

Assessing Climate Change Impacts on Wetland Vegetation and Water Resources through Rainfall-Driven Ecohydrological Indices: Satellite-based evidence from the Kabartal Wetland Region, Bihar

Manu Raj Sharma

fakeersharma@gmail.com

Lalit Narayan Mithila University

Abhishek Akarsh

Lalit Narayan Mithila University

Research Article

Keywords: Climate-resilient, Ecosystem Health, Ecohydrological Change, Kabartal Wetland Region, Rainfall Variability, Water Accessibility and Management, Wetland Sustainability, Water Security, Sustainable Development, Climate Change

Posted Date: October 9th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10859407/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: No competing interests reported.

**Assessing Climate Change Impacts on Wetland Vegetation and Water Resources
through Rainfall-Driven Ecohydrological Indices: Satellite-based evidence from the
Kabartal Wetland Region, Bihar**

Manu Raj Sharma¹ and Abhishek Akarsh²

¹ Assistant Professor, University Department of Geography ^a, Remote Sensing Lab, Advanced
Research Centre ^b, LN Mithila University, Darbhanga, Bihar, India

² Research Scholar, University Department of Geography, Remote Sensing Lab, Advanced
Research Centre ^b, LN Mithila University, Darbhanga, Bihar, India

Corresponding author: fakeersharma@gmail.com

1. Abstract

Wetlands are dynamic socio-ecological systems whose persistence and ecological functioning are strongly regulated by hydroclimatic variability. Changes in precipitation, surface-water availability, vegetation dynamics, and atmospheric evaporative demand can alter wetland hydrology, ecosystem productivity, and resilience, particularly under increasing climatic and anthropogenic pressures. This study evaluates the long-term ecohydrological transformation of the Kabartal Wetland Region (KWR) sBihar, India, by integrating climatic, hydrological, evapotranspiration, and satellite-derived ecological indicators. Long-term rainfall variability and trends were assessed for 1901–2024 using the Seasonality Index (SI), Rainfall Anomaly Index (RAI), 90% dependable rainfall, Modified Mann–Kendall (MMK) test, and Sen’s slope, while actual evapotranspiration (ET) and potential evapotranspiration (PET) were analysed for 2002–2024. Landsat-derived Modified Normalized Difference Water Index (MNDWI) and Normalized Difference Vegetation Index (NDVI) were used to quantify changes in surface-water extent and vegetation cover during pre- and post-monsoon periods between 1989 and 2024.

The results reveal a substantial contraction of wetland surface-water extent, declining from 31 to 14 km² (54.83%) during pre-monsoon and from 44 to 19 km² (56.81%) during post-monsoon between 1989 and 2024. Rainfall exhibited strong seasonality, with SI values predominantly ranging from 0.8 to 1.4, indicating prolonged dry periods and concentration of precipitation within a short monsoonal window. RAI analysis indicates a progressive shift from predominantly wet conditions towards more frequent negative rainfall anomalies, particularly after 2000. Annual rainfall declined significantly across Begusarai, Samastipur, and Khagaria,

with Sen's slopes of -1.54 , -1.72 , and -2.34 mm yr^{-1} , respectively, while monsoonal rainfall also exhibited significant decreasing trends. Historical mean annual rainfall of approximately 1,131, 1,170, and 1,154 mm in the three districts is projected to decline to about 1,025, 1,054, and 985 mm by 2044, respectively. Despite the region's generally humid, water-surplus character, the ET–PET relationship shows pronounced seasonal moisture limitation, with annual PET ranging from approximately 1,950–2,450 mm compared with ET of only 350–650 mm. Rainfall was positively correlated with ET ($r = 0.5$) and latent heat flux ($r = 0.5$) but negatively correlated with PET ($r = -0.5$), demonstrating the sensitivity of ecosystem water use to precipitation availability and atmospheric demand.

The convergence of declining rainfall, increasing rainfall variability, reduced surface-water extent, vegetation degradation, and persistent ET–PET disequilibrium indicates that KWR is undergoing a progressive transition from a predominantly water-surplus wetland system towards increasing seasonal hydro ecological stress. These findings highlight the need to restore river–wetland connectivity, protect wetland catchments and vegetation, regulate water extraction and land-use conversion, enhance monsoon-water retention, and strengthen community-based and climate-resilient wetland governance. Such integrated interventions are essential to maintain wetland ecological integrity, strengthen regional water security, and advance Sustainable Development Goal 6 (SDG 6) on sustainable water management.

Keywords: Climate-resilient; Ecosystem Health; Ecohydrological Change; Kabartal Wetland Region; Rainfall Variability; Water Accessibility and Management; Wetland Sustainability; Water Security; Sustainable Development; Climate Change

2. Introduction

Wetlands are distinct, environmentally diverse ecosystems formed by the interaction of biospheric and hydrological processes, making them a valuable environmental resource [1] It accounts for about 6% of the Earth's total surface [2] and is regarded as one of the most productive ecosystems, contributing significantly to nutrient biogeochemical cycling and providing vital functions, including water purification, flood attenuation, groundwater recharge, nutrient cycling, carbon sequestration, sediment trapping, habitat, biodiversity and climate stabilisation [3] [4]. The Ramsar Convention has categorised wetlands into three groups: Marine and Coastal Wetlands, Inland Wetlands, and Human-made Wetlands, which are further divided into 42 groups. The Convention on Wetlands Global Wetland Outlook 2025

estimates that, since 1970, 411 million hectares of wetlands have been lost worldwide, representing a 22% reduction in global extent, with an average annual rate of decline of 0.52%. Furthermore, 25% of the world's remaining wetlands are classified as in a poor ecological state, and their status is steadily worsening [5].

Climate change and human activities altogether have degraded approximately 50% of the wetlands globally over the past few decades, altering their ecosystems and biogeochemical processes. It has resulted in a reduction in the value of ecosystem services, biodiversity loss, and a decline in the availability of water resources of the wetlands [6]. Since 1950, numerous geographical regions have seen increased aridity, as evidenced by historical records of precipitation, streamflow, and drought indices [7]. Between 1970 and 2015, 21%-35% of the world's wetlands were lost, with some regions losing more than 50% of their total area [8]. A study on the wetlands of the Liaohe River Basin, China, demonstrates that anthropogenic activities impose greater pressure on wetland degradation than climate change. Model projections estimate that the wetland area, which is expected to cover 1575.82 km² in 2030, will decline to 1015.63 km² in 2090, accompanied by a loss of suitable habitats for coastal vegetation, highlighting the need for targeted conservation [9]. Using hydrological modelling and soil moisture data [10] forecast that climate change will result in a net area loss of at least 6,000 sq. km. (about 1%) in inland Ramsar wetlands by 2100.

A global assessment shows that a one-meter rise in sea level, driven by climate change, would place coastal wetlands worldwide at risk of horizontal shift or permanent loss of nearly 10% in Asia (notably in India, Bangladesh, and Myanmar), compared with 6% in South America, 5% in South Africa, 2.6% in North America and Europe, and 0.5% in Australia [11]. Rising temperatures affect wetland functioning; if global warming reaches 1.5-2 °C, the wetlands' ability to sequester greenhouse gases may be reduced by 57% [9].

The impact of climate change, such as increasing temperatures, erratic precipitation, and prolonged droughts, has led to a reduction in the surface area of the Lake Chad Wetland by approximately 90% [12]. Hamun Hilmand Lake in Afghanistan declined by 96.4% between 2008 and 2022 due to prolonged drought and decreasing rainfall [13]. Climate change in the Tibetan Plateau has driven rising temperatures and increased precipitation variability, leading to the conversion of palustrine wetlands to grasslands and their degradation [14]. Between 2000 and 2017, rising temperatures and declining precipitation led to a reduction in wetland areas in

West Bengal, with Bhomra, Mathura, and Chandania wetlands shrinking by 57.68%, 37.20%, and 44.07%, respectively, negatively impacting fish production [15].

Variations in temperature and precipitation patterns affect water availability and quality, disrupting the functioning of wetland ecosystems. A future temperature and precipitation forecast using canESM2 and hadGEM2 climate models, combined with MNDWI-based area estimation, indicates that the Arjan Wetland in Iran will experience a decline in extent and face increasing drought conditions [16]. Droughts reduce the water availability of wetlands, resulting in vegetation loss and a decrease in water quality, affecting the entire wetland food web [17]. Wetlands store nearly 30% of global soil carbon [18]. However, climate change-driven degradation may potentially alter their role from carbon sink to carbon source [19].

Agriculture accounts for nearly 70% of global freshwater withdrawals, and despite growing competition for water, agricultural withdrawals continue to increase [20]. Inland wetland degradation is primarily driven by water abstraction and drainage for agriculture, which disrupts natural hydrological cycles and leads to hydrological droughts [21]. Global food demand is expected to rise as the global population reaches 9.7 billion by 2050, leading to intensified fertiliser and pesticide use within or near wetlands, which results in nutrient enrichment, impacting the ecology, including eutrophication, invasive species proliferation, nutrient leaching, and shifts in species composition [22]. In Iran's Amirkalayeh International Wetland, analyses of sediment and water revealed toxic element concentrations exceeding permissible limits in areas affected by agricultural surface runoff from intensive rice cultivation [23]. In Bihar's Kabartal wetland, trace element concentrations exceed permissible limits, primarily due to the use of excessive fertilisers in agricultural practice in and around the wetlands, which disrupts the ecosystem [24].

Remote sensing, GIS, and large learning models/Machine Learning Models enable high-resolution wetland ecosystem mapping for land cover classification and change detection [25]. Using remote sensing and geospatial techniques, Burullus wetland experienced significant ecological decline in 2016 and 2019 compared to 1984 and 1986, mainly due to LULC changes, human interventions, and resource overuse [26]. In the El-Burullus wetland, Egypt, remotely sensed data indicate that wetland and bare soil extents have diminished while vegetation cover has increased [27]. Multi-temporal remote sensing and geospatial techniques analysed that the area of the Tianjin wetland in China declined between 1990 and 2020, with a net loss of 655.64 km² due to urbanisation [28]. Machine learning-based assessments of land use and land cover

dynamics in the Long Xuyen Quadrangle of the Mekong Delta (Vietnam) reveal a substantial decline in wetlands, accompanied by an expansion of arable croplands and aquaculture, driven by increasing urbanisation and agricultural intensification [29]. NDWI and MNDWI analysis of Ropar wetland showed a slight decline in the water body [30], while NDVI and MNDWI assessment of Rasik Beel revealed alterations in shallow water areas [31]. In the Meyghan wetland, SPI and MNDWI analyses revealed an increasing trend in drought, driven by declining moisture content [32]. The extent of the Kabartal Wetland has been declining, as indicated by analyses using the MNDWI and NDVI indices [33]. The area of Lake Kabartal has reduced by 66% between 1986 and 2010 [34].

Wetland ecosystems are primarily composed of vegetation, which is vital for regulating hydrological and biogeochemical cycles and land-surface energy exchange [35], and contribute to climate change mitigation by sequestering atmospheric carbon [36]. There are numerous aquatic plant species in wetlands, including water hyacinth (*Pontederia crassipes*), water lily (*Nymphaea*), mosquito fern (*Azolla pinnata*), lotus (*Nelumbo nucifera*), and many others [37] which demonstrate phytoremediation potential by absorbing heavy metals and various pollutants from water, making them viable for cleaning polluted aquatic ecosystems [38]; [39]. Climate change and increasing human interference have led to a decline in the proportion of wetland vegetation worldwide [40]. Aquatic vegetation in India's wetlands is highly dependent on precipitation and surface temperature and declines due to sedimentation, turbidity, and water-level alterations, thereby reducing light availability for plant growth [41]. In Baiyangdian Wetland, a freshwater ecosystem in China, extreme precipitation caused widespread mortality of dominant vegetation (reeds and lotus), thereby significantly reducing overall ecological quality [42]. Coral bleaching events are increasing due to rising sea temperatures [43], and 99 per cent of corals could be lost with 2°C of warming [44].

India, with its varied topography and climatic zones, comprises 24,90,584 wetlands (area greater than 0.1 hectares), covering 5.12 per cent of the country's geographic area [45], and 101 Ramsar sites. Bihar, a hydrologically diverse and flood-prone state with a monsoonal climate, comprises 2,53,438 wetlands covering 476520.6 hectares, approximately 5 per cent of its geographic area [45]. This region lies within the Indo-Gangetic Plain, where seasonal flows feed numerous depressions forming natural wetlands [46]. In northern Bihar, wetlands are sustained primarily by monsoonal precipitation and annual streams such as the Adhwara group, Baghmati, Kosi, Gandak, and Budhi Gandak [47]. Bihar has six Ramsar sites. Lake Kabartal is a Ramsar site and one of India's largest natural oxbow lakes. North Bihar districts such as

Darbhanga, Madhubani, Araria, Madhepura, Saharsa, Supaul, Purnea, Kishanganj, and Katihar are experiencing ecological imbalance and declining water bodies due to hydro-climatic stress, rising LST, and dense aquatic vegetation in shallow water systems [48]. The decreasing rainfall trend in Madhubani, Bihar, is significantly influencing the wetland water quality, productivity, biodiversity, and annual groundwater recharge [47]. The Ganga riparian wetlands in Patna are in crisis due to agricultural drainage, water system control, and urban development activities, including excavation, filling, and draining [49]. An optimum balance between livelihood, conservation and utilisation will ensure the sustainability of the wetlands.

This study aims to analyse spatiotemporal variation in eco-hydrological changes in the KWR. Comprehensive research is lacking, which is crucial for understanding wetland dynamics and mitigating their impacts on humans. Understanding the interrelationship between rainfall variability and ecological changes is essential, as this region lies between the Budhi Gandak and Baghmata Rivers and supports an agrarian economy highly dependent on rainfall.

3. Study area

The Kabartal Wetland Region (KWR) is located in the lower Indo-Gangetic Plains in the administrative state of Bihar, India, which is home to numerous wetlands of various sizes and configurations. Pedologically, it is one of India's most fertile regions with substantial scope for agricultural development. It is a densely populated region where most people depend on agriculture for their livelihood, and the economy depends on the timely onset of rainfall, which affects agriculture and allied activities.

The Kosi-Gandak interfan zone of the East Ganga Plains (EGP) is extensively dotted with numerous wetlands. This region is fluvially highly dynamic. The Budhi Gandak and Baghmata are the major rivers flowing through this interfluvium, along with numerous seasonal and local streams. Owing to the flat terrain and aggradation regime, most rivers in this region exhibit decadal-scale avulsions and are termed 'hyperavulsive'. The Budhi Gandak and Baghmata Rivers drain the Mithila plains and exhibit a meandering morphology (Fig. 1). The Budhi Gandak River in the west and the Baghmata River in the east form the boundaries of this region. This region encompasses Begusarai, Samastipur and Khagaria districts. The KWR contains numerous wetlands, including Lake Kabartal, one of the largest natural oxbow lakes in India. It formed from the meandering of the Budhi Gandak River, a tributary of the Ganga, in the geological past. The region's average elevation is 44 m above mean sea level. This region falls within the subtropical monsoon (Cwa) climatic zone, where the monsoon is the predominant

season and significantly affects wetland dynamics and land use. The average annual rainfall in this region ranges between 1100 and 1200 mm, which is mainly contributed by the south-westerly monsoon [50]. The Kabartal Wetland Region experiences high rainfall variability, resulting in recurrent floods and droughts that threaten the wetland's sustainability.

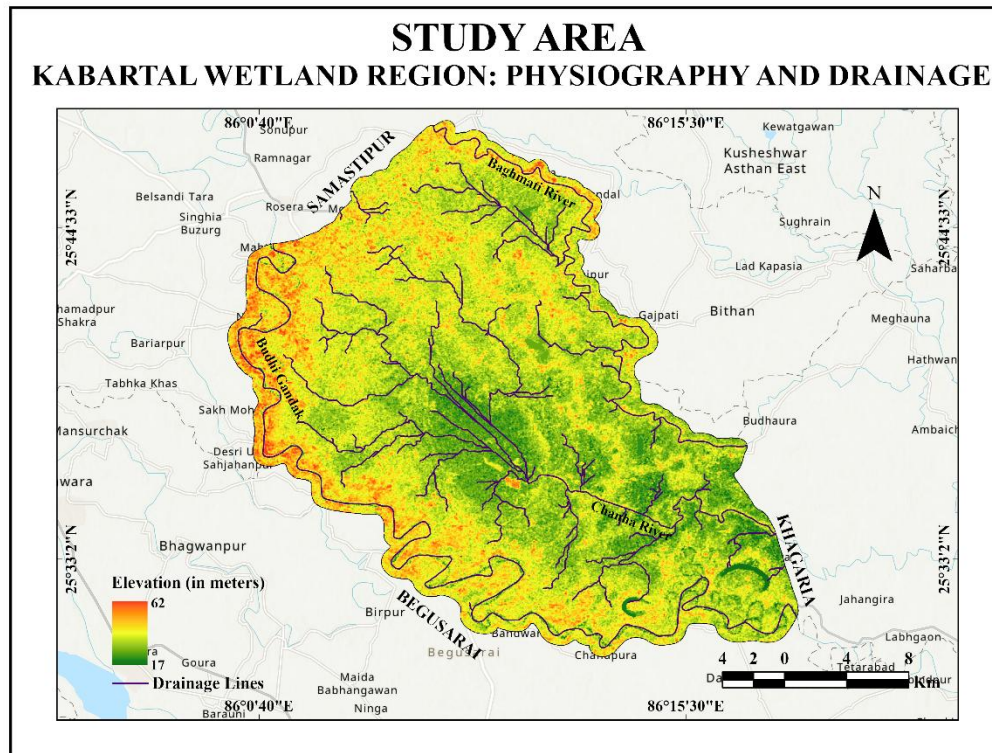


Fig. 1: Study Area
Source: Based on SRTM DEM, USGS

4. Objectives

The study aims to analyse the ecohydrological changes in the wetlands of the Kabartal Wetland Region (KWR) by examining variations in hydrological and ecological conditions over time. It further seeks to assess seasonal and annual rainfall variability, interdependencies, and long-term trends within the KWR to understand their implications for regional hydrological processes. The study also aims to project future rainfall trends to identify potential declines in precipitation and associated changes in water availability. Finally, it seeks to determine how rainfall variability affects the sustainability and ecological functioning of wetlands in the KWR, with particular emphasis on the implications of changing precipitation regimes for wetland persistence and resilience.

5. Data Sources and Methodology

The study integrates rainfall variability and satellite-based indicators to assess spatiotemporal ecohydrological changes in the KWR. Here, secondary data sources were utilised and grouped into two categories. The first group includes remotely sensed satellite data from the United States Geological Survey (USGS) Earth Explorer. The Digital Elevation Model (DEM) of the Kabartal Wetland Region was obtained from the USGS Shuttle Radar Topography Mission (SRTM) with a spatial resolution of 30 m. Satellite imagery from Landsat 8 OLI (Operational Land Imager) and Landsat 5 TM (Thematic Mapper) with a spatial resolution of 30 meters was collected for the period 1989 to 2024 for hydrological analysis. Here, Landsat Collection 2 Level-2 datasets were utilised as these are analysis-ready surface reflectance and temperature data after removing atmospheric distortions and do not require further corrections.

Long-term monthly rainfall data (1901-2024) were obtained from the India Meteorological Department (IMD) to examine rainfall variability, trends, and patterns. Here, district-wise rainfall data were utilised over gridded data as the study area is relatively small, incorporating few grid cells, which would yield a uniform value for the entire region, making them less effective for capturing microclimatic variations. We identified missing rainfall values and replaced them with the mean of previous years through an imputation method. Seasons were categorised as Winter (Jan-Feb), Pre-Monsoon (Mar-May), Monsoon (June Sept), and Post-Monsoon (Oct-Dec).

Evapotranspiration regulates moisture circulation and water evaporation, which are essential components of the hydrological cycle. Terra MODIS (MOD16A2GF product) datasets, a gap-filled 8-day composite at 500 m resolution, were used to analyse the evapotranspiration dynamics in the KWR from 2002-2024. These values have been converted to actual evapotranspiration (mm per 8-day period) with a recommended scale factor of 0.1. Monthly, seasonal, and annual actual and potential evapotranspiration were evaluated to assess moisture demand in this region. The aridity index, water deficit, and standardized water deficit were computed to determine moisture availability and hydrological stress in the region. Correlation analysis was done to understand the relationship between rainfall, ET and PET.

For ecological evaluation, indices such as the Modified Normalised Difference Water Index (MNDWI) and the Normalised Difference Vegetation Index (NDVI) were employed, and for hydrological assessment, the Seasonality Index, Rainfall Anomaly Index, Dependable Rainfall, and the Modified Mann-Kendall Test were utilised. Maps, graphs, and tables have been prepared using ArcGIS Pro, Python, and Microsoft Excel.

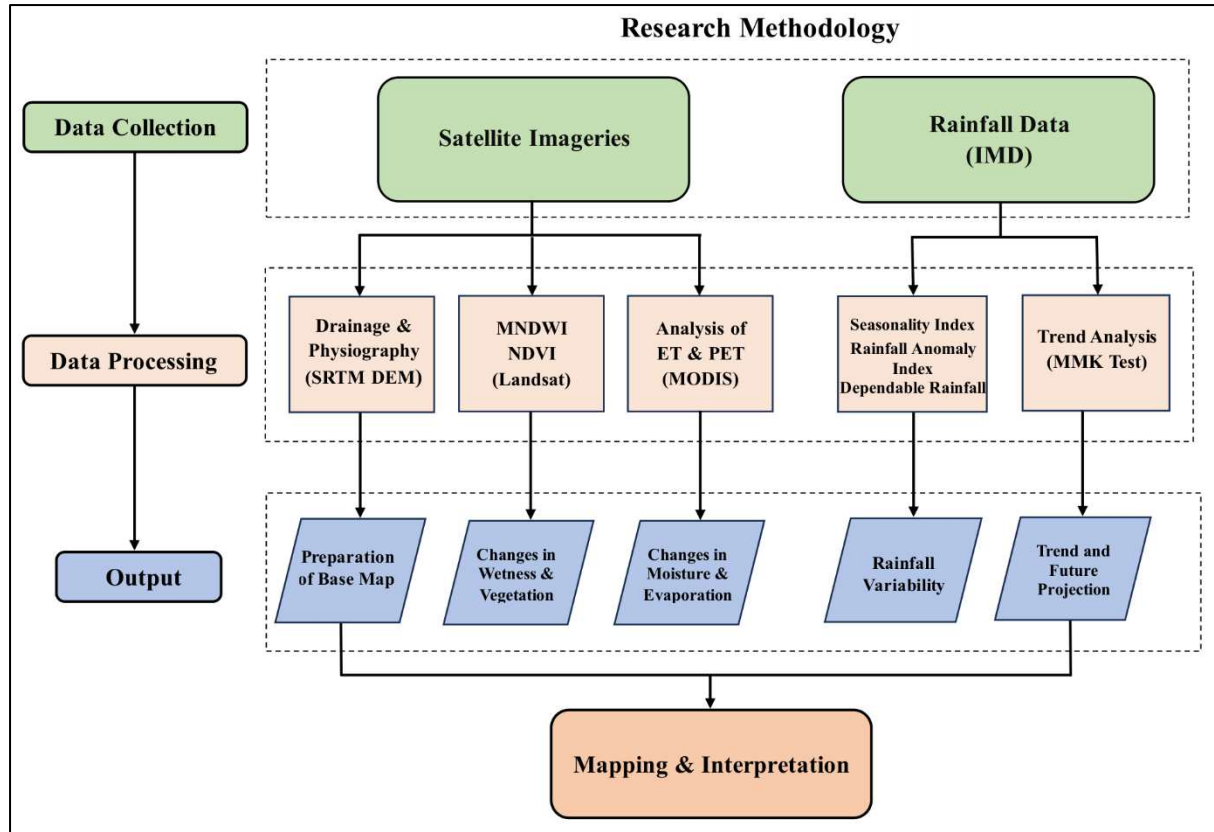


Fig. 2: Data Sources and Methodology

5.1 Modified Normalized Difference Water Index (MNDWI)

MNDWI is a water-based index that identifies water-related features (wetness) of the landscapes using the green (GREEN) and short-wave infrared (SWIR) bands [51]. This index detects the presence of surface water in areas influenced by vegetation and soil moisture [30].

$$MNDWI = \frac{GREEN - SWIR}{GREEN + SWIR}$$

The MNDWI value ranges from -1 to +1, with positive values indicating wet areas and negative values indicating dry areas. MNDWI is preferred over NDWI (Normalized Difference Water Index) as it enhances the distinction between water bodies and built-up land by amplifying the reflectance response of water while suppressing that of built-up areas, soil, and vegetation, which generally have negative values.

5.2 Normalized Difference Vegetation Index (NDVI)

NDVI is a quantitative assessment of biomass, vegetation health, and growth that measures the difference between near-infrared (NIR) and red (RED) components of electromagnetic radiation. The NDVI value ranges between -1 and +1, with densely vegetated areas trending

toward positive values and water and built-up areas having approximately zero or negative values.

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

5.3 Seasonality Index (SI)

The seasonality index assesses the degree of variability in rainfall regimes [52]. It helps to identify the rainfall regimes based on the monthly rainfall distribution and ideally, the values range between 0 (if all the months have equal rainfall) to 1.83 (if total annual precipitation occurs in one month only) [53]. The region exhibits a seasonal pattern only when SI exceeds 0.6 (Fig. 3). The higher the seasonality index, the greater the variability in water resources and scarcity over time, making the area more sensitive to droughts.

Extreme, almost all rain in 1-2 months	Most rainfall in 3 months or less	Markedly seasonal with a long drier season	Seasonal	Rather seasonal with a short drier season	Equable but with a definite wetter season	Very equable
≥1.20	1-1.19	0.8-0.99	0.6-0.79	0.4-0.59	0.2-0.39	≤0.19

Fig. 3: Seasonality Index
Source: Based on classification by [52]

5.4 Rain Anomaly Index (RAI)

The Rainfall Anomaly Index (RAI) measures the frequency and intensity of dry and wet years and identifies anomalies [54]. It uses a ranking system in long-term data to assign magnitudes to positive and negative precipitation anomalies (Table 1) using a normalization process.

Table 1. Rainfall Anomaly Index

	Rainfall Regime	RAI Categories
A.	Extremely wet	≥ 3
	Very wet	2 to 2.99
	Moderately wet	1 to 1.99
	Slightly wet	0.5 to 0.99
B.	Near normal	-0.49 to 0.49
C.	Slightly dry	-0.99 to -0.5
	Moderately dry	-1.99 to -1
	Very dry	-2.99 to -2
	Extremely dry	≤ -3

Source: [55]

5.5 Dependable Rainfall

Rainfall expected to occur in a given period with a certain probability is defined as dependable rainfall [56]. Dependable rainfall is usually determined by long-term frequency analysis; it is the minimum rainfall required to sustain water resources and supports effective planning for irrigation, agricultural activities, and wetlands.

5.6 Modified Mann-Kendall Test (MMK Test)

The Mann-Kendall test is a non-parametric statistical method extensively used in numerous studies for analysing seasonal and annual trends of rainfall [2]. It detects monotonic trends in a time series and is suitable for analysing data with outliers, non-linear trends, and non-normally distributed variables. The MMK test determines the significance of the change, while Sen's slope approach estimates the rate of change in rainfall indices [57]. Graphs of the MMK test have been prepared in MS Excel.

6. Results and Discussions

Ecohydrological changes are alterations in hydrological–ecological interactions driven by variation in rainfall, groundwater, climate, and anthropogenic activities, affecting vegetation, water availability, and ecosystems. This study highlights the dynamic interrelationship among rainfall variability, changing evapotranspiration mechanisms, water availability, vegetation responses, and the hydrological conditions of water bodies.

6.1 Ecological Parameters

Ecological parameters provide insights into the functioning and overall health of wetland ecosystems, as variations in moisture, water availability and vegetation cover can influence habitat, biodiversity, and ecosystem health. Wetness, the spatial extent of water bodies, and vegetative cover have been analysed using MNDWI and NDVI. These indices provide a comprehensive view of ecohydrological changes and their implications for wetland ecosystems.

6.1.1 Spatial Distribution of Wetness using MNDWI

MNDWI is a hydrological indicator that utilises the short-wave infrared (SWIR) and green (GREEN) spectral bands to enhance water body extraction by reducing the influence of built-up land and vegetation. To understand the impact of monsoonal rainfall within a single climatic

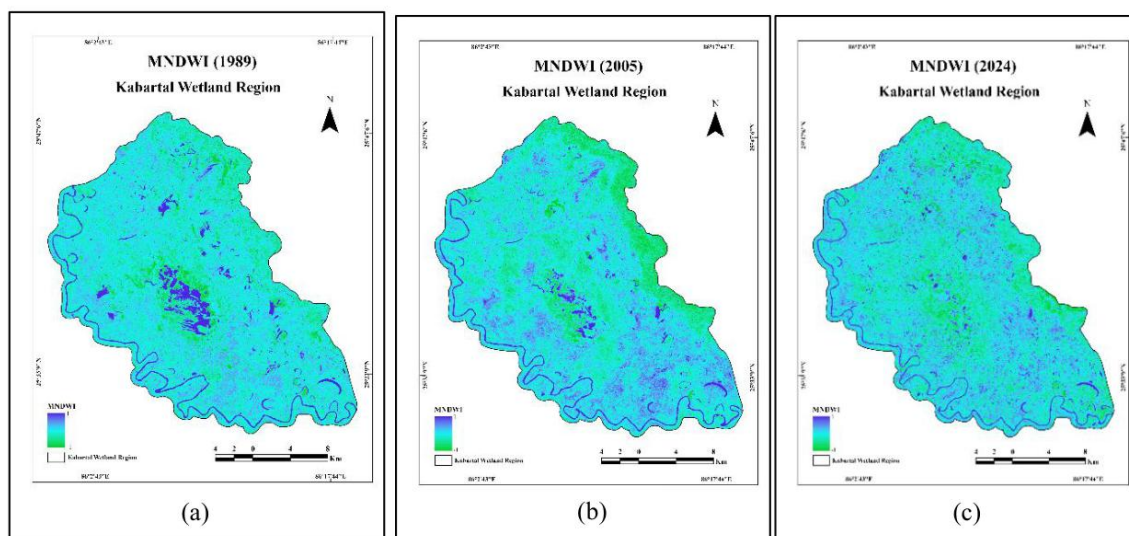
cycle, the pre-monsoon and post-monsoon variations in the Kabartal Wetland Region have been analysed between 1989 and 2024. After analysing the results, it is evident that the wetness and area of water bodies in the Kabartal Wetland Region have decreased over the years in both seasons.

Lake Kabartal is centrally located within the KWR, while numerous other wetlands are distributed mainly in the northern and southeastern regions, where wetness remains relatively high. Areas surrounding rivers and wetlands also show higher wetness because of their proximity to water sources. The pre-monsoonal wetness conditions for 1989, 2005, and 2024 are shown in Fig. 4a-4c, where the value of MNDWI ranges between 0.18 and -0.31, 0.09 and -0.34 and 0.09 and -0.292, respectively, which indicates that wetness levels were highest in 1989, particularly within and around the wetlands and water bodies. Lake Kabartal exhibited the highest wetness (0.18) in 1989; however, a marked decline in 2005 and a drastic reduction (0.09) in 2024, along with an increase in vegetation, bare soil and built-up areas. A similar pattern is observed during the post-monsoonal season (Fig. 4d-4f), with values ranging from 0.22 to -0.72, 0.2 to -0.32 and 0.15 to -0.46 for 1989, 2005 and 2024, respectively. In 1989, extensive wetlands of varying sizes were prominent in the northern and southeastern regions, but they had significantly decreased by 2005 and were severely reduced in 2024, with Lake Kabartal showing very little wetness in the latter years.

In 1989, wetland areas during the pre-monsoon and post-monsoon seasons were 31 sq. km. and 44 sq. km., respectively. By 2005, these areas had decreased substantially to 15 sq. km. during the pre-monsoon season and 22 sq. km. during the post-monsoon season. In 2024, they fell to 14 sq. km. during the pre-monsoon season and 19 sq. km. during the post-monsoon season. Overall, wetlands declined by 54.83% during the pre-monsoon period and 56.81% during the post-monsoon period between 1989 and 2024 (Table 2). MNDWI analysis identifies a substantial temporal reduction in wetness and surface-water extent across both seasons in the Kabartal Wetland Region.

Spatial Distribution of Wetness using MNDWI

Pre Monsoon



Post Monsoon

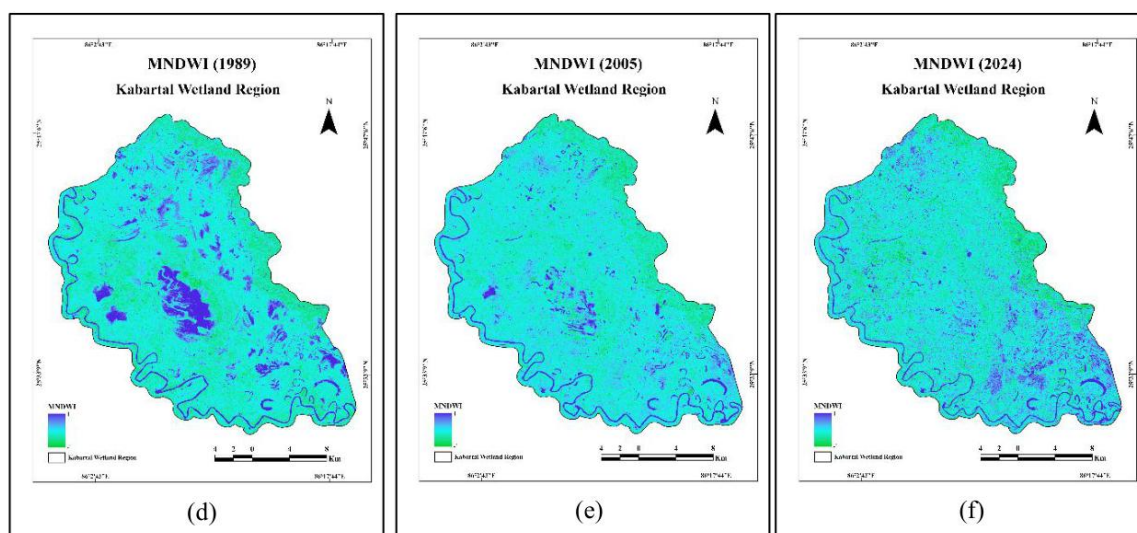


Fig. 4: Spatial Distribution of Wetness using MNDWI

Table 2: Area of Waterbodies calculated using MNDWI

Year Season	1989	2005	2024	Change (1989-2024)	Change % (1989-2024)
Pre Monsoon	31 sq. km.	15 sq. km.	14 sq. km.	17 sq. km.	54.83
Post Monsoon	44 sq. km.	22 sq. km.	19 sq. km.	25 sq. km.	56.81

Source: Computed by the authors based on Landsat Data

This reduction in wetland area is expected to be affected by both natural and anthropogenic factors. Climate change-induced variations in rainfall patterns and trends have adversely affected wetlands, most of which depend on seasonal precipitation for recharge. Increasing human encroachment for residential, commercial, and agricultural expansion (Fig. 5) has changed land use and land cover, accelerating wetland loss and degradation.

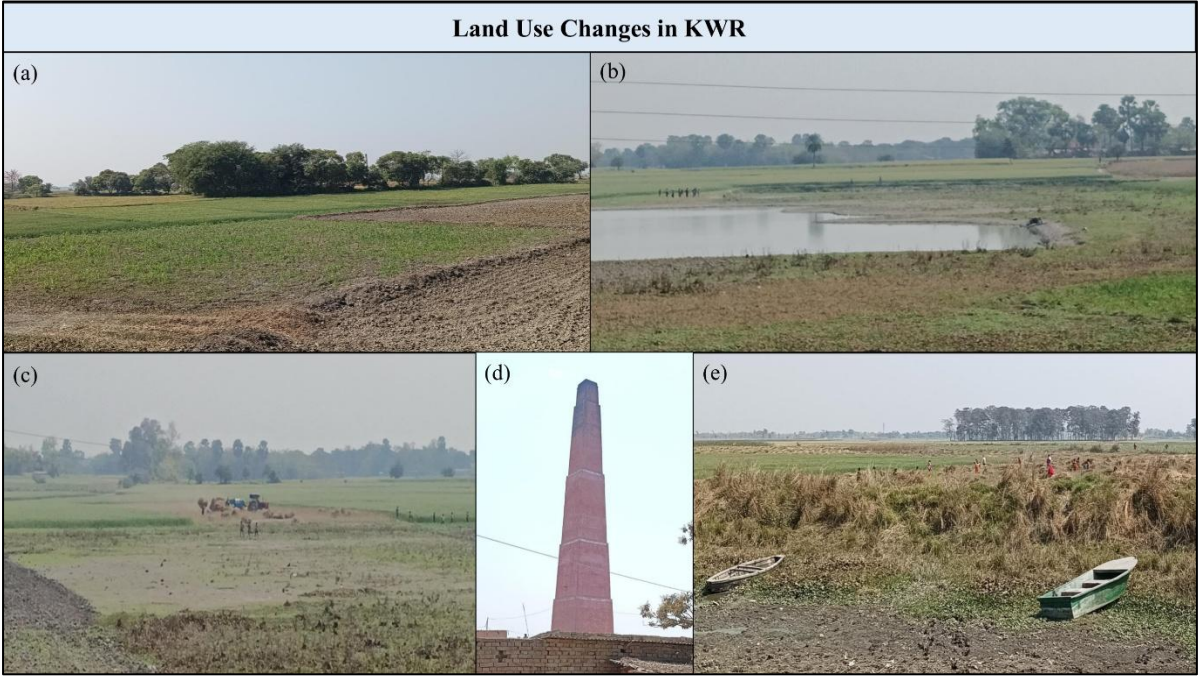


Fig. 5: Land use changes in KWR

(5a) Agricultural practices on dry wetland areas in KWR; (5b) Wetland water extraction for agricultural use; (5c) Transporting harvested crops by tractor from wetland farmland; (5d) Brick kiln in the vicinity of Lake Kabartal; (5e) Cultivated agricultural land in the wetland

6.1.2 Analysing Vegetation Cover using NDVI

The Normalized Difference Vegetation Index (NDVI) is an efficient indicator of vegetative growth and photosynthetic activity, exhibiting vegetation type and vegetative cover in ecological monitoring. Vegetation dynamics are associated with climatic variables such as rainfall and temperature, which impact growth patterns and phenological cycles. Vegetation impacts climate by regulating biogeochemical cycles, mitigating greenhouse gas accumulation and climate warming and modulating moisture and cloud formation via transpiration, hence influencing regional and global precipitation patterns. Some of the common aquatic vegetation in this region are *Nymphaea nouchali* (blue water lily), *Nymphaea alba* (white water lily), *Nelumbo nucifera* (lotus), *Pontederia crassipes* (water hyacinth), *Ipomoea aquatica* (water

spinach), *Limnophila indica*, *Gratiola officinalis* and many more. Here, vegetative cover has been analysed using NDVI during the pre-monsoon and post-monsoon periods for 1989, 2005, and 2024.

The spatiotemporal distribution indicates high vegetative cover in the water-rich region, particularly around water bodies. NDVI value for the pre-monsoon season ranges from 0.41 to -0.08, 0.38 to -0.04 and 0.43 to -0.03 in 1989, 2005 and 2024, respectively. In 1989, the pre-monsoon regime exhibited higher vegetative cover in the northern and western parts of the KWR. The higher vegetation density is evident in the southern part of Lake Kabartal. The green cover was reduced in 2005, with little vegetation in the northern region of the study area. The vegetative cover was significantly reduced in the pre-monsoon season of 2024 (Fig. 6a-6c).

In the post-monsoon season, NDVI values ranged from 0.47 to -0.12, 0.46 to -0.1 and 0.4 to -0.01 in 1989, 2005 and 2024. The concentration of vegetation is highest in the post-monsoonal season of 1989, with dense vegetation in the northern part, whereas in 2005 it decreased substantially. In 2024, it decreased further, but there were patches of green cover in the northeastern part and in Lake Kabartal, mainly due to excessive nutrient concentrations that cause eutrophication. In the southeastern region, sand, water, and barren lands have replaced vegetative cover during the post-monsoonal period in 2024 (Fig. 6d-6f). The loss of vegetation is expected to be related to changing rainfall patterns, the decline of water bodies, and irresponsible human activities.

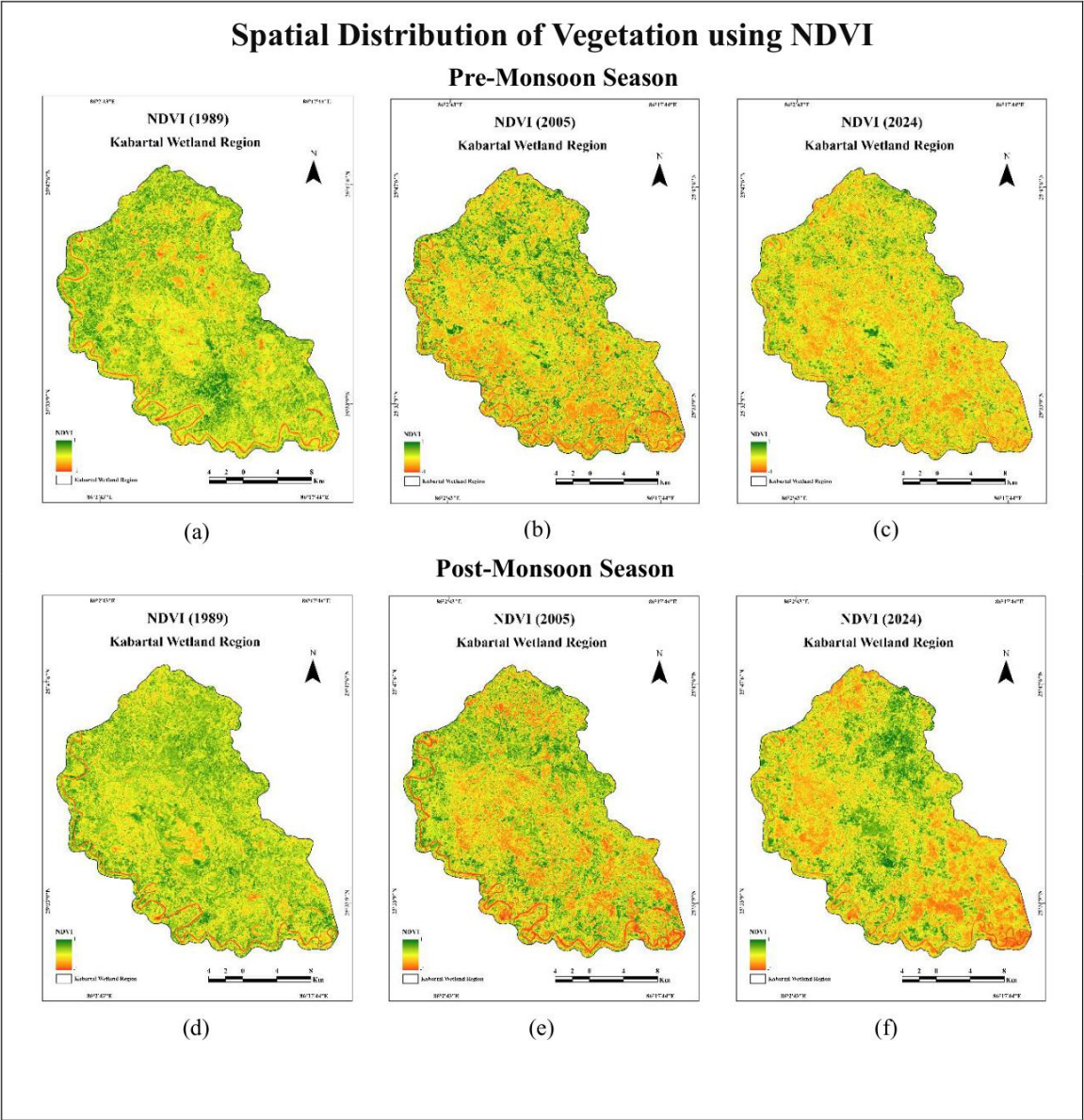


Fig. 6: Spatial Distribution of Vegetation using NDVI

6.2 Hydrological Parameters

Hydrological parameters are the primary drivers of changes and succession in wetland ecological processes and of the seral stages, succession, and extinction of wetlands. Rainfall variability, trends, and patterns have been evaluated under hydrological parameters using various indices. Variability, trends, and patterns influence ecological productivity, thereby affecting the livelihoods and food security of the dependent population.

6.2.1 Evaluation of Rainfall Distribution using Seasonality Index (SI)

The seasonality index quantifies intra-annual rainfall variability, useful for efficient water resource management in the KWR wetlands. It helps to evaluate the intensity of wet and dry phases, which directly influence water availability, flooding patterns, ecological processes, and

overall wetland hydrology. The seasonality index was computed for the period 1901-2024 to analyse long-term variations in rainfall patterns over 124 years. SI has been computed for all three administrative districts, as the datasets were available on the district scale only. As shown in Fig. 3, lower seasonality index values indicate a more uniform distribution of monthly rainfall throughout the year, whereas higher values signify that rainfall occurs within one or two months.

The results show variation in rainfall seasonality across the Kabartal Wetland Region. The range primarily falls between 0.8 and 1.4, indicating a strongly seasonal rainfall pattern, with long dry periods and most rainfall occurring within three months. Seasonality remained low with minimal variation until 1960. There is an upward trend in seasonality in Begusarai, while Samastipur and Khagaria display downward trends, though these are not statistically significant.

In Begusarai (Fig. 7a), the SI value remains low throughout the first six decades, indicating a strongly seasonal pattern with a long dry season. After 1960, fluctuations in seasonality increase, with some values exceeding 1.3, signifying extreme conditions where all rainfall occurs within 1-2 months of the year. In the last two decades, seasonality has been rising, with more frequent spikes. The trend line is upward, suggesting that most rainfall will occur within three months of the year, thereby extending the dry season. Samastipur (Fig. 7b) shows highly variable seasonality indices. In 1905, the SI exceeded 1.20, indicating an extreme condition. Between 1920 and 1960, the SI fluctuated but mostly remained low. Over the next 20 years, values increased, then steadily decreased. The trend line indicates a decreasing trend, which is not significant. In Khagaria (Fig. 7c), the value was low during the first two decades. The SI increased in subsequent years, indicating that most rainfall occurs within 3 months, with some years exhibiting an extreme rainfall regime in which nearly all rainfall occurs within 1-2 months of the year. This will cause dry conditions for most of the year.

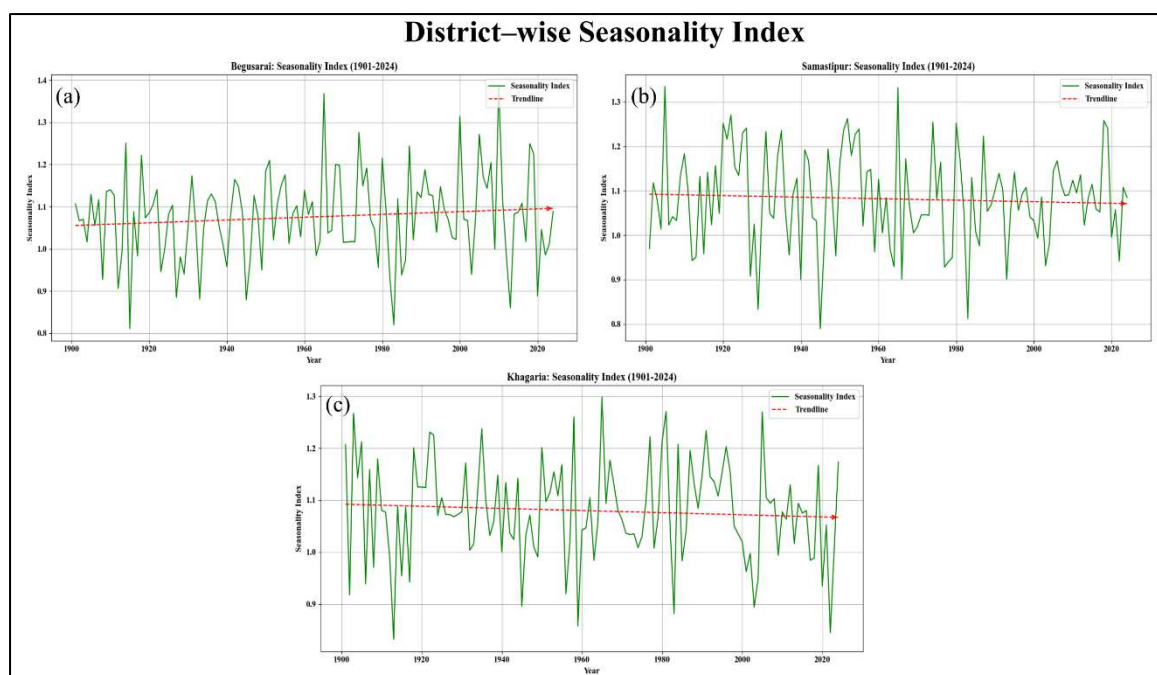


Fig. 7: District-wise Seasonality Index

The analysis shows that KWR receives most of its rainfall within a short period, particularly during the Southwest monsoon. Rainfall is unevenly distributed throughout the year. During the rainy months, heavy precipitation occurs in short intervals, resulting in flooding. Conversely, other months of the year, except rainy months, receive scant rainfall, resulting in reduced soil moisture and drought-like conditions that affect agriculture and allied activities, the main drivers of this region's economy. Therefore, in addition to drought-resistant crop varieties, rainwater harvesting techniques must be adopted.

6.2.2 Assessment of Rainfall Variability through Rainfall Anomaly Index

The Rainfall Anomaly Index is a meteorological index that quantifies variations in rainfall and helps to identify dry spells and extreme wet periods. An analysis of RAI for the period 1901-2024 reveals significant variability in rainfall across the Kabartal Wetland Region (KWR). Wet years are more common in 1901-1940, while a steady increase in dry years occurs in the last two decades throughout the KWR (Fig. 8). The trend line indicates an overall shift toward negative rainfall anomalies in the region (Fig. 8a-8c). Before 1960, wet years predominated, but thereafter, the rainfall regime shifted toward negative anomalies, leading to more frequent dry years. RAI shows that the rainfall regime is changing from moderately wet to moderately dry conditions. After 2000, the number of dry years increased sharply, indicating a notable change in rainfall patterns. In the last two decades, 2010 was the driest year at KWR, followed by 2018. This highlights an increase in rainfall variability in frequency and intensity, shifting

toward negative anomalies and reflecting a significant change in rainfall patterns in the KWR. Declining rainfall and recurring dry years have stressed water bodies' extent, thus disrupting ecological balance. This hydrological stress has led to reduced vegetative growth and wetland shrinkage in recent years.

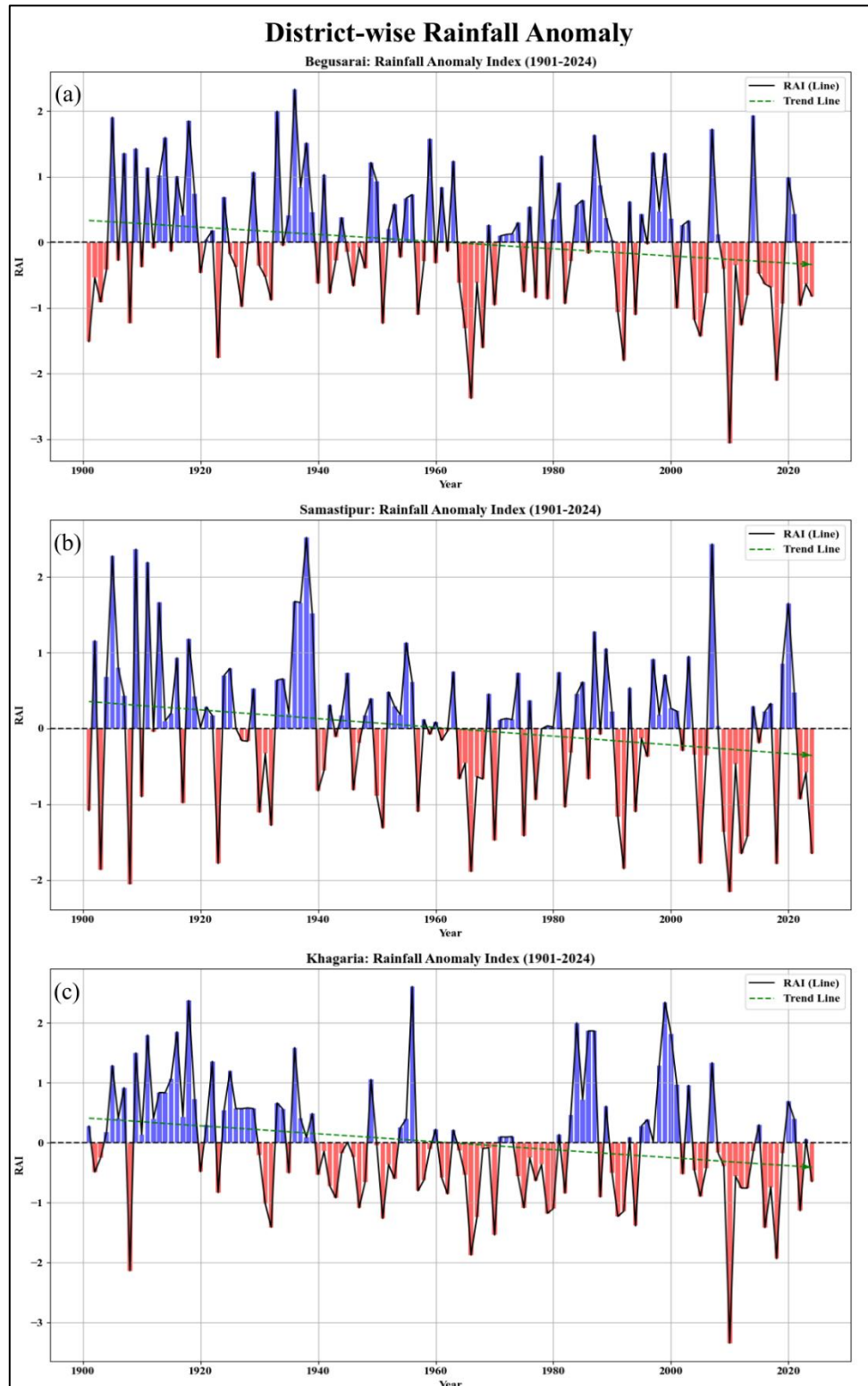
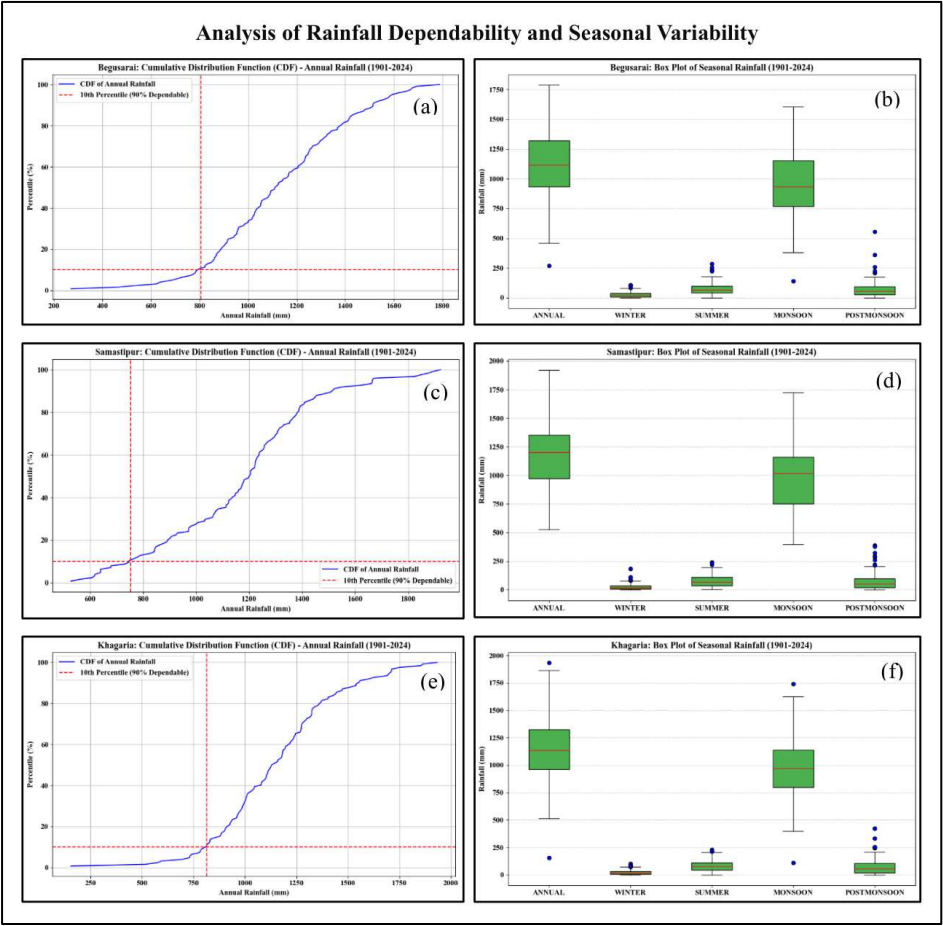


Fig. 8: District-wise Rainfall Anomaly in KWR

449

450 **6.2.3 Minimum Expected Rainfall using Dependable Rainfall**

451 Dependable rainfall is another important hydroclimatic index used to estimate the minimum
452 assured water requirement for water resource assessment and planning in a region. This study
453 depicts the expected rainfall from 1901 to 2024. It was computed at the 10th percentile,
454 corresponding to 90% dependable rainfall. This indicates that in 90% of years, rainfall will be
455 equal to or greater than the estimated dependable rainfall value, whereas only 10% of years
456 will have rainfall below this threshold. This is the minimum rainfall required to fulfil the
457 region's water needs and is suitable for assessing drought risk, water resource management,
458 and agricultural planning.



459

460 **Fig. 9: Analysis of Rainfall Dependability and Seasonal Variability in KWR**

461 The box plots (Fig. 9b, 9d, and 9f) indicate that annual and seasonal rainfall exceed the
462 dependable rainfall value, indicating that KWR receives sufficient rainfall to sustain its water
463 activities. The Kabartal Wetland Region receives most of its rainfall during the monsoon
464 season, with minimal rainfall in winter, summer, and post-monsoon seasons.

Table 3: Patterns of Dependable Rainfall in KWR

Dependable Rainfall (in mm) (1901-2024)	Begusarai	Samastipur	Khagaria
Winter	0	0.29	0
Summer	17.83	20.24	23.4
Monsoon	666.67	625.2	683.2
Post Monsoon	12.79	8.69	8.14
Annual	805.03	752.5	813.34

Source: Computed by the authors based on IMD Rainfall data

467 The annual dependable rainfall values for Begusarai (Fig.9a), Samastipur (Fig.9c) and
 468 Khagaria (Fig.9e) were 805.03 mm, 752.50 mm, and 813.34 mm, respectively; however, the
 469 mean annual rainfall (Begusarai $\approx$ 1100 mm, Samastipur $\approx$ 1180 mm and Khagaria $\approx$ 1150 mm) is
 470 significantly higher than the dependable rainfall in all districts.

471 In Begusarai, the mean annual rainfall is about 1100 mm, exceeding the annual dependable
 472 rainfall, with substantial interannual variability ranging from approximately 500 mm to 1800
 473 mm. A few years received less than 300 mm of rainfall, indicating marked dry spells, while
 474 some years recorded extremely high rainfall. During the monsoon season, the mean value
 475 ranges between 900 mm and 1000 mm, accounting for the largest share of annual rainfall;
 476 observed values range from 400 mm to 1600 mm, representing weak to prolonged monsoon
 477 years. Winter rainfall is low, with a mean of around 20 mm, though outliers of around 60-80
 478 mm indicate occasional rainfall from western disturbances. Although summer rainfall is
 479 generally low, a few outliers of 250-300 mm are associated with convective thunderstorms.
 480 Post-monsoonal rainfall is generally mild to moderate, averaging approximately 200 mm, with
 481 outliers ranging from 300 to 500 mm due to cyclonic events. Across all seasons, mean rainfall
 482 exceeds dependable rainfall, indicating adequate overall rainfall but uneven distribution.

483 In Samastipur, the annual mean rainfall is approximately 1200 mm, again exceeding the
 484 dependable rainfall value, with observed values ranging from approximately 500 mm to 1900
 485 mm. The monsoon season dominates the annual rainfall pattern, with a mean value of
 486 approximately 1000 mm; observed rainfall ranges from 400 mm to 1700 mm, indicating weak
 487 or strong monsoons. Winter precipitation has a mean of approximately 20 mm, with occasional
 488 outliers exceeding 200 mm due to western disturbances. Summer rainfall is low, with a mean
 489 of approximately 50 mm; some outliers exceed 250 mm due to pre-monsoon thunderstorm
 490 events. Post-monsoon rainfall is generally around 200 mm, with extreme values of 300-400
 491 mm associated with cyclonic influences. As observed in Begusarai, mean rainfall exceeds

dependable rainfall across all seasons, indicating sufficient rainfall but an irregular seasonal distribution.

In Khagaria, annual mean rainfall is approximately 1150 mm, exceeding the dependable rainfall value, with annual variability ranging from 500 mm to 1850 mm; outliers at 200 mm and 1950 mm indicate extreme drought and flood events. Monsoonal rainfall remains the chief contributor, with a mean of approximately 950 mm and values ranging from 400 mm to 1650 mm, indicating weak or prolonged monsoons. Winter rainfall is low, with a mean near 20 mm, although some outliers up to 100 mm occur due to western disturbances. Summer rainfall has a mean of approximately 50 mm, with outliers of up to 250 mm associated with convective and pre-monsoon activity. The post-monsoon season experiences mild to moderate rainfall of approximately 200 mm, with occasional outliers exceeding 400 mm due to cyclonic events. As in other districts, the mean rainfall across all seasons exceeds the dependable rainfall, indicating adequate overall precipitation but uneven seasonal distribution.

The mean annual rainfall for KWR is substantially higher than the corresponding 90% dependable rainfall, indicating rainfall dependability in the region. This region requires an effective water management plan to retain monsoon rainfall for use during dry spells. Robust flood management infrastructure and drought-mitigation measures are needed to support effective development in this region.

6.2.4 Analysis of Seasonal and Annual Rainfall Trends Using MMK Test

The Modified Mann–Kendall (MMK) test is a non- parametric test used to detect significant trends (increasing or decreasing) in rainfall time-series data. Alterations in the region's precipitation patterns can adversely affect wetlands, agricultural productivity, food security, land utilisation, land cover, biodiversity, and the area's overall climate and livelihoods. Therefore, understanding long-term historical rainfall trends is essential.

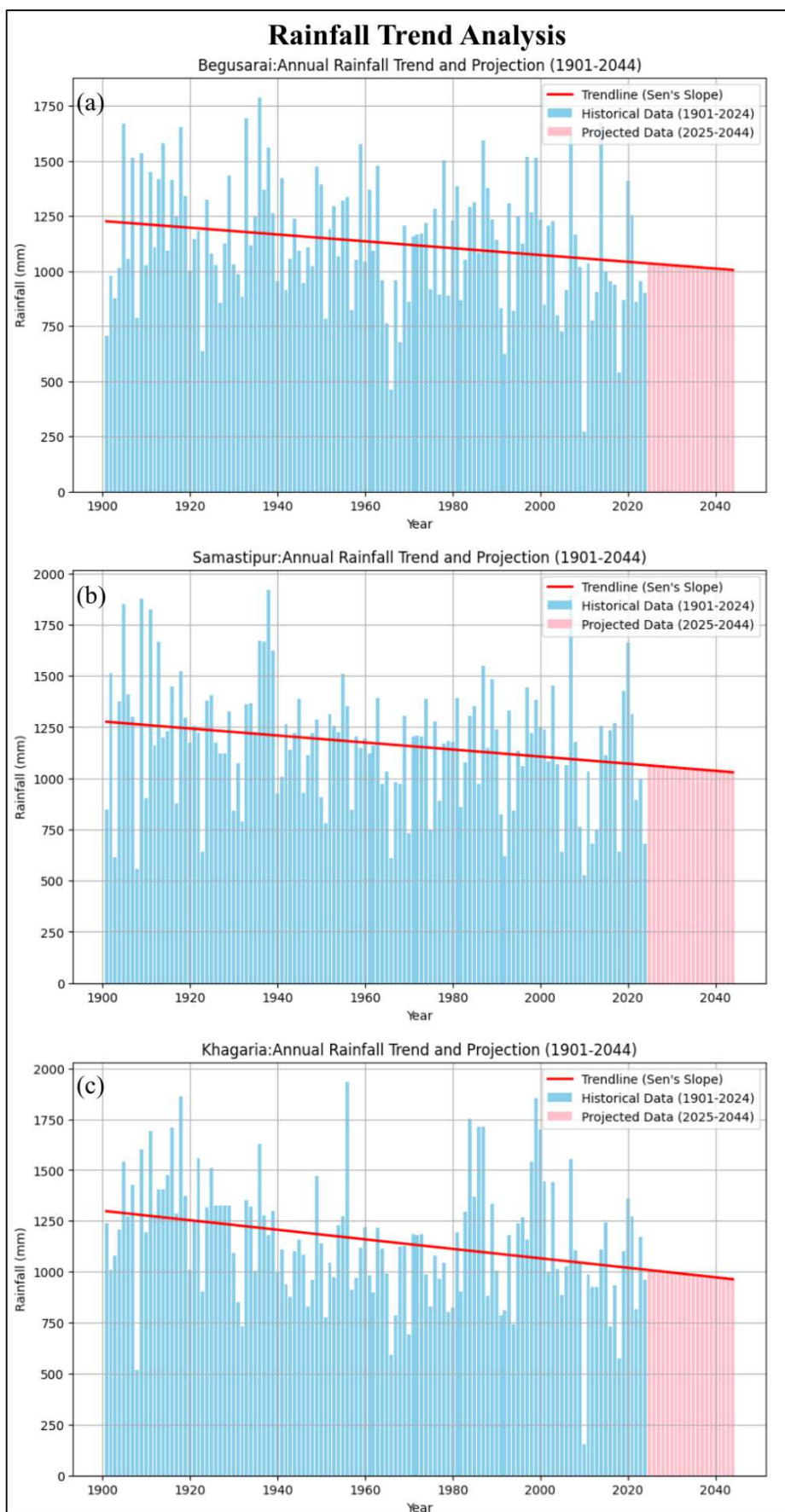
The results of the MMK test and Sen's Slope are presented in Table 4, where the Z_s score values from 1901 to 2024 show the trend of rainfall, while the value of Sen's Slope indicates a decreasing rate of rainfall per annum. Annual rainfall declined significantly from 1901 to 2024 across the Kabartal Wetland Region. The Sen's Slope value for all three districts, Begusarai, Samastipur and Khagaria (highest), revealed a decreasing rainfall rate of 1.54 mm, 1.72 mm and 2.34 mm per year.

Table 4: Seasonal and Annual MMK Trend Analysis in KWR

Districts	Begusarai			Samastipur			Khagaria		
Seasons	Z _s -Score	Sen Slope	Interpretation	Z _s -Score	Sen Slope	Interpretation	Z _s -Score	Sen Slope	Interpretation
Winter	-3.78	-0.18	Significant Decreasing	-2.58	-0.11	Significant Decreasing	-4.05	-0.18	Significant Decreasing
Summer	-0.46	-0.05	Non-significant Decreasing	1.73	0.23	Non-significant Increasing	0.44	0.05	Non-significant Increasing
Monsoon	-2.69	-1.35	Significant Decreasing	-2.87	-1.91	Significant Decreasing	-3.46	-2.21	Significant Decreasing
Post-Monsoon	0.56	0.05	Non-significant Increasing	0.60	0.06	Non-significant Increasing	2.13	0.18	Significant Increasing
Annual	-2.38	-1.54	Significant Decreasing	-2.29	-1.72	Significant Decreasing	-2.61	-2.34	Significant Decreasing

Source: Computed by the authors based on IMD Rainfall data

Seasonal analyses of rainfall data collected for the winter, summer, monsoon, and post-monsoon seasons were executed independently for each district (Table 4). Rainfall shows a significant decreasing trend across all districts of the study area during the winter season. In summer, Begusarai showed a non-significant decreasing trend, whereas Samastipur and Khagaria showed a non-significant increasing trend. Increasing summer rainfall weakens the monsoon. This rainfall is of little use as much of the available water is lost due to high evapotranspiration. The results showed a significant decrease in monsoon rainfall across all districts in the Kabartal Wetland Region. Decreasing rainfall in the region indicates an erratic monsoonal pattern and a weakened Bay of Bengal branch of the monsoon in recent years. Rainfall during the post-monsoon season has been increasing; Begusarai and Samastipur showed insignificant increases, whereas Khagaria showed a significant increase. This increase in post-monsoon rainfall is attributable to delayed monsoon onset and cyclonic activity. Overall, annual rainfall is decreasing significantly during the monsoon and winter seasons in KWR. Rainfall does not increase significantly throughout the summer and post-monsoon seasons, except in summer in the Begusarai district. This increase in summer rainfall will negatively affect groundwater recharge and soil moisture, reducing agricultural output and creating water shortages for daily needs, as evaporation remains high during summer and reduces rainwater absorption.



543

544

Fig. 10: Rainfall Trend Analysis in KWR

Rainfall trend has been projected for the next 20 years (2024-2044). The annual Z_s -scores are -2.38, -2.29, and -2.61 for Begusarai, Samastipur, and Khagaria, respectively, indicating a significant decrease in rainfall across all districts of the Kabartal Wetland Region. According to the study, the average annual rainfall in Begusarai during 1901–2024 was 1,131 mm. Over the next two decades, annual rainfall is projected to decline to approximately 1,025 mm, indicating a decline of about 100 mm by 2044 (Fig. 10a). Similarly, the average annual rainfall in Samastipur and Khagaria during 1901–2024 was 1,170 mm and 1,154 mm, respectively. By 2044, rainfall in these districts is projected to decline to approximately 1,054 mm in Samastipur (Fig.10b) and 985 mm in Khagaria (Fig.10c). This corresponds to a decrease of about 100 mm in Samastipur and 160 mm in Khagaria. Overall, the projected rainfall estimates indicate a downward shift in both the trend and pattern of precipitation in the coming decades. This projected decline in precipitation emphasises proper adaptation measures to address potential effects on water availability and agriculture.

6.3 Multi-Temporal Analysis of Evapotranspiration Dynamics

The relationship between actual evapotranspiration (ET) and potential evapotranspiration (PET) in KWR illustrates a hydrological linkage between water availability and atmospheric demand, integrating climate energy conditions with soil moisture and overall water balance. Estimating evapotranspiration is crucial for understanding Earth's energy and water budget, ecosystem dynamics, and effective water resource management [58] which is influenced by factors like radiation, vapour pressure deficit, air temperature, soil moisture, wind speed and vegetation coverage. To assess the spatial and temporal variations in ET and PET, Terra MODIS (MOD16A2GF) datasets for 2002–2024 were used. Variations in ET and PET in the wetlands have a notable impact on the hydrological conditions, influencing wetland health, spatial extent, water level, and ecological balance.

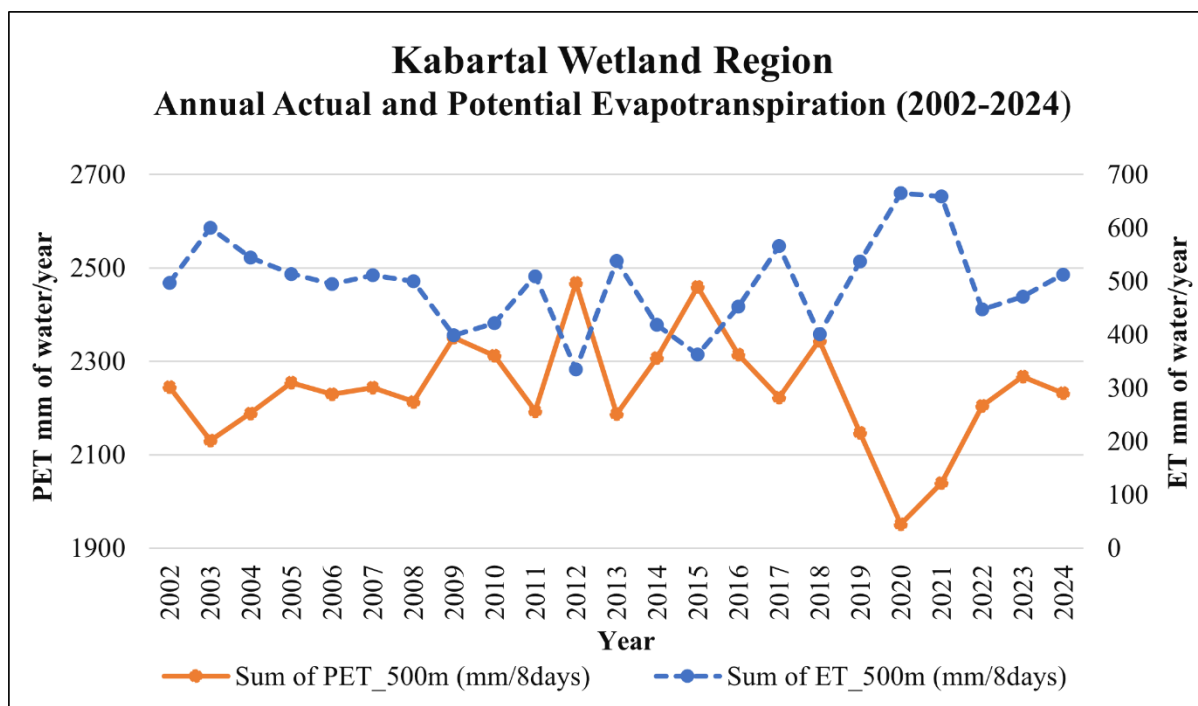
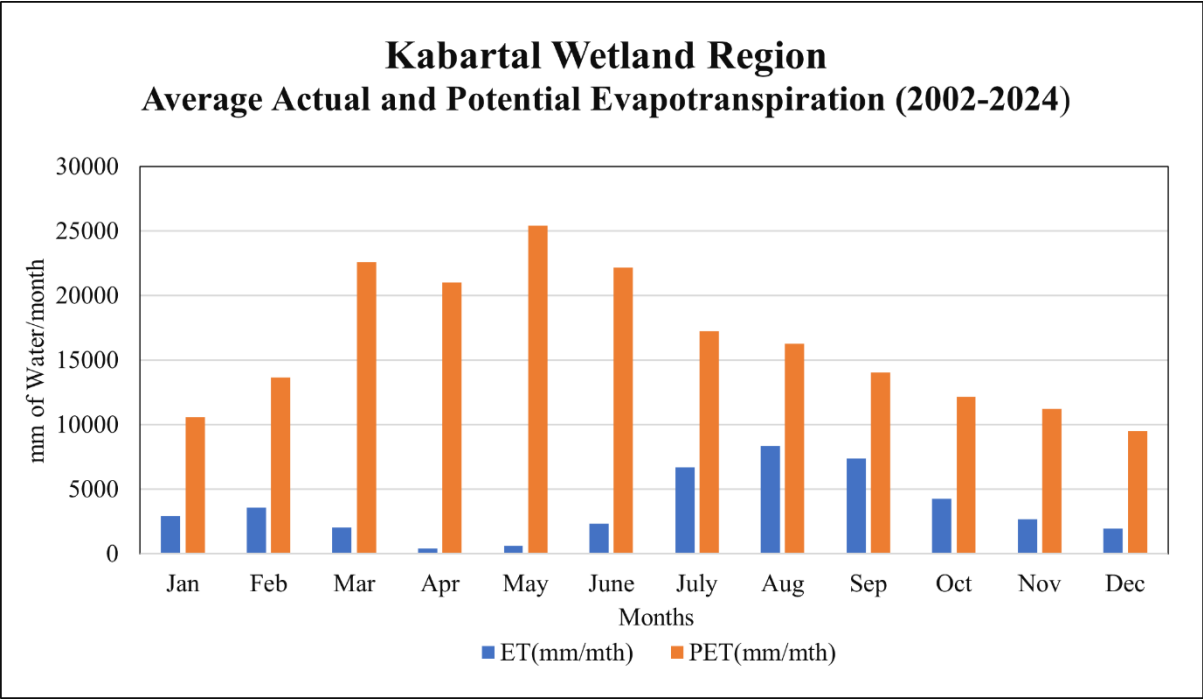


Fig. 11: Annual Actual & Potential Evapotranspiration

The annual trends of ET and PET in the Kabartal Wetland Region from 2002 to 2024 depict a dynamic coupling between climatic conditions and the availability of water. The discrepancy between actual water loss from the surface and the atmospheric demand for moisture is illustrated by comparing the annual ET and PET of KWR (Fig.11). The annual PET value ranges between 1950 mm/year and 2450 mm/year, indicating high atmospheric demand for moisture, while the annual ET value shows significant fluctuations, ranging between 350 mm/year and 650 mm/year, reflecting a limited amount of moisture available for evaporation and transpiration. High PET values coincide with low ET and vice versa, suggesting that water availability is a limiting factor for evapotranspiration. The gap between ET and PET has increased after 2018, indicating a growing imbalance between actual water availability and water demand. The persistent gap between PET and ET throughout the study period indicates that the atmospheric demand is not entirely fulfilled, indicating periodic water stress. PET has increased in recent years while ET has shown a decreasing trend, with substantial variation. This decline in ET indicates inadequate water availability and may be linked to the decreasing pattern of rainfall in KWR.



588

589

Fig. 12: Average Actual & Potential Evapotranspiration

590

591

592

593

594

595

596

597

598

599

600

601

Fig. 12 illustrates the average monthly ET and PET of KWR from 2002 to 2024, with the blue and orange bars representing actual ET and PET, respectively. It shows a clear contrast between ET and PET in KWR, with PET remaining consistently high throughout the years. The bar graph shows that PET is higher from March to June, peaking in May, indicating a significant need for moisture during the pre-monsoon season. During the summer months, especially from March to June, PET peaks due to high temperatures, but ET stays relatively low because of insufficient moisture. After the onset of the monsoon, PET declines due to the effects of monsoon rain and low temperatures. In the post- monsoonal season, PET is at its minimum due to sufficient water availability and soil moisture. There's a little increase in PET in the winter season. ET is lowest during the pre-monsoonal season, with the minimum value in May due to low availability of water. ET is at its highest during the monsoon season, with a peak in August due to adequate seasonal rainfall.

602

603

604

605

606

607

The highest gap between ET and PET is observed during April and May, indicating a notable water-stress period in the pre-monsoon season. This is due to long daylight hours, high solar insolation, rising temperatures, and low humidity, which altogether raise atmospheric evaporative demand, but limited water availability limits actual evapotranspiration, resulting in a pronounced ET–PET disparity. In contrast, during August and September, the difference between ET and PET becomes relatively low, indicating a comparatively water-balanced

condition. The monsoonal rain during this period maintains adequate soil moisture and provides sufficient water for evapotranspiration, reducing water stress in the wetland region.

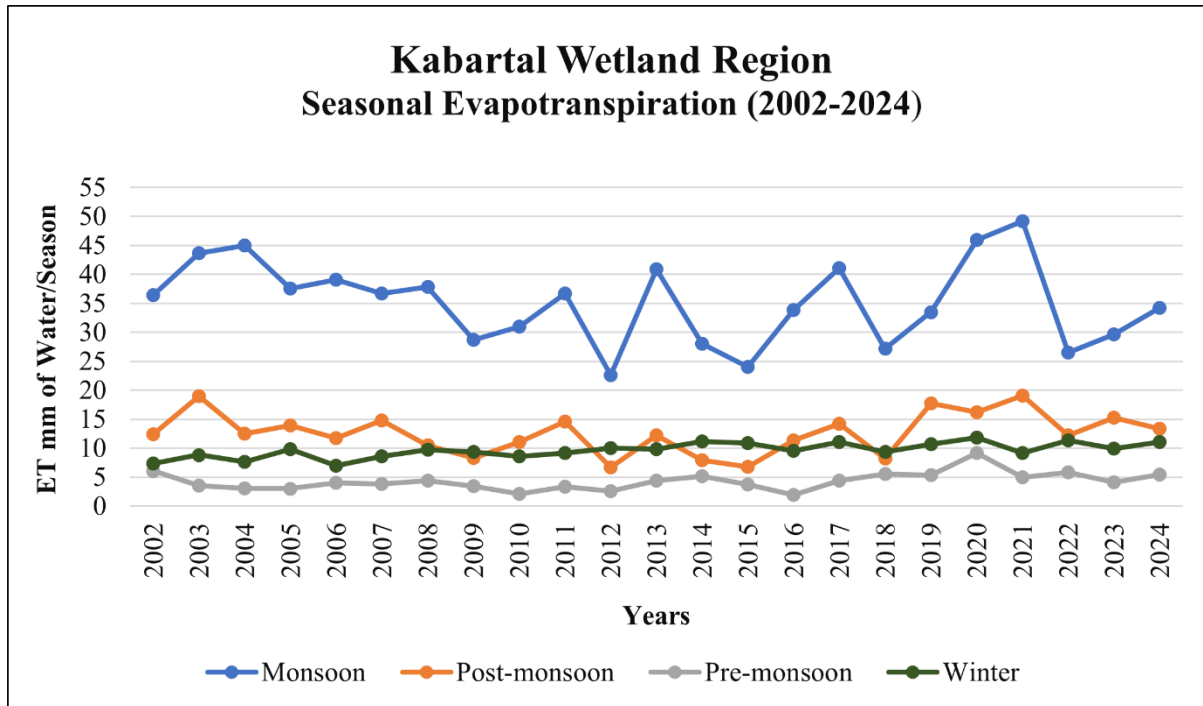


Fig. 13: Seasonal Evapotranspiration

Seasonal analysis of actual ET and PET is important for understanding the hydrological dynamics and water-stress conditions of wetlands, as these parameters reflect the balance between atmospheric water demand and available moisture. Fig. 13 presents the seasonal ET of KWR from 2002 to 2024 across four seasons: pre-monsoon, monsoon, post-monsoon and winter. ET ranges between 22 and 50 mm of water/season in monsoon, the highest among all the seasons, indicating substantial water availability and enhanced vegetation due to sufficient monsoonal rainfall. Contrary to this, ET values during the other three seasons remained comparatively low and relatively stable, with post-monsoon ET varying between 6-19 mm of water/season, winter ET ranging between 6-12 mm of water/season and pre-monsoon ET, being the lowest one, fluctuating only between 1-9 mm of water/season. This reflects moisture deficiency, limited surface water availability, and sparse vegetation cover during the dry season. There is pronounced variability in monsoonal ET observed after 2011, indicating changing rainfall patterns, climate anomalies and changing hydrological conditions in KWR. The prevalence of high ET during the monsoon season implies that wetland replenishment is primarily seasonal and temporary, while persistently low ET throughout the other seasons indicates prolonged water deficit and hydrological stress within the wetland ecosystem.

The interannual seasonal trends of PET in KWR for the years 2002–2024 are illustrated in Fig. 14. The seasonal analysis indicates that PET peaks during the monsoon season, varying between 82 and 118 mm of water per season, while the pre-monsoon season also exhibits relatively high PET values ranging from 90 to 102 mm of water per season. Conversely, lower PET values are evident during the post-monsoon season (38–60 mm of water per season) and the winter season (24–40 mm of water per season). The monsoon season shows substantial variability in PET, indicating variable rainfall patterns, whereas pre-monsoon PET remains relatively stable.

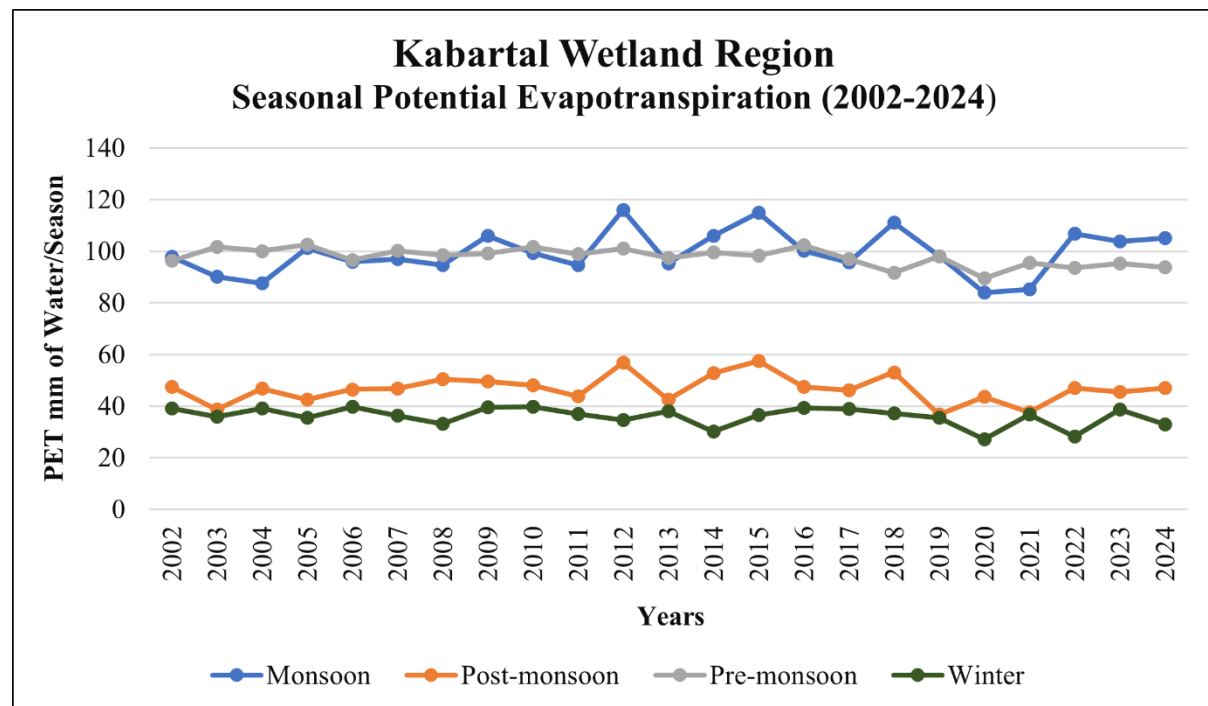


Fig. 14: Seasonal Potential Evapotranspiration

During the pre-monsoon season, wetland area (from MNDWI analysis) in KWR declined due to high PET values, driven by increased water loss. In contrast, the post-monsoon season showed increased wetland extent driven by adequate monsoonal rainfall and relatively mild temperatures, resulting in lower ET and PET and indicating the role of seasonal rainfall in sustaining and replenishing these water bodies.

The analysis of evapotranspiration dynamics in the Kabartal Wetland Region indicates that both ET and PET play a crucial role in hydrological variability and wetland functioning. PET is higher than ET across all seasons and months, reflecting insufficient water to meet atmospheric demand and indicating hydrological stress associated with insufficient rainfall, reduced soil moisture, and seasonal water scarcity in KWR. The coexistence of water surplus

during wetter periods and water deficit during drier periods highlights variability in the regional water balance, directly affecting wetland extent, ecological stability, agricultural productivity, and irrigation requirements.

To address these issues, KWR wetlands should be reconnected to rivers, and feeder channels should be opened and kept obstruction-free to allow seasonal flooding that refills the wetlands. Planning and constructing embankments and dams along the Budhi Gandak and Baghmati rivers should not disrupt wetland connectivity and should consider wetland conservation. Excessive water extraction for irrigation from KWR wetlands must be regulated, while rainwater harvesting should be promoted to maintain adequate water levels. Agricultural expansion and settlements around the region's wetlands are reducing the catchment area by altering surface runoff and disrupting hydrological connectivity, reducing wetland recharge. Therefore, establishing buffer zones around Lake Kabartal and other KWR wetlands is essential to protect them from adverse land-use and land-cover changes.

6.4 Correlation Assessment of Hydro-Climatic Indicators in the KWR

Correlation analysis determined the associations among rainfall, ET (evapotranspiration), PET (Potential evapotranspiration) and LE (Latent heat flux) (Fig. 15a) across multiple temporal scales from 2002 to 2024 in the Kabartal Wetland Region. The findings revealed positive correlations between rainfall and ET (0.5), and between rainfall and LE (0.5). A moderate negative correlation between rainfall and PET (-0.5) indicated an inverse relationship, with lower rainfall corresponding to higher PET. The elasticity of ET with respect to rainfall and PET showed that evapotranspiration increases by about 0.65% and decreases sharply by about 2.4% with a 1% rise in rainfall and PET, respectively (Fig. 15b), indicating that ET is sensitive towards rainfall and PET in the KWR. Correspondingly, the relationship between rainfall and ET (Fig. 15c) shows a little positive trend, indicating ET increases with rainfall. The lag correlation indicates time-shifted relationships between rainfall and ET. In the lag correlation plot, values are scattered without showing any trend or pattern, which is mainly due to the high variability of rainfall in this KWR (Fig. 15d). The analysis found that the previous year's rainfall does not regulate ET; rather, it is controlled by the same year's water availability, indicative of less water storage or trapping in the region.



Fig. 15: Hydro Climatic Variables in KWR

Hydro-climatic variables are highly dynamic in the KWR (Fig. 15e). Rainfall showed high variability with a consistent decrease in the recent period. Rainfall trends are decreasing in this region, with extreme wet and dry years. ET increases or decreases with rainfall fluctuations. The increase in ET is less proportional to rainfall because it is controlled not only by precipitation but also by multiple factors, such as temperature, PET, land cover, soil moisture, and rainfall seasonality. PET is inversely related to rainfall and ET. Here, PET is high, and ET is low, indicating a shortage of water and soil moisture. The analysis of the aridity index

revealed that KWR is humid in nature, as most years cluster between 1.25 and 1.75 (Fig. 15f). Between 2002 and 2024, 16 years had a water surplus ($P > PET$), supporting wetland recharge and expansion, while 7 years had a water deficit ($P < PET$), leading to wetland shrinkage. The aridity index showed a non-significant declining trend, with recent years (2021-2024) being drier than average. KWR is a water surplus area, except in some years. However, overall water availability decreased in recent years from 1000 mm in 2002 to 200 mm in 2024 (Fig. 15g) and is expected to decline further in the near future. Despite being a water surplus region, ET remains low. This is due to the erratic and uneven distribution of rainfall, which leads to increased surface runoff rather than infiltration, limiting soil moisture storage and reducing water available for evapotranspiration. The standardised water deficit plot (Fig. 15h) indicates a highly variable region with extreme drought and wet years. Values range from 0.2 in 2002 to -0.6 in 2024, indicating wet to dry anomalies, with a slight tendency toward drier conditions. Overall, the Kabartal Wetland Region is a water-surplus region; however, it faces limited water availability for evapotranspiration. The declining rainfall trend imposes future water stress in this region, making the wetlands vulnerable to dry conditions.

7. Ecosystem resilience at the crossroads of climate change, development, and governance

Ecosystem resilience refers to an ecosystem's capacity to absorb disturbances and persist while maintaining its fundamental structures, processes, and functions under changing environmental conditions [59]. Accelerating climate change and intensifying human interventions are driving rapid shifts and increased uncertainty in ecosystems worldwide, affecting freshwater, marine, and terrestrial systems both structurally and functionally, and altering key environmental processes [60]. Wetlands, which exist at the interface of land, water, and human development, are particularly vulnerable due to their complex biological, physical, and socio-economic composition. The long-term health and resilience of wetlands depend on the capacity of hydrological cycles, vegetation structure, and land-use patterns to regulate material transport, energy flows, and ecological interactions [61].

Random precipitation regimes, rising temperatures, and widespread vegetation loss are intensifying wetland vulnerability and undermining their structural integrity and functional resilience. In India, these climate-induced stresses are compounded by extensive anthropogenic pressures, including land conversion for infrastructure, real estate expansion, road networks, and altered catchment dynamics. Hydrological modifications through dams, embankments,

river channelisation, sand mining, and excessive groundwater extraction disrupt natural flow regimes, erode wetland connectivity, and diminish their capacity to buffer floods and sustain dry-season water availability. Embankment on the River Budhi Gandak in KWR disrupted its connectivity with Lake Kabartal, reducing natural recharge and lowering water levels, increasing flood and drought risks, causing ecological imbalance and impacting the dependent communities' livelihoods. Riparian wetlands, such as Lake Kabartal, and floodplains are particularly at risk because they are often treated as vacant land rather than as integral components of active river systems. The extent of wetlands and vegetative cover in KWR has significantly reduced due to rising temperatures and diminishing rainfall trends and patterns, impacting the ecological and hydrological integrity of the wetlands. KWR receives most of its annual rainfall in a short span, leading to flooding and dry spells in the region.

Enhancing wetland resilience warrants hydrological rejuvenation by restoring natural connectivity among rivers, floodplains, feeder channels, and associated wetlands. Regulating water inflows and outflows to maintain seasonal flooding and drying cycles is essential for sustaining ecological processes, nutrient exchange, and habitat diversity. Protecting wetland catchments and preventing physical blockages caused by roads and embankments are critical to restore natural hydrological functionality. In the Kusheshwarthan Wetland of Darbhanga, construction of embankments and a railway route through the wetland is impacting its resilience capacity.

Vegetation in KWR plays a central role in wetland resilience by stabilising soils, regulating evapotranspiration, and supporting biodiversity. PET is considerably greater than ET across all seasons and months in KWR, indicating an insufficient amount of water available to meet atmospheric demand. Conserving and enhancing vegetative cover through the protection of native plant species such as *Barringtonia acutangula*, *Syzygium cumini*, *Salix tetrasperma*, *Ficus glomerata* (*Ficus racemosa*), and *Bambusa bambos*. Control of invasive species, such as water hyacinth (*Eichhornia crassipes*), bush weed (*Ipomoea carnea*), *Xanthium strumarium* and restoration of degraded habitats are vital for maintaining ecosystem stability. Establishing vegetative buffer zones around wetlands, such as around Lake Kabartal, can further reduce external disturbances, filter pollutants, and limit encroachment from surrounding land uses.

The KWR's economy is reliant on agriculture, and farming methods are entirely dependent on seasonal rainfall. Staple crops such as wheat and rice are significantly affected by variations in monsoon rainfall [57]. This reduction in rainfall will affect agricultural output, worsen the

economy and lead to unemployment and migration. The highest migration trend is concentrated towards metropolitan areas such as Delhi, Mumbai, Surat, and Kolkata, owing to the higher density of industrial units, which provide greater employment opportunities across various sectors, including construction, manufacturing, and textiles [62]. Industrial growth in neighbouring states such as Jharkhand, Haryana, Punjab, Delhi, and Maharashtra also attracts farmers to work as labourers [63]. A reduction in rainfall is adversely affecting the region's livelihoods, thereby increasing the push factor for seasonal migration.

Community participation is a cornerstone of resilient wetland management. Wetland-dependent communities, such as the *Nishad community*, have historically coexisted with and managed these ecosystems and are actively engaged in conservation and restoration efforts. Nishad community is a major riverine and fishing group which includes *Sahnis*, *Mallah*, *Kewat*, and more, who reside near the rivers and wetlands and work as fishermen, boatmen, net makers, and river farmers. Providing alternative, sustainable livelihood opportunities can reduce excessive dependency pressures and empower communities to serve as long-term stewards of wetland ecosystems. Public awareness and capacity-building initiatives like *Mission Sahbhagita* and the *Wetland Mitra* scheme are essential to enhance understanding of the ecological, hydrological, cultural, and economic value of wetlands and to encourage responsible resource use.

Institutional and governance reforms are equally critical for strengthening wetland resilience. Wetlands authorities in Bihar, like the Bihar State Wetland Authority (BSWA), often face constraints stemming from inadequate staffing, limited financial resources, and competing administrative mandates, resulting in weak planning and implementation. NGO'S bridge the gap between government bodies and locals through self-help groups, community participation and capacity-building initiatives. Bridging capacity gaps and engaging academic researchers through interdisciplinary training in hydrology, ecology, GIS and remote sensing, environmental law, and community-based governance is imperative. Ultimately, wetlands of KWR must be managed not as isolated entities or aesthetic landscapes, but as functional components of broader basin and catchment systems. An integrated approach can ensure that wetlands continue to function as *lebensraum*, adaptive ecosystems supporting biodiversity, water security, and climate resilience for both present and future generations.

8. Conclusion and Way Forward

The study aimed to investigate the rainfall-driven ecohydrological changes in the Kabartal Wetland Region. The study used MNDWI and NDVI to evaluate ecological changes, while the Seasonality Index, Rainfall Anomaly Index, Dependent Rainfall, and Modified Mann-Kendall Tests were used to analyse hydrological changes.

MNDWI and NDVI showed that wetland and vegetative cover in KWR decreased between 1989 and 2024. This shrinkage of wetlands and reduction in vegetative cover are attributable to declining rainfall. Wetness and vegetation were relatively low during the pre-monsoon season due to low rainfall, while both increased during the post-monsoon season as a result of higher rainfall and moisture availability.

The seasonality index indicates that most rainfall occurs within three months, with long dry seasons. Similarly, rainfall exceeded the dependable rainfall value, but most occurred during the monsoon season. The Rainfall Anomaly Index indicates that the rainfall pattern is shifting toward a negative anomaly, from moderately wet to moderately dry, in the Kabartal Wetland Region. The annual and seasonal rainfall trends in the Kabartal Wetland Region were determined using the Sen slope index and the modified Mann-Kendall test. The annual rainfall pattern is gradually declining in the study area. Projected rainfall statistics for the next 20 years also indicate that precipitation will continue to decline.

Overall, the study found that the Kabartal Wetland Region is experiencing decreasing rainfall, with most occurring during the monsoonal period or in short-duration events. This will cause frequent and short-period meteorological drought-like conditions in the study area, adversely affecting the region's water resources, particularly the wetlands. The wetlands surrounding agricultural farms will face greater stress, as during the dry season water from the wetlands will be used for irrigation, reducing water levels and affecting vegetation, aquatic species, and water quality. Additionally, during the rainy months, heavy rainfall can cause flooding and degrade the wetland ecosystem. That's why a better water resource management strategy must be framed and implemented to conserve and store water during the wet period and utilize it during the dry period.

Wetlands are ecologically and economically significant and play an important role in biodiversity conservation, groundwater recharge, flood control, water purification, carbon sequestration, livelihoods, and food production. Based on these results, the impact of climate change is evident in the wetlands of KWR. Decreasing annual rainfall, as well as erratic rainfall

(i.e., early or late monsoon arrival), is negatively affecting the health of KWR wetlands. Wetland shrinkage will affect flora and wildlife, including nesting grounds for birds, habitats for numerous organisms, and migratory birds. Lake Kabartal has also shrunk, affecting water quality, nutrient cycling, and ecological stability, reducing the number of migratory birds and forcing dependent communities to migrate owing to a lack of economic prospects. Wetland loss will eventually result in flooding since they act as a buffer zone for excess water. Because the region's economy depends heavily on agriculture and allied activities, wetland loss would reduce employment opportunities and drive population migration. Migration of dependent communities like the *Nishaad* communities will eventually degrade wetlands, as these communities are the primary conservers of these ecosystems in their natural form.

Wetlands are being degraded by both natural and anthropogenic factors. An awareness-raising effort should be undertaken to inform people about the importance of wetlands. Otherwise, it will adversely affect Sustainable Development Goals (SDGs) 1 (no poverty), 2 (zero hunger), 6 (clean water and sanitation), and 14 (life below water), which must be achieved by 2040. A sustainable, effective wetland management strategy should be developed to conserve these ecosystems.

Acknowledgement

The authors acknowledge the Advanced Research Centre Lab at L. N. Mithila University, Darbhanga; the United States Geological Survey (USGS); and the India Meteorological Department for their support in conducting this research.

Funding

The author(s) received no financial support for the research and/or publication.

Disclosure statement

The authors declare no conflicts of interest regarding this study.

Data Availability Statement

All data used to support the findings of this study are publicly available.

The Landsat datasets were obtained from the United States Geological Survey (USGS) Earth Explorer platform (<https://earthexplorer.usgs.gov>).

Monthly Rainfall datasets were obtained from the India Meteorological Department (<https://mausam.imd.gov.in>).

Authors' Contribution

In this study, two authors have contributed as follows: study conceptualization and design: 1st author (Manu Raj Sharma); methodology and software: 1st author; data collection: 2nd author (Abhishek Akarsh); mapping, analysis and interpretation of results: 1st and 2nd authors; manuscript preparation and drafting: 2nd author; manuscript restructuring and critical review: 1st author; validation and final approval of the manuscript: 1st and 2nd authors.

Conflict of Interest:

The authors have not declared any conflict of interest.

Clinical trial number:

Not applicable.

Ethics, Consent to Participate, and Consent to Publish declarations:

Not applicable

Funding:

The authors received no funds or financial assistance for this work.

9. References

1. Ganguly L, Mondal S, Chakraborty S, Ghosh A. Geological and Ecological Analysis of Munia-2 Wetland: Understanding Its Role in the Sundarban Deltaic Region, West Bengal. *Deltas of the World*. Springer; 2026. p. 77–100. https://doi.org/10.1007/978-3-032-16261-8_3
2. Sharma MR, Das SK. Integrated eco-hydrological and vegetation productivity analysis of wetland landscapes in Madhubani, Bihar (2002–2024). *Sci Rep*. 2026; <https://doi.org/10.1038/s41598-026-60072-1>
3. Sharma MR, Das SK, Shankar A, Chandel VBS. Climate Change and Sustainable Adaptation: An Analysis of the Effects of Rainfall Variability on Wetland Ecosystems in

- 868 Madhubani, Bihar, India. Sustainable Development Goals Series. Springer; 2026. p. 33–50.
869 https://doi.org/10.1007/978-3-031-96977-5_3
- 870 4. Gupta D, Kumar Ranjan R, Parthasarathy P, Ansari A. Spatial and seasonal variability in the
871 water chemistry of Kabar Tal wetland (Ramsar site), Bihar, India: multivariate statistical
872 techniques and GIS approach. *Water Science and Technology* [Internet]. IWA Publishing;
873 2021;83:2100–17. <https://doi.org/10.2166/wst.2021.115>
- 874 5. Robertson H, Fennessy S, Hilton G, Job N, Kumar R, Simpson M, et al. Global Wetland
875 Outlook 2025: Valuing, conserving, restoring and financing wetlands. Gland, Switzerland;
876 2025 Jul. <https://doi.org/10.69556/GWO-2025-eng>
- 877 6. Karimi V, Karamidehkordi E, Farhadian H, Bijani M, Singh G. Mapping socio-institutional
878 studies of biodiversity governance and climate change justice in wetland ecosystems.
879 *Environmental and Sustainability Indicators* [Internet]. Elsevier B.V.; 2025;27.
880 <https://doi.org/10.1016/j.indic.2025.100789>
- 881 7. Dai A. Increasing drought under global warming in observations and models. *Nat Clim*
882 *Chang* [Internet]. 2013;3:52–8. <https://doi.org/10.1038/nclimate1633>
- 883 8. Fluet-Chouinard E, Stocker BD, Zhang Z, Malhotra A, Melton JR, Poulter B, et al. Extensive
884 global wetland loss over the past three centuries. *Nature* [Internet]. 2023;614:281–6.
885 <https://doi.org/10.1038/s41586-022-05572-6>
- 886 9. Chen K, Liang S, Cong P, Sun Z. Establishment of wetland conservation networks in
887 response to climate change and anthropogenic activities: A case study from the Liaohe River
888 Basin in Liaoning Province, China. *Ecol Indic*. Elsevier B.V.; 2025;171.
889 <https://doi.org/10.1016/j.ecolind.2025.113184>
- 890 10. Xi Y, Peng S, Ciais P, Chen Y. Future impacts of climate change on inland Ramsar wetlands.
891 *Nat Clim Chang*. 2021;11:45–51. <https://doi.org/10.1038/s41558-020-00942-2>
- 892 11. Nevermann H, AghaKouchak A, Shokri N. Sea level rise implications on future inland
893 migration of coastal wetlands. *Glob Ecol Conserv*. Elsevier B.V.; 2023;43.
894 <https://doi.org/10.1016/j.gecco.2023.e02421>
- 895 12. Olusola JA, Olofin EO, Eludoyin AO, Awotoye OO. Climate Change and the Fragility of
896 the Lake Chad Wetlands: Threats to Biodiversity and Ecosystem Services. In: Leal Filho W,
897 Nagy GJ, Ayal DY, editors. *Handbook of Nature-Based Solutions to Mitigation and Adaptation*

898 to Climate Change [Internet]. Cham: Springer Nature Switzerland; 2023. p. 1–22.
 899 https://doi.org/10.1007/978-3-030-98067-2_170-1

900 13. Ibrahim MT, Zaryab A, Ali S, Hasani M. Key Drivers Impacting Water Resources of
 901 Afghanistan Under Rapid Climate Change Conditions. *Water Conservation Science and*
 902 *Engineering*. Springer Nature; 2025;10. <https://doi.org/10.1007/s41101-025-00394-9>

903 14. Zhang Y, Yan J, Cheng X. Advances in impact of climate change and human activities on
 904 wetlands on the Tibetan Plateau. *Shengtai Xuebao* [Internet]. Science Press; 2023;43:2180–93.
 905 <https://doi.org/10.5846/stxb202111153202>

906 15. Sarkar UK, Das Ghosh B, Puthiyottil M, Das AK, Lianthuamluaia L, Karnatak G, et al.
 907 Spatio-temporal change analysis of three floodplain wetlands of eastern India in the context of
 908 climatic anomaly for sustainable fisheries management. *Sustain Water Resour Manag*
 909 [Internet]. Springer Science and Business Media Deutschland GmbH; 2021;7.
 910 <https://doi.org/10.1007/s40899-021-00529-5>

911 16. Heidarzadeh N, Eghbal M, Esmaeili N, Panaghi K. Predicting the impact of climate change
 912 on the area of wetlands using remote sensing. *Theor Appl Climatol*. 2024;155:5593–606.
 913 <https://doi.org/10.1007/s00704-024-04969-9>

914 17. Mahdian M, Hosseinzadeh M, Siadatmousavi SM, Chalipa Z, Delavar M, Guo M, et al.
 915 Modelling impacts of climate change and anthropogenic activities on inflows and sediment
 916 loads of wetlands: case study of the Anzali wetland. *Sci Rep. Nature Research*; 2023;13.
 917 <https://doi.org/10.1038/s41598-023-32343-8>

918 18. Singh S, Goyal MK, Saikumar E. Assessing Climate Vulnerability of Ramsar Wetlands
 919 through CMIP6 Projections. *Water Resources Management*. Springer Science and Business
 920 Media B.V.; 2024;38:1381–95. <https://doi.org/10.1007/s11269-023-03726-3>

921 19. Salimi S, Almuktar SAAAN, Scholz M. Impact of climate change on wetland ecosystems:
 922 A critical review of experimental wetlands. *J. Environ. Manage. Academic Press*; 2021.
 923 <https://doi.org/10.1016/j.jenvman.2021.112160>

924 20. The State of Food and Agriculture. The State of Food and Agriculture 2020. FAO; 2020
 925 Nov. <https://doi.org/10.4060/cb1447en>

- 926 21. Hu S, Niu Z, Chen Y, Li L, Zhang H. Global wetlands: Potential distribution, wetland loss,
927 and status. *Science of the Total Environment* [Internet]. Elsevier B.V.; 2017;586:319–27.
928 <https://doi.org/10.1016/j.scitotenv.2017.02.001>
- 929 22. Robertson H, van Dam A, de Souza M, Amerasinghe P, Finlayson M, Kumar R, et al.
930 Wetlands and agriculture: impacts of farming practices and pathways to sustainability. Gland,
931 Switzerland; 2022 Jun. <https://doi.org/10.69556/strp.bn13.22.eng>
- 932 23. Hashemi N, Keshavarzi B, Amini-Birami F, Biester H, Zafarani GG, Zarei M. Potentially
933 toxic elements in sediment and water of Amirkalayeh Wetland: Impacted by intensive rice
934 farming. *Environ Monit Assess* [Internet]. Springer Science and Business Media Deutschland
935 GmbH; 2025;197. <https://doi.org/10.1007/s10661-025-14139-7>
- 936 24. Kaushik H, Ranjan R, Ahmad R, Kumar A, Prashant, Kumar N, et al. Assessment of trace
937 metal contamination in the core sediment of Ramsar wetland (Kabar Tal), Begusarai, Bihar
938 (India). *Environmental Science and Pollution Research* [Internet]. 2021;28:18686–701.
939 <https://doi.org/10.1007/s11356-020-11775-z>
- 940 25. Mondal I, Bandyopadhyay J, Hossain SA, Altuwaijri HA, Roy SK, Akhter J, et al.
941 Evaluating the effects of rapid urbanization on the encroachment of the east Kolkata Wetland
942 ecosystem: a remote sensing and hybrid machine learning approach. *Environ Dev Sustain*
943 [Internet]. Springer Science and Business Media B.V.; 2025;27:14781–813.
944 <https://doi.org/10.1007/s10668-024-05832-7>
- 945 26. Hotaiba AM, Salem BB, Halmy MWA. Assessment of Wetland Ecosystem's Health Using
946 Remote Sensing – Case Study: Burullus Wetland – Ramsar Site. *Estuaries and Coasts*
947 [Internet]. Springer; 2024;47:201–15. <https://doi.org/10.1007/s12237-023-01274-y>
- 948 27. Nasser Mohamed Eid A, Olatubara CO, Ewemoje TA, Farouk H, El-Hennawy MT. Coastal
949 wetland vegetation features and digital Change Detection Mapping based on remotely sensed
950 imagery: El-Burullus Lake, Egypt. *International Soil and Water Conservation Research*
951 [Internet]. International Research and Training Center on Erosion and Sedimentation and China
952 Water and Power Press; 2020;8:66–79. <https://doi.org/10.1016/j.iswcr.2020.01.004>
- 953 28. Wang B, Zhang W, Zhang L, Xu S, Liu X, Wang Y. Anthropogenic Activities Drive the
954 Spatiotemporal Changes of Wetland Area in Tianjin, China. *Environ Manage*. Springer;
955 2025;75:2059–77. <https://doi.org/10.1007/s00267-025-02182-6>

- 956 29. Dinh TT, Nguyen H, Phuong NT. Machine learning-based analysis of wetland loss and
957 agricultural expansion dynamics in the Long Xuyen Quadrangle, Vietnamese Mekong Delta
958 (1990–2023). *Environmental Challenges*. Elsevier B.V.; 2025;20.
959 <https://doi.org/10.1016/j.envc.2025.101265>
- 960 30. Pandey A, Singh K, Sharma A. Integrating NDWI, MNDWI, and Erosion Modeling to
961 Analyze Wetland Changes and Impacts of Land Use Activities in Ropar Wetland, India. *J Sci*
962 *Ind Res (India)*. National Institute of Science Communication and Policy Research;
963 2023;82:1208–19. <https://doi.org/10.56042/jsir.v82i11.3175>
- 964 31. Debnath M, Alam K, Islam N, Hossain S, Sarkar B, Roy R. Land Use Land Cover Change
965 Detection using remote sensing Indices in Rasik. 2023; [https://doi.org/10.21203/rs.3.rs-](https://doi.org/10.21203/rs.3.rs-3446641/v1)
966 [3446641/v1](https://doi.org/10.21203/rs.3.rs-3446641/v1)
- 967 32. Khusfi ZE, Khosroshahi M, Naeimi M. Evaluating and monitoring of moisture variations
968 in Meyghan wetland using the remote sensing technique and the relation to the meteorological
969 drought indices [Internet]. 2019. <http://girs.iaubushehr.ac.ir>
- 970 33. Singh M, Sinha R. Hydrogeomorphic indicators of wetland health inferred from multi-
971 temporal remote sensing data for a new Ramsar site (Kaabar Tal), India. *Ecol Indic* [Internet].
972 2021;127:107739. <https://doi.org/10.1016/j.ecolind.2021.107739>
- 973 34. Prakash B, Kumar R. Strategies for Wetland Conservation: Study of Kanwar Wetland,
974 Begusarai. *International Journal of Science and Research* [Internet]. 2018;8.
975 <https://doi.org/10.21275/ART20194346>
- 976 35. Ye X chun, Meng Y ke, Xu L gang, Xu C yu. Net primary productivity dynamics and
977 associated hydrological driving factors in the floodplain wetland of China's largest freshwater
978 lake. *Science of the Total Environment* [Internet]. Elsevier B.V.; 2019;659:302–13.
979 <https://doi.org/10.1016/j.scitotenv.2018.12.331>
- 980 36. Lou H, Banerjee A, Mango J, Khan U, Singh SK. Understanding vegetation change in
981 northern Tanzania: interactions between climate variability and human activity. *Physics and*
982 *Chemistry of the Earth* [Internet]. Elsevier Ltd; 2025;141.
983 <https://doi.org/10.1016/j.pce.2025.104064>
- 984 37. Shil T. Aquatic and Wetland Plants of India EIACP PC-RP on Biodiversity (Flora) Botanical
985 Survey of India [Internet]. 2025. <https://www.envis.nic.in>

38. Yang H, Tan T, Ren G, Liu Y, Liu Z, Xia S, et al. The dual nature of water hyacinth (*Pontederia crassipes*): Environmental threats and sustainable solutions [Internet]. *Water Biology and Security*. KeAi Communications Co.; 2025. <https://doi.org/10.1016/j.watbs.2025.100359>
39. Mohd Saad FN, Remlee NN, Zakarya IA, Kamaruddin MA, Izhar TNT, Ibrahim MH, et al. Phytoremediation potential of *Azolla pinnata* on water quality and nutrients from agricultural water. *Desalination Water Treat* [Internet]. Desalination Publications; 2022;271:38–47. <https://doi.org/10.5004/dwt.2022.28810>
40. Zhang M, Lin H, Long X, Cai Y. Analyzing the spatiotemporal pattern and driving factors of wetland vegetation changes using 2000-2019 time-series Landsat data. *Science of the Total Environment* [Internet]. Elsevier B.V.; 2021;780. <https://doi.org/10.1016/j.scitotenv.2021.146615>
41. Gujrati A, Pradhan R, Nayak P, Singh RP, Nidamanuri RR. Monitoring Aquatic Vegetation Dynamics in Large Indian Wetlands Using Multi-Seasonal Sentinel-2 Observations. *Remote Sens Earth Syst Sci* [Internet]. Springer Nature; 2025;9. <https://doi.org/10.1007/s41976-025-00258-9>
42. Luo H, Xu Y, Han Q, Zhang L, Feng L. Remote sensing assessment of ecological quality of Baiyangdian wetland in response to extreme rainfall. *Remote Sens Appl* [Internet]. Elsevier B.V.; 2024;36. <https://doi.org/10.1016/j.rsase.2024.101284>
43. Shabani F, Raie M, Kabiri K. Studying the impact of sea surface temperature (SST) changes and El Niño phenomenon on coral reefs bleaching around Kish Island in the northern Persian Gulf: A remote sensing approach. *Deep Sea Res 2 Top Stud Oceanogr* [Internet]. Elsevier Ltd; 2025;224. <https://doi.org/10.1016/j.dsr2.2025.105550>
44. IPCC. Impacts of 1.5°C Global Warming on Natural and Human Systems. *Global Warming of 15°C* [Internet]. Cambridge University Press; 2022. p. 175–312. <https://doi.org/10.1017/9781009157940.005>
45. Gupta PK, Patel JG, Bhandari RJ, Parmar M, Rathore BP, Mishra I, et al. Indian wetlands: A High Resolution Remote Sensing Assessment and Analysis [Internet]. Ahmedabad; 2024. https://vedas.sac.gov.in/content/vcms/downloads/atlas/Wetlands/wetland_L4_atlas_12March2024.pdf. Accessed 27 Aug 2026

- 1016 46. Verdhien Anand. Wetland formation and reclamation in the flood prone areas: a case study
1017 in Bihar, India. Modern Cartography Series [Internet]. 2021. p. 581–602.
1018 <https://doi.org/10.1016/B978-0-12-823895-0.00021-X>
- 1019 47. Das SK, Sharma MR. Mapping long-term Transformation of Wetlands and Annual Rainfall
1020 Variability in Madhubani District (1975-2022). Current World Environment [Internet]. Enviro
1021 Research Publishers; 2024;19:251–68. <https://doi.org/10.12944/cwe.19.1.22>
- 1022 48. Tarate SB, Singh IS, Raut SM, Madane DA. Waterbody decline and warming trends in
1023 aquatic ecosystems of selected districts of North Bihar in India (1995–2024): A remote sensing
1024 perspective. Theor Appl Climatol. Springer; 2025;156. [https://doi.org/10.1007/s00704-025-](https://doi.org/10.1007/s00704-025-05820-5)
1025 [05820-5](https://doi.org/10.1007/s00704-025-05820-5)
- 1026 49. Barman A, Jha R, Rajak F. Impact of Urbanisation and Encroachment in wetlands, a case
1027 study of Ganga riparian wetlands, Patna Impacts of Urbanization and Encroachment in urban
1028 wetlands, a Case study of Ganga Riparian wetlands in Patna. Adrian [Internet]. 2020 [cited
1029 2026 Aug 10];3.
1030 https://scholar.google.com/citations?view_op=view_citation&hl=en&user=p3iPL44AAAAJ
1031 https://scholar.google.com/citations?view_op=view_citation&hl=en&user=p3iPL44AAAAJ
&citation_for_view=p3iPL44AAAAJ:zYLM7Y9cAGgC. Accessed 10 Aug 2026
- 1032 50. India Meteorological Department. Monthly Rainfall Data Series. 2025.
- 1033 51. Rashid MB. Monitoring of drainage system and waterlogging area in the human-induced
1034 Ganges-Brahmaputra tidal delta plain of Bangladesh using MNDWI index. Heliyon [Internet].
1035 Elsevier Ltd; 2023;9. <https://doi.org/10.1016/j.heliyon.2023.e17412>
- 1036 52. Walsh RPD, Lawler DM. Rainfall Seasonality: Description, Spatial Patterns And Change
1037 Through Time. Weather [Internet]. 1981;36:201–8. [https://doi.org/10.1002/j.1477-](https://doi.org/10.1002/j.1477-8696.1981.tb05400.x)
1038 [8696.1981.tb05400.x](https://doi.org/10.1002/j.1477-8696.1981.tb05400.x)
- 1039 53. Stosic T, Tošić M, Lazić I, da Silva Araújo L, da Silva ASA, Putniković S, et al. Changes
1040 in rainfall seasonality in Serbia from 1961 to 2020. Theor Appl Climatol [Internet]. Springer;
1041 2024;155:4123–38. <https://doi.org/10.1007/s00704-024-04871-4>
- 1042 54. Aydin M. Evaluation of the Usability of the Rainfall Anomaly Index (RAI) Instead of the
1043 Standard Precipitation Index (SPI). Iranian Journal of Science and Technology - Transactions
1044 of Civil Engineering [Internet]. Springer Science and Business Media Deutschland GmbH;
1045 2025;49:763–85. <https://doi.org/10.1007/s40996-024-01516-4>

- 1046 55. Rao Gr, Sowjanya A, Shekhar D, Naik Bns, Kiran B. Rainfall analysis over 31 years of
1047 Chintapalle, Visakhapatnam, High Altitude and Tribal zone, Andhra Pradesh, India. MAUSAM
1048 [Internet]. India Meteorological Department; 2023;74:685–98.
1049 <https://doi.org/10.54302/mausam.v74i3.818>
- 1050 56. Ucar Y, Kocięcka J, Liberacki D, Rolbiecki R. Analysis of Crop Water Requirements for
1051 Apple Using Dependable Rainfall. Atmosphere (Basel) [Internet]. MDPI; 2023;14.
1052 <https://doi.org/10.3390/atmos14010099>
- 1053 57. Sharma MR, Priya S, Kumari S. Century of Rainfall Dynamics and Drought in Bihar:
1054 Patterns, Trends, and Climatic Variability (1901-2021). Current World Environment [Internet].
1055 Enviro Research Publishers; 2025;20:105–20. <https://doi.org/10.12944/cwe.20.1.9>
- 1056 58. Tanada K, Tasumi M, Murakami H, Moriyama M, Takahashi Y, Ide R, et al. Implementation
1057 and evaluation of a global evapotranspiration index algorithm based on land surface
1058 temperature. Journal of Agricultural Meteorology. Society of Agricultural Meteorology of
1059 Japan; 2026;82:15–30. <https://doi.org/10.2480/agrmet.D-25-00022>
- 1060 59. Liu H, Gao C, Wang G. Understand the resilience and regime shift of the wetland ecosystem
1061 after human disturbances. Science of the Total Environment [Internet]. Elsevier B.V.;
1062 2018;643:1031–40. <https://doi.org/10.1016/j.scitotenv.2018.06.276>
- 1063 60. Ghazinoory S, Bakhtiar A, Safardoust A. A Comprehensive Classification of Ecosystem
1064 Resilience Assessment Methods: Frameworks, Approaches, and Models. Environmental and
1065 Sustainability Indicators [Internet]. 2026;101116. <https://doi.org/10.1016/j.indic.2026.101116>
- 1066 61. Zhang H, Zhou M, Gu C, Xiong Q, Dai W, Zhou S. Wetland ecosystem monitoring and
1067 change prediction based on high-resolution remote sensing data and deep learning.
1068 Microchemical Journal [Internet]. Elsevier Inc.; 2025;219.
1069 <https://doi.org/10.1016/j.microc.2025.115990>
- 1070 62. Sarkar P. Out-Migration from Bihar: Major Reasons and Destinations. Journal of Migration
1071 Affairs [Internet]. Journal of Migration Affairs, Centre for Development Practice and Research,
1072 Tata Institute of Social Sciences; 2019;2:132. <https://doi.org/10.36931/jma.2019.2.1.132-140>
- 1073 63. Das SK, Priya S, Sharma MR. Determinants and Spatial Patterns of Out-Migration from
1074 Madhubani District - A Case Study of BISFI, India. Indian Journal of Spatial Science [Internet].
1075 2024;15:94–8.

1076 https://www.researchgate.net/publication/381578479_Determinants_and_Spatial_Patterns_of
1077 [_Out-migration_from_Madhubani_District_A_case_study_of_BISFI_India](https://www.researchgate.net/publication/381578479_Determinants_and_Spatial_Patterns_of)