Spatiotemporal Analysis of Environmental and Urban Change in Purulia District during the Period 2000 to 2010 Using Spectral Indices

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Abstract

This study presents a spatiotemporal analysis of environmental and urban change in Purulia district, West Bengal, over a decade from 2000 to 2010. A time series of Landsat satellite imagery for the years 2000, 2005, and 2010 was acquired to record changes in vegetation health, surface water content, and built-up area. Three spectral indices, namely the Normalized Difference Vegetation Index (NDVI), the Modified Normalized Difference Water Index (MNDWI), and the Normalized Difference Built-up Index (NDBI) were utilized to reveal the changes. The "image differencing" technique was applied to the derived spectral index maps for two five-year periods (2000–2005 and 2005–2010) and eventually for the entire decade from 2000 to 2010. The resulting change maps were then classified using a thresholding approach to quantify the extent of negative, positive, and no change. The findings highlight a twofold pattern, one marked by environmental degradation and significant water loss in the first half of the decade and the other identified by vegetation decline, alongside a simultaneous but uneven expansion of built-up areas.

Keywords: Spatiotemporal analysis, Landsat, NDVI, MNDWI, NDBI, image differencing, environmental degradation.

1. Introduction

Alterations in the land surface characteristics are critical indicators of the intricate dynamics between anthropogenic activities and the natural environment *(Townshend & Justice, 1986; Singh, 1989)*. In developing regions, rapid and often unplanned changes in Land Use/Land Cover (LULC) can lead to significant environmental consequences, including deforestation, soil erosion, water scarcity, and loss of biodiversity. Monitoring these changes is essential for sustainable resource management, effective environmental planning, and informed decision-making.

The district of Purulia in West Bengal, India, represents an important case study of such environmental and socio-economic challenges. As the westernmost district of the state and the easternmost extension of the Chota Nagpur Plateau, Purulia is characterized by a semi-arid climate, lateritic soils with low water retention capacity, and a high dependence on rain-fed agriculture. These inherent vulnerabilities are compounded by anthropogenic factors such as deforestation and conversion of pervious surfaces to impervious surfaces for settlements.

The introduction and application of remote sensing and Geographic Information System (GIS) has provided a powerful and efficient means to monitor the Earth's surface at various spatial and temporal scales. Satellite-derived spectral indices are particularly effective in illustrating and quantifying specific features such as vegetation, water, and built-up areas. The NDVI is a widely used index for vegetation health and density *(Rouse et al., 1974; Tucker, 1979)*. The MNDWI is sensitive to the moisture content in vegetation and the presence of open water bodies *(McFeeters, 1996; Xu, 2006)*. The NDBI is effective in delineating urban and built-up areas *(Zha, Gao, & Ni, 2003)*.

This study aims to exploit these spectral indices to conduct a comprehensive change detection analysis of Purulia district for the period 2000–2010. By calculating NDVI, MNDWI, and NDBI for the years 2000, 2005, and 2010, and then applying the image differencing technique, the areas that have undergone significant changes in vegetation, water content, and urban infrastructure can be efficiently identified.

The primary objectives of this research are:

a) To calculate and map the NDVI, MNDWI, and NDBI for Purulia district for the years 2000, 2005, and 2010.
b) To apply the image differencing technique to these indices to detect and quantify spatiotemporal changes over two five-year periods (2000–2005 and 2005–2010) and eventually for the entire decade (2000–2010).

c) To analyze the detected changes in the context of the known environmental and socio-economic drivers in the district, such as land degradation and urbanization.

2. Study Area

Purulia district is the westernmost district of West Bengal, India, spanning between 22°43′ and 23°42′ in the North and 85°49′ and 86°54′ in the East (**Fig. 1**). It covers a geographical area of approximately 6,257 km^2. The district is a part of the easternmost extension of the Chota Nagpur Plateau and is characterized by its undulating terrain.

Climate: Purulia has a semi-arid and sub-tropical climate, marked by very hot summers and cool winters. The district is drought-prone and receives an average annual precipitation of about 1100–1500 mm, most of which occurs during the monsoon months. The unpredictable nature of the monsoon at this part of the state often leads to water scarcity.

Geology and Soil: The region is primarily composed of Archean-era granite and gneiss formations. It has predominant lateritic, acidic, and coarse-textured soils, with low organic matter content and poor water-holding capacity, making the land susceptible to erosion.

Socio-economic Profile: Purulia is predominantly a rural district. Agriculture is the mainstay of the economy, which is largely subsistence-based and heavily dependent on the monsoon.

To provide a visual baseline of the district's land surface for the selected years, the true color (**Fig. 2**) and false color (**Fig. 3**) satellite composites are presented, illustrating the imagery used for analysis.

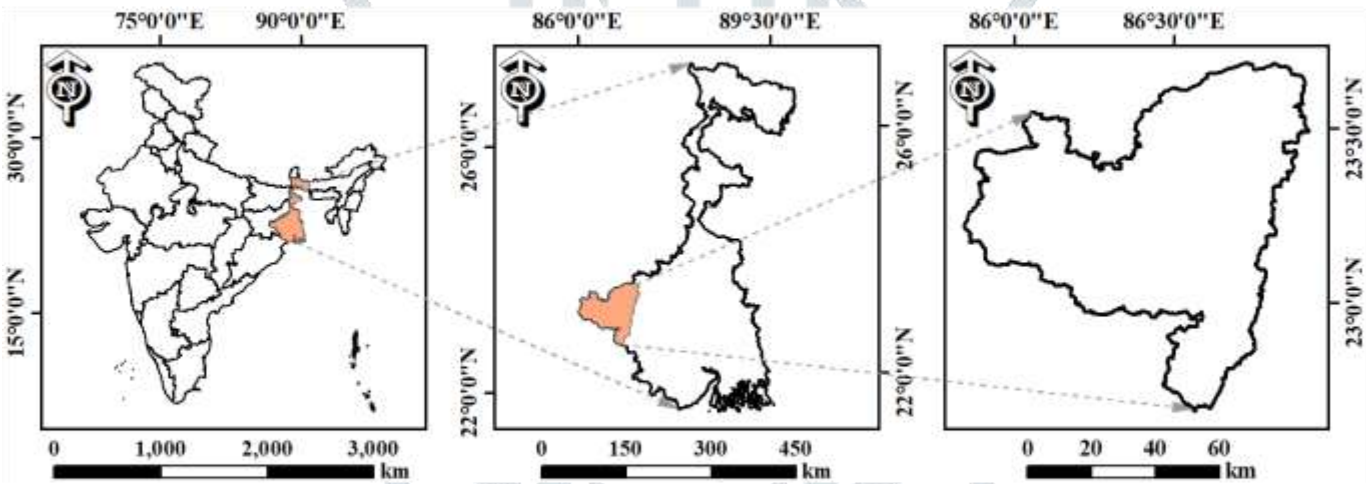

Figure 1 Location map of Purulia.

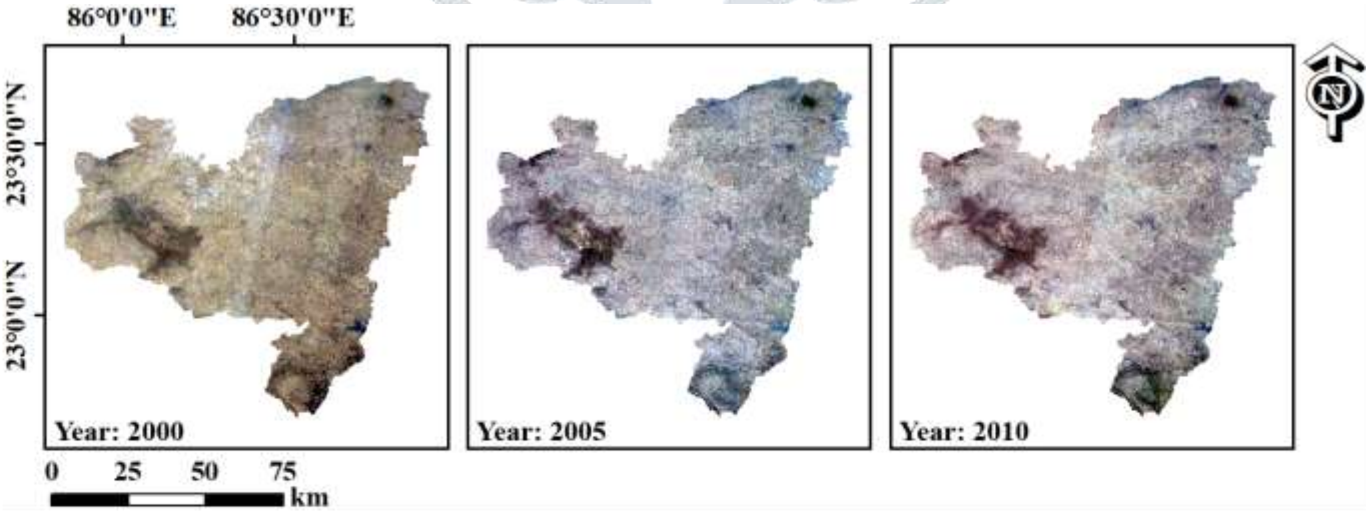

Figure 2 True color composites of the district for the years 2000, 2005, and 2010.

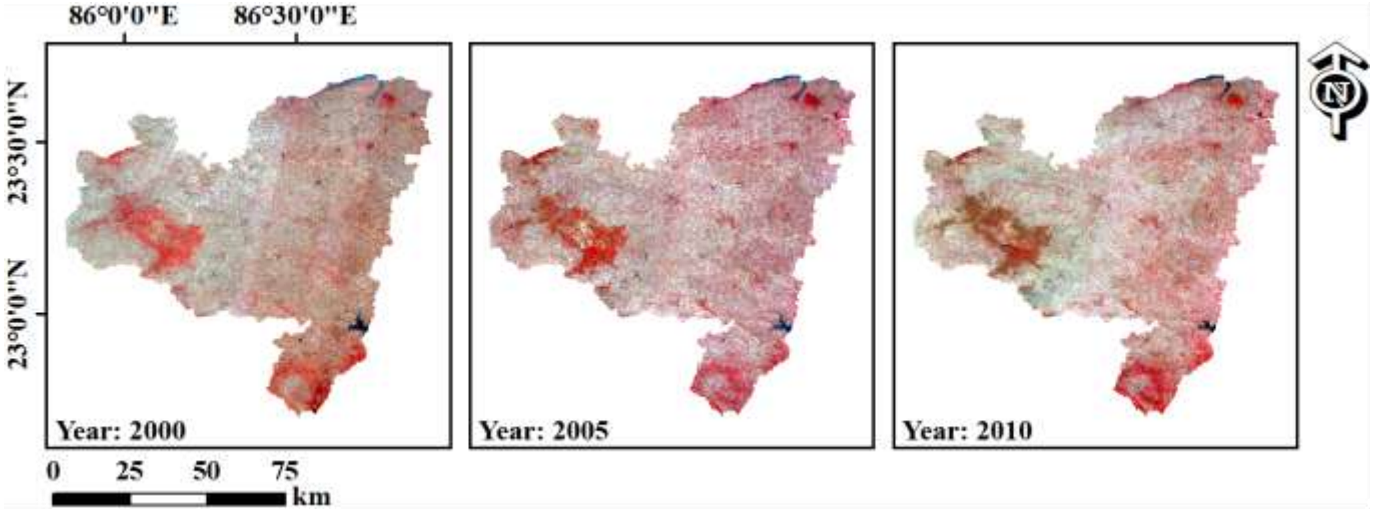

Figure 3 False color composites of the district for the years 2000, 2005, and 2010.

3. Materials and Methods

This study followed a systematic methodology involving data acquisition, pre-processing, index calculation, and change detection.

3.1. Data Acquisition and Pre-processing

The primary data consists of mean surface reflectance images from the Landsat 5 Thematic Mapper (TM) sensor for the years 2000, 2005, and 2010. To minimize contamination, images with less than 5% cloud cover were selected. Standard geometric and radiometric corrections were applied to the images, converting the raw digital numbers (DN) into physically meaningful surface reflectance. Landsat imagery provides an established, long-term record for analyzing spatiotemporal changes *(Jensen, 2005; Roy et al., 2014)*.

3.2. Calculation of Spectral Indices

Three spectral indices were derived for each of the study years using the pre-processed surface reflectance data. The following equations (**Equations 1–3**) were used to calculate the specific indices.

Normalized Difference Vegetation Index (NDVI): This index quantifies the vigor and density of green vegetation, where higher positive values indicate healthier vegetation.

$$NDVI = \frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}} \quad 1$$

Modified Normalized Difference Water Index (MNDWI): This index is used to delineate open water bodies and is highly sensitive to the moisture content in vegetation. It enhances the separation of water from built-up features.

$$MNDWI = \frac{\text{Green} - \text{SWIR1}}{\text{Green} + \text{SWIR1}} \quad 2$$

Normalized Difference Built-up Index (NDBI): This index highlights built-up areas, where values are typically higher compared to other land covers.

$$NDBI = \frac{\text{SWIR1} - \text{NIR}}{\text{SWIR1} + \text{NIR}} \quad 3$$

3.3. Change Detection using Image Differencing

The image differencing technique is one of the most widely applied methods in digital change detection *(Singh, 1989; Lu et al., 2004)* and was employed to detect changes by subtracting the pixel values of the earlier image from the later image for each index. For example, the "difference NDVI image" for the period 2000 to 2005 was calculated from the **Equation 4**.

$$\Delta NDVI_{2000-2005} = NDVI_{2005} - NDVI_{2000} \quad 4$$

This process creates a "difference" image where pixel values represent the magnitude of change. Values close to zero indicate little change, while positive and negative values show an increase or decrease in the index, respectively.

3.4. Thresholding and Change Classification

However, not all detected changes are significant, as minor pixel value variations can be caused by factors like atmospheric differences or sensor noise. To isolate meaningful transformations from this background noise, a threshold of ±0.2 was applied to the "difference" images. Based on this threshold, the change maps were classified into three distinct categories:

a) **Positive Change:** Pixels with a value greater than +0.2 threshold.
b) **Negative Change:** Pixels with a value less than −0.2 threshold.
c) **No Change:** Pixels with values between −0.2 and +0.2 thresholds.

4. Results

The analysis of the spectral indices and their temporal differences reveals significant trends in the environmental and urban landscape of Purulia district between 2000 and 2010.

4.1. NDVI Change Analysis (Vegetation Health)

The NDVI change analysis indicates a fluctuating but overall negative trend in vegetation health over the decade.

Table 1: Area of NDVI Change (2000–2010).

Change Period	Positive Change (km^2)	Negative Change (km^2)	No Change (km^2)	District Area (km^2)
2000-2005	24.64	9.77	6222.29	6256.71
2005-2010	5.21	19.67	6231.83	
2000-2010	21.32	40.94	6194.44	

During the first period (2000–2005), there is a modest gain in vegetation, with a 24.64 km^2 area of the district showing positive change compared to a 9.77 km^2 area experiencing loss. However, this pattern contrastingly reversed in the subsequent period (2005–2010), where a significant area of 19.67 km^2 showed a decline in vegetation health, while only 5.21 km^2 area of the district showed improvement in vegetation health (**Fig. 4**).

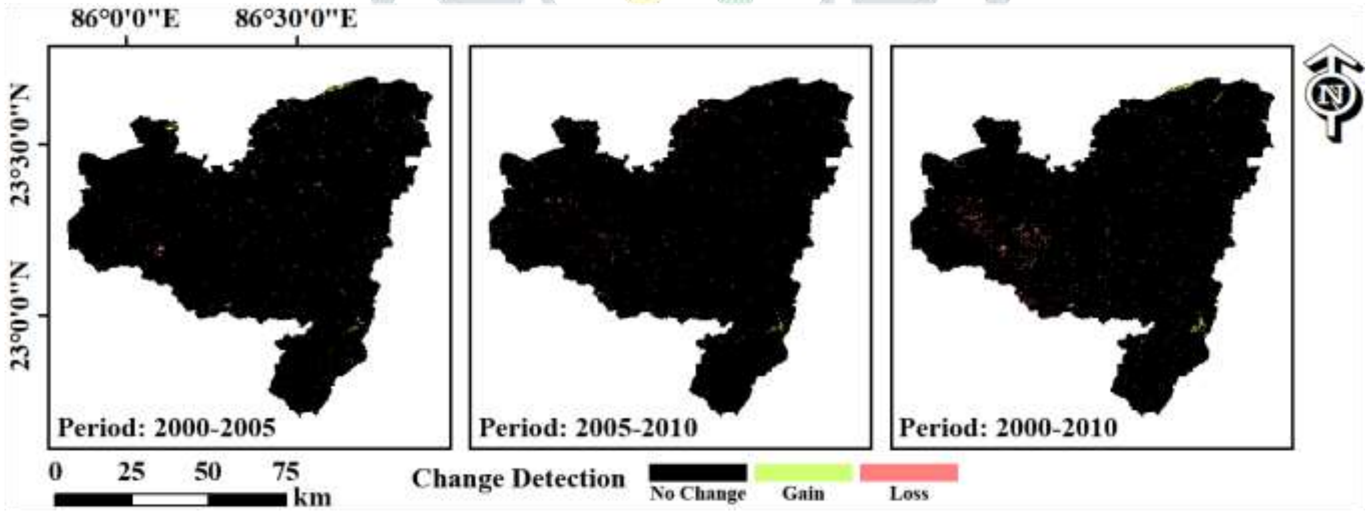

Figure 4 NDVI-based change detection for the periods 2000–2005, 2005–2010, and 2000–2010.

4.2. MNDWI Change Analysis (Water Content)

The analysis of water content, using the MNDWI, indicates severe water stress in the first half of the decade, followed by a period of relative stability.

Table 2: Area of MNDWI Change (2000–2010).

Change Period	Positive Change (km^2)	Negative Change (km^2)	No Change (km^2)	District Area (km^2)
2000-2005	3.09	159.18	6094.44	6256.71
2005-2010	8.62	16.26	6231.82	
2000-2010	5.66	104.48	6146.57	

A substantial negative change in MNDWI was observed between 2000 and 2005, with a loss of 159.18 km^2, indicating a significant reduction in surface water and vegetation moisture. Contrastingly, this pattern was not observed in the 2005–2010 period. The change was minimal, with an area of 8.62 km^2 showing an increase in water content and an area of 16.26 km^2 showing a decrease, resulting in a sustained net loss (**Fig. 5**).

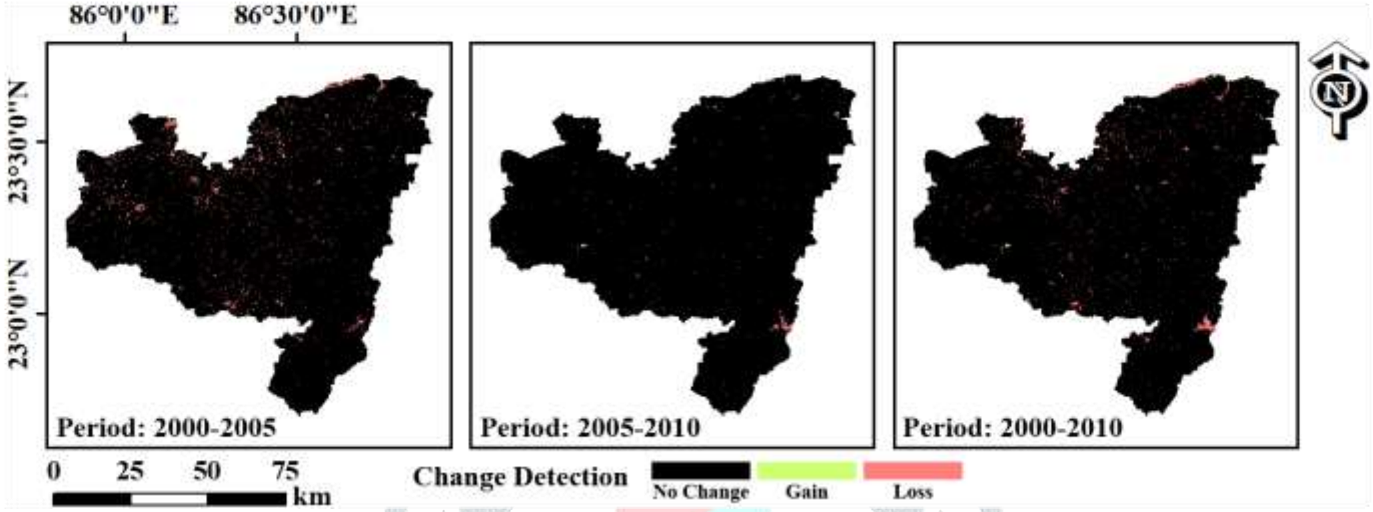

Figure 5 MNDWI-based change detection for the periods 2000–2005, 2005–2010, and 2000–2010.

4.3. NDBI Change Analysis (Built-up Area)

In stark contrast to the environmental indices, the NDBI analysis reveals a notable expansion of built-up areas, though the pace of this expansion slowed significantly over the decade.

Table 3: Area of NDBI Change (2000–2010).

Change Period	Positive Change (km^2)	Negative Change (km^2)	No Change (km^2)	District Area (km^2)
2000-2005	106.18	4.77	6145.76	6256.71
2005-2010	12.5	8.82	6235.39	
2000-2010	139.33	6.05	6111.32	

The period from 2000 to 2005 witnessed a major expansion of built-up areas, with a positive change within a total area of 106.18 km^2. However, the rate of expansion decreased sharply in the second period (2005–2010), with only 12.5 km^2 of new built-up area detected (**Fig. 6**).

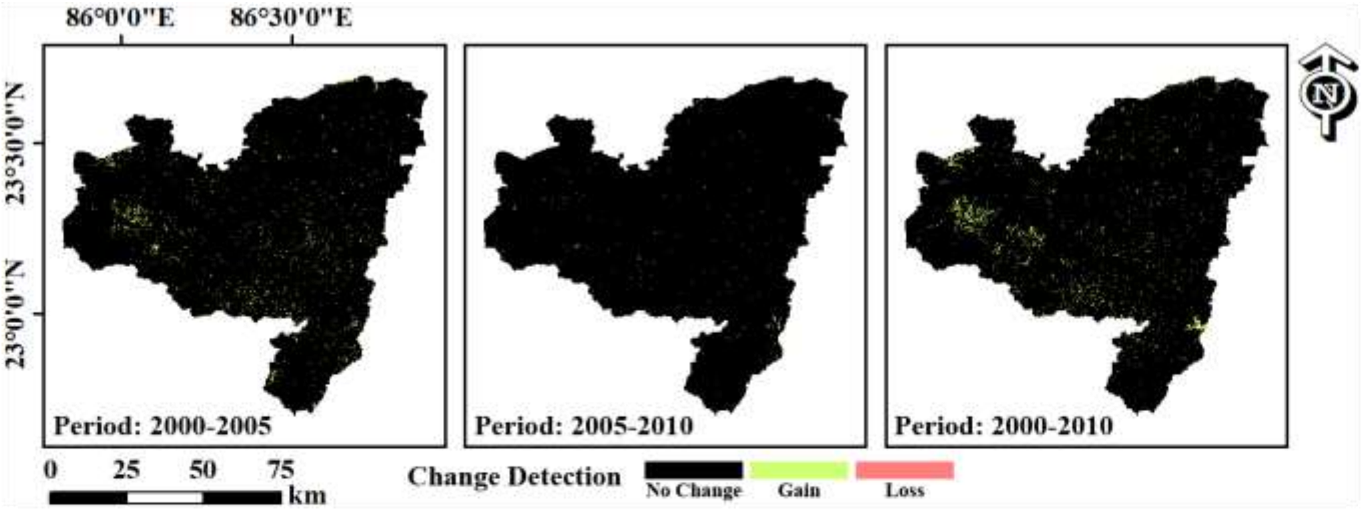

Figure 6 NDBI-based change detection for the periods 2000–2005, 2005–2010, and 2000–2010.

5. Discussion

The quantitative results of this study reveal a complex and dynamic narrative of environmental and urban change in Purulia district between 2000 and 2010. The findings support the concurrent environmental degradation and urban expansion but uncover a multifaceted, shifting course within the decade. The district appears to have undergone two distinct phases, a period of intense, rapid change (2000–2005), followed by a period of consequence and shifting dynamics (2005–2010).

5.1. The Primacy of Water Stress and its Lagged Effect on Vegetation

The most significant finding is the severe decline in water content during the 2000–2005 period, with a net loss of an area of over 156.09 km^2 as measured by the MNDWI. This aligns perfectly with the district's known profile as a drought-prone, semi-arid region heavily dependent on timely monsoons. This initial period of acute water stress appears to be the primary driver of environmental degradation. While water scarcity peaked early, the impact on vegetation was not immediate. Rather, the severe water deficit likely created a lagged effect, with the ecological consequences manifesting in the subsequent 2005–2010 period. This is evidenced by the sharp reversal in the NDVI trend, which saw a net loss of an area of 14.46 km^2 in the latter half of the decade (derived from 19.67 km^2 decline minus 5.21 km^2 gain). This suggests that the region's ecosystems showed some initial resilience but ultimately succumbed to the pressure of prolonged water scarcity, leading to a decline in vegetation health.

5.2. Shifting Urbanization Dynamics

The analysis of the NDBI contradicts the assumption of steady, accelerating urbanization. The data points to a rapid burst of development between 2000 and 2005, with built-up areas expanding by 106.18 km^2, though offset by 4.77 km^2 decline, giving a net gain of 101.41 km^2. This pattern of "front-loaded" growth suggests a surge of anthropogenic activities especially human settlements in the first half of the decade. This was followed by a drastic slowdown, with an expansion of only 3.68 km^2 overall area in the 2005-2010 period. While this expansion signifies economic activity, its occurrence during a period of severe water loss highlights a potential conflict between development and environmental sustainability.

5.3. Decadal Transition (2000–2010)

The decade-long change analysis for Purulia district highlights a dual narrative of environmental degradation and urban growth. NDVI results reveal a net loss of 19.62 km^2 of healthy vegetation (21.32 km^2 gain offset by 40.94 km^2 decline), reflecting the lagged ecological response to persistent water stress. MNDWI analysis confirms this underlying driver, showing a severe overall reduction of 98.82 km^2 in surface water and moisture content despite minor local gains, pointing to worsening hydrological scarcity. In contrast, NDBI results demonstrate substantial built-up expansion, with a net increase of 133.28 km^2 (139.33 km^2 positive change offset by 6.05 km^2 loss), though the pace slowed in the latter half of the decade. Together, these findings depict a district experiencing intensifying drought conditions and vegetation decline, alongside sustained but uneven urban development.

5.4. Implications for Policy and Future Research

The interplay between these trends provides critical insights for regional planning. The clear link between water availability and vegetation health underscores the need for robust water management and drought mitigation strategies to protect the agricultural base and natural ecosystems of Purulia. Furthermore, the uneven pace of urbanization suggests that future development must be planned with careful consideration for its impact on the district's already stressed natural resources.

6. Conclusion and Future Scope

This research successfully employed spectral indices and the image differencing technique to conduct a spatiotemporal analysis of environmental and urban change in Purulia district from 2000 to 2010. The study reveals a dual trend: a significant degradation of the natural environment, evidenced by the net decline in water content during the first half of the decade and subsequent vegetation decline in the latter half, alongside a simultaneous, though uneven, expansion of built-up areas. These findings are consistent with the known environmental challenges of drought and land degradation and the socio-economic reality of a growing population in the district. The index-based approach proved to be a rapid and effective method for identifying the magnitude and location of these changes.

The primary limitation of this study is that while it quantifies the extent of change, it does not identify the nature of the land cover transformations. Therefore, the logical next step is to use the change maps generated in this study as a guide for a more detailed targeted LULC "from-to" analysis. By creating LULC maps for 2000 and 2010 and overlaying them with the identified change hotspots, a change detection matrix can be generated. This will provide crucial insights into the specific processes of land cover conversion, enabling policymakers and planners to formulate more effective strategies for sustainable land management, drought mitigation, and planned urban development in Purulia.

Supplementary Material

High-resolution versions of all figures presented in this study are available in a publicly accessible repository: https://drive.google.com/drive/folders/1B_Rn1DbAARBvJIKzVjKym4E_69y1L4KO?usp=sharing. This repository shall serve as the designated source for supplementary materials related to this article and will also host all future supplementary resources associated with the author's publications in this journal.

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