic variables provides a strong basis for detecting and interpreting broad-scale environmental changes in the Ganga River.

6. Conclusion and Recommendations

This study employed multi-temporal remote sensing techniques and climatic datasets to evaluate how climate variability is reshaping the hydrological, thermal, sedimentary, and geomorphological characteristics of the Ganga River. The integrated analysis reveals a complex but discernible pattern of climate-induced transformations affecting both the physical structure and ecological functioning of the river. The following subsections summarize the major findings, discuss their broader implications for climate resilience, and provide policy and research recommendations aimed at strengthening river basin management under future climatic uncertainty.

6.1 Summary of Major Findings

The assessment of water spread patterns shows a clear reduction in pre-monsoon water extent throughout large segments of the basin, reflecting declining base flow and increased evapotranspiration driven by rising temperatures. While monsoon rains continue to replenish the system, the variability in seasonal flooding and rapid post-monsoon contraction indicates a greater dependence on monsoon rainfall and reduced hydrological stability.

Surface water temperature demonstrated a consistent warming trend, with rates more pronounced in shallow stretches and urban-influenced zones. These thermal shifts are closely aligned with regional atmospheric warming and have implications for riverine ecology, including reduced oxygen availability and altered habitat conditions.

Sediment and turbidity analyses reveal heightened sensitivity to rainfall intensity. Extreme precipitation events correspond with elevated sediment loads, increased turbidity, and expanded erosion zones, while years of deficient rainfall promote sediment deposition and restricted flow channels. Spatial patterns of channel migration indicate widespread morphological instability, driven by fluctuating discharge regimes and intensified hydrological extremes.

Together, these results provide clear evidence that the Ganga River is undergoing significant, climate-linked hydrological and geomorphological changes, with implications for both natural systems and human livelihoods.

6.2 Implications for Climate Resilience in the Ganga Basin

The observed changes highlight emerging vulnerabilities in the Ganga Basin's water security and ecological integrity. Declining dry-season flows challenge agricultural productivity, drinking water supply, and industrial operations in downstream regions. Increasing water temperatures threaten aquatic biodiversity, particularly species dependent on cooler, oxygen-rich environments.

Sediment surges and unstable channel morphology pose ongoing risks to infrastructure, including embankments, navigation routes, and riverbank settlements. Flood management becomes more complex as river behaviour grows increasingly variable and less predictable. These trends suggest that conventional management strategies, based on historical hydrological patterns, may not adequately address future climate uncertainty.

Building climate resilience in the basin will require proactive, adaptive approaches that integrate continuous monitoring, flexible management frameworks, and long-term planning.

6.3 Policy Recommendations

Based on the study's findings, several actionable policy recommendations emerge:

• Develop a comprehensive, basin-wide remote sensing–based monitoring system for real-time tracking of water extent, sediment load, channel migration, and thermal patterns.

• Incorporate climate projections into river basin management plans, ensuring that water allocation, flood control, and irrigation strategies are climate-responsive.

• Implement large-scale catchment restoration programmes to reduce soil erosion, stabilize upstream slopes, and mitigate sediment inflow.

• Regulate activities such as sand mining, unplanned riverfront development, and embankment construction, which can exacerbate channel instability under variable hydrological regimes.

• Establish and enforce ecological flow requirements to sustain riverine ecosystems, particularly during prolonged dry periods.

• Promote inter-state coordination within the Ganga Basin to ensure unified and coherent management strategies across administrative boundaries.

These measures can strengthen the basin's adaptive capacity and help mitigate climate-induced risks.

6.4 Future Research Directions

Although this study provides valuable insights into climate–river interactions, several areas merit further investigation:

• Integrating hydrodynamic modelling with climate scenario analysis to simulate future changes in flow, sediment transport, and channel morphology.

• Examining the combined effects of anthropogenic interventions—such as dam operations, land-use change, and pollution—alongside climate variability.

• Conducting detailed ecological assessments to evaluate how changes in temperature, flow, and turbidity affect aquatic biodiversity and ecosystem services.

• Leveraging advanced remote sensing platforms, including hyperspectral sensors and cloud-computing environments such as Google Earth Engine, to improve temporal and spatial resolution of river monitoring.

• Expanding field-based sediment and water quality measurements to strengthen calibration and improve the accuracy of satellite-derived estimates.

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Such research would enhance understanding of river system responses to climate change and support the development of more effective, science-based adaptation strategies.

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