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Spatio-Temporal Assessment of Land Use Land Cover Changes Affecting Regional Ecology in Patna Urban Agglomeration (PUA) in Bihar, India during 1990 to 2024

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ABSTRACT

Patna is among the cities high populated at risk of ecological and environmental deterioration due to a variety of human activities, such as poor land cover management. One of the most crucial elements of a successful land resource management plan is the evaluation of Land Use Land Cover (LULC). Over the past 20 years, our planet's land cover resources have undergone substantial changes due to rapid development. The Land Use Land Cover (LULC) categories of the Patna Urban Agglomeration (PUA), including water bodies, agricultural land, barren land, built-up areas, and vegetation, were identified using Geographic Information System (GIS) techniques. Three multi-temporal images were analyzed and classified through supervised classification using the maximum likelihood method. By comparing three separately created LULC categorized maps from 1990 and 2024, temporal changes were analyzed. In order to update land cover or manage natural resources, it is vital to use change detection as a tool to identify changes in LULC over time in PUA, Patna between 1990, 2010 and 2024. According to their respective Kappa coefficients, the accuracy rates for 1990, 2010 and 2024 LULC are 91.66 and 94.93, respectively. An accuracy evaluation was conducted to determine the correctness of the classification

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system and to determine the efficacy of the LULC classification maps. One hundred reference test pixels were identified. There have been found significant changes in the LULC were built up area has increased doubled in last thirty-four years of timeline.

Keywords: LULC; GIS; Urban Agglomeration; Ecology; Patna

1. Introduction

Ecology and atmosphere are greatly impacted by Land Use Land Cover Change (LULCC)[1]. Unplanned and unregulated expansion are hallmarks of urbanization in Patna Municipal Corporation (PMC), resulting in environmental damage and urban sprawl[2]. Sustainable urban development depends upon efficient land use planning and development patterns, such as, allocation of commercial, industrial, and residential zones[3]. Chandra emphasizes, the value of land as a vital resource for economic growth, connecting it to industry, agriculture, and settlements[4]. The Urban Heat Island (UHI) phenomena in PMC is highlighted by Yadav et al., who describe the environmental consequences of urbanization across three decades (1990–2022), with a focus on Land Surface Temperature (LST). According to this study, urbanization has led to a decrease in vegetation and a rise in surface temperatures[5]. With an emphasis on Patna, Mishra et al. support the use of technical tools and spatio-temporal studies to solve the problems associated with urbanization[6]. Similar to this, Khan et al. use Landsat satellite images from 1995 to 2015 to examine Patna's periphery expansion and offer long-term insights into LULCC dynamics[7]. Sharma and Pani investigate how urbanization affects alluvial rivers and fluvial geomorphology, with particular reference to Patna. By utilizing the NDVI approach to examine changes in urban green cover[8], Ashraf and Ghose show that during a 25-year period, built-up areas have tripled and vegetation has significantly decreased. Urbanization reduces open green spaces and sustainability[9], according to Rizvi and Raj. The Bihar State Housing Board's involvement in land distribution and housing since the 1970s is assessed by Fatima, who also connects it to Patna's urban planning[10]. Chettry and Surawar use spatiotemporal analysis of Landsat photos from 1991 to 2018 to compare urban sprawl in mid-sized Indian cities, including Patna[11]. While Prakash et al. use advanced remote sensing (PSInSAR) to examine the vertical and horizontal expansion of the Patna Urban Agglomeration from 2015 to 2018[12], Kumar and Rajak concentrate on the insufficient distribution of urban green spaces in PMC[13]. In the middle Gangetic Plain in Patna, Zafar and Kumari evaluate the effects of human activity on the water quality of the Ganga River[14], while Das et al. use NASA's OCO-2 data (2015–2021) to examine CO2 changes in Bihar[15].

Research Gaps

Integrated, long-term evaluations of urbanization in the Patna Urban Agglomeration are desperately needed, given the majority of research only cover a few years between 1990 and 2024. Furthermore, current research frequently focuses on discrete aspects like plant cover, urban sprawl, and Land Surface Temperature (LST), missing multidisciplinary approaches that integrate ecological, socioeconomic, and infrastructure considerations for comprehensive urban planning. A lot of research fails to connect its conclusions to practical policy suggestions. To successfully address the issues of sustainable urban development, governance structures and stakeholder viewpoints must be incorporated. Although sophisticated remote sensing methods are employed, there is a great deal of promise for combining geospatial analytics and AI-based prediction models to predict future urbanization patterns and effects.

Despite the significance of including riverine health into land use planning, little is known about how urbanization and riverine ecosystems interact. Additionally, little research has been done on the relationships between urbanization, Land Use Land Cover Change (LULCC), and the effects of climate change, especially with regard to mitigation measures. Lastly, the allocation of housing, infrastructure, and green areas frequently ignores equality issues, underscoring the necessity of inclusive urban development strategies. Filling up these research gaps would improve knowledge of LULCC in Patna and aid in the development of policies that encourage fair and sustainable urbanization.

2. Statement of Problem

Rapid urbanization has resulted in major Land Use Land Cover Changes (LULCC) in Patna Municipal Corporation (PMC), which have quadrupled in recent decades and are characterized by urban expansion, decreased greenery, and increasing built-up areas [16]. According to Yadav, Kumar, and Swarup this has exacerbated the Urban Heat Island (UHI) effects increasing surface temperature and having a negative correlation with plant cover [5]. Environmental degradation has been made worse by the disruption of hydrological systems and biodiversity caused by encroachment on natural habitats, including wetlands and the Ganga floodplains [14, 17]. Increased industrial and vehicle emissions have also contributed to the region's deteriorating air quality, with notable increase in pollutants including PM 2.5 and NO2 [15]. Actionable policies and sustainable planning are still lacking, even though sophisticated GIS and remote sensing techniques offer insightful information on LULCC [6]. These difficulties highlight the pressing need for integrated approaches in the Patna Urban Agglomeration (PUA) that strike a balance between ecological preservation and urban growth.

3. Study Area

The capital of Bihar state, Patna is the most populated and rapidly expanding city in India. It also serves as the headquarter of Patna district. Situated on the southern bank of the Ganga River, the study area lies between 25°36'45.6372" N, 85°9'31.9500" E (**Figure 1**). Patna Urban Agglomeration's population increased from 1.69 million in 2001 to 2.05 million in 2011 at a compound annual growth rate of (2.1 percent). In contrast, the Patna Urban Agglomeration expanded between 1951 and 2011 at a compound annual growth rate of 3.11 percent. Between 1991 and 2001, Patna Urban Agglomeration grew at one of India's quickest rates, (4 percent) annually.

4. Data Source and Research Methodology

Land Use Land Cover in the study area were analyzed using Landsat series satellite data for 1990, 2010, and 2024. The data has been taken from the United States Geological Survey's (USGS) website. The Landsat archives contained many temporal data sets for the Patna urban area (**Table 1**).

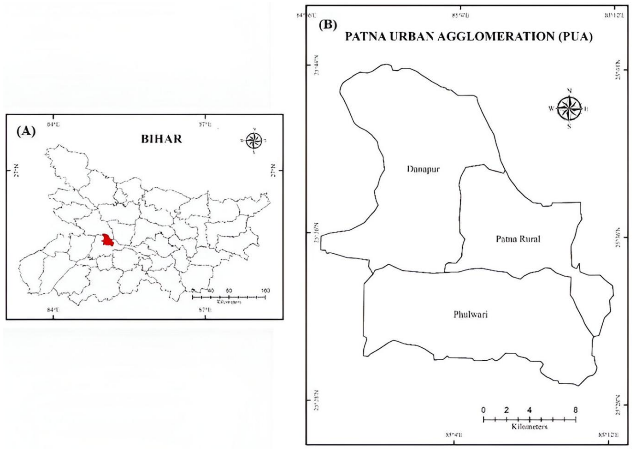


Figure 1. Administrative division of study area. (**A**) District Map of Bihar. (**B**) Administrative division of Patna Urban Agglomeration.

4.1. Database

The methodology for detecting Land Use Land Cover Changes (LULCC) using satellite images involves several structured steps. Initially, satellite images from various sources and years are acquired, including Landsat 5 and 8 1990, 2010 and 2024. These images undergo pre-processing, which includes geometric corrections to eliminate spatial distortions and the creation of subsets to focus on specific study areas. For the OLI Image 8, the relevant study area is extracted for detailed analysis (**Table 2**). To ensure the reliability of the results, an accuracy assessment is conducted using ground truth data and statistical methods. This database structure ensures through documentation and tracking of each step in the LULC change detection process, providing a robust framework for analysis.

4.2. Land Use Land Cover Classification

Except for the years 1990, 2010 and 2024 the temporal satellite data Landsat 7 ETM+ were utilized for the compilation of LULC maps. These LULC Maps undergo geometric corrections to ensure spatial accuracy, and specific study areas are extracted. The images are then subjected to supervised classification, where a classifier is trained using ground truth data to categorize different LULC types. There are two types of image classification: supervised and unsupervised. It is described as the process of assigning pixels to their appropriate classes [18]. Typically, each pixel is viewed as a

Table 1. Data used.

S. No.	Satellite	Sensor	Date and Year	Resolution (Meters)
1	Landsat 5	TM	February, 20, 1990	30
2.	Landsat 8	OLI	March, 12, 2010	30
3.	Landsat 8	OLI	April, 26, 2024	30

Table 2. Technical Specification of Satellite Images

Type			Mechanical Scanner	
Spatial Resolution			30 m	
Spectral Range			0.45µm to 12.5µm	
No. of Bands			08	
Temporal Resolution			16 days	
Year	Path and Row	Spatial Resolution	Description	Satellite
1990	132/46	30 m	Landsat-5	Thematic Mapper (TM)
2010	132/46	30 m	Landsat-7	Thematic Mapper (TM)
2024	132/46	30 m	Landsat-8	Operational Land Imager (OLI)

separate unit made up of values from multiple spectral bands. Supervised classification is described as the process of classifying the rest of the image using a known identity of specific sites in remotely sensed data that represent homogeneous examples of land cover categories.

4.2.1. Accuracy Assessment

Accuracy evaluation or validation is an important stage in the classification of remote sensing data. The total accuracy of the classified image reveals how well each pixel in the classified satellite data correlates to the real ground data [19]. In this study, accuracy tests were undertaken for the years 1990, 2010, and 2024. The three accuracies—Producer's Accuracy, User's Accuracy, and Overall Accuracy—as well as the Kappa Coefficient, have been determined. While performing the categorization and accuracy evaluation, the Anderson Rule of least (85 per cent) accuracy, Anderson (1971) and Anderson et al. (1976) were followed [20, 21].

Kappa Coefficient calculate from the following equation:

No. of correctly classified pixels in each category/total no. of reference pixels (the row total)*100

$$\text{Kappa Coefficient (T)} = \frac{(\text{Ts} * \text{Tcs}) - (\text{Column Total*Row Total})}{\text{Ts2} - (\text{Column Total*Row Total})} * 100 = 91.2\% \quad (1)$$

Where,

Ts = Total Sample

Tcs = Total Corrected Sample

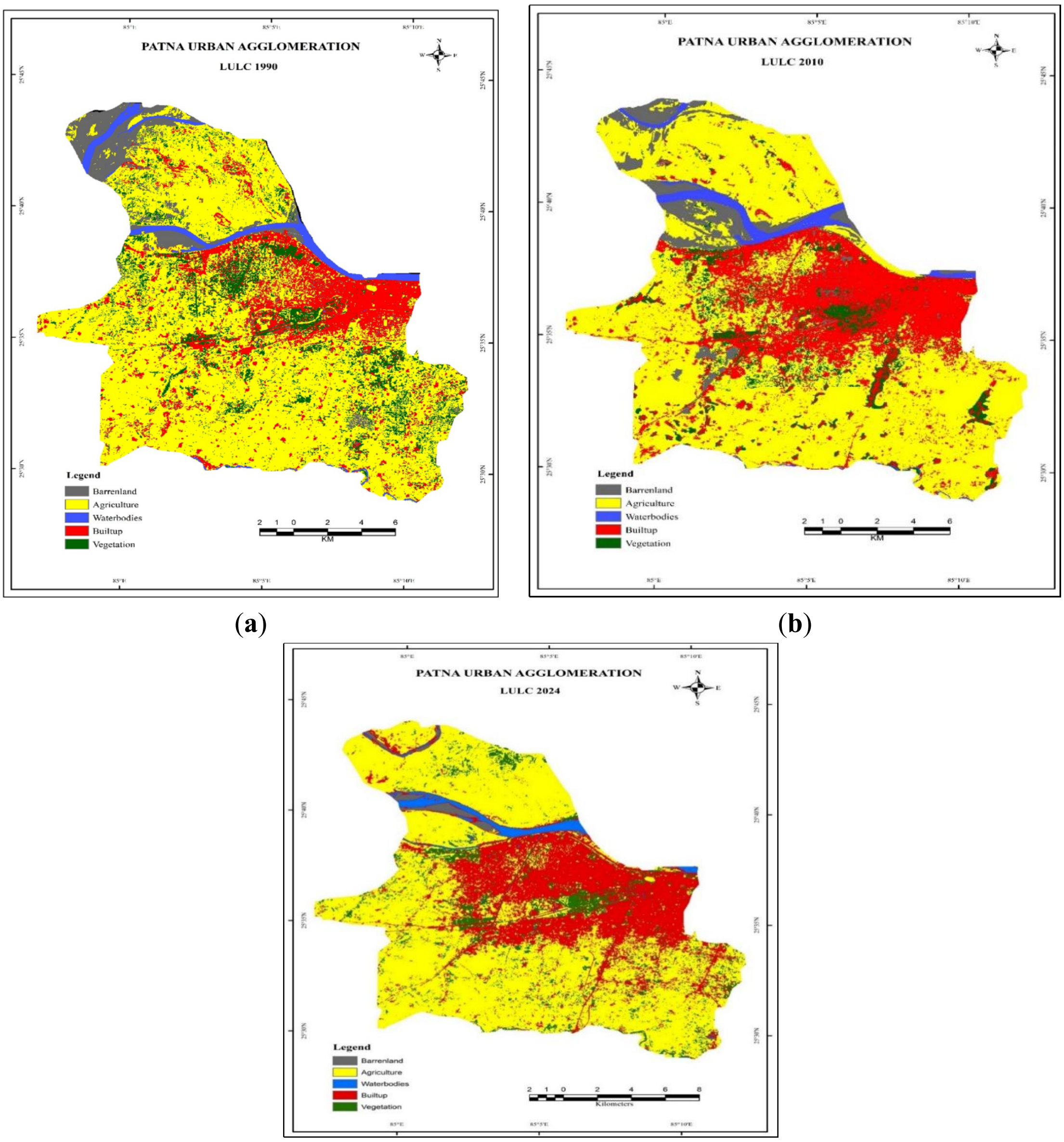
User Accuracy: No. of correctly classified pixels in each category/total no. of reference pixels (the row total)*100.

Producer Accuracy: No of correctly classified pixels in each category/total no of reference pixels (the column total)*100

5. Result and Discussion

5.1. Land Use Land Cover of Patna Urban Agglomeration in 1990

The Land Use Land Cover (LULC) of Patna Urban Agglomeration (PUA) and its environs in 1990 were investigated using Landsat 5 TM data. In 1990, the research area was defined as having five primary Land Use Land Cover classifications. Land Use Land Cover Change give information on resources and their usage for certain purposes. These adjustments are made to the map in order to correctly represent the reality of the surface. The Land Use Land Cover map based on Landsat temporal images show considerable increase in urban expansion in PUA. In 1990, PUA consisted of three urban towns and four circles and spanned an area of 257.38 square kilometers. Agriculture land constituted (64.04 percent) of the PUA area, while built-up areas occupied the second biggest portion of this research area after agriculture 14.91 and (64.04 percent), respectively. These were mostly concentrated in the Ganga River watershed, and barren terrain is related with the river catchment, as well as a small portion of the farm fields around and along the river. This region had some plant cover in the form of parks and ridges; it occupied just (10.89 percent) of the area, including fallow areas (**Figure 2**).



(**c**)

Figure 2. Land Use Land Cover of PUA in (**a**) 1990, (**b**) 2010, to (**c**) 2024.

5.2. Land Use Land Cover for the year 2010

The Land Use Land Cover of Patna Urban Agglomeration and its environs in 2010 were investigated using Landsat 7 TM data. In 2010, five primary land use and land cover classifications were recognized within the research area. Agriculture has dominated 401.91 square kilometers of land area, i.e. (61.09 percent) of the study area, since 1990. As a result, it continued to be the dominating class in the area in 2010. It is followed by built-up areas.

There was 93.40 square kilometers of built-up area overall, making up (23.24 percent) of the research area. The second most notable category is the bare ground, which makes up (6.87 percent) 27.60 square kilometers of the city. Over the past few decades, the water body has been the only class to continuously expand in the city, taking approximately (2.74 percent) 11.01 square kilometers.

5.3. Land Use Land Cover, 2024

Table 3 provides a detailed breakdown of the Land Use Land Cover (LULC) for Patna Urban Agglomeration in 2024. The largest portion of this area, 231.35 square kilometers, i.e. (57.56 percent), is dedicated to agriculture. Built-up areas, which include residential, commercial, and industrial buildings, cover 122.19 square kilometers, accounting for (30.40 percent) of the total area. Vegetation, including forests and other natural green spaces, occupies 33.73 square kilometers, making up (8.39 percent) of the area. Water bodies, such as rivers and lakes, span 9.48 square kilometers, representing (2.36 percent) of the total area. Barren land, which is land devoid of significant vegetation or specific use, covers the smallest portion, with 5.16 square kilometers, or (1.28 percent) of the area. This distribution highlights the predominance of agricultural and urban areas in the region, with smaller proportions of natural vegetation, water bodies, and barren land. The (**Figure 2**) of Patna Urban Agglomeration for 2024 illustrates the Land Use Land Cover (LULC) distribution across the region. The predominant yellow color indicates that a large portion of the area is dedicated to agriculture. Significant red patches highlight urban development and Built up region, especially in the southeastern part of the study area. Scattered green spots denote pockets of natural vegetation, while gray areas indicate sparse Barren land. This detailed representation provides a clear overview of land utilization within the Patna Urban Agglomeration, emphasizing the balance between agricultural, urban, vegetative, and barren areas in the year of 2024.

5.4. Spatio-Temporal Change Detection 1990 –2024

The data on Land Use Land Cover (LULC) changes between 1990 and 2010 reveals significant shifts in the utilization of land. Barren land saw a slight decrease from 28.77 square kilometers (7.16 percent) to 27.60 square kilometers (6.87 percent), likely due to its conversion into more productive uses such as agriculture or urban development. Agricultural land also experienced a decline, reducing from 257.38 square kilometers (64.04 percent) to 245.52 square kilometers (61.09 percent), reflecting pressures from urban expansion or potential degradation of arable land. Water bodies shrank from 12.05 square kilometers (3.00 percent) to 11.01 square kilometers (2.74 percent), indicating possible encroachment, sedimentation, or reduced water availability driven by climate change and human activities. The most notable change was in built-up areas, which expanded significantly from 59.94 square kilometers (14.91 percent) to 93.40 square kilometers (23.24 percent), (55.82 percent) increase driven by urbanization and infrastructure development to meet growing population and economic demands. Conversely, vegetation cover saw a sharp decline from 43.77 square kilometers (10.89 percent) to 24.39 square kilometers (6.07 percent), (44.29 percent) reduction likely caused by deforestation and land clearing for agriculture and urbanization (**Table 3**).

These changes underscore a clear trend of increasing urbanization at the cost of natural land covers such as vegetation and water bodies. While the total area of 401.91 square kilometers remained constant, the internal shifts highlight the need for sustainable land management practices. The loss of vegetation and water bodies raises environmental concerns, including potential impacts on local ecosystems, biodiversity, and climate. Balancing development with ecological conservation is essential to mitigate these adverse effects and ensure long-term sustainability.

Between 1990 and 2010, Built-up areas increased significantly by around 40 square kilometers, reflecting rapid urbanization, while vegetation and agriculture decreased by approximately 20 square kilometers and 10 square kilometers , respectively, indicating land conversion for urban use. Barren land and waterbodies showed minimal or no change (**Figure 3**) The findings highlight urban expansion at the expense of agricultural and vegetative land.

The comparison of Land Use Land Cover (LULC) data between 2010 and 2024 highlights notable changes in the allocation and utilization of land categories. Barren land records a dramatic reduction from 27.60 square kilometers (6.87 percent) to 5.16 square kilometers (1.28 percent), and (81.31 percent) decline. This substantial decrease suggests exten-

Table 3. Spatio-temporal change detection 1990–2010.

LULC 1990			LULC 2010		Change Detection 1990–2010	
CLASS	**AREA (in sq. km.)**	**Area in %**	**AREA (in sq. km.)**	**Area in %**	**AREA (in sq. km.)**	**Area in %**
Waterbodies	12.05	3.00	11.01	2.74	−1.04	−8.67
Builtup	59.94	14.91	93.40	23.24	33.46	55.82
Vegetation	43.77	10.89	24.39	6.07	−19.39	−44.29
Agriculture	257.38	64.04	245.52	61.09	−11.86	−4.61
Barren land	28.77	7.16	27.60	6.87	−1.16	−4.05
TOTAL	401.91	100.00	401.91	100.00	0.00	0.00

sive land reclamation for other purposes, such as agriculture, vegetation restoration, and urban development. Agricultural land also contracted from 245.52 square kilometers (61.09 percent) to 231.35 square kilometers (57.56 percent), (5.77 percent) reduction, likely due to urban expansion and other Land Use changes. Water bodies further declined from 11.01 square kilometers (2.74 percent) to 9.48 square kilometers (2.36 percent), a loss of (13.90 percent), possibly attributable to encroachment or climate-related factors such as reduced water availability (**Table 4**).

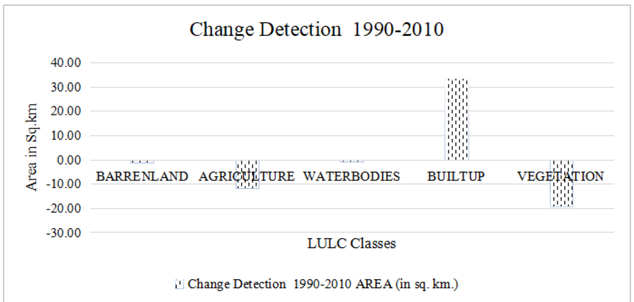


Figure 3. Spatio-temporal Change Detection 1990–2010.

Built-up areas experienced significant growth, increasing from 93.40 square kilometers (23.24 percent) to 122.19 square kilometers (30.40 percent), 30.83 per cent rise driven by ongoing urbanization and infrastructure development to accommodate population and economic growth. In contrast to earlier trends, vegetation cover showed a remarkable recovery, increasing from 24.39 square kilometers (6.07 percent) to 33.73 square kilometers (8.39 percent), (38.32 percent) gain, possibly reflecting successful reforestation, conservation efforts, or natural re-growth (**Table 4**).

Figure 4 shows Land Use Land Cover (LULC) changes from 2010 to 2024, highlighting significant changes in land utilization. Barren land and agriculture have experienced notable reductions in area, while built-up areas have increased significantly, indicating urban expansion. Vegetation shows a slight increase, possibly due to reforestation or natural growth, while waterbodies remain largely unchanged. This suggests a trend of urbanization and reduced agricultural or unused land, with minor increase in vegetation cover.

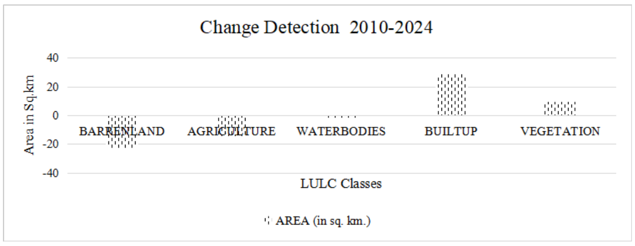


Figure 4. Spatio-temporal Change Detection 2010–2024.

Overall, the total land area of 401.91 square kilometers remained constant, indicating that these changes occurred within the existing boundaries of land cover categories. The decline in barren land and the increase in vegetation are positive indicators of environmental recovery, though they coexist with ongoing challenges like the reduction in water bodies and agricultural land. The sharp rise in urban areas continues to highlight the pressures of development, underscoring the need for a balanced approach to land management that supports both economic growth and environmental sustainability.

5.5. Spatio-temporal Change Detection 1990–2024

Changes in land cover and usage are caused by both human activity and natural processes. One way to track this shift and identify the evolving pattern is through Land Use Land Cover. The city's northeastern region had an increase in built-up between 1990 and 2024, and the pattern indicates that this growth is continuing every decade.

Table 5 shows the Spatio-temporal change detection of Land Use Land Cover (LULC) in the Patna Urban Agglom-

Table 4. Spatio-temporal Change Detection 2010–2024.

LULC 2010			LULC 2024		Change Detection 2010-2024	
CLASS	**AREA (in sq. km.)**	**Area in %**	**AREA (in sq. km.)**	**Area in %**	**AREA (in sq. km.)**	**Area in %**
Waterbodies	11.01	2.74	9.48	2.36	−1.53	−13.90
Builtup	93.40	23.24	122.19	30.4	28.79	30.83
Vegetation	24.39	6.07	33.73	8.39	9.34	38.32
Agriculture	245.52	61.09	231.35	57.56	−14.17	−5.77
Barrenland	27.60	6.87	5.16	1.28	−22.44	−81.31

Table 5. Spatio-temporal Change Detection 1990–2024.

LULC 1990			LULC 2024		CHANGE DETECTION 1990–2024	
Class	**Area (in Sq. Km.)**	**Area in %**	**Area (in Sq. Km.)**	**Area in %**	**Area (in Sq. Km.)**	**Area in %**
Waterbodies	12.05	3.00	9.48	2.36	−2.57	−21.36
Built−Up	59.94	14.91	122.19	30.40	62.25	103.86
Vegetation	43.77	10.89	33.73	8.39	−10.04	−22.94
Agriculture	257.38	64.04	231.35	57.56	−26.03	−10.11
Barren Land	28.77	7.16	5.16	1.28	−23.61	−82.07
Total	401.91	100.00	401.91	100.00	0.00	0.00

eration from 1990 to 2024. From 1990 to 2024, the Patna Urban Agglomeration experienced significant changes in its Land Use Land Cover (**Figure 5**).

In 1990, Barren land covered 28.77 square kilometers (7.16 percent) of the total area, which reduced dramatically to 5.16 square kilometers (1.28 percent) by 2024, showing a decrease of 23.61 square kilometers or (82.07 percent). Agricultural land also observed a reduction, from 257.38 square kilometers (64.04 percent) in 1990 to 231.35 square kilometers (57.56 percent) in 2024, marking a decrease of 26.03 square kilometers i.e. 10.11 per cent. Water bodies shrank from 12.05 square kilometers (3.00 percent) to 9.48 square kilometers (2.36 percent), a reduction of 2.57 square kilometers i.e. (21.36 percent). Built-up areas registered a significant increase, expanding from 59.94 square kilometers (14.91 percent) in 1990 to 122.19 square kilometers (30.40 percent) in 2024, an increase of 62.25 square kilometers i.e. (103.86 percent). Vegetation areas decreased from 43.77 square kilometers (10.89 percent) to 33.73 square kilometers (8.39 percent), showing a reduction of 10.04 square kilometers i.e. (22.94 percent).

Despite these changes in specific land use categories, the total area of the region remained constant at 401.91 square kilometers. These figures highlight a marked shift towards urbanization with a significant increase in built-up areas, while agricultural land, barren land, water bodies, and vegetation areas have all decreased over the last 34-years period.

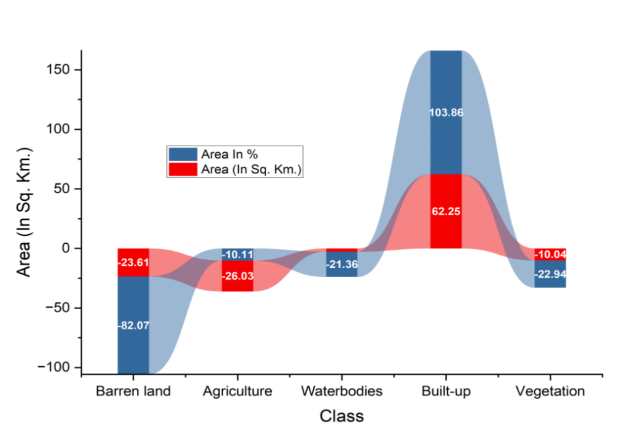


Figure 5. Spatio-temporal Change Detection 1990–2024.

5.6. Accuracy Assessment of Land Use Land Cover Classification

The accuracy evaluation findings for the 1990 categorized map are displayed in. The 1990 categorization map has an overall accuracy of (90.97 percent). Due to the reflectivity of the little huts, the roofs of the homes (iron sheets and thatching grass) that looked like rocks, and agricultural land, agriculture and open landscapes provided the lowest producer's accuracy (83.33 percent). In a similar vein, (92.35 percent) was the kappa coefficient (**Tables 6** and **7**). As a result, the map established the minimal level of accuracy needed for the next post-classification processes.

Table 6. Result of LULC of User and Producer Accuracy, 1990.

User Accuracy		Producer Accuracy	
Water Body	8/8*100 = 99.1%	Water Body	8/8*100 = 99.1%
Built Up	12/12*100 = 99.8%	Built Up	12/12*100 = 99.8%
Vegetation	10/10*100 = 99.7%	Vegetation	19/19*100 = 99.7%
Agriculture	5/6*100 = 83.33%	Agriculture	5/5*100 = 99.7%
Barren Land	5/6*100 = 83.33%	Barren Land	12/12*100 = 99.8%

Note: Total no of correctly classified pixels (diagonal)/Total no of referenced pixels*100 = 55/60*100 = 91.66%.

Table 7. Accuracy Assessment of Land Use Land Cover Classification (1990).

Year 1990	Water Body	Built Up	Vegetation	Agriculture	Barren Land	Total (User)	User Accuracy
Water Body	8	0	0	0	0	8	99.8%
Built up	0	12	0	0	0	12	98.8%
Vegetation	0	0	15	0	2	17	89.47%
Agriculture	0	0	1	10	1	11	91.66%
Barren Land	0	0	4	2	5	12	83.33%
Total (Producer)	8	12	19	12	8	60	
Producer Accuracy	100%	100%	84.21%	88.23%	100%		Overall 91.66%

5.7. Accuracy Assessment of LULC Classification of 2010

An accuracy evaluation was conducted to determine the correctness of the classification system and to determine the efficacy of the LULC classification maps. One hundred reference test pixels were identified. Digital maps of LULC are used to confirm the 2010 categorized image (**Table 8**). According to the accuracy evaluation criteria, the object-based classification attained an overall accuracy of (97.22 percent) (**Table 9**), and the object-based image classification's Kappa coefficient was determined to be (96.4 per cent), both of which are over the acceptable level [20].

Table 8. Result of LULC User and Producer accuracy, 2010.

User Accuracy		Producer Accuracy	
Water Body	6/6*100 = 100%	Water Body	6/6*100 = 100%
Built Up	9/9*100 = 100%	Built Up	9/9*100 = 100%
Vegetation	9/9*100 = 100%	Vegetation	9/10*100 = 90%
Agriculture	6/6*100 = 100%	Agriculture	6/6*100 = 100%
Barren Land	5/6*100 = 83.33%	Barren Land	5/5*100 = 100%

Overall Accuracy: Total no. of correctly classified pixels (diagonal)/Total no of referenced pixels*100 = 35/36*100 = 97.22%.

Table 10 provides a detailed assessment of user and producer accuracy for land cover classification across five categories: Water Body, Built-Up, Vegetation, Agriculture, and Barren Land in 2024. The classification performance is evaluated based on correctly classified and misclassified samples. Water Body achieved a user accuracy of (98.8 percent) with 8 correct classifications out of 10, and no significant misclassification errors (**Table 11**).

Built-Up areas displayed the highest user accuracy at (99.4 percent), with 10 correctly classified samples and minimal confusion with other categories. Vegetation and agriculture achieved user accuracies of (99.2 percent) and (93.33 percent), respectively, with slight misclassifications between these two categories, reflecting their natural overlap in characteristics. Barren Land, however, showed the lowest user accuracy at (80 percent), indicating some confusion with Vegetation.

The producer accuracy indicates how well each category has been correctly identified. Water Body, Built-Up, Vegetation, and Agriculture achieved perfect producer accu-

Table 9. Accuracy Assessment of Land Use Land Cover Classification -2010.

Year 2010	Water Body	Built Up	Vegetation	Agriculture	Barren Land	Total (User)	User Accuracy
Water Body	6	0	0	0	0	6	100%
Built up	0	9	0	0	0	9	100%
Vegetation	0	0	9	0	0	9	100%
Agriculture	0	0	0	6	0	6	100%
Barren Land	0	0	1	0	5	6	83.33%
Total (Producer)	6	9	10	6	5	36	
Producer Accuracy	100%	100%	90%	100%	100%		97.22%
	Article			*Article*		*Article*	

Overall Accuracy: Total no of correctly classified pixels (diagonal)/Total no of referenced pixels*100 = 64/63*100 = 98.43%.

Table 10. Result of LULC User and Producer Accuracy 2024.

User Accuracy		Producer Accuracy	
Water Body	10/10*100 = 98.8%	**Water Body**	10/10*100 = 98.8%
Built Up	1313*100 = 99.4%	**Built Up**	13/13*100 = 99.4%
Vegetation	17/17*100 = 99.1%	**Vegetation**	17/17*100 = 99.1%
Agriculture	14/15*100 = 93.33%	**Agriculture**	15/15*100 = 100%
Barren Land	10/8*100 = 80%	**Barren Land**	8/9*100 = 88.88%

racies (100 percent), showing strong classification reliability (**Table 11**). However, Barren Land had a lower producer accuracy of (88.88 percent), suggesting that not all actual barren land areas were correctly identified. The overall producer accuracy across all categories is (94.93 percent), reflecting an effective classification model with minor areas for improvement, particularly in distinguishing Barren Land from other classes. This accuracy matrix underscores a strong performance in land cover classification, with room for refining specific categories prone to misclassification.

5.8. Overall Accuracy for Land Use Land Cover Classification 1990–2024

Overall classification accuracy and the Kappa coefficient were found to be adequate for the three-time period. For the categorization, the three-accuracy metrics and Producer's Accuracy, User's Accuracy, and Overall Accuracy—as well as the Kappa Coefficient have been computed. For every picture categorization, the Anderson (1976) rule of at least (85 percent) accuracy and [20] have been adhered to as appropriate and accurate.

There are overall accuracy and Kappa Coefficient which described the accuracy level of LULC in PUA. The accuracy rate 1990 and 2024 LULC are (91.66 percent) and (94.93 percent) with their respective kappa coefficient (**Table 12**).

5.9. Impact of Land Use Land Cover Change on Patna Urban Ecology

Land Use Land Cover (LULC) changes significantly influence urban ecosystems. In the context of Patna Urban Agglomeration (PUA), one of the oldest urban centers in eastern India, rapid urbanization, population growth, and infrastructure development have profoundly transformed its landscape over the past three decades (1990, 2010 and 2024). These changes have had both direct and indirect impacts on the city's ecology, affecting biodiversity, hydrology, climate, and human well-being. Patna's population grew significantly, driven by rural-to-urban migration and administrative expansion. This has resulted in the conversion of agricultural lands and natural habitats into residential, commercial, and industrial zones. Infrastructure development i.e. construction of roads, bridges (like the Mahatma Gandhi Setu and JP Setu), and the metro rail project has led to large-scale land alteration. Agricultural Land Conversion: Peri-urban areas observed a reduction in agricultural activities as land was repurposed for urban infrastructure and housing projects. Encroachment on water bodies wetlands and riverine ecosystems along the Ganga, Punpun, and Sone rivers were filled or encroached upon to accommodate urban sprawl.

Table 11. Accuracy Assessment of Land Use Land Cover Classification - 2024.

Year 2024	Water Body	Built Up	Vegetation	Agriculture	Barren Land	Total (User)	User Accuracy
Water Body	8	0	2	0	0	10	98.8%
Built up	0	10	1	2	0	13	99.4%
Vegetation	2	1	6	6	1	17	99.2%
Agriculture	0	2	7	6	0	15	93.33%
Barren Land	0	0	1	0	8	8	80%
Total (Producer)	10	13	17	14	10	63	
Producer Accuracy	100%	100%	100%	100%	88.88%		94.93%

Table 12. Overall Accuracy for Land Use Land Cover Classification.

Year	Overall Accuracy	Kappa Coefficient
1990	91.66	91.20
2010	97.22	96.40
2024	97.59	94.93

5.10. Impact of Land Use Land Cover Change on Patna Air Quality

Over the past three decades, PUA has experienced substantial demographic and infrastructural changes, evidenced by the data from 1990 to 2024. As per Census of India 2011, the population of the city has more than doubled, growing from 1,127,000 in 1990 to 2,633,000 in 2024.This rapid population increase has necessitated significant urban expansion, with the built-up area enlarging from 59.94 square kilometers to 122.19 square kilometers over the same period. This urban sprawl reflects the city's response to the increasing demand for residential, commercial, and industrial spaces to accommodate its growing population.

Concurrently, as per Regional Transport Authority, the number of registered vehicles has surged dramatically. In 1990, the city had 18,654 registered vehicles, which escalated to a peak of 110,572 by 2019. However, a notable decline to 78,769 by May 2024 suggests possible interventions such as stricter vehicular regulations, improvements in public transportation systems, or economic factors influencing vehicle ownership. The expansion in population, built-up area, and vehicle numbers has had a profound impact on air quality. As per Patna Pollution Control Board, the concentration of fine particulate matter (PM 2.5) rose from 102.341 μg/m³ in 1990 to 141.62 μg/m³ in 2024, while coarse particulate matter (PM 10) levels increased from 145.2 μg/m³ to 181.98 μg/m³ (**Table 13**). These increase indicate deteriorating air quality, likely driven by heightened vehicular emissions, industrial activities, and construction dust. Similarly, nitrogen dioxide (NO2) levels have surged from 5.8 μg/m³ to 12.7 μg/m³, further pointing to increased vehicular and industrial emissions.

Ozone (O3) levels have almost doubled, from 16.2 μg/m³ in 1990 to 32.3 μg/m³ in 2024. This rise may be attributed to higher temperatures and increased sunlight, which promote ozone formation, along with elevated emissions of precursors such as nitrogen oxides (NOx) and volatile organic compounds (VOCs). Sulfur dioxide (SO2) levels have also more than doubled from 3.09 μg/m³ to 7.2 μg/m³, linked to industrial activities and the burning of fossil fuels. These trends have significant health and environmental implications. The persistent rise in pollutants like PM 2.5, PM 10, NO2, and SO2 poses severe health risks, including respiratory and cardiovascular diseases, asthma, and other chronic conditions (**Table 13**). Elevated ozone levels can exacerbate respiratory problems and lung diseases. Environmentally, the increase in pollutants contributes to issues like acid rain, smog formation, and reduced visibility, while the expansion of the built-up area may lead to habitat loss and urban heat island effects.

To mitigate these impacts, comprehensive strategies are essential. Pollution control measures, such as stricter emissions standards for vehicles and industries, promotion of cleaner technologies, and enhancing green cover within urban areas, are crucial. Sustainable urban planning practices, including the development of eco-friendly infrastruc-

Table 13. Trend of Urbanization and Air Pollution.

Year	Population	Built-Up Area	No. of Registered Vehicles	PM 2.5	PM 10	NO2	O3	SO2
1990	1127000	59.94	18654	102.341	145.2	5.8	16.2	3.09
2010	2024000	93.4	73304	119.298	162.897	8.9	24.9	5.42
2024	2633000	122.19	78769 (till May)	141.62	181.98	12.7	32,3	7.2

Source: Censes of India, Bihar State Pollution Control Board, Ministry of Road Transport & Highways.

ture, improved public transportation, and promotion of non-motorized transport, can reduce dependency on private vehicles. Additionally, raising public awareness about the health impacts of air pollution and encouraging community participation in pollution reduction initiatives are vital for achieving long-term improvements in air quality.

5.11. Overall Effects on Ecology

The study highlights the consequences of fast urbanization, population expansion, and land use changes as it looks at the ecological changes in the Patna Urban Agglomeration (PUA) between 1990 and 2024. Vegetation cover fell by (22.94 percent) over this time, affecting ecosystem services including temperature control and carbon sequestration as well as biodiversity. Water bodies shrunk by (21.36 percent), which decreased groundwater recharge, disturbed aquatic ecosystems, and raised the danger of flooding. (10.11 per cent) decrease in agricultural land has an impact on green cover, soil health, and food security. The expansion of built-up areas by (103.86 percent) exacerbated pollution, habitat loss, and the Urban Heat Island (UHI) impact. Despite reducing soil deterioration, the reduction of bare land resulted in the loss of possible areas for water management and flora. These changes have contributed to increased air pollution, UHI effects, altered hydrology, and a fragmented urban ecosystem. The manuscript calls for balancing development with ecological conservation to ensure a sustainable urban environment in PUA.

6. Conclusions

Changes in Land Use Land Cover are dynamic phenomena that evolve over time. In urban areas, Land Use Land Cover are primarily more active. Following globalization in 1990, Patna emerged as a major global metropolis and industrial hub, which led to an increase in the number of settlers. People have changed the catchment area's size by encroaching on it and constructing illegally both inside and outside of it. The report emphasizes agriculture as the main land use and notable urban expansion, especially in the Ganga River catchment area. Between 1990 and 2024, Patna Municipal Corporation's LULC modifications resulted in notable urban development and economic progress. Addressing these challenges requires a multi-stakeholder approach that prioritizes sustainable urban development while preserving the city's natural ecosystems. By integrating green practices into urban planning, Patna can work towards a more resilient and ecologically balanced future. Protecting and restoring the Ganga floodplains and urban wetlands is essential for maintaining hydrological balance. Adopting environmentally friendly zoning laws and Land Use policies to balance development and ecological conservation. Raising awareness among citizens about the importance of ecological conservation can foster community-led initiatives.

Author Contributions

The all authors have contributed the significantly in this research as E.R. and S.A. conceptualized the study; P.S. and P.K. designed the methodology; N.K. handled the software and visualization; A.K.S. and V.K.S. contributed to data collection and resources; M.K. curated the data; E.R. prepared the original draft, and P.S. and S.A. reviewed and edited the manuscript. P.S. supervised the study. All authors have read and approved the final manuscript.

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Data Availability Statement

All data supporting the reported results are provided within the manuscript. Additional data can be made available upon reasonable request.

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Conflict of Interest

All the authors also declare that there is no conflict of interest in relation to the research, authorship, and publication of this study.

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