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Linking Vegetation Health and Water Risk of Wetlands in Vaishali District Through NDVI, SAVI, MNDWI, and WRI (2014–2024)

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Abstract: **The study of wetlands is a major concern these days. There is a significant shift in the wetland ecosystem, both geographically and hydrologically, as well as ecologically and biologically. Wetlands are well defined by their presence of water in a particular region. As it plays a vital role in maintaining the balance between ecology and hydrology and is the primary supporter of biodiversity, it is highly beneficial for sustaining livelihoods that depend on it. To evaluate the spatial-temporal changes in the wetland ecology and hydrology of Vaishali district for the period 2014-2024. Both pre- and post-monsoon conditions were studied using remote sensing techniques with Landsat 8 and 9 data from the USGS Earth Explorer platform. For the depth analysis of the study area, four indices were used: NDVI, SAVI, MNDWI, and WRI. These indices help assess vegetation and extract water features. The study highlights the holistic view of the eco-hydrology of the Vaishali. Where major contractions in vegetation and water have been observed over the decades. Due to annual precipitation, water expands during the post-monsoon season. The study emphasizes the importance of wetlands and their conservation. As the livelihood of the surrounding people depends on it. Day by day, climate change, population growth, and changing land-use patterns directly or indirectly impact the overall health of the wetland. Proper conservation and management help fulfil the Sustainable Development Goals, including those for life below water and life on land.**

Keywords: **Wetland, Remote Sensing, NDVI, SAVI, MNDWI, WRI.**

1. INTRODUCTION

Wetlands have been described both as "**the kidneys of the landscape**" for the functions they perform in the hydrological and chemical cycles, and as "biological supermarkets" for the extensive food webs and rich biodiversity they support (Mitsch & Gosselink, 2015). Wetlands are various types, such as marsh, fen, peatland, or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salt, including areas of marine water, the depth of which at low tide does not exceed six meters (Ramsar Convention Secretariat, 2010). As an important natural resource, it supports a great diversity of life worldwide. It also provides habitat for both animals and plants (Prasad et al., 2002; Biswas Roy et al., 2015). Despite their importance to the environment and to humans, today's wetlands are under threat from increasing human demands and alterations in environmental and climatic conditions. Wetland losses are widespread worldwide (Mahdavi et al., 2018; Brinkmann et al., 2020). At present, the total area covered by wetlands in India is 1,359,951 ha. (Ramsar.org). It reveals that at least 400 million hectares of wetlands have been lost since 1970, with nearly a quarter of those remaining in a degraded state. These losses significantly impact water availability, biodiversity, climate stability, and human well-being.

To enhance the understanding and monitoring of wetlands, the government promotes the development of wetland inventories and wetland atlases using remote sensing techniques. Remote Sensing (RS) and GIS techniques provide a holistic overview of the geospatial and temporal aspects. In recent years, satellite imagery and Geographical Information

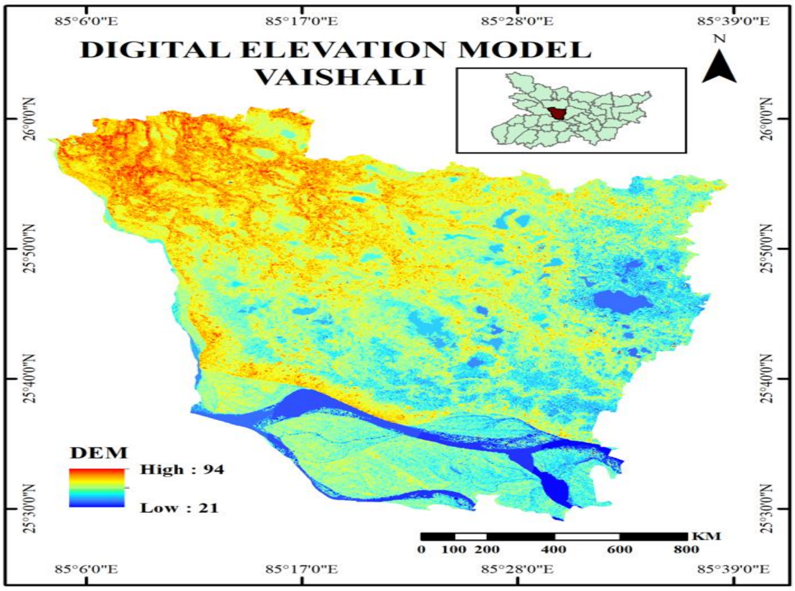
Systems (GIS) have proven effective tools for monitoring wetlands. Several spectral indices, which are composites of surface reflectance at various wavelengths. So it can analyze spatial-temporal changes in the research area (Eid et al., 2020; Laonamsai et al., 2023; Sharma & Das, 2025). For Wetland monitoring and mapping, multiple indices are used in eco-hydrological analysis. The Normalized Difference Vegetation Index (NDVI) and the Soil Adjusted Vegetation Index were used in an ecological study. For water body detection, the Modified Normalized Difference Water Index (MNDWI) and Water Ratio Index (WRI) were utilized (Eid et al., 2020; Chaoyong et al., 2024).

Despite their ecological importance, Wetlands in Bihar are increasingly threatened by population pressure, agricultural expansion, and climatic variability. It lies in a fertile part of the Gangetic plain. Vaishali district is located in the northern part of Bihar, where the Ganga River divides the state into two parts (Wetland Atlas, 2010). Hence, the significance of the current study lies in providing insight into vegetation health and water risk scenarios in the Vaishali district between 2014 and 2024. The study evaluates wetland habitat condition and identifies areas of great concern. Both pre-monsoon and post-monsoon conditions were investigated to better understand the eco-hydrological dynamics of the study area. The governing body must address these issues to ensure proper management and implementation of laws and achieve sustainable wetland management.

2. STUDY AREA

Vaishali district is located in northern Bihar. The study area lies between 25°41′N–25.68°N and 85°13′E–85.22°E, covering a total area of 2036 km². The district is bounded in the north by Muzaffarpur, in the south by Patna (River Ganga), in the east by Samastipur, and in the west by the Saran districts. (River Gandak) (District Profile-District Planning and Monitoring Cell 3).It is naturally defined by its boundaries, formed by the flow of two major rivers, the Gandak and the Ganga, which make the region very fertile. The region looks green, with plants and trees growing in a semi-tropical monsoon climate. However, the months of May-June are hot, and December-January are cold (DPIS, Vaishali). The total wetland area in the district is 17148 ha, including 275 small wetlands with an area of less than 2.25 ha, which comprise about 9 percent of the district's geographical area. Rivers/streams, lakes, ponds, natural waterlogged areas, ox-bow lakes, and meanders contribute to the wetland extent (Bihar Wetland Atlas, 2010). The District's Demography Profile, according to the 2011 census, shows a population of 3,495,249, with 18,47,049 males and 16,48,191 females. The district's overall literacy rate is 68.6%.

Fig.1: Study Area map of Vaishali District



Source: Prepared by Author using SRTM DEM

3. OBJECTIVE OF THE STUDY

- To study the Geospatial assessment of Wetland Ecology in Vaishali District during 2014–2024
- To investigate Ecohydrological changes in Vaishali district through various indices: NDVI, SAVI, MNDWI, and WRI

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4. DATA SOURCES AND METHODOLOGY

4.1 Acquisition of Satellite Imagery

Remote Sensing data, derived from satellite observations, are essential for eco-hydrological analysis of the study area. The data were collected from secondary sources. Satellite imagery and toposheets were used in the study. All satellite imagery was downloaded from the USGS Earth Explorer website, and Landsat 8 data were used. For the geographical study, toposheets were used as the base map, obtained from the Survey of India (SOI). The followings toposheet were used: 72F/4, 72F/8, 72G/1, 72G/2, 72G/5, 72G/6, 72G/7, 72G/9, 72G/10, and 72G/11.

After that, using remote sensing techniques, an SRTM DEM was generated for the study area. Various indices, including NDVI, SAVI, MNDWI, and WRI, were calculated. All maps were prepared using ArcGIS software.

Table 1: Details of the datasets used for the study

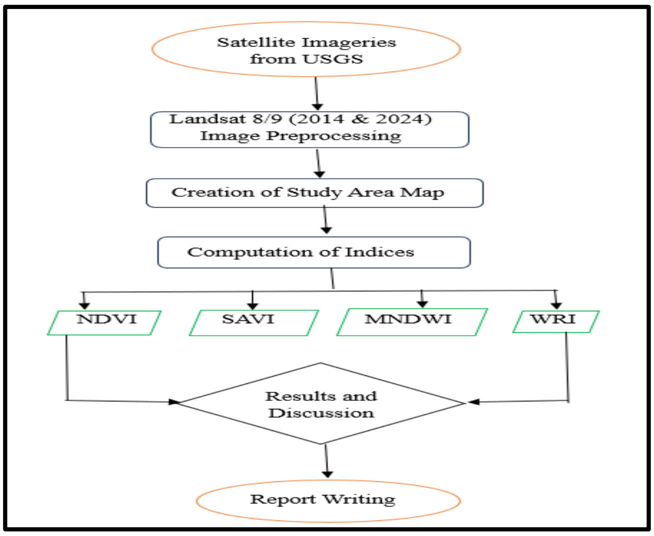
Sources	*Satellite*	*Sensor*	*Year*	*Date*	*Row*	*Path*
USGS Earth Explore	Landsat_8	OLI_TIRS	2024	05/03/24	42	141
	Landsat_9	OLI_TIRS		24/11/24	42	141
	Landsat_8	OLI_TIRS	2014	27/04/14	42	141
	Landsat_8	OLI_TIRS		21/11/14	42	141

4.2 Methodology of Eco-hydrological Analysis of the Study Area

The flow chart below shows the work process of the study, which is done in three sections

To begin with Preprocessing of the Satellite imagery and preparation of the study Area. Second, calculating the Indices. Then analysis of the result and report writing.

Fig. 2: Research Methodology



4.3 Calculation of Various Indicators

4.3.1. NDVI (Normalized Difference Vegetation Index)

To determine how the vegetation cover changed during the course of the study, the Normalized Difference Vegetation Index (NDVI) was calculated. The most often used metric for assessing vegetation cover is the NDVI. It evaluates vegetation health and canopy density using red (RED) and near-infrared (NIR) bands (Das & Mishra, 2024).

$$\mathbf{NDVI = (NIR-Red) / (NIR+Red)}$$

It has values between -1 and +1. Soil or bare patches of rock or sand, and urban areas, are represented by very low NDVI values (-0.1 or lower). The water cover is zero. Low-density vegetation is represented by moderate values (0.1 to 0.3), and thick canopy vegetation is indicated by high values (0.6 to 0.8)(Ramachandra and Kumar, 2009; Ramachandra, 2012; M & M, 2019).

4.3.2. SAVI (Soil Adjusted Vegetation Index)

The SAVI was calculated using Huete's (1988) equation for the study (Kadhum & Ati, 2025). A modified NDVI that incorporates a soil brightness correction factor derived from NIR and RED bands is ideal for areas with low vegetation density (Galodha et al., 2025). The Soil-Adjusted Vegetation Index reduces the impact of soil brightness by using red (RED) and near-infrared (NIR) wavelengths. SAVI is designed to correct for instability, where L is a canopy background adjustment factor; a value of 0.5 was found to reduce differences in soil brightness and eliminate the need for further calibration across various soil types. It was discovered that the change essentially removes the soil-induced variability in vegetation indices. The waterbody's SAVI values ranged from -0.53 to 0.05 (Eid et al., 2020).

$$\mathbf{SAVI = (NIR - Red) / (NIR + Red + L) \times (1 + L)}$$

(where L is a soil adjustment factor, commonly 0.5)

4.3.3. MNDWI (Modified Normalized Difference Water Index)

Waterbodies are identified from satellite images using the Modified Normalized Difference Water Index (MNDWI). In satellite imagery, it effectively differentiates between urban and watery regions. This technique is an improved method for detecting water bodies, as it uses the visible green (GREEN) and short-wave infrared 1 (SWIR1) spectral bands. MNDWI is appropriate for extracting water features across a variety of land cover types because it effectively minimizes confusion between water bodies and populated regions (Girma et al., 2025). Positive MNDWI values indicate the presence of water bodies, while negative values correspond to noise. (Xu 2006).

$$\mathbf{MNDWI = (Green - SWIR) / (Green + SWIR)}$$

Water bodies in MNDWI exhibit (+) values, while soil, settlements, and vegetation are characteristically expressed with negative values. The MNDWI ranges from 1 to -1 for water bodies (Akram et al., 2023; Chaoyong et al., 2024; Mishra et al., 2025).

4.3.4. WRI (Water Ratio Index)

The Water Ratio Index (WRI) is a measure that detects water bodies by using four spectral reflectance bands. It takes water's dominating spectral reflectance into consideration. It is determined by dividing the total reflectance of near-infrared and short-wave infrared 1 (SWIR1) bands by the reflectance of visible green (GREEN) and red (RED) spectral bands. For waterbodies, the WRI value is higher than 1(Shen et al., 2010; Deoli et al. 2021; Laonamsai et al., 2023; Tarate et al., 2025).

$$\mathbf{WRI = (GREEN + RED) / (NIR + SWIR1)}$$

WRI shows values, in general, greater than 1 for water (Gautam et al., 2015).

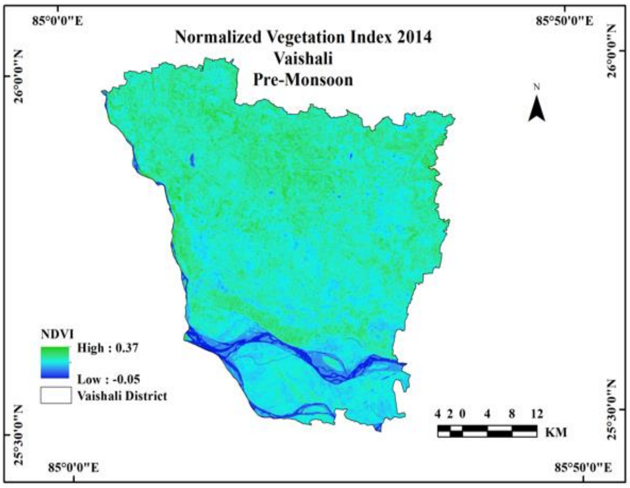
5. RESULTS AND DISCUSSION

In the present study, four indices, i.e., NDVI, SAVI, MNDWI, and WRI, were integrated ecological and hydrological assessment of the Vaishali district

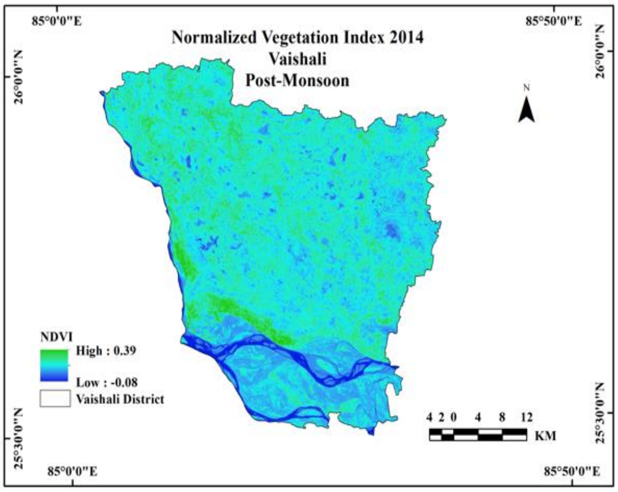
5.1 Analysis of NDVI

The Normalized Difference Vegetation Index (NDVI) maps for the Vaishali district from 2014 to 2024 illustrate the changes in vegetation health and distribution over this period. The blue shades show the water bodies. Where green areas depict the vegetation. The result varies with seasonal changes. In 2014, during the pre-monsoon period, the maximum NDVI is 0.37, and the minimum is -0.05. It depicts an increase in the built-up areas and a slight decline in water bodies and agricultural areas. As in post-monsoon conditions, the high NDVI value is 0.39, and the low value is -0.08. In map 2(b), the water bodies are clearly visible as blue patches.

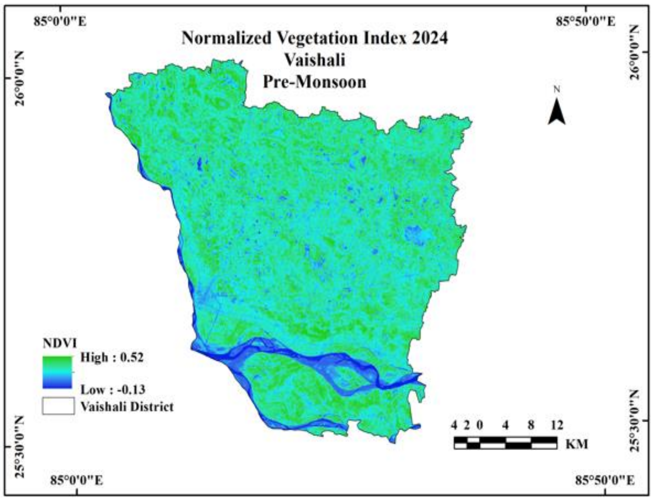
Fig. 2: Map Showing Normalized Vegetation Index for the year 2014-2024



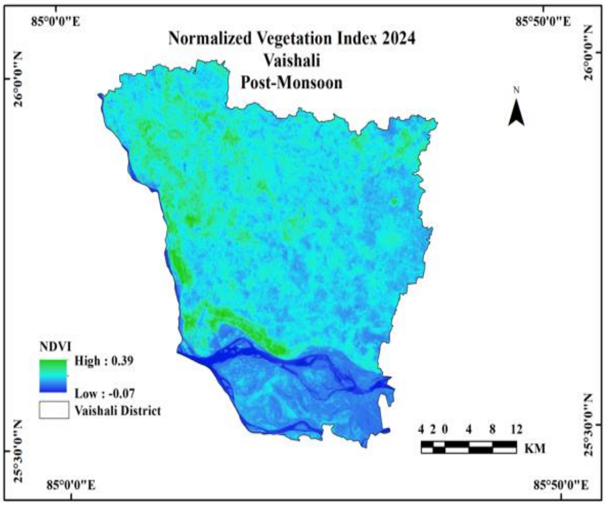
2(a)



2(b)



2(c)



2(d)

In 2024, the pre-monsoon conditions, the high NDVI value is 0.52, and the low value is -0.13. The area surrounding small wetlands is used for agriculture or plantation-style farming. During the post-monsoon season (2024), the NDVI ranged from 0.39 (high) to -0.07 (low). The overall results show that in pre-monsoon conditions, vegetation growth appears to increase, whereas in the post-monsoon period, due to rainfall and recharge of surface water bodies, the land is used for fishing or other purposes. Over the years, the district's vegetation has declined. The green areas, denoting dense vegetation, show varying degrees of expansion and contraction, reflecting natural and anthropogenic influences on the surface water bodies and some parts of the wetland areas. The ecology shifts its patterns directly in response to regional climate change.

5.2 Analysis of SAVI

Figure 3 illustrates significant changes in vegetation dynamics over the years using the Soil Adjusted Vegetation Index (SAVI) from 2014 to 2024 in the Vaishali district. The variations in SAVI values, from yellow (highly urbanized areas) to medium-green vegetation patches and low values indicating water surfaces. In map 3 (a), for the pre-monsoon condition of 2014, the high SAVI value is 0.56, and the low is -0.07. In the post-monsoon season, the maximum value is 0.58, and the minimum is -0.12.

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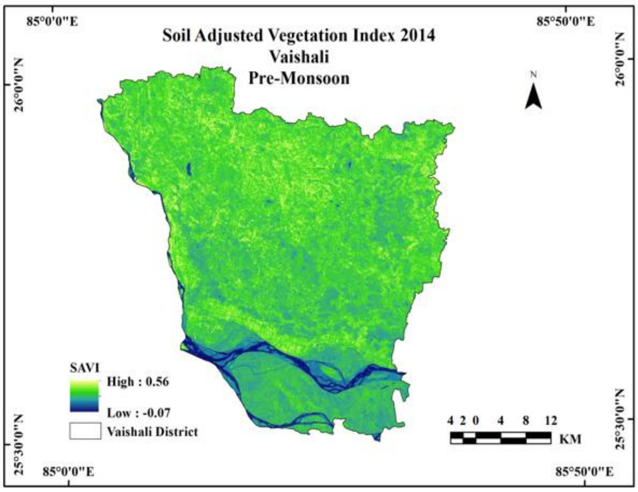
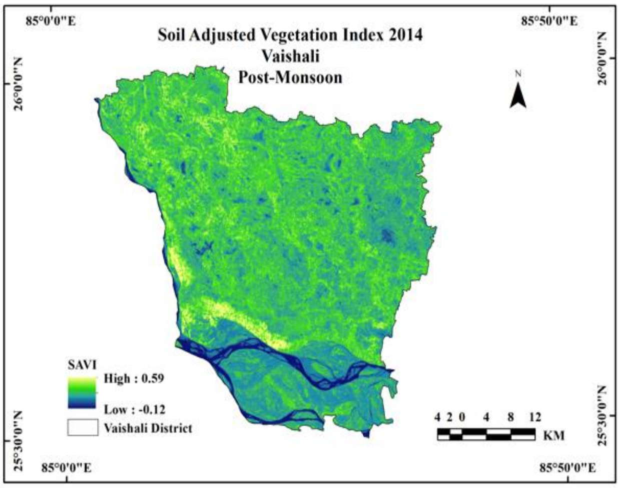
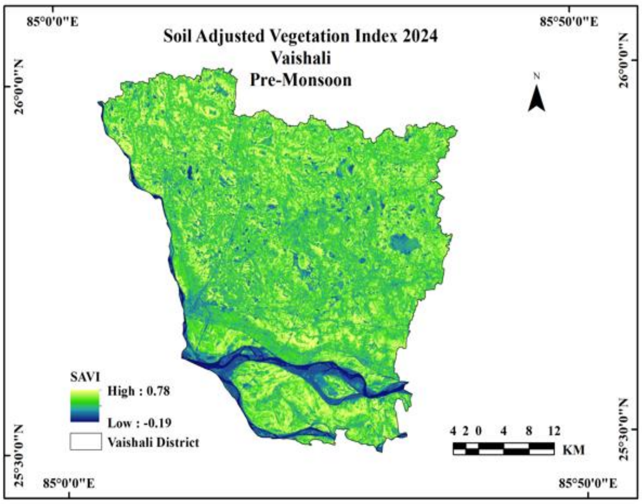
Fig. 3: Map Showing Soil Adjustive Vegetation Index for the year 2014-2024



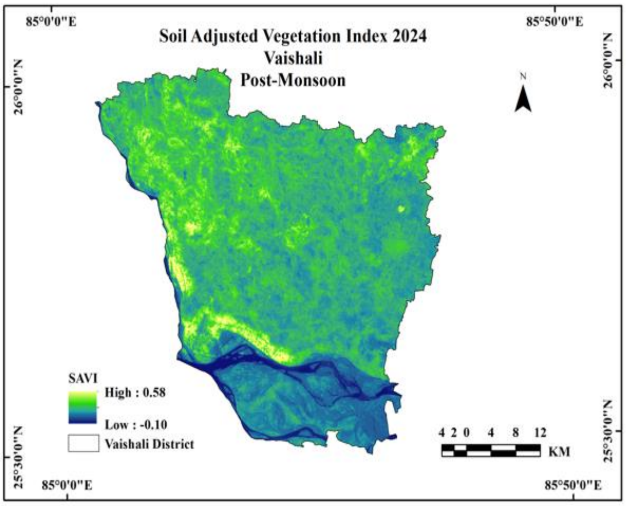
3(a)



3(b)



3(c)



3(d)

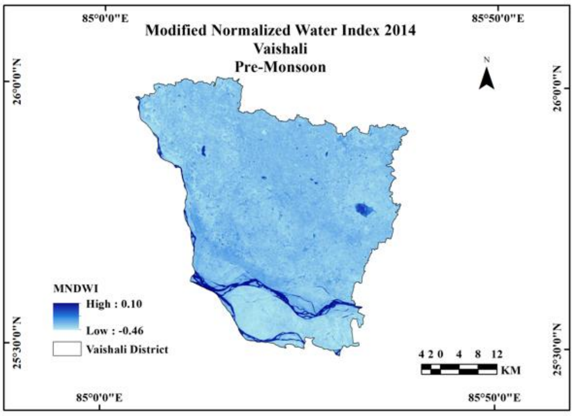
The SAVI shows better results for vegetation analysis than NDVI. As the map above shows, vegetation growth resulting from shifts in land-use practices and conservation efforts is underway. The built-up areas are clearly visible in yellow, and moderate vegetation growth is evident around the Gandak and Ganga rivers, as well as in some wetland and river water bodies.

5.3 Analysis of MNDWI

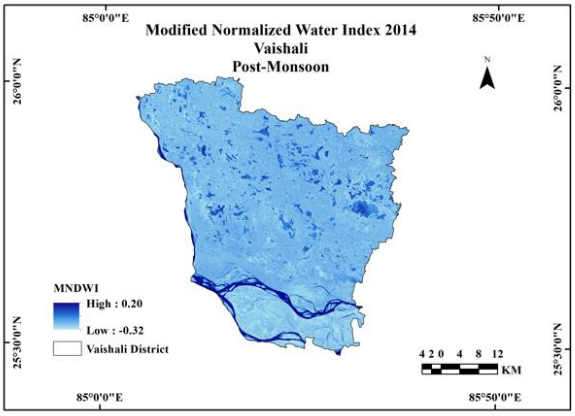
The Modified Normalized Difference Water Index (MNDWI) for the Vaishali district. The hydrological analysis using spatial-temporal changes for the period 2014 to 2024. Over this period, water bodies undergo changes in both the pre-monsoon and post-monsoon seasons. The figures below show the MNDWI, which is classified into two categories: water bodies and non-water bodies. High MNDWI values indicate dark blue patches of surface water bodies, while lower values indicate agricultural, vegetated, and built-up areas.

In 2014, during the pre-monsoon period, the high MNDWI value is 0.10, and the low value is -0.46. During post-monsoon, the high value is 0.20, and the low value is -0.32.

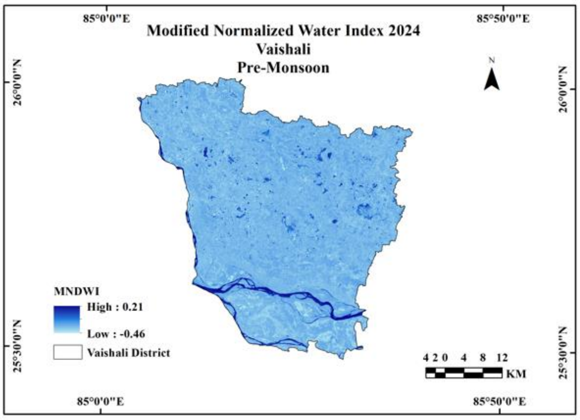
Fig. 4: Map Showing Modified Normalized Water Index for the year 2014-2024



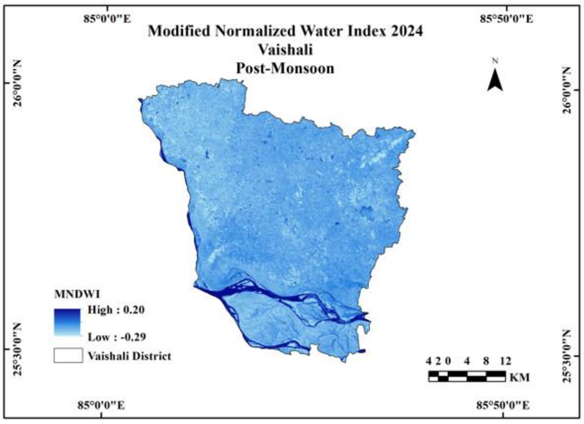
4(a)



4(b)



4(c)



4(d)

In 2014, the wetlands and rivers, such as the Gandak and Ganga, showed a contraction in area, with wetland areas of 63.2 sq. km during pre-monsoon and 149.56 sq. km during post-monsoon. As in Figure 13, it's clearly visible that there is a high amount of wetness in the rivers coursing as well as in the wetland areas. In 2024, during the pre-monsoon, the waterbody area is 79.21 sq. km., and during the post-monsoon, it is 87.99 sq. km. As a result, the wetlands of the Vaishali district are highly dependent on rainfall. There is a significant increase in open surface water during the post-monsoon season and a decrease in the pre-monsoon season.

The western side of the district meets the water requirement, and the southern side is met by both the Gandak and the Ganga. The districts' wetlands, such as Baraila, Billi Tal, Salah Chaur, Hariya Chaur, and Tal Sihan, contain water that supports the livelihoods of surrounding communities year-round. The region's hydrology has shifted over the years and is highly affected by climate change and anthropogenic activities, including population pressure, land-use changes, and the overexploitation of Nature.

5.4 Analysis of WRI

In this section of the present study, the water ratio index will be used as an indicator of water availability in the study area. The WRI is the quantitative measure of the efficacy of water utilization. Vaishali district is blessed with two main sources of water: the perennial rivers Ganga and Gandak. These two rivers cover certain areas in the district, including Lalganj, Hajipur, and Mahnar. This district also has other water sources, including Salah Chaur, Billi Taal, and Baraila Wetland. The comparative analysis of 2014 and 2024 is conducted during the present monsoon and post-monsoon periods. The maps below highlight the differences between the pre-monsoon and post-monsoon periods in 2014 and 2024. The WRI in the pre-monsoon season in 2014 is 0.52 in the northern part of the district, which is low, and 1.16 in the adjacent areas of the river Gandak, which is considered high.

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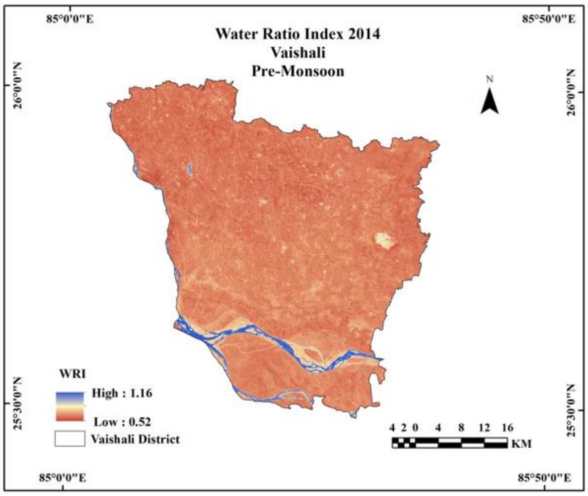
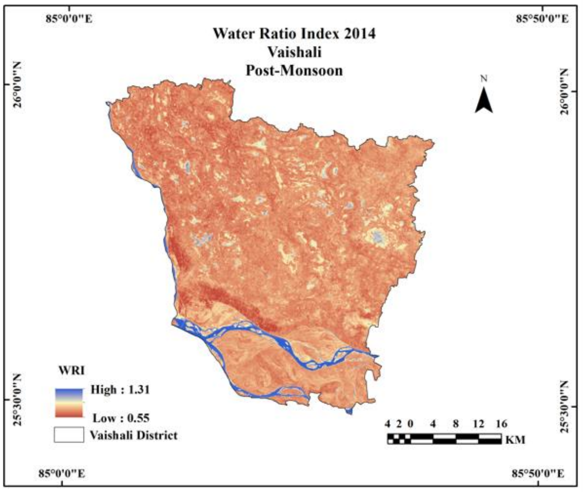
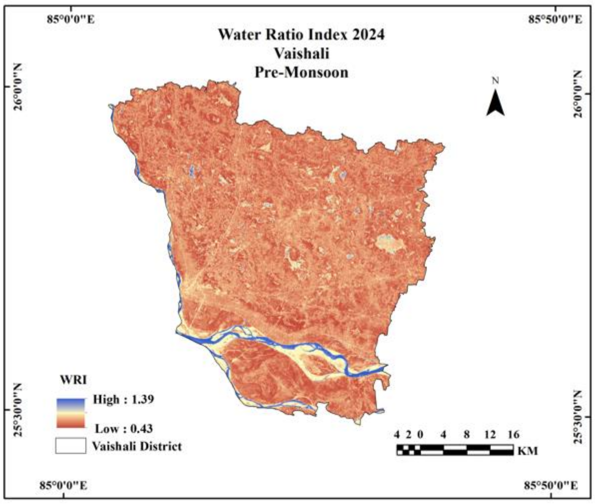
Fig. 5: Map Showing Water Ratio Index for the year 2014-2024



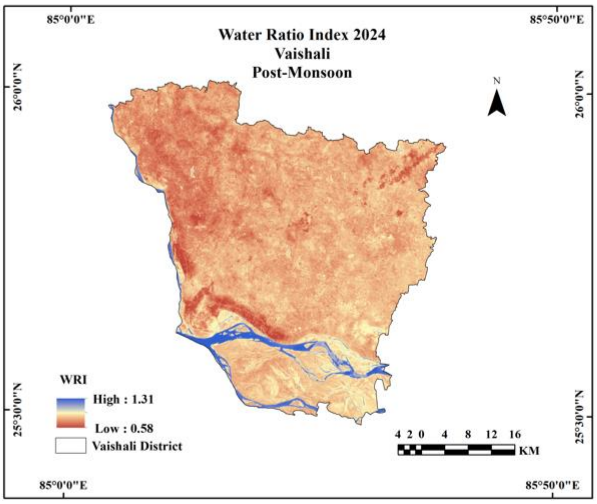
5(a)



5(b)



5(c)



5(d)

The WRI of the post-monsoon is fairly high, i.e., 1.36 at the river Gandak, but it is low, i.e., 0.55, in areas away from the water source. As for 2024, the map shows a high WRI of 1.39, higher than in 2014, even during the pre- and post-monsoon seasons that year. The post-monsoon variation in 2024 shows a high WRI value of 1.31. Areas such as Mahnar, Hajipur, and Hazrat Janadaha benefit most during the post-monsoon period. The northern areas, such as Lalganj and Mahua, and the north-eastern areas face water stress and are drier than other areas even in the post-monsoon. These variations in pre- and post-monsoon clearly affect the lives of people concentrated in different parts of the district. The WRI accurately reflects the equilibrium between water availability and demand in both periods. In areas where water is available, the population clearly depends on it for their needs, while areas facing water stress require more water to meet those needs.

6. CONCLUSION

In this study, a detailed analysis of the ecological and hydrological conditions is highlighted by using remote sensing techniques. Various indices, such as NDVI, SAVI, MNDWI, and WRI, are studied. The ecology of the Vaishali district has declined over the decades, and hydrometeorological patterns are shifting in response to changes in annual precipitation, wetland recharge, and land use. Based on vegetation health and water dynamics, there is a need for proper management and conservation of the wetland. Spatial and temporal analysis help us monitor the wetland ecology. The use of multidimensional indices further allows us to focus on preserving the wetland environment and on how we can benefit the communities living in the surrounding areas.

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