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The Impact of Urbanization on Wetland Ecology in Delhi Using AWEI and GIS

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ABSTRACT

This study examines the spatial and temporal patterns of wetland degradation in Delhi from 1991 to 2021 using remote sensing and GIS techniques. The Automated Water Extraction Index (AWEI) was applied to pre-monsoon Landsat imagery to delineate surface water bodies over the past 30 years accurately. Supervised classification was employed to generate land use maps, while census data was utilized to analyze urbanization trends across the region. Classification accuracy was assessed using Google Earth reference data through a confusion matrix, ensuring the reliability of the land cover analysis. Results reveal a significant decline in wetland extent, especially in densely populated and rapidly urbanizing districts such as North West, South, and East Delhi. During this time, the urban population increased from 52.7% to 97.4%, accompanied by a 70.2% expansion of built-up areas, while wetlands contracted from 32.9 km² to 30.2 km². South Delhi experienced the most severe wetland loss, with water body coverage dropping from 0.800% to 0.025%, whereas North East and Central Delhi maintained higher wetland coverage due to the influence of the Yamuna River and targeted conservation efforts. The study highlights the strong linkage between urban growth and wetland decline, which threatens biodiversity, groundwater recharge, and ecological stability. These findings emphasize the urgent need for integrated urban planning and conservation policies to safeguard wetlands, thereby promoting sustainability and water security in the National Capital Region.

Keywords: Wetland ecology; Urbanization; GIS; Land Use

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1. Introduction

Over the past three decades, Delhi has witnessed unprecedented urban expansion, leading to significant transformations in its natural landscape, particularly the decline of wetlands and surface water bodies. Water is a critical resource essential for human survival and the health and sustainability of natural ecosystems. According to the UN World Water Development Report (2019)[1], nearly one-third of the global population lacks access to clean and safe drinking water[2]. In developing nations, the growing disparity between the demand for and supply of potable water presents an increasingly challenging problem. Preserving surface water bodies, including wetlands—such as natural lakes, artificial ponds, and canal systems—is essential to ensuring long-term water security[3].

Urbanisation is reshaping the global landscape, with developing countries, particularly in Asia, experiencing the most rapid urban expansion. In 1800, only 3 per cent of the worldwide population resided in cities; this figure rose to 14 per cent by 1900 and surged to approximately 47 per cent, or 2.8 billion people, by 2000[4]. While urbanisation is often associated with economic development and infrastructural growth[5], it simultaneously places stress on natural resources, particularly wetlands and ecological systems.

Wetlands, regarded as some of the most productive and valuable ecosystems on Earth, are acutely vulnerable to the impacts of urbanisation[6]. Urban expansion frequently involves the conversion of natural and semi-natural landscapes, such as agricultural land, unpaved rural tracts, and wetlands, into impervious built-up areas, altering the hydrological cycle and ecosystem functioning[7]. This transformation is particularly evident in rapidly urbanising cities such as Delhi, the capital of India, which is experiencing unprecedented demographic and spatial growth.

Delhi's population has grown exponentially, from 1.47 million in 1951 to 32.94 million in 2023[8]. Accompanying this demographic shift is a dramatic increase in the city's spatial footprint, from 201.36 km² in 1951 to 1,467 km² by 2011[9]. This expansion has substantially affected the city's water resources, resulting in a substantial demand-supply gap. Delhi receives an estimated 1,066 million m³/day of potable water against a demand of 1,476 million m³/day[10].

Groundwater, a critical component of Delhi's water infrastructure, plays a vital role in sustaining both human consumption and ecological processes[11]. However, unsustainable groundwater extraction and increasing pollution from anthropogenic activities have severely compromised its quality and quantity[12]. Over the past two decades, Delhi has faced mounting water insecurity, exacerbated by declining recharge rates and over-dependence on finite sources[13].

The United Nations[14] projects that urban growth in Asia and Africa will continue accelerating, with cities like New Delhi and Mumbai experiencing some of the highest growth rates between 1990 and 2030. In this context, the sustainable management of Delhi's hydrological systems—including rivers, wetlands, canals, and groundwater—is crucial. Effective policy interventions, conservation initiatives, and integrated urban planning are necessary to balance the demands of urbanisation with the imperative of environmental protection.

In recognition of this, central and state governments have launched various policy initiatives to protect urban wetlands. These include the National Wetland Conservation Programme, the National Lake Conservation Plan , and the Wetland (Conservation and Management) Rules, among others. Recent efforts, such as the Atal Bhujal Yojana and the Jal Shakti Abhiyan, highlight a growing emphasis on urban water conservation[2].

Delhi currently hosts 573 water bodies and wetlands, comprising 11 natural lakes and 352 artificial ponds [6]. Notably, between 2001 and 2011, the total area covered by water bodies in Delhi increased from 1.02 percent (5.56 sq. miles) to 1.87 percent (10.16 sq. miles), despite extensive urban expansion[15]. Between 1981 and 2015, the area of water bodies showed a marginal increase from 2,110.4 hectares to 2,146 hectares, suggesting the possibility of successful conservation efforts or variations in mapping techniques[16]. Nevertheless, the overall ecological pressure remains severe due to encroachments, land-use changes, and the steady transformation of wetlands into built-up zones.

Despite the availability of fragmented data on urban growth and hydrological degradation, there is a lack of comprehensive, spatially disaggregated analysis examining how urbanisation has affected wetland dynamics across different districts of Delhi over time. Addressing this research gap is critical for advancing urban sustainability discourse in rapidly growing cities.

Accordingly, the present study sets out the following objectives:

- To map and analyse the spatial and temporal patterns of wetland transformation in Delhi from 1991 to 2021.
- To study the trends of population growth and urbanisation of Delhi
- To assess the land-use changes of Delhi from 2000 to 2022
- To correlate the urban expansion and urbanisation of Delhi with Wetland loss.

Through these objectives, the study aims to contribute to evidence-based urban planning and promote integrated water resource management strategies in Delhi and similar fast-growing urban regions. The novelty of this study lies in its integration of multi-decadal remote sensing data, population statistics, and land use/land cover (LULC) classifications to examine the spatiotemporal relationship between urban growth and wetland transformation across all administrative districts of Delhi. Unlike earlier studies that focus on isolated wetlands or broad-scale environmental degradation, this research provides a district-level, data-driven evaluation of wetland change linked to urbanisation patterns over 30 years. This approach not only enhances spatial specificity but also offers actionable insights for policymakers and urban planners.

2. Materials and Methods

2.1. Study Area

Delhi, covering an area of 1,483 square kilometres, is situated between the latitudes 28°24′17″N and 28°53′00″N and longitudes 76°50′24″ E and 77°20′37″ E (**Figure 1**). It lies within the Indo-Gangetic Alluvial plains, with an elevation of 198 to 220 meters above sea level. The study area comprises 11 districts: Central Delhi, East Delhi, New Delhi, North Delhi, North East Delhi, North West Delhi, Shahadra, South Delhi, South East Delhi, South West Delhi, and West Delhi.

STUDY AREA
MAP OF DELHI INDIA

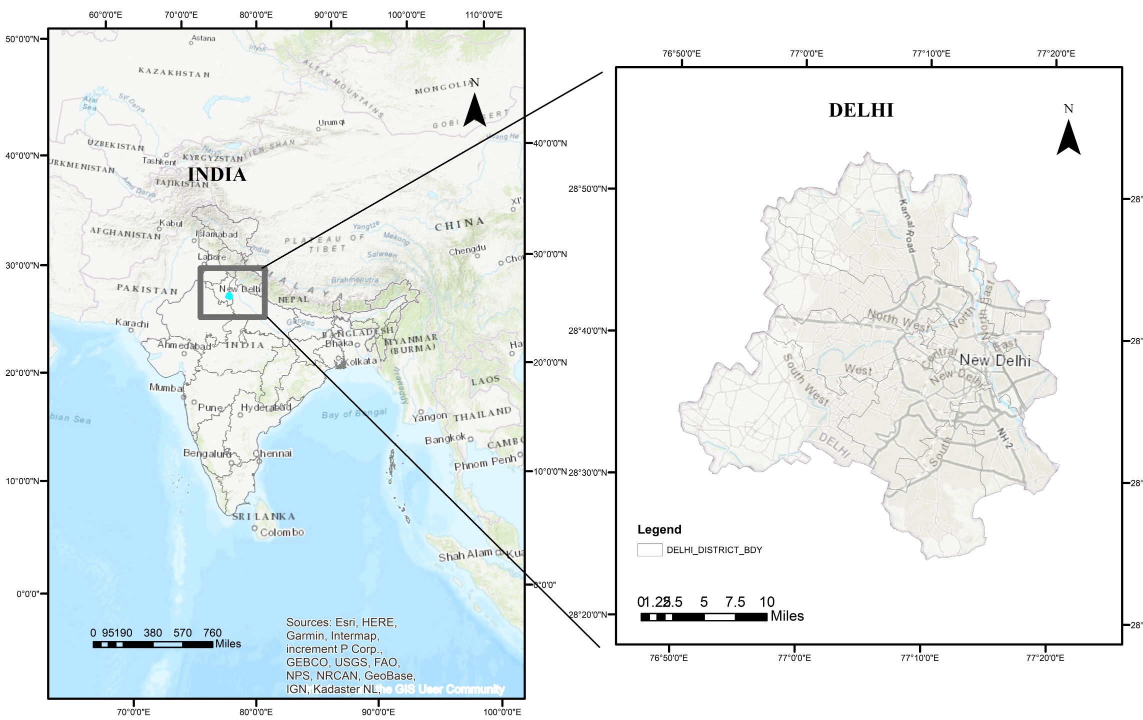

Figure 1. Location Map of the Study Area.

Source: Prepared by Author.

Delhi experiences a climate ranging from humid subtropical to semiarid. Generally, dry winters last from November to January. The city endures hot and humid summers from April to July, followed by the monsoon season in July and August, bringing heavy rainfall and winds from the Arabian Sea. During the summer months, temperatures typically range between 25°C and 45°C, while in December and January, they drop significantly, ranging from 22°C to as low as 5°C [17]. The geological makeup of Delhi-NCR is a mix of ancient and more recent rock formations. Most of the region, about 95 per cent, is covered by Quaternary sediments, which are relatively younger deposits. The remaining 5 per cent comprises much older rocks from the Delhi Supergroup, dating back to the Meso to Neoproterozoic era. These ancient rocks, mainly found in the southern and southwestern parts of Delhi, belong to the Alwar and Ajabgarh series and are made up of metasedimentary formations [18].

The rocks of the Delhi Supergroup have undergone significant geological changes over time, showing different types of folds, such as tightly packed, open, and asymmetrical formations, often layered on top of one another [19]. Hard rocks in the region are covered by much younger, loose sediments from the Quaternary to Recent periods [20]. The Yamuna River's active floodplain mainly consists of coarser materials like pebbles, gravel, and sand. In contrast, its older floodplains contain finer sediments, including silt, hardened calcium carbonate nodules (kankar), and layers of sand mixed in between [21]. The Yamuna River's active floodplain mainly consists of coarser materials like pebbles, gravel, and sand. In contrast, its older floodplains contain finer sediments, including silt, hardened calcium carbonate nodules (kankar), and layers of sand interspersed throughout [21].

Delhi currently relies on various interconnected water resources to meet its diverse needs. In 2022, the major types of water resources managed and utilized by the Delhi Jal Board and other agencies in the city include the Yamuna River, which produced 375 million gallons per day (MGD); the Ganga River, which produced 240 MGD; Bhakra Storage, which produced 218 MGD; and Groundwater, which produced 80 MGD [22].

The North district of Delhi has relatively shallow groundwater levels and often experiences waterlogging during the monsoon season. Excess surface runoff and floodwaters in low-lying areas are frequently diverted into drains and rivers as rejected recharge, further complicating water management efforts [11]. Wetlands, such as the Najafgarh Lake southwest of Delhi, are essential ecological units within the urban ecosystem, contributing to groundwater recharge, biodiversity conservation, and local climate regulation [23]. Approximately 50 per cent of the global population resides in urban areas, which is expected to rise [24].

2.2. Methodology

This study employs Geographic Information System (GIS) and Remote Sensing (RS) techniques to evaluate urbanisation's spatial and temporal dynamics in Delhi's wetland systems over 30 years. As defined by the Ramsar Convention, wetlands are "areas of 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 metres." This broad definition encompasses natural lakes, artificial ponds, swamps, marshes, and river systems—many of which are integrated within the urban fabric. In the context of this study, only urban wetlands—including rivers, lakes, ponds, and swamps/marshes located within Delhi's urban administrative boundaries—have been selected for analysis. The terms wetlands, water bodies, and surface water are used interchangeably to refer to visible hydrological features within the urban landscape of Delhi, as detected through remote sensing. These terminologies have a very nuanced distinction. The methodology includes the integration of satellite imagery, geospatial datasets, and LULC classification to identify and analyse patterns of wetland transformation and urban expansion. To ensure consistency in water detection, all Landsat images analyzed were from the pre-monsoon season, minimizing seasonal variability in surface water extent.

The primary data sources consist of multi-temporal satellite imagery from the Landsat missions—specifically, Landsat 5 TM, Landsat 7 ETM, and Landsat 8 OLI—for the years 1991, 2001, 2011, and 2021 (**Table 1**). These datasets were selected to ensure consistent spatial and spectral resolution throughout the study period. In addition to Landsat imagery, high-resolution data from Google Earth were utilised to assist in data collection for training and classification validation. Complementary data, including population statistics, were obtained from the Census of India and Delhi government repositories to contextualise spatial changes in demographic trends. Before classification and analysis, the satellite images underwent standard pre-processing steps using ArcGIS.

Table 1. Specifications of the Landsat Datasets

S. No	Satellite	Sensor	Spectral Bands	Date of Acquisition	Spatial Resolution	Average Cloud Cover
1	LANDSAT 5	MSS	**Band 1:** Blue	14/03/1991	30 Meters	30 per cent
			Band 2: Green	20/01/2001		
			Band 3: Red	16/01/2011		
			Band 4: Near-Infrared (NIR)	June 2000 and 2010 (LULC)		
			Band 5: Shortwave Infrared			
			Band 7: Shortwave Infrared			
2	LANDSAT 8	OLI & TIRS	**Band 1:** Coastal Aerosol	09/04/2021	30 Meters	30 per cent
			Band 2: Blue	June 2022 (LULC)		
			Band 3: Green			
			Band 4: Red			
			Band 5: Near-Infrared (NIR)			
			Band 6: Shortwave Infrared			
			Band 7: Shortwave Infrared			

Supervised classification was conducted using the Maximum Likelihood Classifier (MLC) method to analyse land use and land cover changes. Training samples for the classification were derived through field knowledge and reference data obtained from Google Earth. The classified images for 2000, 2010, and 2024 were categorised into five major classes: built-up areas, vegetation, wetland, barren land, and agricultural land. Post-classification accuracy assessment used error matrices and kappa coefficients, ensuring statistical validation of classification results.

To delineate wetland with higher precision, especially in complex urban environments where shadows and built-up features often interfere with spectral separability, the study employed the Automated Water Extraction Index with Shadow (AWEI_SH). This index enhances water detection accuracy by reducing misclassification from vegetation, impervious surfaces, and shadowed regions. The AWEI_SH was calculated for each temporal image using the respective band combinations [25–27].

For Landsat 5,

AWEI_SH=Blue+2.5×Green−1.5× (NIR+SWIR1) − 0.25×SWIR 2

AWEI_SH = Band1+ 2.5×Band 2−1.5× (Band4+Band5) − 0.25×Band 7

For Landsat 8,

AWEI_SH = Blue +2.5 × Green − 1.5× (NIR+SWIR1) −0.25 × SWIR 2

AWEI_SH = Band 2+2.5× Band 3−1.5× (Band 4+Band 5) − 0.25 × Band 6

The calculated index was then thresholded to identify water features, which were converted into vector format for further spatial analysis and comparison with LULC maps. Temporal and spatial change detection was conducted by comparing classified LULC maps from 2000, 2010, and 2024. District-level statistics were generated to understand the varying impacts of urban expansion on wetlands across Delhi. Zonal statistics and spatial overlay tools in ArcGIS were used to quantify changes in the extent of wetland and to correlate these changes with population growth and urban sprawl.

3. Results and Discussions

3.1. Demographic Structure of Delhi

Figure 2 illustrates the population growth of Delhi from 1901 to 2011 based on decennial Census data, revealing a steady upward trend over 110 years. Starting at approximately 405,819 in 1901, the population grew gradually to around 917,939 by 1941. A significant surge began in 1951, following India's independence and the Partition, with the population rising to 1.74 million and continuing to escalate rapidly, reaching 5.73 million in 1981, 9.4 million in 1991, and 13.9 million in 2001. By 2011, Delhi's population had reached nearly 16.8 million. This dramatic demographic shift underscores the influence of migration, economic development, and expanding urban infrastructure.

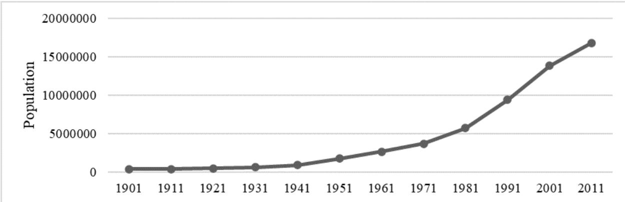

Figure 2. Population Change of NCT Delhi.

Source: Census of India.

Figure 3 presents the decadal population growth rates, further highlighting periods of accelerated expansion. Early decades saw modest increases—1.98 percent (1901–1911) and 18.04 percent (1911–1921)—but growth became more pronounced in the 1930s and 1940s, with rates of 30.27 percent and 44.29 percent, respectively. The post-Partition influx led to a sharp rise of 89.99 percent in 1951, initiating Delhi's transformation into a significant urban center. Growth remained high in subsequent decades, peaking at 64.45 per cent in 1991. Although it slowed in the 2000s, it remained substantial, 47.02 percent in 2001 and 21.21 percent in 2011, indicating ongoing urbanization.

From 1961 to 2011, population growth was accompanied by a spatial shift. Core districts, such as Central and New Delhi, showed stagnation or decline, while peripheral zones—such as North West, South West, and East Delhi—emerged as new population hubs. This shift reflects the outward expansion of the city, driven by continuous migration and urban development, leading to significant changes in land use, infrastructure, and settlement patterns.

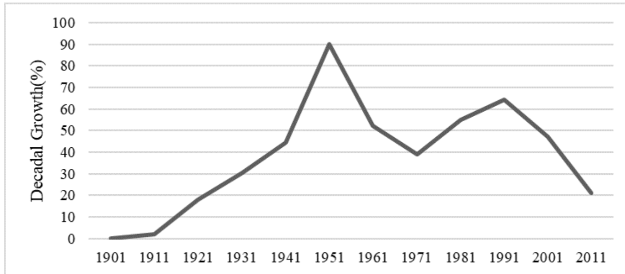

Figure 3. Decadal Growth in Percentage.

Source: Census of India.

3.2. Urbanization in Delhi

The trajectory of urbanization in the National Capital Territory (NCT) of Delhi from 1901 to 2011 reflects a remarkable transformation shaped by colonial infrastructure, post-independence migration, administrative importance, and sustained economic development. Over this period, Delhi's urban population increased nearly 77-fold—from just over 214,000 in 1901 to more than 16.3 million in 2011. Correspondingly, the level of urbanization, defined as the proportion of the population residing in urban areas, rose from 52.74% in 1901 to 97.40% in 2011 (**Table 2**).

Table 2. Urban Population

Census Year	Urban Population	Total Population	Urbanisation Level (per cent)
1901	214,115	405,819	52.74per cent
1911	237,944	413,851	57.50per cent
1921	304,420	488,452	62.32per cent
1931	447,442	636,246	70.33per cent
1941	695,686	917,939	75.78per cent
1951	1,438,175	1,744,072	82.45per cent
1961	2,359,408	2,658,612	88.79per cent
1971	3,647,021	3,693,280	98.75per cent
1981	5,715,231	5,729,131	99.76per cent
1991	8,359,100	9,420,644	88.73per cent*
2001	12,905,780	13,850,507	93.17per cent
2011	16,349,831	16,787,941	97.40per cent

Source: Census of India.

During the early 20th century, urban growth was moderate, with urbanization increasing from 52.74% in 1901 to 75.78% by 1941, mainly due to administrative and commercial expansion under British rule. A significant demographic shift occurred post-independence, with the 1951 Census recording 82.45% urban population, driven primarily by the refugee influx following the 1947 Partition. The period between 1961 and 1981 saw accelerated urbanization as Delhi emerged as a hub for internal migration spurred by industrialization and employment opportunities. By 1981, urbanization peaked at 99.76%. A temporary decline to 88.73% in 1991 reflected methodological changes in the rural-urban classification rather than a fundamental demographic shift. By 2011, the level had stabilized at 97.40%, confirming Delhi's status as a predominantly urban agglomeration.

District-wise data for 2001 and 2011 (**Table 3**) indicate extensive urban saturation across the region. Districts such as Central, East, New Delhi, North, North East, and West were already fully urbanized (100% urban population) by 2001, a status maintained in 2011. These areas constitute the historic and administrative core of the city, characterized by dense infrastructure and mixed land use.

Table 3. District-wise Urbanisation Population

District	Urban Pop (2001)	Urban % (2001)	Urban Pop (2011)	Urban % (2011)
Central	437,189	100.00%	582,320	100.00per cent
East	1,393,282	100.00%	1,707,725	100.00per cent
New Delhi	133,713	100.00%	142,004	100.00per cent
North	779,788	100.00%	887,978	100.00per cent
North East	1,480,713	100.00%	2,240,749	100.00per cent
North West	2,183,164	89.68%	3,651,261	94.82per cent
South	2,268,614	97.63%	2,731,929	97.60per cent
South West	1,746,088	93.94%	2,292,958	95.91per cent
West	2,348,929	100.00%	2,543,243	100.00per cent

Source: Census of India.

Peripheral districts—including North West, South, and South West—also experienced a rise in urban population shares. For example, North West Delhi's urbanization increased from 89.68% in 2001 to 94.82% in 2011, while South West Delhi rose from 93.94% to 95.91%. The South district, though already urban, showed a marginal decrease from 97.63% to 97.60%, indicating maturity in urban development. These trends underscore two interrelated processes: the saturation of core urban zones and the outward spread of urban growth into peripheral districts driven by sprawl, real estate expansion, and continued migration. The distinction between urban and rural spaces has become increasingly blurred, resulting in a nearly contiguous urban landscape across the NCT.

3.3. Land Use Analysis

The urban expansion of Delhi over the past two decades has been marked by pronounced alterations in land use and land cover (LULC), driven by population growth, infrastructural development, and ecological transformation. As the city evolved into one of the world's most densely populated and rapidly urbanizing metropolises, ecologically functional landscapes such as green spaces, forests, and bare lands have increasingly been converted into built-up zones, fundamentally reshaping Delhi's spatial morphology (**Figure 4**).

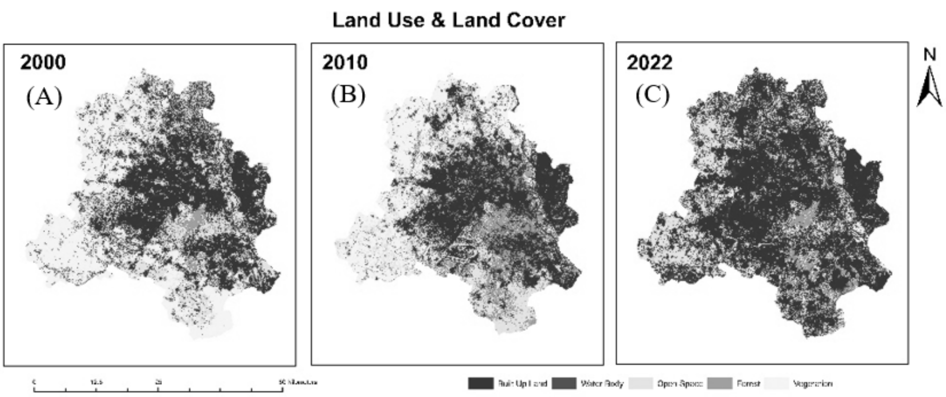

Figure 4. Land Use and Land Cover of Delhi ((**A**) 2000, (**B**) 2020, (**C**) 2022).

Source: Open Source Satellite Data.

Between 2000 and 2022, built-up areas increased from 485.6 km² (32.7%) to 825.6 km² (55.6%)—a net rise of 340.01 km², or 70.2%. This substantial increase reflects the growing demand for residential, commercial, and infrastructural space due to population growth and immigration. Simultaneously, ecologically significant areas saw notable declines. Vegetation cover—including agricultural lands, parks, and green spaces—reduced from 565.4 km² (38.1%) to 398.2 km² (26.8%), marking a loss of 167.2 km². Forested areas similarly declined from 208.9 km² (14.1%) to 131.6 km² (8.9%), indicating a 37% reduction, which raises concerns about biodiversity, carbon sequestration, and urban microclimates (**Figure 5**). Bare land, representing fallow or transitional spaces, also saw a steep drop, from 190.9 km² (12.9%) in 2000 to 98.1 km² (6.6%) in 2022—indicating intensive land consolidation driven by urban sprawl. In contrast, wetland areas (including rivers, ponds, and lakes) remained relatively stable, decreasing only slightly from 32.9 km² (2.2%) to 30.2 km² (2.0%). Despite the minor numerical change, even small reductions in wetland can disrupt urban hydrology, biodiversity, and flood resilience. A decadal analysis shows different patterns of change. From 2000 to 2010, built-up land increased by 216.97 km², accompanied by steep reductions in vegetation (−84.7 km²), forest (−60.34 km²), and bare land (- −70.29 km²). During 2010–2022, although the pace of urban expansion slightly slowed, the city still added 123.04 km² of built-up land. Vegetation and forest areas declined by 82.5 km² and 17.01 km², respectively, while bare land was further reduced by 22.55 km². Wetlands saw small reductions in both decades—1.65 km² in the first and 1 km² in the second. (**Table 4**).

Overall, the LULC transformation from 2000 to 2022 underscores the dominance of urban expansion at the cost of ecological spaces. Built-up land emerged as the fastest-growing class, while vegetation, forest, and bare land consistently declined. Although wetland loss appears numerically modest (−2.65 km²), its ecological significance in terms of urban water regulation and habitat preservation remains substantial (**Figure 5**).

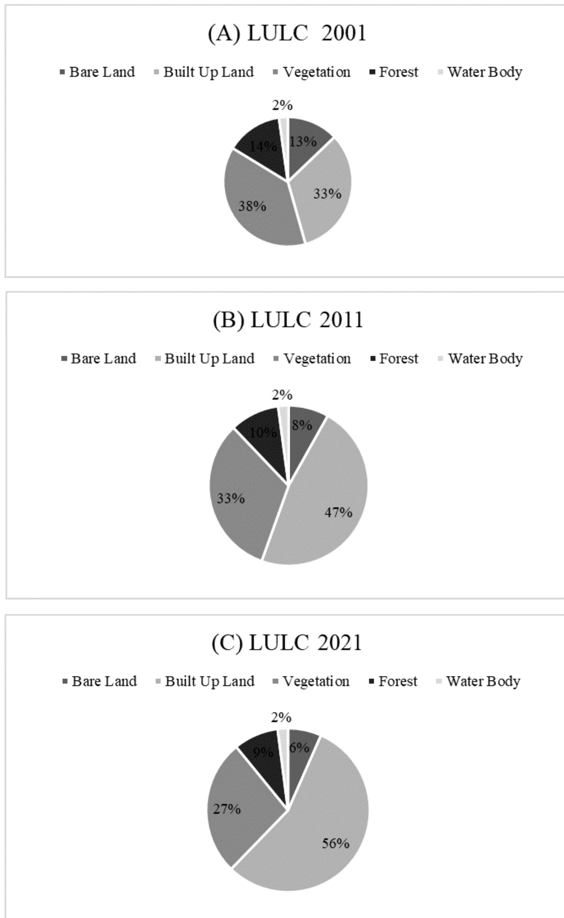

Figure 5. Area Statistics for LULC - (**A**) 2001, (**B**) 2011, and (**C**) 2021.

Source: Open Source data.

Table 4. Decadal Land Use Changes

Land Use Type	2000-2010	2010-2022	2000-2022
Bare Land	-70.29	-22.55	-92.84
Built Up Land	216.97	123.04	340.01
Vegetation	-84.7	-82.5	-167.2
Forest	-60.34	-17.01	-77.35
Water Body	-1.65	-1	-2.65

Accuracy Assessment of the LULC Classification: To evaluate the reliability of the LULC classification results presented for the years 2000, 2010, and 2022, a standard accuracy assessment was conducted using a stratified random sampling approach. Eighty validation points were utilized for each temporal snapshot, distributed proportionally across the five major LULC categories: built-up, vegetation, forest, bare land, and wetland. These validation points were derived from high-resolution satellite imagery, historical maps, and field verification wherever feasible. The accuracy assessment yielded encouraging results, with overall classification accuracies ranging between 81.25 per cent and 88.75 per cent across the three timeframes. Specifically, the year 2000 classification achieved an overall accuracy of 81.25 per cent, the 2010 classification reached 86.25 per cent, and the most recent 2022 classification recorded the highest accuracy at 88.75 per cent (**Figure 5**). The Kappa coefficient values, which measure agreement beyond chance, were found to be 0.79 (2000), 0.84 (2010), and 0.87 (2022), indicating substantial to near-perfect classification reliability.

3.4. Spatio-Temporal Analysis of Surface Water

A spatio-temporal analysis of wetland transformation in Delhi over the past thirty years, based on satellite-derived data and the Automated Water Extraction Index (AWEI), reveals a significant and continuous decline in surface water features. The findings highlight a persistent contraction of wetlands driven by anthropogenic pressure, urban encroachment, and ecological degradation (**Figure 6**).

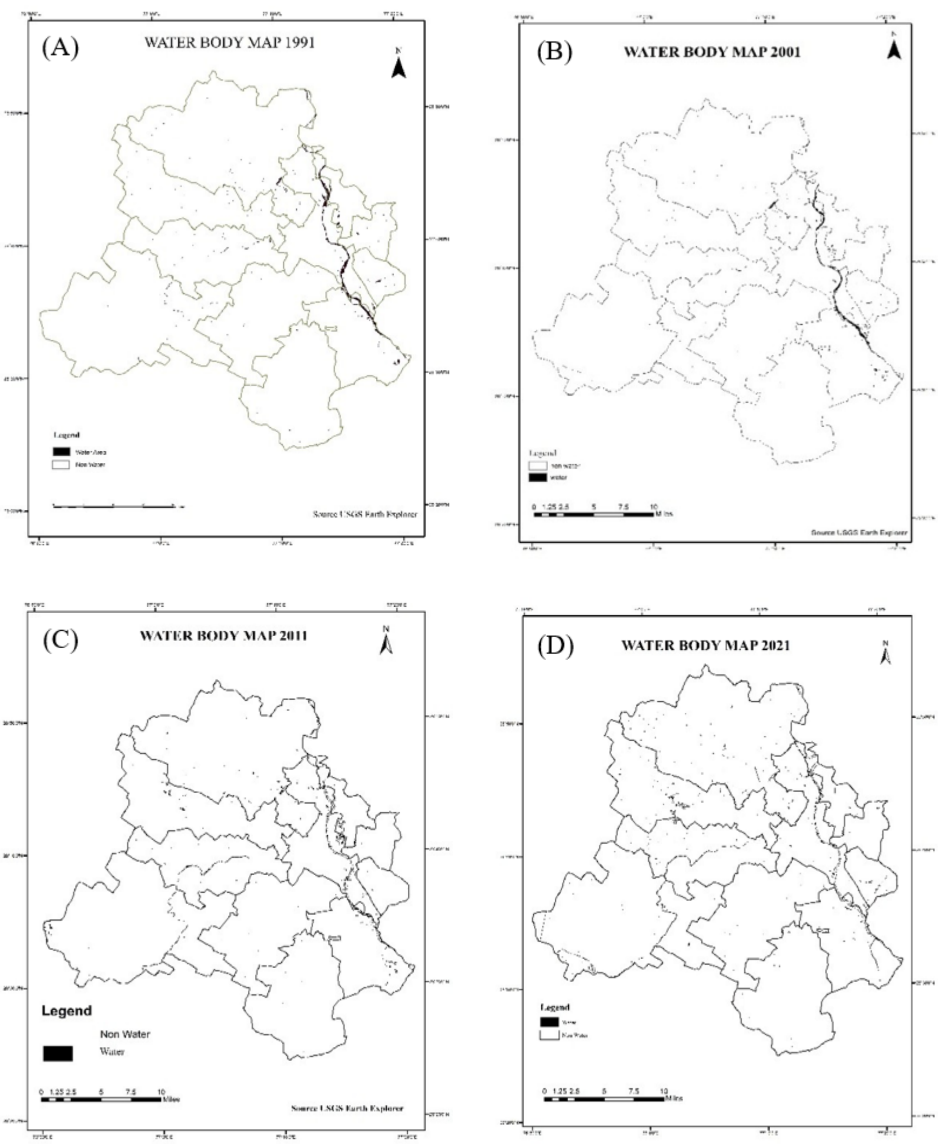

Figure 6. Water Body Extraction using AWEI ((**A**) 1991, (**B**) 2001, (**C**) 2011, (**D**) 2021).

Source: Open Source Satellite Data.

In 1991, Delhi's wetlands were more prominent, with satellite imagery showing extensive surface water features, especially the Yamuna River, which appeared wide and hydrologically healthy. Other significant features included the Najafgarh Wetland and Drain, one of the city's most extensive natural reservoirs, and lakes such as Sanjay, Bhalswa, and Hauz Khas. While early signs of fragmentation were visible, these wetlands retained identifiable spatial extents and contributed to regional hydrology and groundwater recharge. However, evidence of anthropogenic stress was already present, foreshadowing further degradation.

By 2001, the Yamuna River continued to dominate Delhi's hydrological landscape, though its width and water retention showed early signs of stress. Wetlands like Bhalswa, Najafgarh, and Sanjay Lakes remained visible but displayed increasing pressure from pollution and urban development. Fragmentation of peripheral wetlands and encroachment along their banks reflected the impact of expanding built-up areas. Despite relative stability in surface area, the wetlands' functional health was beginning to erode.

The decade between 2001 and 2011 marked a turning point—the spatial extent of all central wetlands visibly contracted. The Yamuna appeared narrower, impacted by reduced inflows, pollution, and sedimentation. The Najafgarh Wetland experienced substantial shrinkage, and many peripheral lakes—especially Hauz Khas and Bhalswa—saw dramatic reductions in surface area, with some approaching near disappearance in mapped imagery. Fragmentation, infilling, and degradation became widespread, revealing the deepening vulnerability of Delhi's aquatic ecosystems.

By 2021, the cumulative effects of unregulated urbanization, ecological neglect, and infrastructural encroachment were stark. The Yamuna, although still prominent, had lost much of its natural floodplain connectivity and was largely channelized and heavily polluted. Najafgarh Lake had shrunk into a narrow, fragmented channel, while Bhalswa Lake suffered severe degradation from solid waste dumping and sewage inflow. Lakes like Hauz Khas and Purana Qila functioned more as heritage or recreational zones than hydrological assets. Sanjay Lake, while still functioning as a rain-fed reservoir, had become encircled by urban infrastructure, further limiting its ecological role.

The trajectory from 1991 to 2021 reflects a clear pattern of wetland shrinkage—both in number and areal extent—across Delhi. This decline results primarily from urban expansion, industrial pollution, encroachment on natural drainage basins, and inadequate watershed management. The continued loss of surface water bodies poses serious challenges to Delhi's ecological resilience, impacting water security, urban flood regulation, microclimate stability, and biodiversity conservation. These patterns highlight the urgent need for integrated water resource management and ecologically informed urban planning.

District-wise analysis provides further insight into spatial variability in wetland trends across Delhi (**Table 5**). The percentages of water bodies were tracked for each district over three decades, revealing distinct patterns shaped by geography, policy interventions, and the intensity of urbanization. Central Delhi maintained the highest percentage of water bodies over the study period, decreasing only slightly from 3.72% in 1991 to 3.261% in 2021. This relative stability can be attributed to its proximity to the Yamuna River and preserved water features within protected government zones and planned urban layouts. Despite minor declines, Central Delhi remains one of the most water-rich districts. East Delhi, in contrast, witnessed a drastic decline—from 0.396% in 1991 and 0.400% in 2001 to just 0.026% in 2011 and 0.016% in 2021. This steep reduction is likely due to the encroachment of smaller wetlands, sediment accumulation, and ongoing pollution of ponds and canals. Although located near the Yamuna, water access in East Delhi has become fragmented and ecologically compromised. The New Delhi district exhibited an irregular trend. The water body percentage declined from 0.033% in 1991 to 0.012% in 2011, followed by a rise to 0.490% in 2021. This increase can be attributed to restoration efforts, especially in the Lutyens' Bungalow Zone and diplomatic enclaves, where planned landscapes and institutional parks contribute to improved water retention. North Delhi saw a continuous and sharp decline in water body share, from 0.279% in 1991 to just 0.001% in 2021. The near-total loss of surface water is linked to canal system degradation, wetland drying, and replacement of agricultural ponds with built infrastructure. This reflects a significant ecological trade-off in favor of urban expansion. North East Delhi, however, showed a contrasting and more encouraging trend. Its water body percentage increased from 2.718% in 1991 to 3.796% in both 2011 and 2021. This district includes major segments of the Yamuna

River and associated wetlands. Its consistently high share reflects the retention of active floodplains and hydrological recharge zones, despite urban pressure. North West Delhi showed minor fluctuations in wetland extent, ranging from 0.047% in 1991 to 0.235% in 2021. The presence of Bhalswa Lake and other small features contributes to this pattern. However, landfill expansion and encroachment likely limit the restoration and expansion of these aquatic zones. South Delhi experienced a sharp and steady decline, from 0.800% in 1991 to 0.025% in 2021(**Table 5**). The transformation of traditional water bodies and agricultural fields into built-up spaces, coupled with the drying of historic tanks, contributed to the loss. While some features like Hauz Khas Lake have seen periodic restoration, they remain too localized to affect district-level statistics significantly. South West Delhi demonstrated a fluctuating trajectory. Its water body area surged from 0.077% in 1991 to 2.164% in 2001—likely due to seasonal inflow into the Najafgarh Wetland system—before declining to 1.636% in 2011 and 0.167% in 2021. The latter drop reflects the continued degradation and fragmentation of Najafgarh due to urban infrastructure and sprawl. West Delhi saw a moderate increase from 0.134% in 1991 to 0.833% in 2001, followed by a gradual decline to 0.304% by 2021. Although lacking central natural wetlands, the district did develop artificial recharge ponds and small reservoirs. However, many were subsequently lost to construction or blocked drainage networks. Shahdara, newly delineated in 2021, reported a very low water share of 0.010%. As a predominantly built-up area carved out of East Delhi, it lacks significant surface water features and reflects the compact urban morphology typical of densely populated districts. South East Delhi, also introduced in the 2021 dataset, displayed a relatively high water share of 1.636%. This district includes parts of the Yamuna floodplain and ecologically significant zones such as the Okhla Bird Sanctuary and Kalindi Kunj Barrage, where ongoing conservation efforts have maintained or restored aquatic systems(**Table 5**).

Table 5. District-Wise Temporal Changes in Wetland

District	1991	2001	2011	2021
Central Delhi	3.720	3.125	3.556	3.261
East Delhi	0.396	0.400	0.026	0.016
New Delhi	0.033	0.046	0.012	0.490
North Delhi	0.279	0.244	0.256	0.001
North East Delhi	2.718	2.318	3.796	3.796
North West Delhi	0.047	0.045	0.235	0.235
South Delhi	0.800	0.021	0.192	0.025
South West Delhi	0.077	2.164	1.636	0.167
West Delhi	0.134	0.833	0.304	0.304
Shahdara	–	–	–	0.010
South East Delhi	–	–	–	1.636

Source: Open Source data.

3.5. Comparative Analysis of Urbanization, Land Use Change, and Water

Wetlands are essential for sustaining urban ecological balance, yet in the National Capital Territory of Delhi, they have experienced marked degradation over the past two decades. This transformation is primarily a consequence of rapid and unregulated urban expansion. Wetlands play critical roles: they buffer floods, regulate microclimates, recharge groundwater, and support biodiversity. Their strategic position in low-lying and marginal zones, however, has made them especially vulnerable to encroachment and repurposing for infrastructure and development. This study presents compelling spatial and temporal evidence of wetland deterioration in Delhi, with urbanization emerging as the dominant driver. From 1901 to 2011, the urban population surged from 52.7% to 97.4%, drastically intensifying land demand in both urban and peri-urban areas. The built-up area expanded from 485.6 km² in 2000 to 825.6 km² in 2022—a 70.2% increase—directly encroaching on ecologically sensitive zones. Consequently, water body area declined from 32.9 km² to 30.2 km², while vegetated land and forest cover shrank from 565.4 km² to 398.2 km² and from 209.1 km² to 131.8 km², respectively, indicating a systemic weakening of Delhi's urban ecological infrastructure. Statistical analysis reinforces these patterns: a near-perfect positive correlation

(+0.99) between urban population growth and built-up area is paralleled by strong negative correlations with vegetation (-0.97) and wetlands (-0.88). This indicates that urban expansion, particularly in the form of impervious surfaces, has systematically displaced hydrologically and ecologically functional landscapes. District-level data underscores this trend. South Delhi saw its water body area plummet from 0.800% in 1991 to just 0.025% in 2021, while East and North Delhi also recorded near-total disappearance of surface water features. South West Delhi, once having the highest wetland coverage (2.164% in 2001), declined to 0.167% by 2021. Only the New Delhi district showed a marginal increase (from 0.012% in 2011 to 0.490% in 2021), possibly due to targeted restoration efforts. In contrast, newer districts like Shahdara and South East Delhi reported negligible wetland presence, reflecting the ecological cost of contemporary urban expansion. Temporal analysis across two key phases—2000–2010 and 2010–2022—reveals that the most significant wetland loss occurred during the earlier period, corresponding with post-liberalization infrastructure growth. During this decade, the built-up area grew by 216.97 km², while vegetation and forest cover declined by 84.7 km² and 60.3 km², respectively. Although urban expansion slowed somewhat from 2010 to 2022 (123.04 km² added), wetland degradation persisted, indicating that ecological attrition had become embedded in Delhi's development paradigm. The continued loss of wetlands has profound implications for the city's environmental resilience. These ecosystems are crucial for mitigating surface runoff and urban flooding, risks amplified by climate variability. Their disappearance also exacerbates the urban heat island effect, disrupts microclimates, and degrades air and water quality. Without deliberate regulatory intervention, Delhi's remaining wetlands—and the ecological services they provide—are likely to face further irreversible decline.

4. Conclusions

This study employs remote sensing and Geographic Information System (GIS) analysis to document a pronounced decline in wetland areas within the National Capital Territory of Delhi over the past three decades, primarily attributable to accelerated urbanization and population growth. Between 1991 and 2021, wetlands in districts such as North West, South, and East Delhi have been extensively converted into urban landscapes, resulting in disrupted hydrological processes, diminished groundwater recharge, and a substantial loss of ecological functions. Socioeconomic drivers—including industrial expansion, major infrastructure projects, and policy-driven urban development—have influenced spatial patterns of urban growth, exacerbating land conversion and wetland degradation. A robust correlation is observed between the expanding urban population, from 52.7% in 1901 to 97.4% in 2011, and the 70.2% increase in built-up area between 2000 and 2022, along with a reduction in wetland extent from 32.9 km² to 30.2 km². While districts such as North East and Central Delhi have retained relatively higher water body coverage owing to the presence of the Yamuna River and targeted conservation efforts, other regions have experienced severe wetland loss, exemplified by South Delhi, where water body area declined markedly from 0.800% in 1991 to 0.025% in 2021. To mitigate this critical environmental challenge, the study emphasizes implementing stringent policy measures, including enforcing zoning regulations to prevent further encroachment, formal designation of wetlands as protected ecological zones, and prioritizing restoration initiatives in the most affected districts. Integrating blue-green infrastructure, such as constructed wetlands and rain gardens, within urban planning frameworks can enhance water retention capacity and strengthen ecological resilience. Surveillance and regulatory mechanisms should be improved through advanced satellite and drone technologies to monitor and effectively penalize illegal land use changes. Public awareness campaigns and community engagement programs play a vital role in fostering local stewardship and participatory conservation efforts. The proliferation of informal settlements and slums has contributed to the expansion of built-up areas; however, their heterogeneous and often unplanned nature complicates accurate classification using satellite imagery, representing a methodological limitation. Reliance on medium-resolution Landsat data may underestimate the presence of small or highly fragmented wetlands, potentially leading to conservative estimates of wetland loss. The use of pre-monsoon imagery reduces seasonal variability, but inter-annual fluctuations in precipitation and hydrological conditions may still affect surface water detection. The study focuses on spatial extent and does not assess changes in water quality or ecological health, indicating areas for future research. These findings and recommendations offer a foundation for protecting Delhi's wetlands, preserving their essential functions in water security, flood mitigation, and urban ecological balance. Safeguarding these ecosystems is crucial for maintaining environmental integrity, sustainable development, climate resilience, and long-term socio-economic stability amid rapid urban expansion.

Author Contributions

R.K.G. developed the initial concept for this article and provided comprehensive editing and oversight. Throughout the process, G.Y. and N.G.M. was responsible for curating the data analysis and ensuring accuracy. A.G. prepared the initial draft and executed the necessary computations while validating the analytical methods employed in this research. Furthermore, A.G., A.S. explored specific approaches and oversaw the interpretation of the findings presented in the study.

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Data Availability Statement

The data used in this study are publicly available from the Census of India, Landsat, and relevant remote sensing repositories.

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Confict of Interest

The authors declare that they have no conflicts of interest related to the publication of this paper.

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