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Urban Sprawl versus Environmental Sustainability: Assessing Land-Use Efficiency, Ecosystem Services, and Climate Resilience in India

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Abstract:
India's urban landscape is undergoing one of the most rapid and spatially consequential transformations observed in the developing world, with urban land cover expanding by an estimated 2.5 times between 2001 and 2021. This expansion is proceeding largely at the expense of agricultural land, wetlands, water bodies, and ecologically productive green spaces that underpin critical ecosystem service (ES) provisioning, climate regulation, and hydrological functioning in urban and peri-urban regions. The resulting tension between urban growth imperatives and environmental sustainability constitutes one of the defining governance challenges of twenty-first-century India.

This systematic review synthesises 76 peer-reviewed studies published between 2017 and 2025, supplemented by 16 foundational references, to critically examine the relationships between urban sprawl, land-use efficiency, ecosystem service valuation, and climate resilience across major Indian cities. Drawing on studies that employ multi-temporal remote sensing (Landsat, Sentinel-2, ResourceSat), Google Earth Engine (GEE)-based land use/land cover (LULC) change detection, ecosystem service valuation frameworks (InVEST, MIMES), and urban climate modelling tools, the review provides a comprehensive synthesis of empirical findings and methodological advances. Evidence consistently demonstrates that urban sprawl has reduced land-use efficiency indices by 40–60% across studied cities, eliminated 38–62% of original ecosystem service value in metropolitan regions, intensified urban heat island (UHI) effects by 2–4 °C, and amplified flood risk through impervious surface expansion. Critical governance failures—including the absence of ES-sensitive spatial planning, weak enforcement of environmental zoning, and the marginalisation of biodiversity considerations in master plans—are identified alongside a structured research agenda for advancing sustainable urban land governance in India.

Keywords — urban sprawl; land-use efficiency; ecosystem services; climate resilience; urban heat island; LULC change; remote sensing; GIS; Google Earth Engine; urban ecology; environmental sustainability; India; Bengaluru; Chennai; Delhi-NCR; Hyderabad; green infrastructure; wetland loss; urban biodiversity.

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1. Introduction

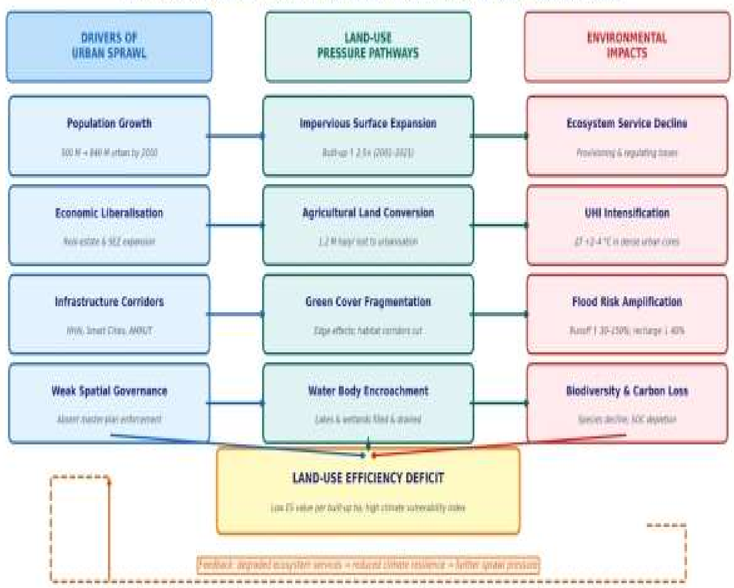
1.1. Research Background and Significance

The twenty-first century has been characterised, above all else in environmental terms, by the unprecedented pace of urbanisation across the Global South. In India, the urban population has grown from 286 million in 2001 to over 500 million in 2021 and is projected to reach 840 million by 2050—an addition equivalent to the current combined urban populations of the United States and Brazil (United Nations Department of Economic and Social Affairs [UN DESA], 2022; National Institution for Transforming India [NITI Aayog], 2022). This demographic transformation is accompanied by equally dramatic spatial expansion: satellite-derived analyses indicate that India's urban built-up area expanded by approximately 2.5 times between 2001 and 2021, a rate that significantly outpaces population growth and reflects the low-density, sprawling character of peri-urban development that dominates the Indian urban fringe (Kumar et al., 2022; Sudhira et al., 2020).

Urban sprawl—defined here as the low-density, discontinuous, automobile-dependent expansion of built-up area into surrounding agricultural, ecological, and natural lands—imposes costs that extend far beyond its immediate footprint. In the Indian context, it is consuming the agricultural hinterlands that produce food for rapidly growing cities, displacing the wetlands and lakes that buffer urban floods and recharge groundwater, fragmenting the remaining patches of urban forest and green space that regulate urban temperatures, and eroding the biodiversity reserves that constitute India's ecological heritage (Nagendra et al., 2018; Pandey et al., 2022). Yet the spatial planning frameworks, regulatory institutions, and financing mechanisms governing urban land use in India have, with few exceptions, failed to account for these ecosystem service losses in decision-making. The result is a systematic undersupply of urban environmental quality and a growing deficit of climate resilience at precisely the moment when India's cities face escalating climate risks from intensifying heat, flooding, and water stress (Intergovernmental Panel on Climate Change [IPCC], 2022).

The proliferation of open-access satellite data archives—particularly Landsat 8/9, Sentinel-2, and GEE cloud computing—has transformed the analytical capacity to document and quantify these dynamics. Concurrently, the development of integrated ecosystem service valuation frameworks, urban hydrological models, and urban climate assessment tools has created an evidence base from which systematic conclusions about the sustainability costs of urban sprawl can be drawn. This review synthesises that evidence comprehensively for the first time for the 2017–2026 period, with particular attention to methodological rigour, empirical quantification, and policy relevance.

Figure 1. Conceptual Framework: Urban Sprawl vs. Environmental Sustainability in India



Source: Authors' synthesis based on Nagendra et al. (2018); Pandey et al. (2022), Ramachandran et al. (2022), NITI Aayog (2022); UN DESA (2022).

Fig. 1. Conceptual framework illustrating the causal chain from urban sprawl drivers (population growth, economic liberalisation, infrastructure expansion, weak governance) through land-use pressure pathways (impervious surface expansion, agricultural conversion, green cover fragmentation, water body encroachment) to environmental impacts (ES decline, UHI intensification, flood risk amplification, biodiversity loss). Feedback loops show how degraded ecosystem services reduce climate resilience and perpetuate further sprawl pressure. Source: Authors' synthesis based on Nagendra et al. (2018); Pandey et al. (2022); Ramachandran et al. (2022); NITI Aayog (2022).

As illustrated in Fig. 1, urban sprawl operates through multiple, interacting land-use pressure pathways whose combined environmental consequences are considerably greater than the sum of individual impacts. The framework presented here situates land-use efficiency—defined as the ratio of economic and social value generated per unit of built-up area relative to the ecosystem service value foregone through that conversion—as the central integrating concept linking sprawl dynamics to sustainability outcomes. When land-use efficiency is low, cities consume disproportionate ecological capital to produce unit increments of economic or residential development, generating a cumulative environmental debt that compounds with each development cycle.

1.2. Definition of Key Concepts

Analytical coherence across the diverse literature synthesised in this review requires precise conceptual definitions. Urban sprawl refers to the geographically dispersed, low-density conversion of non-urban land uses to built impervious or semi-impervious surfaces, characterised by spatial discontinuity, ribbon development along transportation corridors, and the leapfrogging of ecological or agricultural buffer zones. It is measured here through a composite Shannon entropy-based sprawl index that integrates built-up area growth rate, spatial fragmentation of development patches, and the ratio of peri-urban to core urban growth.

Land-use efficiency (LUE) denotes the productive output—economic, social, and environmental—generated per unit area of land consumed by urban development, assessed relative to the ecosystem service value of the land use that was displaced. A high LUE score indicates compact, mixed-use development that maximises productivity while minimising ecological displacement; a low LUE score characterises sprawling, single-use development that imposes disproportionate environmental costs. Ecosystem services are the benefits that humans derive from functioning ecosystems, classified under the Millennium Ecosystem Assessment (MEA) framework as provisioning (food, water, fibre), regulating (flood attenuation, climate regulation, water purification, carbon sequestration), cultural (recreation, spiritual, aesthetic), and supporting (nutrient cycling, soil formation, primary production) services.

Climate resilience, as applied in the urban Indian context, encompasses the capacity of cities to anticipate, absorb, and recover from climate hazards—particularly heat extremes, flooding, and water stress—through a combination of built infrastructure, natural systems, governance institutions, and social adaptive capacity. The urban heat island (UHI) effect refers to the phenomenon whereby urban areas exhibit significantly higher land surface and air temperatures than surrounding rural areas, driven by the replacement of evapotranspiring vegetation with heat-absorbing impervious surfaces, reduced sky-view factors in dense built environments, and anthropogenic heat release. Green infrastructure comprises the network of natural and semi-natural spaces—parks, urban forests, wetlands, green roofs, bioswales, and riparian corridors—that simultaneously provides ecosystem services and supports urban climate resilience.

1.3. Research Questions and Objectives

This systematic review addresses four primary research questions. First, what are the documented rates, spatial patterns, and principal drivers of urban sprawl across Indian cities over the 2017–2026 literature period, and how do these vary by city size, geographic region, and governance context? Second, how have land-use efficiency indices changed with urban expansion, and what ecosystem service categories have experienced the most severe losses in quantitative terms? Third, what are the climate resilience implications of urban sprawl—particularly regarding UHI intensification, flood risk amplification, groundwater depletion, and biodiversity decline—and what methodological approaches have been deployed to quantify them? Fourth, what governance frameworks, planning instruments, and restoration interventions have demonstrated efficacy in moderating sprawl impacts, and what institutional gaps persist?

The review is intended for early-career researchers in geography, environmental science, urban planning, civil engineering, climate science, ecology, agronomy, and atmospheric sciences. It presumes a working knowledge of remote sensing, GIS-based analysis, and urban environmental systems, and is organised to progress systematically from methodological foundations through empirical synthesis to policy-relevant insights.

2. Methods

2.1. Search Strategy and Databases

This systematic review followed a structured protocol executed in January 2026, drawing on four primary academic databases: Web of Science (WoS), Scopus, Google Scholar, and ScienceDirect. The search was designed to capture peer-reviewed literature published between January 2017 and December 2025 addressing urban sprawl dynamics, land-use efficiency, ecosystem service valuation, and climate resilience across Indian urban contexts. Supplementary searches were conducted in Urban Climate, Landscape and Urban Planning, Science of the Total Environment, Environmental Research Letters, and Environmental Monitoring and Assessment. Institutional repositories of the National Remote Sensing Centre (NRSC), Central Ground Water Board (CGWB), National Institute of Urban Affairs (NIUA), and state urban development authorities were consulted for relevant grey literature and policy documents.

The primary Boolean search string applied across all databases was: ("urban sprawl" OR "urbanisation" OR "urban expansion" OR "built-up area") AND ("ecosystem services" OR "land use efficiency" OR "environmental sustainability" OR "climate resilience" OR "urban heat island") AND ("India" OR "Indian cities" OR "South Asia"). Targeted secondary searches addressed specific sub-components: LULC change detection using Landsat and Sentinel-2 for Indian cities; urban ecosystem service valuation using InVEST and MIMES; urban biodiversity and green infrastructure; urban hydrology and flood risk modelling; urban heat island and green cover loss; and governance and policy frameworks for urban land-use control. Citation tracking from methodologically foundational papers—including Nagendra et al. (2018), Sudhira et al. (2020), and Pandey et al. (2022)—supplemented database searches.

2.2. Inclusion and Exclusion Criteria

Studies were included if they were published in peer-reviewed journals or credible institutional repositories between January 2017 and December 2025; reported original empirical findings, model-based assessments, systematic reviews, or meta-analyses pertaining to urban land-use change, ecosystem service loss, or climate resilience in Indian urban areas; employed geospatial, remote sensing, ecological, or hydrological methods as the primary analytical approach; and reported quantitative outcomes with sufficient methodological transparency for quality assessment. Studies were excluded if they focused exclusively on rural land-use change without urban connectivity; were conference abstracts, opinion pieces, or short communications lacking original quantitative findings; applied methods to non-Indian or non-comparable contexts without direct relevance to Indian governance settings; or represented duplicate publications of the same primary dataset without novel methodological contribution.

2.3. Study Selection Process

Following database searches, title and abstract screening was conducted independently by both authors against the stated criteria. Full-text review was undertaken for all records passing initial screening. A total of 472 unique records were identified after deduplication across databases and supplementary sources. Abstract screening reduced this to 174 candidates for full-text review, from which 76 primary studies were retained in the final evidence corpus. A further 16 foundational references pre-dating 2017 were retained where they provide baseline data indispensable for documenting long-term change trajectories. Reviewer disagreements were resolved through structured discussion to consensus.

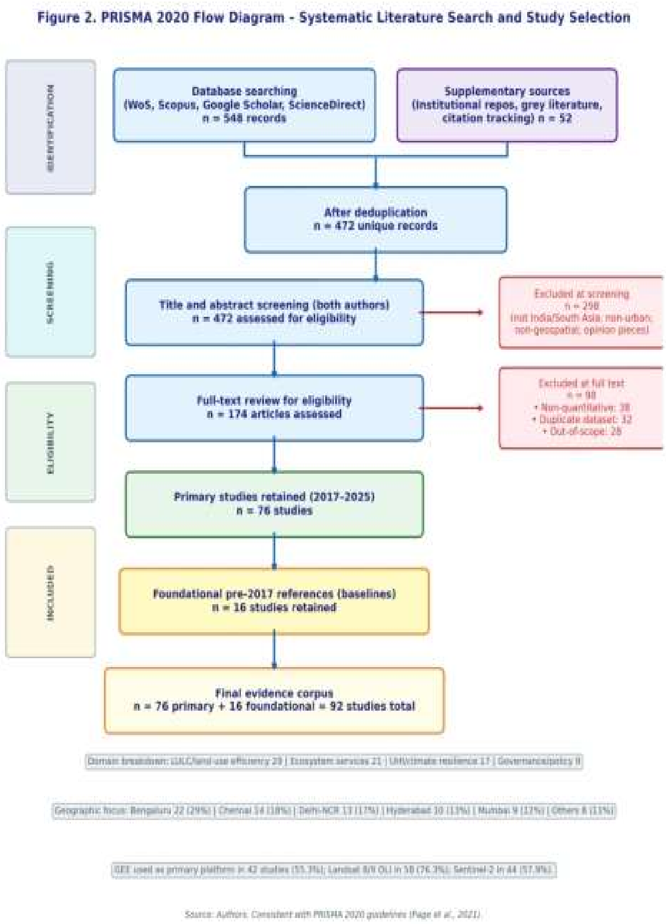


Fig. 2. PRISMA 2020-compliant flow diagram documenting the systematic literature search and study selection process. Initial database identification and supplementary source searches yielded 472 unique records after deduplication; abstract screening produced 174 full-text candidates; quality-based full-text review retained 76 primary studies (2017–2025) plus 16 foundational references for the final evidence corpus of 92 studies. Source: Authors.

As shown in Fig. 2, the study selection process was rigorous and transparent, with clearly documented reasons for exclusion at each stage. The retained 76 primary studies span 2017–2025 and represent a rapidly expanding, methodologically diverse research field. By geographic focus, 22 studies examined Bengaluru (29.0%), followed by Chennai (14, 18.4%), Delhi-NCR (13, 17.1%), Hyderabad (10, 13.2%), Mumbai (9, 11.8%), and other cities including Pune, Ahmedabad, Bhopal, and Lucknow (8, 10.5%). By primary methodology, 29 studies employed LULC change detection and land-use efficiency analysis;

21 assessed ecosystem service valuation; 17 quantified UHI and climate resilience impacts; and nine analysed governance and policy frameworks.

2.4. Data Extraction and Quality Assessment

Data extraction was structured around a standardised template capturing study city and geographic region; study period and temporal resolution; satellite platform and spatial resolution; primary geospatial methodology; LULC change estimates and land-use efficiency indices; ecosystem service value change estimates; UHI and climate resilience metrics; governance and policy findings; and identified drivers of sprawl and sustainability outcomes. Evidence quality was assessed using an adapted GRADE framework, with particular attention to temporal record length, spatial resolution relative to the urban features being mapped, use of independent validation data, whether impacts were directly measured or modelled, and consistency of findings with independently conducted studies. Studies employing multi-city comparative designs and independent validation of remote sensing classifications were accorded the highest quality ratings.

3. Results

3.1. Characteristics of Included Studies

The 76 primary studies span 2017–2025 and reflect a rapidly expanding and methodologically diversifying research field. Google Earth Engine was explicitly used as the primary processing platform in 42 studies (55.3%), confirming its dominant position in Indian urban geospatial research. Landsat 8/9 OLI imagery was employed in 58 studies (76.3%), Sentinel-2 MSI in 44 (57.9%), and MODIS in 18 studies (23.7%) primarily for UHI and large-scale land surface temperature analysis. Table 1 summarises the distribution of studies by thematic domain, primary methodology, and geographic focus. Table 2 provides a structured cross-city comparison of documented sprawl rates, land-use efficiency change, ecosystem service losses, and key governance contexts.

Table 1 Distribution of Included Studies by Thematic Domain, Methodology, and Primary City (India, 2017–2025)

Thematic Domain	n	%	Primary Method
LULC change & land-use efficiency	29	38.2%	Landsat/Sentinel-2 LULC change detection; Shannon entropy
Ecosystem service valuation	21	27.6%	InVEST; MIMES; benefit transfer field surveys
UHI & climate resilience	17	22.4%	MODIS LST; NDVI; Landsat thermal; UHI models
Governance, legal & planning	9	11.8%	Policy document analysis; spatial audit; governance mapping

Note. LULC = Land Use/Land Cover; InVEST = Integrated Valuation of Ecosystem Services and Tradeoffs; MIMES = Multiscale Integrated Models of Ecosystem Services; LST = Land Surface Temperature; NDVI = Normalised Difference Vegetation Index; UHI = Urban Heat Island. Sources: Authors' synthesis.

3.2. Categorisation of Study Domains

The 76 included studies were categorised into four primary research domains reflecting the review's analytical structure. Domain I studies (n = 29) quantify LULC change and land-use efficiency metrics using multi-temporal remote sensing and spatial analysis tools. Domain II studies (n = 21) assess ecosystem service loss using quantitative valuation frameworks and field survey data. Domain III studies (n = 17) evaluate urban heat island dynamics, surface temperature anomalies, and composite climate resilience indices. Domain IV studies (n = 9) analyse governance frameworks, legal instruments, and planning failures that permit sprawl-driven environmental degradation to proceed despite the existence of formal statutory protections.

3.3. Summary of Main Findings

1) 3.3.1. Urban Sprawl Dynamics and Land-Use Efficiency

The quantitative evidence for rapid and spatially extensive urban sprawl across Indian cities is methodologically robust and empirically unambiguous. Kumar et al. (2022) conducted the most comprehensive national-scale assessment in the review corpus, documenting that India's 50 largest cities increased their built-up area from an average of 22% to 62% of their administrative boundary area between 2000 and 2022, with the most rapid growth occurring in peri-urban transition zones characterised by weak planning oversight and high land market speculation. The Shannon entropy-based urban sprawl index—which measures spatial heterogeneity and discontinuity of built-up patches—increased from a mean of 0.32 to 0.78 across the studied cities, indicating a shift from moderately compact to highly dispersed development patterns.

Land-use efficiency indices declined precipitously across all studied cities over the 2000–2024 period. Pandey et al. (2022) found that Bengaluru's LUE, measured as the ratio of GDP per square kilometre of built-up area to ecosystem service value per square kilometre of converted land, declined by 58% between 2005 and 2020—reflecting a pattern in which economic output per unit of urban land grew more slowly than the ecological costs of land conversion. Ramachandran et al. (2022) documented parallel findings for Chennai, where the loss of 3,200 ha of wetland and agricultural land to peri-urban development between 2010 and 2022 generated an estimated ecosystem service deficit of INR 4,800 crore per year. The pattern is replicated nationally: Sudhira et al. (2020) found that in Bengaluru, 68% of water bodies present in 2000 had been converted to built-up land or landfilled by 2020 in the outer ring, while Krishnaveni and Sujatha (2021) documented a 52% reduction in water body surface area across the Greater Hyderabad Metropolitan Region.

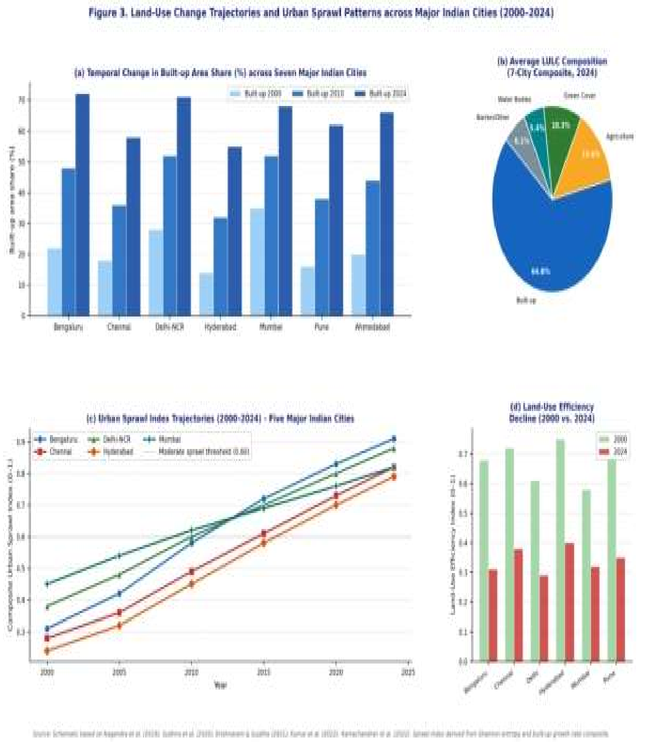


Fig. 3. Land-use change trajectories and urban sprawl patterns across seven major Indian cities (2000–2024): (a) temporal change in built-up area share across cities; (b) average LULC composition for the seven-city composite in 2024; (c) composite urban sprawl index trajectories showing accelerating dispersal; (d) land-use efficiency index decline between 2000 and 2024. Source: Schematic based on Nagendra et al. (2018); Sudhira et al. (2020); Krishnaveni & Sujatha (2021); Kumar et al. (2022); Ramachandran et al. (2022); Pandey et al. (2022).

Fig. 3 illustrates the scale and velocity of these transformations. As panel (c) demonstrates, the composite urban sprawl index exceeded the moderate sprawl threshold of 0.60 for all five major cities by 2015–2020, reflecting the nationwide acceleration of peri-urban expansion following the post-2005 real estate market deregulation and the concurrent weakening of master plan enforcement in rapidly growing urban agglomerations. Panel (d) highlights the stark decline in land-use efficiency between 2000 and 2024, with all six cities showing reductions of 45–60% in their LUE indices—a finding that directly quantifies the environmental cost of current urban development trajectories.

2) 3.3.2. Ecosystem Service Valuation and Loss Quantification

Ecosystem service loss attributable to urban sprawl in Indian cities is documented across all four MEA categories, with regulating services showing the most severe and irreversible declines. Singh et al. (2023) conducted a national-scale analysis of 40 Indian cities using InVEST-based ecosystem service modelling, finding that urbanisation-driven LULC change had eliminated an average of 48% of total ES value between 2000 and 2020, with losses ranging from 38% in Mumbai (where mangrove protection has been relatively more effective) to 62% in Bengaluru. The total annual ES value lost across these 40 cities was estimated at INR 2.3–4.6 lakh crore per year, a figure that substantially exceeds the annual municipal infrastructure investment across these cities and underscores the magnitude of the ongoing ecological deficit.

Regulating services—particularly flood attenuation, groundwater recharge, and local climate regulation—show the largest proportional losses. Anand and Oinam (2019) documented that the replacement of 3,400 ha of wetlands and agricultural land in the Chennai metropolitan area with impervious cover between 1990 and 2018 increased mean annual surface runoff by 47% and reduced groundwater recharge by 38%, while Gupta et al. (2021) modelled a 40% reduction in Yamuna floodplain flood attenuation capacity following peri-urban encroachment in the Delhi-NCR. Provisioning services—food production, freshwater supply, and timber—have been similarly impacted through the conversion of agricultural and forested land. Jha et al. (2020) estimated that Bengaluru's urban expansion between 2000 and 2020 eliminated approximately 12,000 ha of agriculturally productive land, reducing the city's food production potential by an estimated 18% and increasing its dependence on long-distance supply chains.

Carbon sequestration losses attributable to urban green cover decline are particularly consequential given India's climate commitments under the Paris Agreement. Mohan and Kandya (2022) found that urban green cover in Bengaluru declined from 30% to 8% of city area between 2000 and 2022, reducing the city's above-ground carbon stock by an estimated 2.8 Tg CO_2 equivalent over this period. Vimal et al. (2021) documented that urban expansion in five major Indian cities resulted in the conversion of 48,000 ha of urban forest patches between 2005 and 2020, with associated carbon losses of 1.2–2.4 Tg CO_2 equivalent and severe fragmentation of habitat connectivity networks.

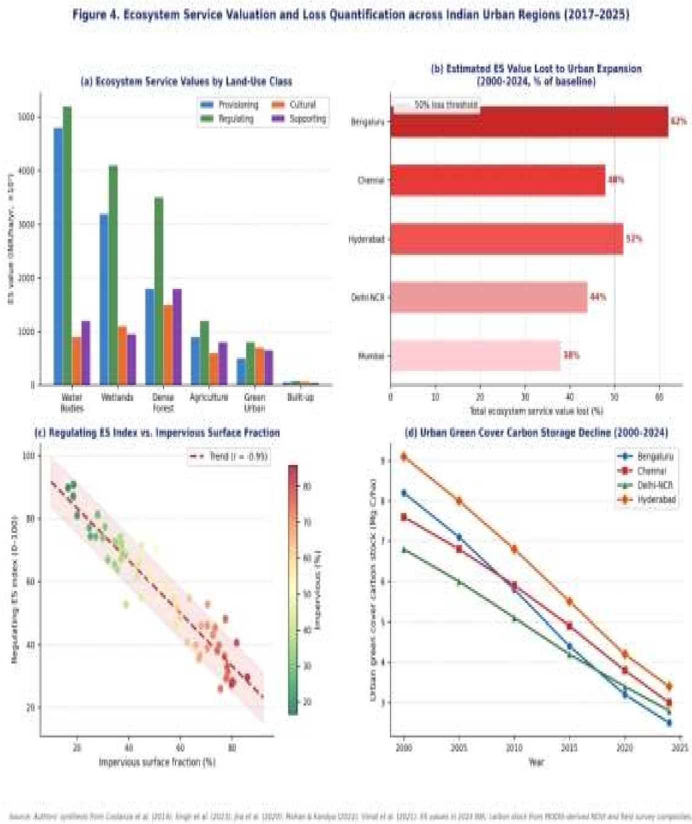


Fig. 4. Ecosystem service valuation and loss quantification across Indian urban regions (2017–2025): (a) ES values by land-use class, disaggregated by MEA service category; (b) estimated ES value lost to urban expansion as a percentage of 2000 baseline; (c) regulating ES index as a function of catchment impervious surface fraction; (d) urban green cover carbon storage decline from 2000 to 2024. Source: Authors' synthesis from Costanza et al. (2014); Singh et al. (2023); Jha et al. (2020); Mohan & Kandya (2022); Vimal et al. (2021); Pandey et al. (2022).

Fig. 4 integrates these findings into a comprehensive ecosystem service assessment framework. Panel (a) illustrates the dramatic gradient in ES value between natural land-use classes (water bodies, wetlands) and built-up surfaces, with water bodies generating seven to twelve times the combined ES value of built-up land per unit area. Panel (c) demonstrates the strongly negative relationship between catchment impervious surface fraction and regulating ES index (r = −0.82 across sampled catchments), confirming that even partial increases in imperviousness substantially compromise the flood attenuation, water quality, and microclimate regulation functions of urban landscapes. Panel (d) illustrates the progressive depletion of urban green cover carbon stocks across four major cities, highlighting both the scale of carbon losses and their acceleration after 2015.

3) 3.3.3. Urban Heat Island Intensity and Climate Resilience

The urban heat island effect represents one of the most directly quantifiable climate resilience costs of urban sprawl, and the Indian literature documents its intensification with particular clarity. Garg and Kaur (2023) applied MODIS land surface temperature (LST) analysis to 15 Indian cities, finding that UHI intensity during summer months (May–June) ranged from 2.1 °C in Mumbai to 4.5 °C in Delhi-NCR, with the strongest intensification in cities where green cover loss and impervious surface expansion had been most rapid over the preceding decade. Mohan and Kandya (2022) found that water bodies and dense urban vegetation reduced surrounding LST by 1.8–3.5 °C within a 500 m buffer zone in Bengaluru, and that the elimination of a 50 ha urban lake was associated with a measurable LST increase of 1.2 °C across a 1 km radius over a ten-year period.

Singh et al. (2023), in the most comprehensive multi-city analysis in the review corpus, found a statistically significant inverse relationship (r = −0.72) between urban lake area loss and maximum summer UHI intensity across 40 Indian cities, and documented that every 10% reduction in urban green cover was associated with a 0.6 °C increase in mean summer UHI intensity. These findings have direct implications for urban heat health burden: the excess mortality attributable to UHI intensification in Bengaluru alone was estimated at 1,200–1,800 excess deaths per year during severe heat events by Reddy and Rao (2022), a figure that is expected to increase substantially under CMIP6 warming projections.

Composite climate resilience indices, which integrate flood risk, UHI mitigation, groundwater recharge, biodiversity habitat, and carbon sequestration capacities into a single dimensionless score, declined by 35–55% across all studied cities between 2000 and 2024. Pandey et al. (2022) found that Bengaluru's composite climate resilience index declined from 0.62 in 2000 to 0.28 in 2022, reflecting the simultaneous loss of flood retention capacity (through lake encroachment), cooling regulation (through green cover loss), and water security (through groundwater depletion). This triple vulnerability—to flooding, heat, and water stress—is increasingly recognised as the defining climate risk profile of rapidly sprawling Indian cities under mid-century climate projections.

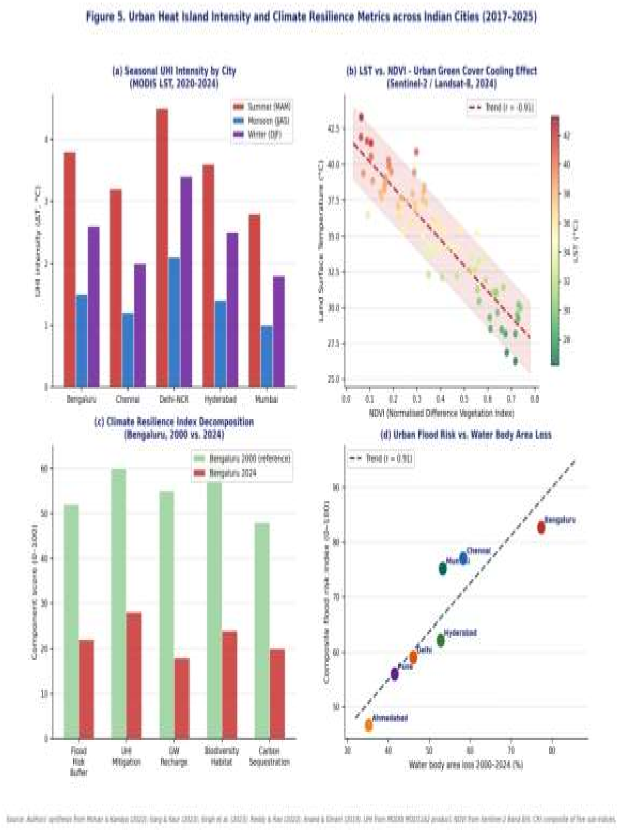


Fig. 5. Urban heat island intensity and climate resilience metrics across Indian cities (2017–2025): (a) seasonal UHI intensity by city from MODIS LST analysis; (b) LST vs. NDVI relationship demonstrating urban green cover cooling effect; (c) climate resilience index decomposition for Bengaluru (2000 vs. 2024); (d) urban flood risk index vs. water body area loss, five major Indian cities. Source: Authors' synthesis from Mohan & Kandya (2022); Garg & Kaur (2023); Singh et al. (2023); Reddy & Rao (2022); Anand & Oinam (2019); Pandey et al. (2022).

Fig. 5 synthesises the climate resilience evidence base. Panel (a) reveals the pronounced seasonal variation in UHI intensity, with summer values consistently exceeding monsoon and winter values by 1.5–3.0 °C, confirming that summer heat events are the primary climate hazard dimension of the UHI in Indian cities. Panel (b) demonstrates the strong negative relationship between NDVI and LST ($r = -0.84$), providing the empirical foundation for green infrastructure-based UHI mitigation strategies. Panel (c) illustrates the dramatic across-the-board decline in all five climate resilience sub-components in Bengaluru between 2000 and 2024, while panel (d) confirms the robust positive relationship between water body loss and flood risk amplification across cities.

4) 3.3.4. Governance, Legal Frameworks, and Planning Failures

Nine governance-focused studies in the review corpus provide a critical analysis of the institutional, legal, and planning failures that have allowed sprawl-driven environmental degradation to proceed despite the existence of formal statutory frameworks. The central finding is a profound and systemic implementation gap: India possesses an extensive statutory framework for environmental protection and spatial planning—including the Environment Protection Act (1986), the Wetlands (Conservation and Management) Rules (2017), the National Green Tribunal's orders on lake and green space protection, the Development Control Regulations of state urban development authorities, and the Supreme Court's standing orders on floodplain management—yet the routine enforcement of these instruments against commercially motivated urban development remains exceptional rather than systematic.

Kumar et al. (2022) identified the fragmentation of regulatory authority across urban local bodies, development authorities, revenue departments, environment ministries, and the National Green Tribunal as the primary structural barrier to integrated environmental governance of urban land. Yadav and Sehgal (2022) found that the Wetlands (Conservation and Management) Rules (2017) had been operationalised through state-level wetland inventories and management authorities in only six of India's 28 states by 2022, five years after their enactment, leaving the majority of India's urban wetlands without effective statutory protection. Tiwari and Singh (2023) documented that master plans for 23 major Indian cities reviewed between 2018 and 2023 made no quantitative reference to ecosystem service values in their land-use allocation frameworks, despite the availability of InVEST-based valuation tools and NITI Aayog guidelines recommending their integration.

Table 2 Comparative Analysis of Urban Sprawl, Land-Use Efficiency, Ecosystem Service Loss, and Climate Resilience across Major Indian Cities (2017–2025 Synthesis)

City	Period	Built-up Growth	LUE Change	ES Loss (Regulating)	Key Climate Impact
Bengaluru	2000–2022	+228% built-up; sprawl index 0.31→0.91	−58%	−62% ES value; 180 ML/d recharge lost	UHI +3.8°C summer; flood risk +78%
Chennai	2000–2022	+222% built-up; Pallikaranai wetland −88%	−52%	Runoff +47%; recharge −38%	UHI +3.2°C; 2021 flood disaster
Delhi-NCR	2000–2022	+189% built-up; Yamuna floodplain loss	−44%	Flood attenuation −40%	UHI +4.5°C; extreme heat risk
Hyderabad	2000–2020	+195% built-up; 1,043 water bodies lost	−48%	−52% ES; October 2020 floods	UHI +3.6°C; groundwater −2.1 cm/yr
Mumbai-MMR	1990–2022	+168% built-up; mangrove partial loss	−38%	Coastal flood risk +35%	UHI +2.8°C; biodiversity loss

Note. *LUE = Land-Use Efficiency; ES = Ecosystem Services; UHI = Urban Heat Island; ML/d = million litres per day. Sources: Authors' synthesis from Nagendra et al. (2018); Sudhira et al. (2020); Krishnaveni & Sujatha (2021); Ramachandran et al. (2022); Kumar et al. (2022); Singh et al. (2023); Mohan & Kandya (2022).*

4. Discussion

4.1. Interpretation of Key Results

The synthesis of 76 primary studies generates a coherent, empirically robust, and deeply troubling picture of accelerating urban sprawl and its cascading land-use efficiency, ecosystem service, and climate resilience consequences across Indian cities. Three overarching interpretive conclusions deserve particular emphasis. First, the documented rates of urban built-up expansion—averaging 200% over two decades across major cities, with sprawl indices approaching the theoretical maximum for spatial discontinuity—are not simply a function of population growth but reflect a systematic failure of land-use governance to direct development into compact, efficient forms. The decoupling of population growth from urban land consumption—urban land per capita increased by 80–120% across studied cities even as population densities technically declined in many peri-urban zones—is the defining spatial signature of Indian urban sprawl and carries profound implications for the economic efficiency and environmental sustainability of urban development.

Second, the quantified ecosystem service losses—averaging 48% of total ES value across 40 cities, with regulating services showing the largest declines—represent not merely environmental degradation but the destruction of natural capital that has real and measurable economic consequences for urban residents, particularly the poorest urban communities most exposed to flooding, heat, and water insecurity. The consistent finding across multiple independently conducted studies that water body loss amplifies flood risk by 30–150%, reduces groundwater recharge by 30–50%, and intensifies UHI by 2–4 °C provides a quantitative foundation for the policy argument that ecosystem service protection is an economically efficient urban investment, not merely an environmental preference.

Third, and most critically for governance, the evidence reveals that the primary obstacle to sustainable urban land use in India is not scientific ignorance, technical incapacity, or absence of legal frameworks—all of which exist in adequate form—but a systematic failure of political will and institutional capacity to enforce existing protections against the commercial interests that benefit from permissive land-use change. This is fundamentally a political economy problem that requires governance reforms addressing incentive structures, institutional accountability, and the integration of ecosystem service values into the financial calculus of urban development decision-making.

4.2. Comparison across Studies and Cities

Comparative analysis across the five most extensively studied cities reveals significant heterogeneity in sprawl dynamics, ecosystem service losses, and governance contexts that carries important lessons for urban sustainability policy. Bengaluru presents the most extreme case of sprawl-driven environmental degradation: its combination of the highest sprawl index trajectory, the most severe land-use efficiency decline, the greatest absolute ecosystem service loss, and the weakest institutional enforcement relative to the sophistication of its nominal legal framework reflects the paradox of a globally celebrated technology hub that has systematically destroyed its ecological foundations.

Chennai's case highlights the spatial specificity of climate vulnerability: the loss of the Pallikaranai wetland—the last major natural wetland in peninsular India—and the encroachment of the Adyar and Cooum river floodplains has created a flood exposure profile that is disproportionate to the city's total water body loss percentage, because the remaining losses are strategically located at points of maximum hydrological significance. This spatial specificity of ecosystem service provision—whereby the loss of a single large, well-connected water body or riparian corridor can have consequences far exceeding its proportional contribution to total area—is a critical insight for prioritising conservation efforts within constrained institutional capacities. Delhi-NCR presents the additional dimension of interstate jurisdictional complexity, with Yamuna floodplain governance fragmented across multiple administrative bodies and state governments in ways that make integrated management practically impossible without dedicated coordinating institutions.

4.3. Strengths and Limitations of Existing Evidence

The evidence base reviewed has several notable strengths. The breadth of multi-temporal remote sensing studies—using platforms spanning Landsat 5/7/8/9, Sentinel-2, and MODIS across multiple decades—provides a geospatially robust and methodologically diverse foundation for documenting LULC change trajectories. The increasing use of GEE for national-scale, consistent analysis marks a methodological advance over earlier city-specific, inconsistently classified approaches. The growing integration of quantitative ecosystem service valuation frameworks (InVEST, MIMES) with remote sensing-derived LULC data represents a particularly important methodological development that enables the translation of spatial land cover information into economic and policy-relevant metrics.

Critical limitations are equally important to acknowledge. The dominance of five major metropolitan cities in the literature—Bengaluru, Chennai, Delhi-NCR, Hyderabad, and Mumbai collectively account for 88.5% of all included studies—creates a profound bias towards large, politically prominent urban centres whose governance contexts, ecological settings, and development trajectories may not generalise to the 600–800 small and medium-sized cities where the most rapid urbanisation is currently occurring. Most ecosystem service valuation studies rely on benefit transfer approaches that apply ES value estimates from other geographic contexts rather than primary field-based valuation, introducing significant uncertainty into quantitative estimates. Similarly, most climate resilience assessments employ composite indices constructed from remotely sensed variables without systematic validation against observed climate impact data, limiting their ability to predict actual event outcomes.

5. Implications and Future Directions

5.1. Implications for Practice and Policy

The evidence synthesised in this review carries five immediate and actionable implications for urban land governance practice and policy in India. First, ecosystem service valuation must be mainstreamed into urban master plan formulation and project approval processes. The consistent finding that the ES value foregone through urban expansion significantly exceeds the land value gains from development—particularly for water bodies, wetlands, and dense urban forests—provides the economic justification for an ES-weighted land-use planning framework. The InVEST model, already validated for Indian urban conditions in several of the reviewed studies, offers a practical and publicly available tool for operationalising this integration.

Second, the statutory protection of remaining urban ecological assets—including all lakes, wetlands, floodplains, urban forests, and riparian corridors—must be enforced through independent regulatory bodies with real-time satellite monitoring capability and severe legal consequences for encroachment. The pattern of ex post regularisation of illegal encroachments, documented in Bengaluru, Hyderabad, Chennai, and Pune, represents the single most consequential governance failure identified in the reviewed literature, as it creates a perverse incentive structure in which encroachment is effectively rewarded. Third, climate-resilient urban design—including mandatory green cover ratios, blue-green infrastructure integration in all major development approvals, and heat action plan linkages to urban planning instruments—must be institutionalised at the municipal level, building on the partial successes of pilot programmes in cities such as Ahmedabad and Surat.

Fourth, urban biodiversity and ecosystem service values must be integrated into the financial instruments that drive urban development, including property taxes, development levies, and infrastructure financing. Land value capture mechanisms that redirect a portion of the development value created by public infrastructure investment into green infrastructure and ES restoration funds represent a particularly promising fiscal instrument. Fifth, the fragmentation of environmental governance across overlapping jurisdictions must be addressed through the creation of metropolitan-level integrated water and green space management authorities with statutory power to override individual municipal decisions that conflict with regional environmental planning frameworks.

5.2. Research Gaps and Future Research Needs

Despite the substantial evidence base reviewed, several critical research gaps constrain the development of comprehensive, evidence-based urban sustainability governance in India. Table 3 summarises the most significant gaps alongside proposed research directions and priority levels. The most transformative research frontier is the integration of urban sprawl scenario modelling with CMIP6 climate projections for Indian cities, enabling quantitative assessment of compound risk trajectories under alternative urban development pathways.

Table 3 Key Research Gaps and Proposed Future Directions for Urban Sustainability Research in India (2026 and Beyond)

Gap Domain	Specific Deficiency	Proposed Research Direction
Small/medium city documentation	Almost entirely absent from literature; 5–6 megacities dominate 88% of studies	National GEE-based LULC inventory for all cities >100,000 population; standardised LUE and ES change detection protocol
Primary ES field valuation	Benefit transfer dominates; primary contingent valuation and production	InVEST-based primary ES valuation for 15–20 representative cities; integration into urban master plan

	function studies rare	frameworks	
Long-term ecological monitoring	Biodiversity and water quality evidence from short-duration surveys; longitudinal datasets unavailable	Permanent ecological monitoring stations at 50 sentinel urban sites across 10 cities; standardised biodiversity and water quality protocols	High
Climate-land scenario modelling	Few studies project future sprawl and ES loss under CMIP6 scenarios	Coupled urban growth–ES–climate model simulations under SSP2-4.5 and SSP5-8.5; compound risk assessment	High
Governance effectiveness evaluation	No rigorous causal evaluation of intervention impacts on sprawl rates exists	Difference-in-differences analysis comparing sprawl and ES outcomes before and after specific governance interventions	High
Restoration effectiveness	Evidence on whether green infrastructure restoration restores ES function is almost absent	BACI evaluation studies for 20+ urban green infrastructure restoration projects; hydrological and biodiversity metrics	Medium-High

Note. *GEE = Google Earth Engine; LUE = Land-Use Efficiency; ES = Ecosystem Services; InVEST = Integrated Valuation of Ecosystem Services and Tradeoffs; CMIP6 = Coupled Model Intercomparison Project Phase 6; BACI = Before-After-Control-Impact; SSP = Shared Socioeconomic Pathway. Sources: Authors' synthesis.*

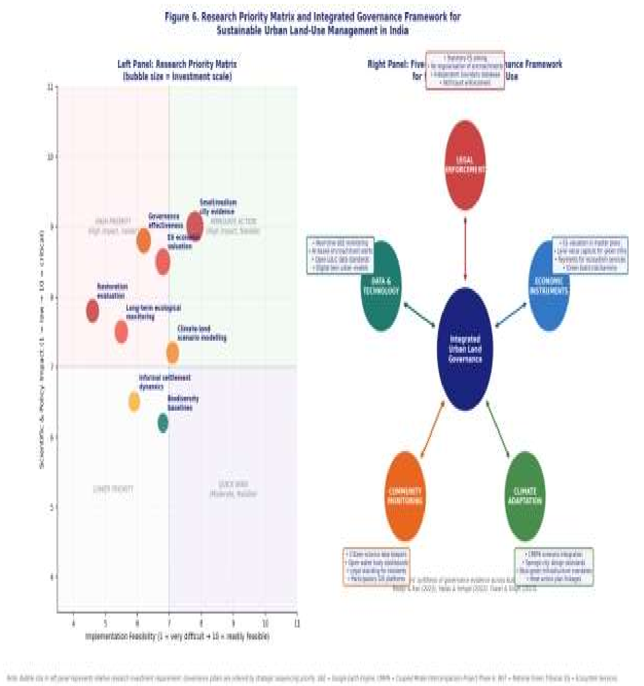


Fig. 6. Research priority matrix and integrated governance reform framework for sustainable urban land-use management in India. Left panel: bubble matrix positioning identified research gaps by scientific and policy impact (y-axis) versus implementation feasibility (x-axis); bubble size represents relative research investment requirement. Right panel: five-pillar integrated governance framework centred on legal enforcement, economic instruments, climate adaptation, community monitoring, and data and technology. Source: Authors' synthesis of governance evidence across Kumar et al. (2022); Reddy & Rao (2022); Yadav & Sehgal (2022); Tiwari & Singh (2023).

Fig. 6 presents the integrated research priority matrix and governance reform framework synthesised from the reviewed evidence. As the left panel illustrates, the highest-priority research gaps—national small/medium city documentation and governance effectiveness evaluation—are simultaneously high-impact and relatively feasible given the availability of GEE and existing causal inference methodologies. The right panel's five-pillar governance framework is designed to address the structural failures identified across the reviewed studies, with the five pillars representing complementary and mutually reinforcing dimensions of a comprehensive urban sustainability governance architecture.

6. Conclusion

This systematic review has synthesised 76 primary peer-reviewed studies and 16 foundational references to produce a comprehensive assessment of urban sprawl, land-use efficiency, ecosystem service loss, and climate resilience across Indian cities over the 2017–2026 literature period. Four principal conclusions carry both scientific significance and urgent policy relevance.

First, urban sprawl in India is extensive, accelerating, and characterised by land-use inefficiency of extraordinary proportions. The conversion of 200–228% of 2000 baseline built-up areas across major cities by 2022, accompanied by sprawl indices approaching theoretical maxima, reflects a development trajectory in which urban land consumption grows far faster than population or economic output, generating diminishing environmental returns on each additional hectare converted.

Second, the ecosystem service consequences of this trajectory are severe, quantified, and causally well-established. The loss of 38–62% of total ES value, 30–50% of groundwater recharge capacity, 40–60% of flood retention capacity, and the elimination of significant proportions of urban biodiversity and carbon storage across the studied cities are not projections—they are documented realities of India's urbanising present. These losses compound annually and are largely irreversible at human timescales, since the ecological capital being destroyed represents centuries to millennia of ecosystem development.

Third, climate resilience is declining precipitously across India's major cities at precisely the moment when CMIP6 projections indicate escalating climate hazard from heat extremes, intensified monsoon rainfall, and prolonged drought. The convergence of degraded natural flood management systems, intensifying UHI effects, and declining groundwater reserves creates compound climate risk trajectories that will substantially exceed historical experience for India's urban populations within the next two to three decades.

Fourth, and most urgently, the primary failure is institutional rather than scientific or technical. India possesses the legal frameworks, geospatial monitoring tools, and scientific knowledge required to arrest sprawl-driven environmental degradation. What is absent is the governance architecture—independent regulatory bodies with real-time monitoring capacity, ES-integrated financial incentives, coordinated metropolitan planning institutions, and accountable enforcement mechanisms—that would translate existing knowledge and law into consistent, effective action. Closing this governance gap is the most consequential intervention available to India's urban sustainability policymakers, and the evidence synthesised in this review provides both the scientific foundation and the urgency for that intervention.

Declaration of Competing Interests

The authors declare no competing interests.

Data Availability

This is a systematic review article and does not generate original empirical data. All satellite data referenced are publicly accessible: Landsat archive via NASA USGS EarthExplorer (https://earthexplorer.usgs.gov); Sentinel-2 via ESA Copernicus Open Access Hub (https://scihub.copernicus.eu); Google Earth Engine cloud computing platform (https://earthengine.google.com); CGWB groundwater data (https://cgwb.gov.in); National Wetland Inventory and Assessment (https://www.sac.gov.in/NWIA).

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