WRI INDIA

WORKING PAPER

URBAN BLUE-GREEN CONUNDRUM: A 10-CITY STUDY ON THE IMPACTS OF URBANIZATION ON NATURAL INFRASTRUCTURE IN INDIA

SAHANA GOSWAMI, SAMRAT BASAK, AAKASH MALIK, AND RAJ BHAGAT PALANICHAMY

EXECUTIVE SUMMARY

Highlights

- Urbanization in India consumes ecologically sensitive zones, natural infrastructure, and permeable open spaces to create developed, saleable land. This study by WRI India uses open-source, high-resolution satellite imagery to estimate the changes in spatial extent of built-up areas and natural infrastructure such as blue cover (water bodies), green cover, and permeable open space across India's 10 most populated cities. In addition, the impact on groundwater recharge is estimated from the conversion of natural spaces with higher recharge potential to concretized surfaces with lower recharge potential.

- Between 2000 and 2015, the built-up area in these 10 cities increased on average by 47 percent and 134 percent within 0–20 km of the city center (core) and 20–50 km (periphery), respectively. Simultaneously, blue cover decreased by 15 percent. About 44 percent of this new development is located in zones with high and very high recharge potential, and an estimated 300 billion liters of water per year is now diverted away from underground aquifers.

- Natural infrastructure in urban areas also functions as a buffer against climate change driven extreme weather events and therefore is an important adaptation and mitigation measure for increased urban resilience.

CONTENTS

Executive Summary 1
Introduction 7
Study Design and Methodology 7
Urban Development and Natural Infrastructure Change 12
The Future of Urbanization and Natural Infrastructure In India 34
Appendices 37
Abbreviations 104
Glossary 104
Endnotes 105
References 106
Acknowledgments 112
About the Authors 112
About WRI India 112

Working Papers contain preliminary research, analysis, findings, and recommendations. They are circulated to stimulate timely discussion and critical feedback and to influence ongoing debate on emerging issues. Most working papers are eventually published in another form and their content may be revised.

Suggested Citation: Goswami, S., S. Basak, A. Malik, R.B. Palanichamy. 2023. "Urban Blue-Green Conundrum: A 10-City Study on the Impacts of Urbanization on Natural Infrastructure in India." Working Paper. WRI India. Available online at https://doi.org/10.46830/wriwp.19.00062.

Impact of Urbanization on Natural Infrastructure in India

Urbanization all over the world is typically associated with increases in the spatial extent of urban built-up areas (Mahendra and Seto 2019). India remains an urbanizing nation and is expected to double its urban population from about 400 million in 2018 to about 800 million by 2050 (United Nations 2019). The extent of urban areas is set to increase dramatically to support the growing population, with estimates suggesting that 70 to 80 percent of the infrastructure needed in 2030 is yet to be built (Friedman 2014). Land use in India is already highly inefficient, leading to conversion of 85 percent more land to urban uses in comparison with the urban population being supported (Güneralp et al. 2020). All this new construction will have profound and far-reaching impacts on urban centers and their surroundings. However, there is limited research and forecasting on how these new developments interact with and impact natural infrastructure and ecological and hydrological systems.

An increase in paved surfaces such as roads and buildings irreversibly changes natural infrastructure, ecosystems, and hydrological surface and subsurface flows in urban areas. The loss of natural infrastructure has complex interlinked consequences such as reduced groundwater recharge leading to dropping aquifer levels and increased rainwater runoff leading to higher flood risk. In addition, the high pressure of development in and around urban centers leads to new development being sited on high-risk, vulnerable zones such as floodplains, lake beds, and low-lying areas.

This paper analyzes the relationship between urbanization (increase in built-up area) and natural infrastructure change (blue and green cover) for India's 10 most populated cities. Rapid urbanization in India has been characterized by the growth of concretized and impermeable landscapes over agricultural lands and natural spaces such as woodlands, lakes, rivers, and wetlands. Such changes are visible across many cities in India, and software such as Google Earth and Google Earth Engine enables users and urban practitioners to extract and view historical satellite imagery of cities and changes in urban built-up areas over time (see Figure ES-1).

Systematic multicity studies of the impacts of urbanization on natural infrastructure (blue and green cover) in India and its consequences are few. In this study, we look at the 10 most populated cities in India over a 15-year period (2000–2015) to estimate the changes in the spatial extents of the built-up area, blue cover, and the vegetation change trend. This time interval was selected to make the available satellite imagery consistent across all 10 study cities. These spatial changes are assessed for regions located 0–20 km and 20–50 km from the city center to understand the variations between core-city and peri-urban regions. The 0–20 km region encompasses the municipal boundary of all the cities, and the 20–50 km region describes the area of influence of the city (World Bank 2013).

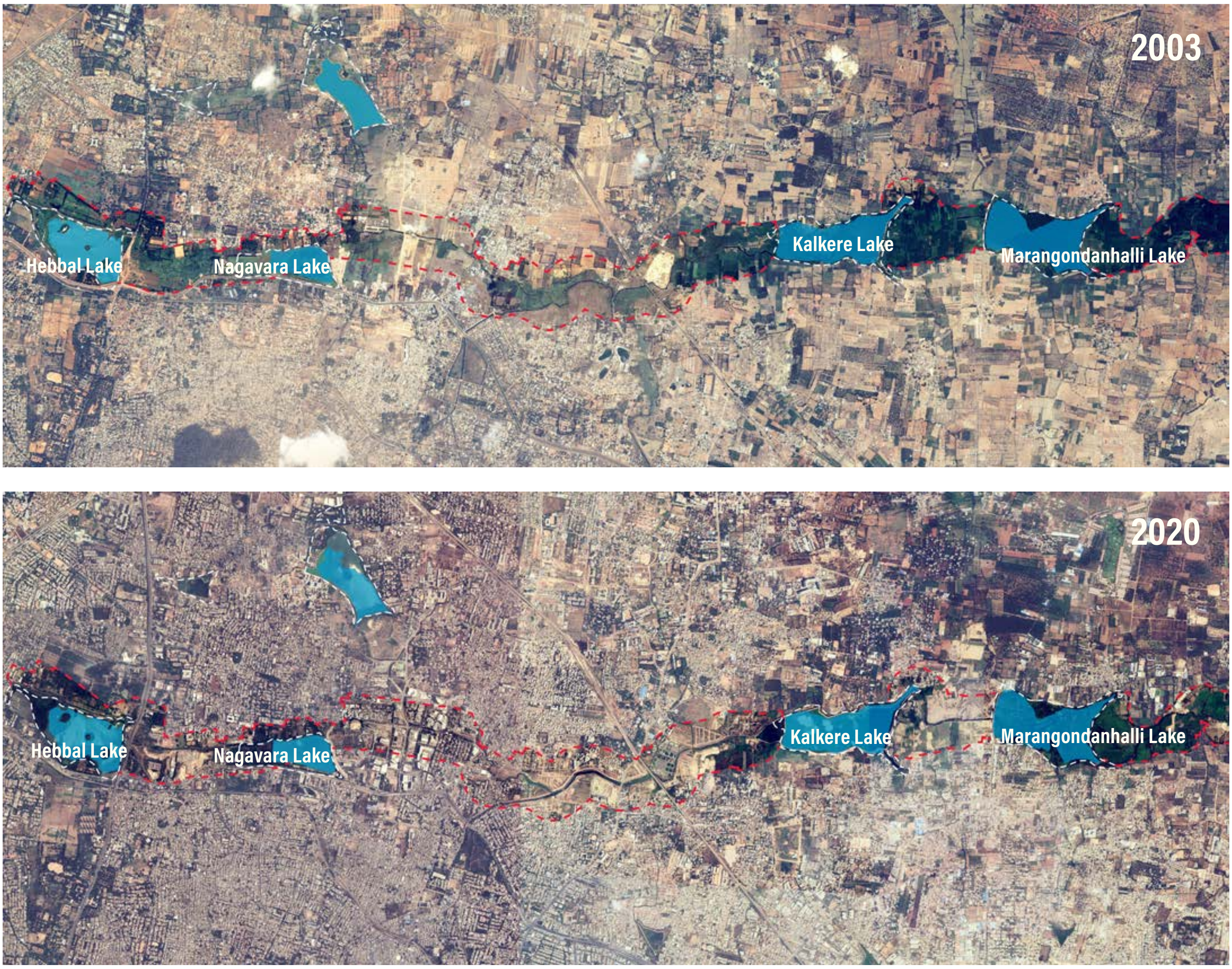
Indian cities, like many regions in the Global South, face challenges related to unregulated and informal settlements, urban poverty, and inequity. The urban water risks of water scarcity and flooding exacerbate these disparities by placing a greater burden on the urban poor and vulnerable communities,[1] who often reside in high-risk locations and lack the resources to cope with climate shocks (Chu et al. 2019). Where development is unregulated (both for formal and informal settlements), blue cover, green cover, and permeable open spaces are rapidly consumed to create built-up areas of "higher economic value." Emerging research links the specific impacts of urbanization to various types of natural infrastructure (either green cover or blue cover) in a number of cities in the Global North and South (Blum et al. 2020; Wu et al. 2019).

About This Working Paper

This working paper seeks to expand our knowledge of urbanization and its impacts on the surrounding natural landscapes in India. We study the urbanized region of India's 10 most populated cities to examine the relationship between urban (built-up) expansion and changes in blue-green infrastructure such as surface waters, green cover, and recharge zones. Improving the interactions between urbanization and natural infrastructure in these 10 cities can significantly impact the well-being of about 30 percent of India's urban population.

Remote sensing data and satellite imagery are used to monitor urbanization and changes in blue-green infrastructure between 2000 and 2015 in the 10 study cities. The cities studied are Ahmedabad, Bengaluru, Chennai, Delhi, Hyderabad, Jaipur, Kolkata, Mumbai, Pune, and Surat. The correlation between urbanization and natural infrastructure is studied in two spatial intervals of 20 km (0–20 km) and 50 km (20–50 km) from the center of each of the study cities. Satellite imagery enables the actual spatial extents of urban areas vis-à-vis built-up

Figure ES-1 | **Satellite Images Showing Extensive Conversion of Natural Drains and Low-Lying Buffer Spaces between Lakes in Nagwara (North) Bengaluru to Built-Up Area between 2003 and 2020**



Sources: Survey of India 1978a; Base Maps: Google Earth Pro 2003; Google Earth Engine 2021.

areas, blue cover, and green cover change trend to be studied. The study uses existing spatial assessment and analysis methods to estimate the spatial extents of various built and natural features in 10 Indian cities. It examines changes in extent beyond administrative boundaries, as urbanization processes are not bounded by these jurisdictions. The study considers a 50 km region around each study city to estimate the changes.

This study is limited to establishing correlations between increases in built-up area and impacts on natural infrastructure as observed from satellite imagery only. Changes to natural infrastructure in urban areas are driven by various interconnected factors including urbanization, climate change driven weather extremes, and other human activities (such as agriculture and quarrying). The use of spatial intervals (0–20 km and 20–50 km) helps assess how the built-up area, blue space, and vegetation change trend and recharge zones are distributed between core-city and peripheral areas, and whether blue-green spaces in core-city and peripheral areas are differentially impacted by the growing urban footprint.

Methodology

Built-up area is derived from the settlement layer as provided by the European Commission–Joint Research Centre's (EC-JRC) Global Human Settlements Layer's built-up grid. This layer is filtered for the study years (2000 and 2015), and settlement data for a 50 km radius from the city center for the 10 study cities are considered (settlement data of other urban and rural areas are masked). The original 30 m resolution of the EC-JRC Global Human Settlements Layer is used.

Blue cover (water bodies) is estimated by calculating the Modified Normalized Difference Water Index (MNDWI) from satellite images. Images from years of severe drought or extreme rainfall can give anomalous estimates. To discount such errors, the images are assessed for two study epochs instead of for a single study year (1997–2002 and 2013–2017). This study filters satellite imagery to access cloud-free images for the indicated time period and thus uses only a limited set of appropriate images to assess blue cover. Even if greater water extents are present in certain images or on-ground, these may not be captured because images are filtered to obtain consistent cloud-free imagery across all 10 study cities.

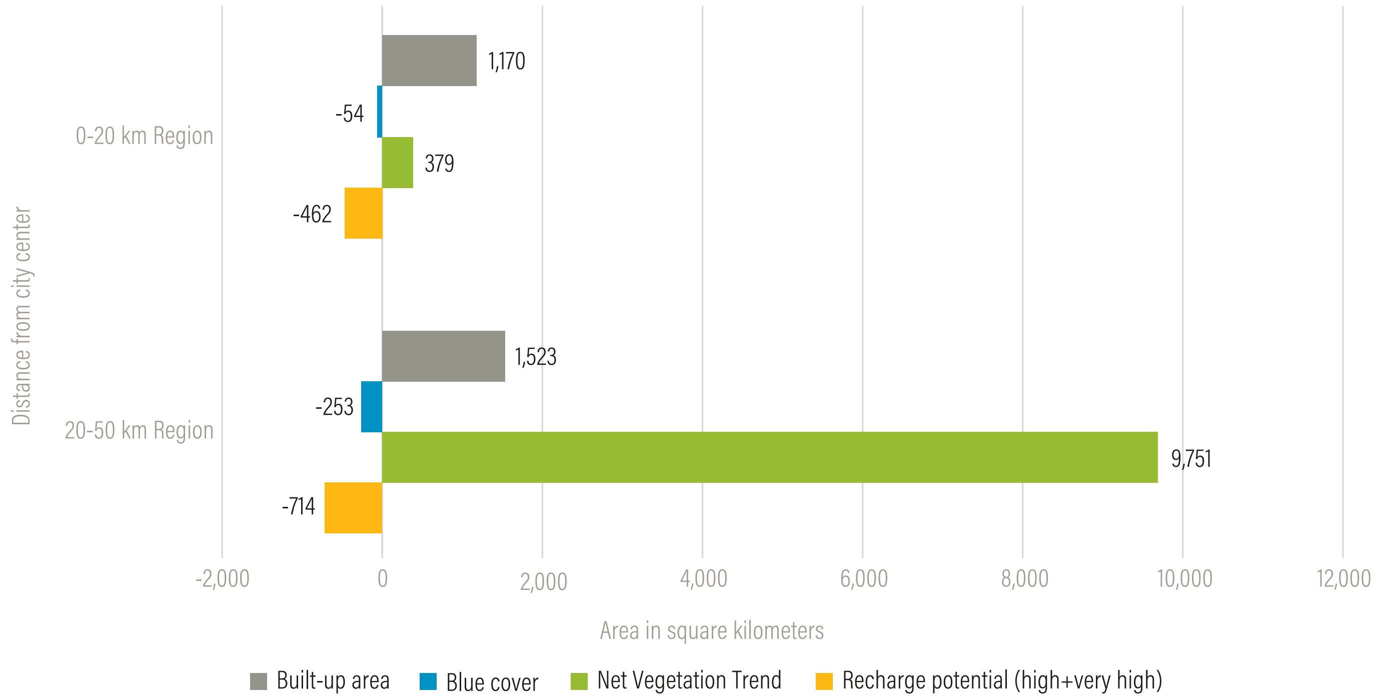
The vegetation change trend analysis detects the change in a pixel's green cover over a period. This is calculated from the change in the observed green signature represented by the Normalized Difference Vegetation Index (NDVI) value. A pixelwise linear regression trend is used to estimate the vegetation change trend and is a commonly used model in remote sensing established by Fensholt and Proud (2012).

Groundwater recharge potential is estimated using the method described in the report titled "The Impact of Climate Change on Groundwater Availability" (Mvandaba et al. 2019). The potential is derived from the NDVI (Chen 1996) and slope of the land surface (taken from the digital elevation model [DEM]). The method used in this study is limited to the use of satellite imagery and other open-source remote sensing information. It does not use soil maps with detailed infiltration coefficients or evapotranspiration rates derived from on-ground studies. Further, the recharge potential statistics are used to derive the lost volume of recharge. The volume of water not entering aquifers is estimated as the product of the area, rainfall, and recharge coefficient, less the infiltration into the built-up area at a nominal rate.

Results and Discussion

The study cities experienced (on aggregate) an increase in built-up area and net vegetation change trend in the 20–50 km study regions between 2000 and 2015 (see Figure ES-2). The

Figure ES-2 | **Aggregate Changes across 10 Study Cities: Increase in Built-Up Area and Net Vegetation Trend, Loss in Blue Cover and Recharge Potential in 0-20 and 20-50 km Regions**



Notes: Net vegetation change trend for a study region is a sum of all the estimated areas with increasing and decreasing vegetation changes. A net positive vegetation change trend indicates that areas with increasing vegetation trends are more than areas where vegetation is declining. Conversely, a net negative vegetation change trend indicates that decrease is occurring in a larger area.
Source: WRI authors.

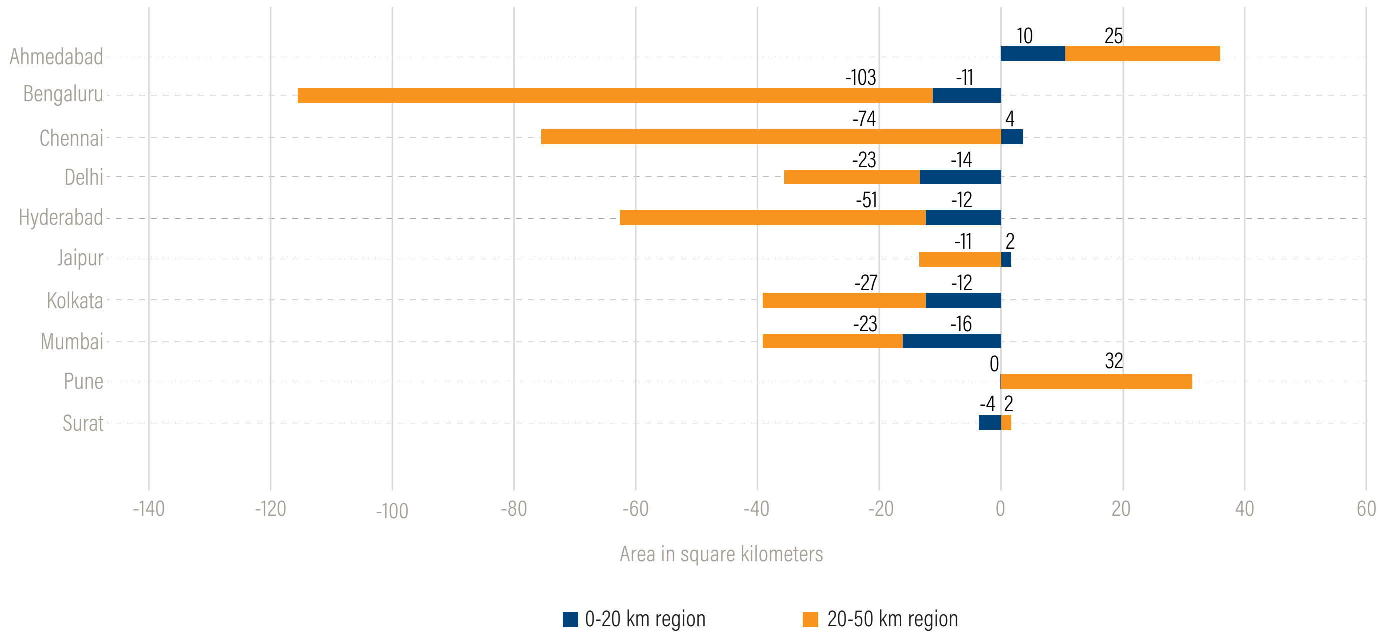
vegetation change trend measured as the change in the NDVI is primarily low-level change (both losses and gains) and indicates minor shifts in green cover and not decreases or increases in dense forest. Across all 10 study cities, blue cover and recharge potential have been lost in the same period. A greater change is seen in the 20–50 km region.

Surface water lost across the 10 cities between 2000 and 2015 is estimated to be 307 sq. km (square kilometers), a 15 percent decrease. This area is equivalent to almost 43,000 football fields, with each field having an area of 7,140 sq. m (square meters). The minimum volumetric loss assuming a 3 m depth[2] for all these water bodies is 900 billion liters across the 10 cities, a volume that could potentially meet about 60 percent of the annual demand added to the 0–50 km region around these cities.[3] Blue cover has decreased in all cities except Ahmedabad (0–50 km region). Chennai and Jaipur experienced minor increases in the 0–20 km region, and Pune experienced a significant increase in the 20–50 km region (Figure ES-3).

The blue cover increase in Ahmedabad is spatially contained primarily in the Sabarmati River and the Narmada Main Canal; in the 2013–17 study period, the river and canal accounted for 80 percent of the blue cover in the city's 20–50 km region. Thus, although overall Ahmedabad performs better than the other study cities, the co-benefits accruing from the increase (groundwater recharge, microclimate benefits) are not likely to be distributed across the entire city.

Green cover has been both lost and gained in the study cities. Changes in green cover are primarily designated as low-level loss or gain; that is, a change in the NDVI denotes minor shifts in green cover and not decreases or increases in dense forest. A net aggregate 10,000 sq. km of low-level gain has occurred across all the 10 cities. This low-level gain is not uniformly distributed within each city, with about 84 percent of it occurring in the 20–50 km (peripheral) region. Overall an area of 7,400 sq.km is estimated to have a decreasing vegetation trend, with 33 percent of this decline occurring in the 0–20 km region. In six of the cities (Bengaluru, Chennai, Delhi, Hyderabad, Jaipur, and Pune), losses exceed gains in the 0–20 km region. Changes to green cover need to be cautiously interpreted, as complex interacting factors driven by human activity and

Figure ES-3 | **Blue Cover has Decreased Significantly in 8 of the 10 Study Cities**



Notes: Blue cover has decreased in all cities except Ahmedabad (0–50 km region). Chennai and Jaipur have slight blue cover increase in the 0-20 km region, and Pune has increase in the 20-50 km region.
Sources: WRI authors.

climate change influence vegetation change trends in urban regions. Gains in core-city areas might be driven by increased water availability from improved water supply and/or leakages from aging water supply and sanitation networks. The green cover increase in core areas aligns with the available maps of water and sanitation networks in cities such as Delhi. In peripheral areas, low-level green cover gains could be attributed to increased and intensified groundwater-based agricultural activity.

It is estimated that 44 percent (1,177 sq. km) of new development between 2000 and 2015 has come up on areas with high or very high recharge potential (in the 0–50 km urban region of the study cities). Recharge potential is estimated as a function of the vegetation and slope of the land surface. Thus, highly vegetated, low-lying, flatter areas have high recharge potential, and steep hillsides with low vegetation levels have low recharge potential. High groundwater recharge potential zones have been extensively occupied and converted to developed areas. The water diverted away from aquifers due to the replacement of all types of recharge zones (very low, low, medium, high, and very high recharge potential zones) with paved surfaces is estimated to be about 300 billion liters annually. This volume could have possibly have met about 20 percent of the new urban demand, assuming 100 lpcd (liters per capita per day), created across all the 10 cities by the addition of about 39 million people between 2000 and 2015.

Natural infrastructure decreases can be connected to reduced surface and groundwater availability in the study cities. Water utilities try to meet the ever-growing demand by seeking to source water supply from larger (but typically more distant) surface water bodies such as reservoirs and rivers (IIHS 2014), which increases the embedded energy and costs of water supply. Simultaneously, reports from the Central Ground Water Board, India's national agency assessing groundwater resources across the country, suggest that most of the study cities have depleted and overexploited aquifers (CGWB 2017). Thus, on the one hand demand has increased due to the growing population, and on the other hand critical local surface and groundwater resources are being depleted.

Urban development alters the environment, causing biophysical disruption of natural systems, such as changes in groundwater infiltration, rate (and volume) of rainwater runoff, and loss of vegetation. In this study, we find that the 10 largest metropolitan areas in India increased their built footprint by 52 percent (in the 0–50 km region) between 2000 and 2015 at the expense of their surface water bodies and high groundwater recharge zones. The lost surface water bodies and groundwater diverted away from aquifers could have provided water to meet the needs of a fifth to half of the new urban population added to these cities in the study period. These biophysical disruptions will eventually have social and economic impacts on urban dwellers and regions, such as increased water scarcity, loss to life and property due to urban floods, heat-stress-induced risk to health and reduced productivity, and increased costs to urban water utilities for supplying water from distant sources.

Policy Implications

The current form of urbanization is disconnected from the natural environment and is associated with various negative outcomes for cities, such as water scarcity, increased groundwater stress, and increasing incidence of urban flooding. The choices made by public and private development agencies regarding where and how to develop can mitigate or exacerbate biophysical disruptions. Using scientific evidence to accurately identify the correlations between urbanization, loss of natural infrastructure, and increasing climate shocks and stresses can enable the state and municipal authorities to strengthen urban planning and development in the future. Measures such as identifying areas of high recharge potential (as done in this study) and retaining high permeability in these areas, restricting building activity in high-risk areas such as floodplains and (ephemeral and permanent) lake beds, and incorporating blue-green infrastructure solutions can be steps toward a resource-sufficient and resilient urban future.

State and municipal authorities can use spatial and on-ground evidence to embark on a paradigm shift in planning in which an integrated urban blue-green approach is undertaken to conserve and restore natural spaces, water bodies, aquifers, and other ecosystems to increase urban resilience. Diversion and/or regulation of development to areas with fewer natural infrastructure resources and close replication of the functions of these natural systems through nature-based solutions (restored urban wetlands, rain gardens, green roofs) can serve as alternatives to the present trend of unmanaged urban expansion.

We recommend that state and city authorities adopt an integrated urban blue-green approach to urban planning and development regulation using spatial and on-ground evidence to conserve and restore natural spaces, water bodies, aquifers, and other ecosystems to increase urban resilience. Natural infrastructure in urban areas can also function as a buffer against climate change driven extreme weather events and therefore is an important adaptation and mitigation measure to increase urban resilience. Valuing natural infrastructure as a key component of the urban (water) infrastructure can expand the range of solutions available to urban water managers and enable city regions to reduce risks and become more resilient and livable. Later research can build on this study to identify the specific causes of natural infrastructure degradation and explore solutions and strategies to prevent the loss of blue-green spaces during urbanization.

INTRODUCTION

A visible consequence of the present form of urbanization (including planned, unplanned,[4] and unmanaged[5] urban development) is the significant loss of natural infrastructure (blue cover and permeable open spaces), particularly in regions in the Global South such as India (The Nature Conservancy 2018). Blue cover and permeable open spaces (together considered *natural infrastructure* in this document) provide a host of ecosystem services such as clean water supply, aquifer recharge and flood control, microclimate control, improved air quality, and healthy and thriving biodiversity. Natural infrastructure also provides a buffer against climate change driven extreme weather events in urban areas. Such natural systems are important adaptation and mitigation measures for increased urban resilience. Access to such natural spaces offers positive health and well-being outcomes for urban residents.

Urbanization in regions in the Global South converts natural and managed permeable spaces such as forested or agricultural land to developed land of higher economic value. Loss of natural infrastructure due to increased urban built footprint is typically followed by an increased incidence of urban floods (Blum et al. 2020), increasing stress on groundwater aquifers, and heat stress (Zipperer et al. 2020). These negative outcomes cause tangible losses to life and property, reduce productivity, and increase the costs of access to water resources. Further, urban social and economic inequalities are reinforced or exacerbated as the urban poor and vulnerable communities that bear the brunt of these negative outcomes lack the financial and social capital to manage these shocks (Hallegatte et al. 2020).

A comprehensive analysis of the changes in natural infrastructure in and around urban areas is necessary to identify and forecast ecosystem risks through a science-based and evidence-driven approach.

STUDY DESIGN AND METHODOLOGY

This study assesses the spatial extent of the built-up area (impermeable or less permeable surfaces), blue cover (water bodies), green cover changes (vegetation), and permeable open spaces (all non-built-up areas) between 2000 and 2015 for the 10 most populated cities in India. These assessments use spatial analysis methods such as the Normalized Difference Vegetation Index (NDVI) and Modified Normalized Difference Water Index (MNDWI).

Research Question and Hypothesis

In this working paper, we examine the relationship between urbanization (increase in built-up area) and natural infrastructure change (in blue-green cover) across India's 10 most populated cities. We look at all development in the urban region, not distinguishing between formal and informal settlements, as regulations in these cities vis-à-vis urban development and natural infrastructure protection are either absent or weak.[6]

Our hypothesis is that an increase in built-up area (considered a marker of urbanization) leads to concurrent decreases in all natural infrastructure (water bodies and vegetation, denoted respectively as blue and green cover). To evaluate our hypothesis, we assess spatial maps of the study regions between 2000 and 2015. We look at regional changes in urban built-up area, blue cover, and green cover change trend, the impacts on areas of high groundwater recharge potential, and the impact of a change in built-up area on the natural infrastructure in core and peripheral areas.

Table 1 | **Details of Data Used to Estimate Built-Up Area, Blue Cover, and Vegetation Change Trend**

	STUDY YEAR/ PERIOD	DATA ANALYZED	DATA SETS USED		DETAILS IN
			DIRECTLY FOR ANALYSIS	TO DEMONSTRATE OTHER FEATURES	
Built-Up Area	2000, 2015	Settlement layer, Population	European Commission–Joint Research Center (EC-JRC) Global Human Settlements Layer, Built-up Grid	EC-JRC Global Surface Water Mapping Layers, v1.0 (maximum blue cover extents between 1984 and 2017)	Appendic C
Blue Cover	Epochs of 1998-2002 and 2013-2017	Modified Normalized Difference Water Index (MNDWI)	United States Geological Sur-vey (USGS) Land-sat 5[a] Thematic Mapper Collec-tion 1 Tier 1 Top of Atmosphere Reflectance USGS Landsat 8[b] Collection 1 Tier 1 Top of Atmosphere Reflectance		Appendic D
Vegetation Change Trend	1997–2017	Normalized Dif-ference Vegeta-tion Index (NDVI) trend analysis	USGS Landsat 5, 7, 8 Thematic Mapper Collection 1 Tier 1 32-Day NDVI Composite (1986– 2012) USGS Landsat 5 Thematic Mapper Collection 1 Tier 1 Top of Atmo-sphere Reflectance	EC-JRC Global Surface Water Mapping Layers, v1.0 (maximum blue cover extents between 1984 and 2017)	Appendic E

Notes:
[a] Landsat 5 gives imagery from 1984 to 2012.
[b] Landsat 8 gives imagery from 2013 to 2017.

City Selection

The study cities are Ahmedabad, Bengaluru, Chennai, Delhi, Hyderabad, Jaipur, Kolkata, Mumbai, Pune, and Surat (see Appendices A and B). These cities were selected as they are the 10 most populous cities in India and housed about a third of India's urban population in 2015. These cities also show significant changes in urban built-up area, offering an opportunity to understand the overall impacts of an increasing urban footprint on natural infrastructure across core and peripheral urban regions.

Data Sources

Open-source satellite imagery is analyzed to estimate the changes in the spatial extents of built-up area, blue cover, and green (vegetation) cover for the study years (2000–2015). The data from these layers in conjunction with digital elevation models (DEMs) are used to arrive at the groundwater recharge potential for the study cities.

Table 1 highlights the datasets used, their sources, and the analyses performed in this study. The detailed approach and methodology used to generate maps and derive statistics are presented in Appendices A–G.

Satellite Imagery and Remote Sensing Processes

We chose two study years, 2000 and 2015, for the various themes, primarily using imagery from the Landsat satellites (5 and 8). This was to maintain consistency across available data for all the 10 study cities so that the aggregate impacts could be assessed. The assessment of satellite imagery from two specific years (2000 and 2015) is applicable to built-up area. For blue cover and the vegetation change trend, the method is slightly altered to account for seasonal and annual variations that can occur due to extreme rainfall or drought conditions in specific years. The Landsat 5 satellite images are available from 1984, and the maximum water extents recorded between 1984 and 2017 are used to delineate the maximum blue cover/ water body outline (Pekel et al. 2016). Changes to blue cover are analyzed for two study epochs: 1998–2002 and 2013–2017 (Appendix D). Urban blue cover such as lakes, streams, and wetlands may possibly have had larger extents in years prior to the availability of remotely sensed data (i.e., 1984). These details may be mentioned in the literature and official records (e.g., in Survey of India maps and revenue records) but are not used for spatial analysis here.

The changes in built-up area, blue cover, green cover, and groundwater recharge potential are analyzed in two spatial intervals (0–20 and 20–50 km) from the city core[7] for each of the study cities. Studies on metropolitan urbanization and suburbanization in India indicate that areas of up to a 50 km distance from the urban core are experiencing a boom in various sectors such as manufacturing and real estate; development of new towns with high populations; and an increase in employment opportunities (World Bank 2013). The use of these spatial intervals helps assess how blue and permeable open spaces are distributed between the core-city and peripheral areas[8] and whether blue-green spaces in core-city and peripheral areas are differentially impacted by changes in the urban built-up footprint.

Study Limitations

- **Boundary variations between administrative (official) records and spatial mapping:** The extent of blue cover and vegetated areas estimated using satellite imagery may not coincide with the extents described in official documents such as revenue maps. Such variations are possible as official maps typically delineate only administrative boundaries and not the hydrological extents of a water body. This study uses satellite-observed data between 1984 and 2017 to conduct all the spatial analysis. Google Earth imagery and Survey of India maps are used in images to visually represent some of the findings.

- **Demarcating the study area as core and periphery instead of using municipal boundaries:** The municipal boundary for all the study cities has been modified in the study period. Therefore, to ensure data consistency over the assessment years, we chose 0–20 and 20–50 km spatial intervals to define the study zones.

- **Consistency of satellite imagery:** Satellite imagery is available for almost 50 years starting in the 1970s, but the quality of this data varies across the 10 study cities.[9] To ensure consistency across images, we used only Landsat 5 and 8 imagery.

- **Accounting for seasonal/annual variations:** Blue cover and green cover are affected by the annual rainfall, and analysis of images from a low rainfall year might skew statistics to indicate a smaller area of blue cover and vegetation change. To account for anomalous years with rainfall deviations or high cloud cover, for blue cover change this study analyzed satellite imagery for epochs[10] instead of for a single year. For vegetation change, the timeline 1997–2017 was considered to establish the trend across the study area.[11]

- **Urban flooding:** We do not explore the issue of urban flooding in depth in this paper as it depends on a range of factors (rainfall volume, duration, subsurface drainage networks) that have not been modeled for this study.

- **Tracing concurrent changes and correlations between aggregated built-up area and natural infrastructure without describing causal relations:** Observation of spatial imagery offers insights into the distribution of the built environment and the impacts on natural infrastructure, such as conversion of open spaces to roads, housing layouts, and business districts and encroachment of water bodies. This study looks at the aggregated values for built-up area and natural infrastructure in the two study periods of 2000 and 2015. Hence, the analysis does not track development and the loss of blue-green infrastructure on small spatial and temporal scales, which could give more insight into cause-effect relationships. Other factors such as agricultural activity and climate change act in conjunction with development to also impact the natural infrastructure in urban areas. Recognizing the complexity of the influencing factors, we do not describe a causal relationship between urbanization (change in built-up area) and natural infrastructure (see Box 1).

Box 1 | **Various Types of Water Loss Seen in Satellite Imagery**

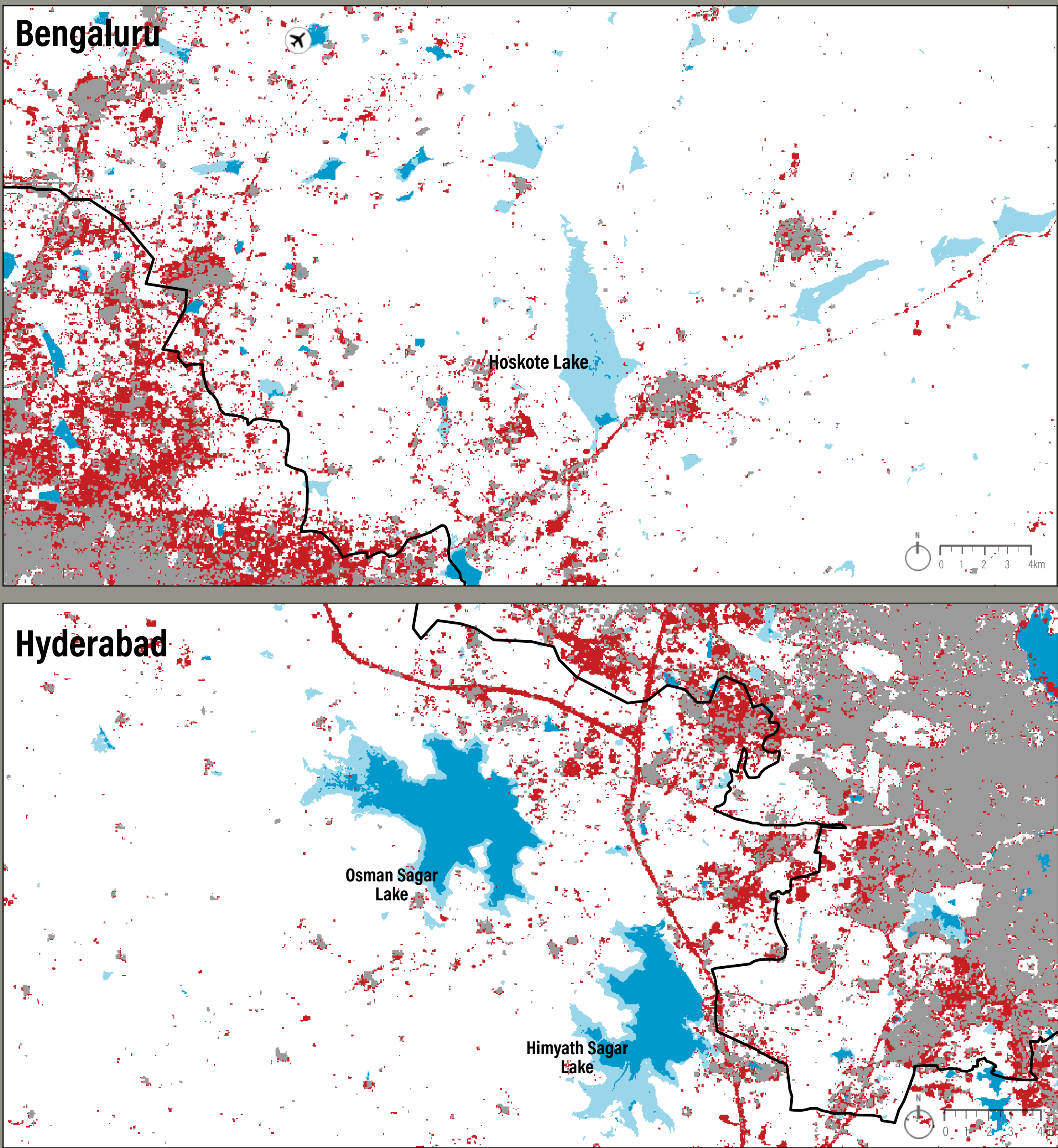
Changes visible in satellite images are insufficient to establish a causal relation between built-up area and natural infrastructure changes. When pixels identified as blue cover are converted to developed land, the causal link is clear; however, when such pixels disappear in an area but are not converted directly into built-up area, a clear causal link cannot be established. Consider the case of the following water bodies to illustrate the two ways that decrease in blue cover is visualized. In the case of the Kamuni Cheruvu and Chinna Maisamma Cheruvu lakes in Hyderabad, comparing historical satellite images (2000 and 2015) shows that the built-up area has encroached onto the lakes, directly reducing the extent of the water body (Figure B1.1). In contrast, the extents of many other water bodies have decreased without any corresponding increase in the built-up area in the vicinity (Figure B1.2).

Figure B1.1. | **Satellite Images Showing Significant Encroachment of Lake Extents and Valley Space in Kamuni Cheruvu and Chinna Maisamma Cheruvu (North-West) Hyderabad between 2003 and 2020**

Sources: Survey of India 1978b; Base Maps: Google Earth Pro 2003; Google Earth Engine 2021.

The extent of the Hoskote lake in peri-urban Bengaluru has decreased by about 97 percent between 2000 and 2015. Similarly, extents of the Himayat Sagar and Osman Sagar in Hyderabad have decreased by 44 percent and 31 percent, respectively. An increase in the built-up area in these regions has not replaced the blue cover, making it difficult to establish if an increase in the urban area has caused the loss of blue cover. Land use change (from natural landscape to agriculture), climate change, and overexploited groundwater aquifers offer alternative explanations for these decreases.[a]

Figure B1.2. | **Hoskote Lake (North Bengaluru) and Osman and Himayat Sagar Reservoirs (Southwest Hyderabad) Show a Decrease in Surface Water Extents between 2000 and 2015 Despite No Increase in Built-Up Area in the Immediate Surroundings**



- Built-Up Area 2000
- Built-Up Area added by 2015
- Maximum Surface Water Extent in 1998 - 2002
- Maximum Surface Water Extent in 2013 - 2017
- Municipal Boundary

Notes: Light blue areas show where the water extents have decreased.
Sources: Built-up area- European Commission 2016; Maximum surface water- EC-JRC/Google n.d.

Sources: a. USGS 2003; Zhu et al. 2015.

URBAN DEVELOPMENT AND NATURAL INFRASTRUCTURE CHANGE

In this section, we present the findings, discuss interpretations, and offer inferences regarding changes to built-up area, blue cover, and vegetation change. The study also detects the change in the groundwater recharge potential for the urban region and estimates the lost volume of recharge due to the new developments added between 2000 and 2015.

A. Change in Urban Built-Up Area

The urban footprint across all the 10 study cities expanded rapidly between 2000 and 2015, with much of the urban expansion occurring beyond the municipal boundaries. Most cities expanded their municipal boundaries in the mid-2000s, despite which development continued to occur beyond the officially designated urban zone. A multiplicity of challenges emerged due to this pattern of urban growth, not least the gaps in urban service delivery (water supply, sanitation, waste management), especially in the peripheral areas of these cities.

Findings

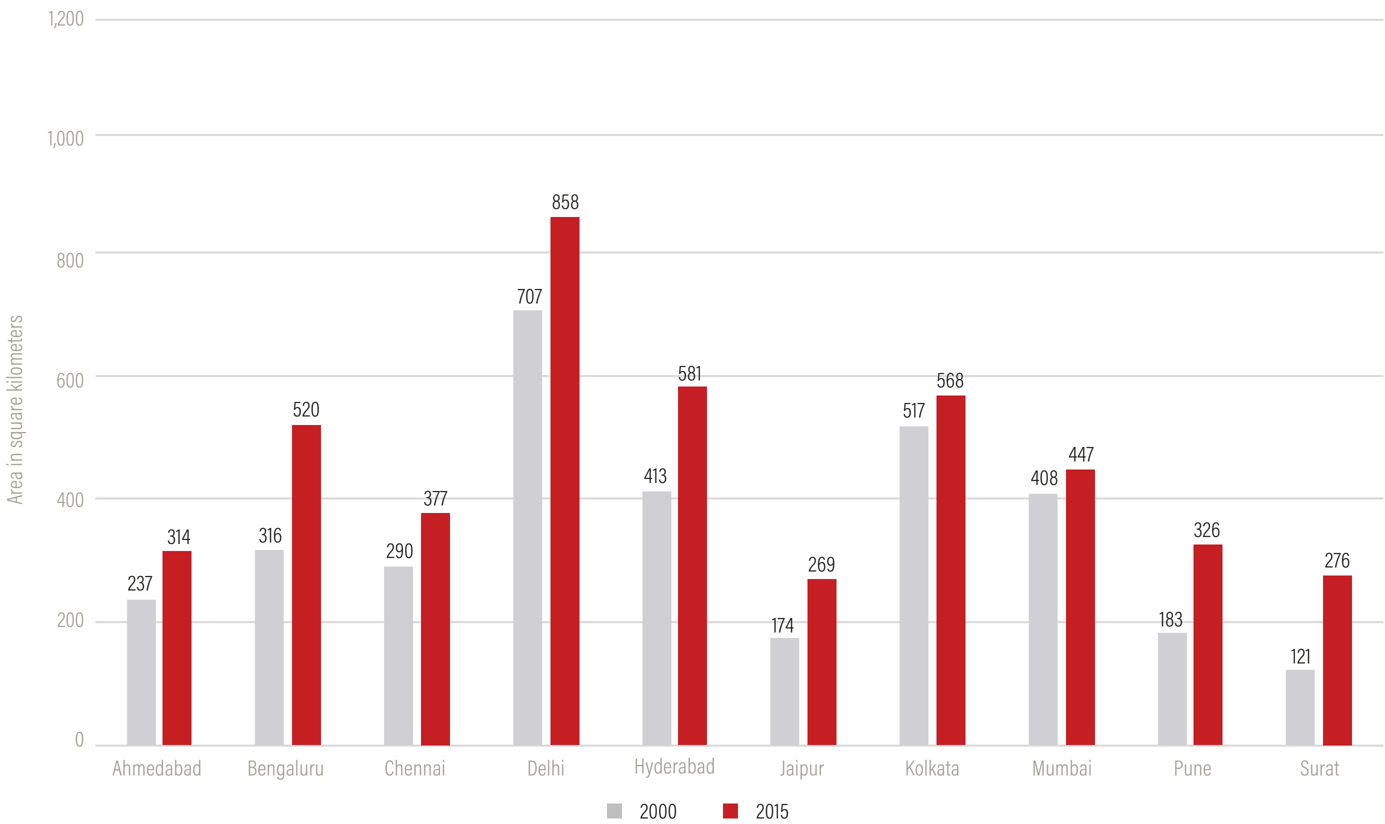
The built-up area increased across all 10 cities (Figure 1), with about 2,700 sq. km of new developed land added in the 0–50 km region between 2000 and 2015 for all 10 cities. The graphs in Figures 1 and 3 represent the built-up area (horizontal expansion) in square kilometers in the 0–20 km and 20–50 km spatial intervals for the years 2000 and 2015.

Discussion

Peripheral areas (20–50 km region) accounted for a higher percentage of change in built-up area, with the increases ranging from 30 percent in Kolkata to 412 percent in Pune. The core-city area described as the 0–20 km region experienced in excess of 50 percent growth only in Jaipur, Bengaluru, Pune, and Surat. Across all the 10 study cities, 43 percent of the new built-up area is located in the core-city regions compared to 57 percent in the peripheral areas, indicating the primacy of growth in the peripheries.

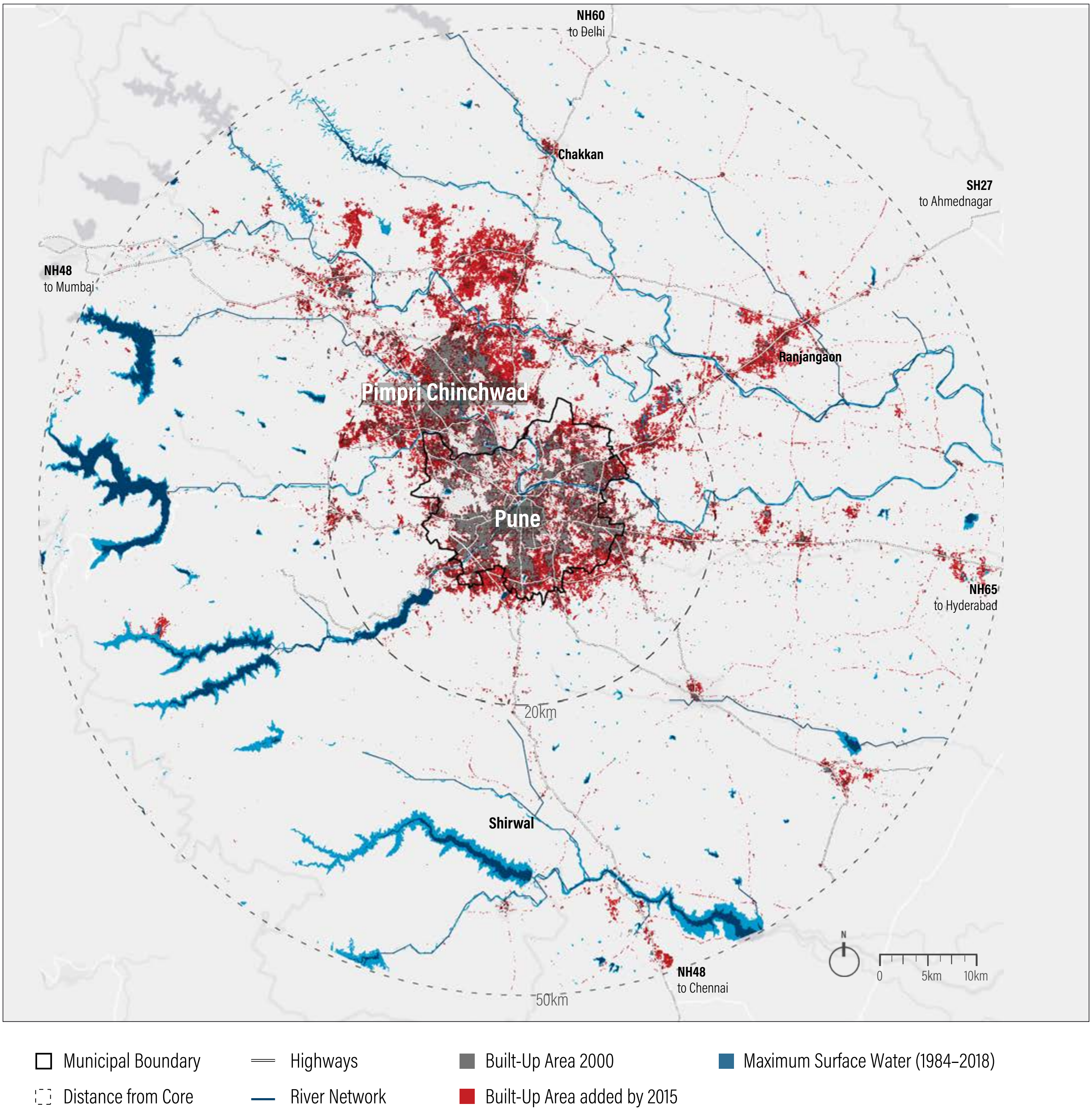
Note that the percentage increase indicates only the change relative to the original value. For example, Pune is one of the cities with the highest percentage increases: a 78 percent increase in the 0–20 km region with 143 sq. km

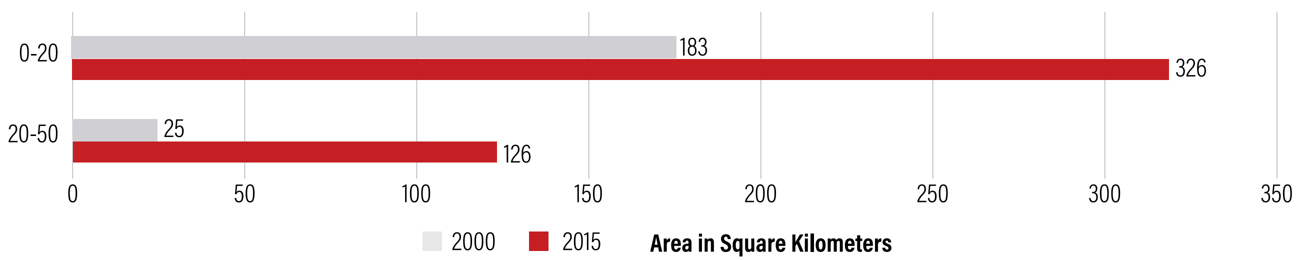
Figure 1 | **Built-Up Area Has Increased in All the Study Cities between the Years 2000 and 2015 in the 0-20 km Region**



Notes: Built-up area has increased in all the study cities between 2000 and 2015 in the 0–20 km region.
Source: WRI authors

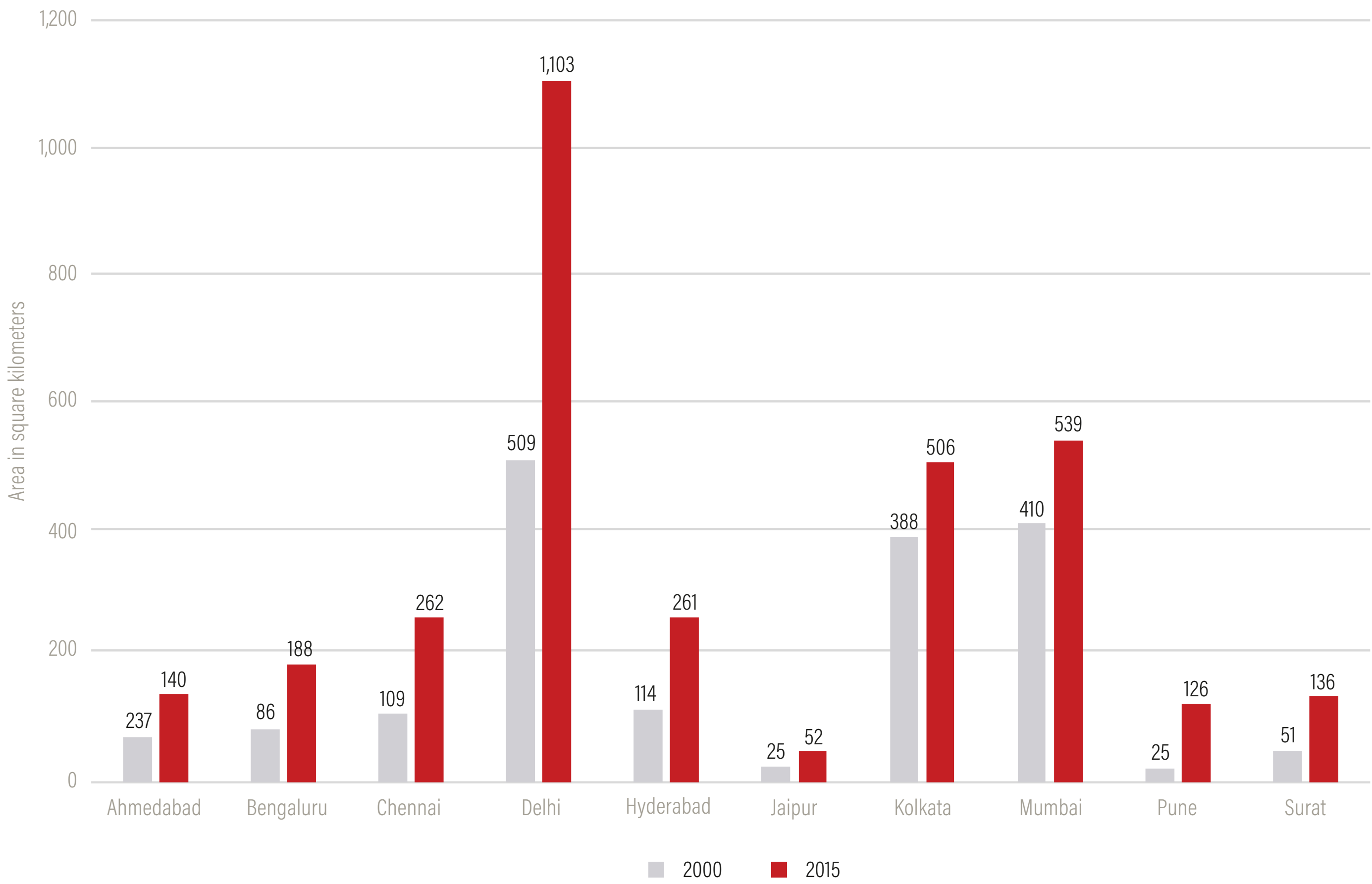
Figure 2 | **Built-Up Area in Pune Has Expanded Significantly beyond the Municipal Boundary between 2000 and 2015**





Notes: Much of the development has expanded toward the north and east of the city along roadways.
Sources: Built-up area – European Commission 2016; Maximum Surface Water –- EC-JRC/Google n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

Figure 3 | **Built-Up Area Has Increased Significantly in All the Study Cities between the Years 2000 and 2015 in the 20–50 km Region**



Source: WRI authors

and a 412 percent increase in the 20–50 km region, with 101 sq. km added between 2000 and 2015 (Figure 2). The percentage change in the periphery is quite high because Pune had very little built-up area in the periphery in 2000.

Inference

The urban footprint has expanded in both the core-city and peripheral areas. The increase in the built-up area in the 0–20 km region in Delhi, Mumbai, and Kolkata is less than 30 percent. Factors responsible for this low change could be already densely developed areas (Mumbai); regulations restricting urban development (Delhi/New Delhi Municipal Council); physical constraints on urban expansion; sluggish real estate sector due to restrictive policies or high land prices; and challenges to land acquisition. For all 10 cities there is a higher percentage increase in the built-up area in peripheral regions (85 percent) in comparison with the core areas (35 percent). Given fewer restrictions on development in peripheral areas, entities (government and private) could choose to develop any land, but the trend in most cities is to occupy natural infrastructure spaces such as lake beds and wetlands owing to the weak enforcement of environmental regulations (Kundu 2003) in these regions.

B. Blue Cover Change

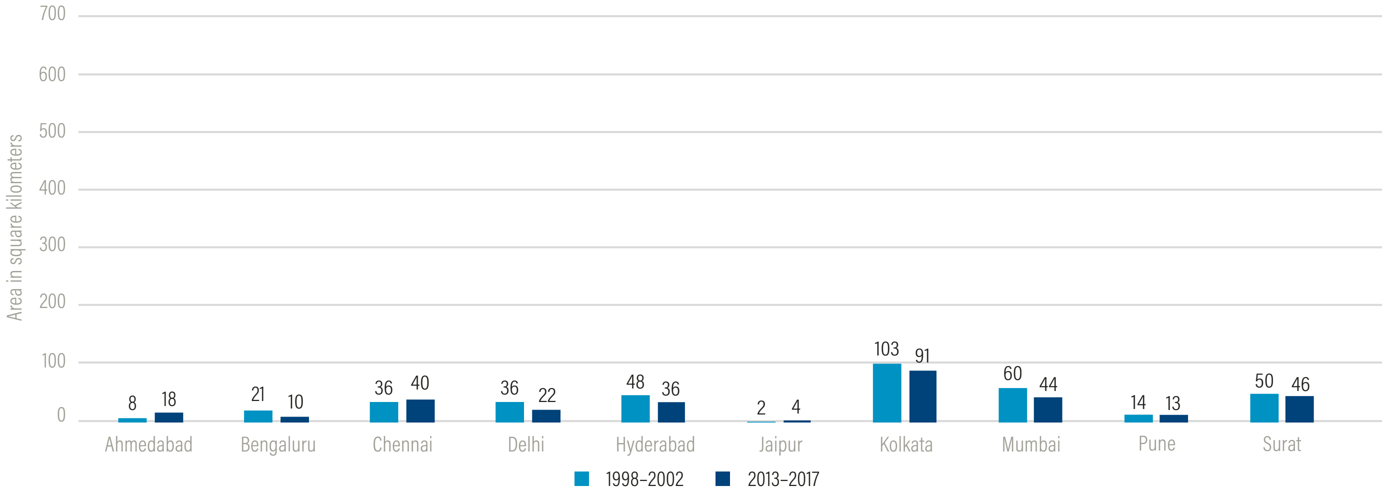
Urbanization is seen as one of the key modifiers of blue cover, which is significantly impacted as observed in the 10 study cities. The replacement of natural surfaces, water bodies, agricultural lands, vegetation, and forested lands with built-up area such as buildings, pavements, and roads alters the hydrological characteristics of urban areas, leading to changes in stormwater runoff, evapotranspiration, and infiltration (Whitford et al. 2001) and reduces local water (both surface water and groundwater) availability.

Findings

In Figures 4 and 5, the amount of blue cover in the two study epochs (1998–2002 and 2013–2017) in the 10 study cities is shown in square kilometers for the 0–20 and 20–50 km study regions, respectively.

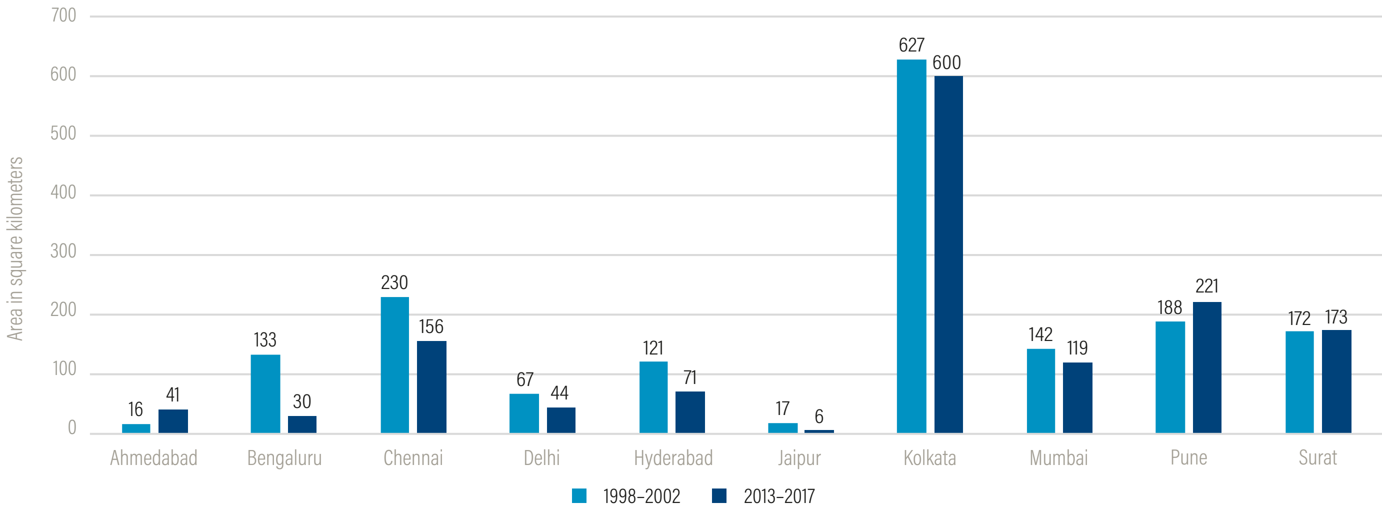
Ahmedabad is the only city that shows an increase in blue cover in both the 0–20 km and 20–50 km regions for the study period: 125 percent (10 sq. km added) and 150 percent (25 sq. km added) increases in the 0–20 and 20–50 km regions, respectively (see Box 2).

Figure 4 | **Blue Cover has Decreased in 7 of the 10 Study Cities in the 0–20 km Region**



Notes: Blue cover in the 0–20 km region has decreased in all cities except in Ahmedabad, Chennai, and Jaipur.
Sources: WRI authors.

Figure 5 | **Blue Cover Has Decreased in 7 of the 10 Study Cities the 20–50 km Region**



Notes: Ahmedabad and Pune are the only cities showing a significant increase in blue cover in the 20–50 km region.
Sources: WRI authors.

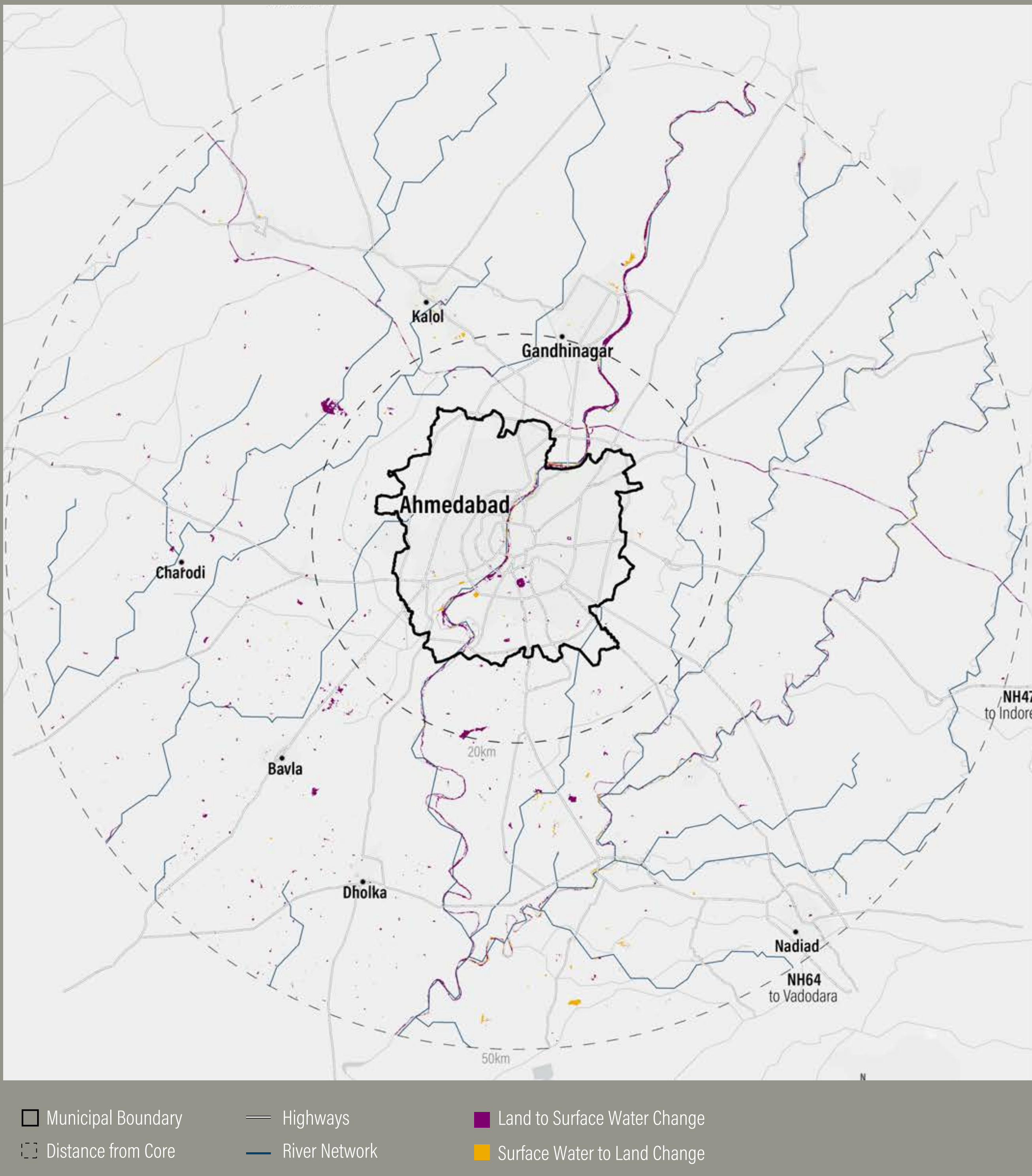
Box 2 | **Ahmedabad's Blue Cover Anomaly**

The loss of water bodies such as lakes and ponds has been a consistent trend in Ahmedabad, despite judicial judgments,[a] citizen advocacy, and activism supporting the protection and rejuvenation of water bodies.[b] Thus, the aggregate increase in blue cover in Ahmedabad needs to be examined in depth.

Analyzing the spatial distribution of the blue cover increase in Ahmedabad indicates that the Sabarmati Riverfront and the Narmada Main Canal are the primary areas detected as blue cover (Figure B2.1). The river and canal together account for around 60 percent and 88 percent of the blue cover identified in the 0–20 and 20–50 km regions, respectively.

The gain seen in the study period is therefore primarily due to the Sabarmati River and the canal network. In purely numerical terms, Ahmedabad's increase in blue cover would be considered a benefit, but satellite images enable us to identify the spatial distribution of the changes. The blue cover improvement in Ahmedabad is spatially contained, and the co-benefits accruing from this improvement (groundwater recharge, microclimate benefits) are not distributed across the city. Thus, although in aggregate Ahmedabad performs better than the other study cities, the blue cover increase is unlikely to have citywide impacts.

Figure B2.1. | **High Conversion of Land to Surface Water (Blue Cover Increase) in Ahmedabad (Gujarat) between the Two Study Epochs (1998–2003 and 2013–2017)**



Notes: Much of the blue cover increase is localized to the length of the Sabarmati River and the Narmada Canal.
Sources: Surface Water Extent – USGS n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia .

Sources: a. Shailesh R. Shah vs. State of Gujarat 2002. b. Desai 2020; DNA 2014; Parmar 2021.

Discussion

Considering all 10 cities, the total area of blue cover lost in the 0–50 km region is about 307 sq. km, which is equivalent to the size of almost 43,000 football fields. A reservoir of this area (307 sq. km) assumed to have a uniform depth of 3 m (MoEF 2008) could have stored almost 900 billion liters[12] of water, a valuable and limited resource that is now lost to these cities. Bengaluru has the highest proportion of blue cover loss, with a 74 percent decrease seen between the two study epochs (see Figure 6).

The population of the 10 cities increased by almost 39 million between 2000 and 2015 in the 0–50 km region. The 900 billion liters lost due to the loss of blue cover could potentially have met about 60 percent of the additional water demand[13] of this added urban population.

Changes to surface water extents have been derived in other research projects using tools such as the Deltares Aqua Monitor, which indicates changes in surface water by categorizing pixels as water converted to land surface or vice versa (Donchyts et al. 2016). Further, the tool uses globally applicable calibration methods, which may not account for certain unique local characteristics. We use a similar methodological approach, but account for local variations (for example, the presence of temporary blue cover such as flooded fields is discounted as it can be considered a water use and not a water resource) to arrive at the final estimate of blue cover change for the 10 study cities.

Blue cover reduction is observed (in eight of the study cities in the 0–50 km region) due to either a decrease in the extent of water in the water body between the two study epochs; encroachment (formal or informal developments) into the water body as delineated by the observed maximum extents; or full encroachment of the water body (no water is seen in recent satellite imagery). (see Box 3)

Inference

The changes (reduction) to blue cover could be attributed to a combination of the following four causes.

- Climate change induced variability in rainfall (Kulkarni et al. 2020)
- Overextraction of groundwater near blue cover areas (near lakes and streams) (USGS 2003)
- Imposition of a hydraulic barrier (built-up area) impacting natural hydrological flows (infiltration and runoff) (Frazer 2005)
- Direct encroachment of flood plains and lake beds for construction activity (Sridhar and Sathyanathan 2020)

Box 3 | Detailed Look at Blue Cover Change in Select Cities and Locations

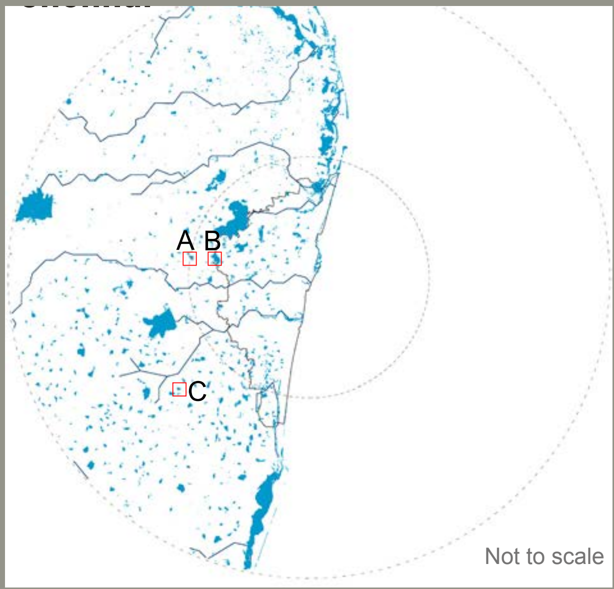
A detailed micro-level study in Chennai and Hyderabad (see Figure B3.1) indicates the loss of blue cover in 2020 (compared to the lake extents as described in Survey of India maps from the 1970s). These water bodies are seen to be partially or completely encroached upon in 2020.

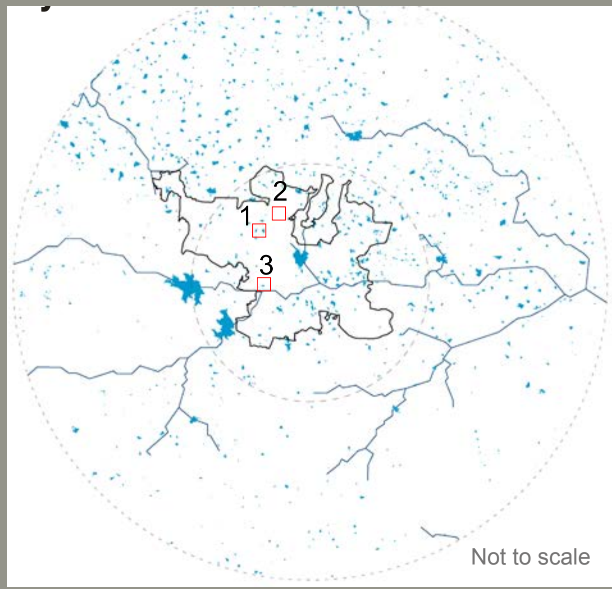
A direct consequence of the replacement of such natural infrastructure with built-up area such as roads and buildings is the increased risk of flooding in these spaces. As lakes form naturally in low-lying areas and natural depressions, the gradient of the land continues to drain stormwater into these locations, and new developments face the risk of flooding. We do not explore the issue of flooding in depth, as it is dependent on a range of other factors (rainfall volume, duration, subsurface drainage networks), but a correlation has been found between the loss of blue cover and increased incidence of flood events.[a]

This loss of blue cover is not a recent phenomenon, and case examples from the 1990s (with remote sensing evidence) and earlier (literary documentation) indicate that lake areas have been constantly encroached upon and converted into developed land until only neighborhood names preserve the memory of the former water body.[b]

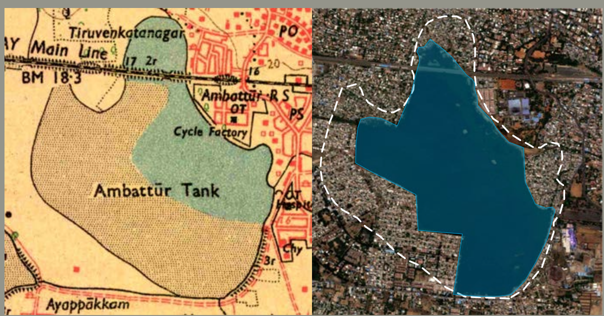
Policies for the protection of water bodies have to be enacted at the state level and implemented locally by the local urban authorities.[c] Existing national programs for the protection of urban water bodies, such as the National Plan for Conservation of Aquatic Ecosystems,[d] are ineffective as cities may be unable to implement them. Some of the study cities restrict development in buffer zones around water bodies. These areas are standard measurements for categories and do not respond to the unique size and characteristics of different water bodies, as seen in Hyderabad[e] or are arbitrarily and unscientifically modified by government authorities, as done in Chennai.[f] Finally, alongside the risk that lakes and streams face due to encroachment, the water availability and pollution levels of watersheds are impacted by changes to their hydrological flows caused by increasing urbanization.[g]

Figure B3.1. | **Decreased Lake Extents in Chennai and Hyderabad since 1975 Due to Conversion to Built-Up Areas**



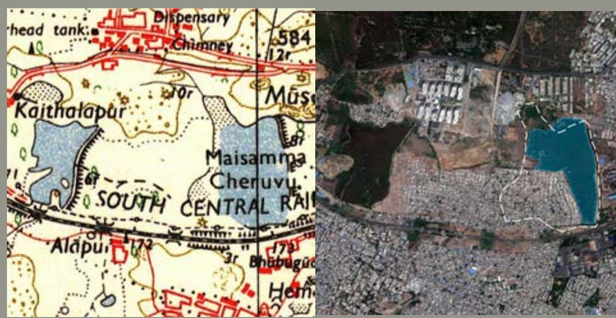


A- Kolathur Lake

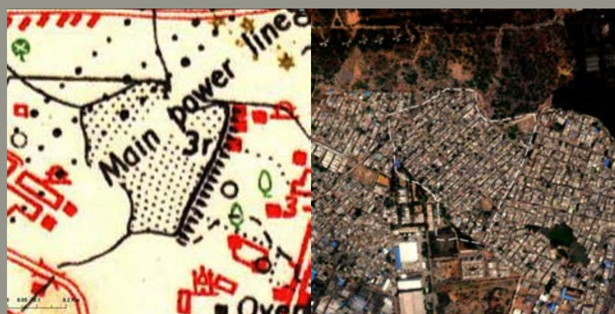


B- Ambattur Lake

C- Konnur Lake



1- Chinna Maisamma Lake



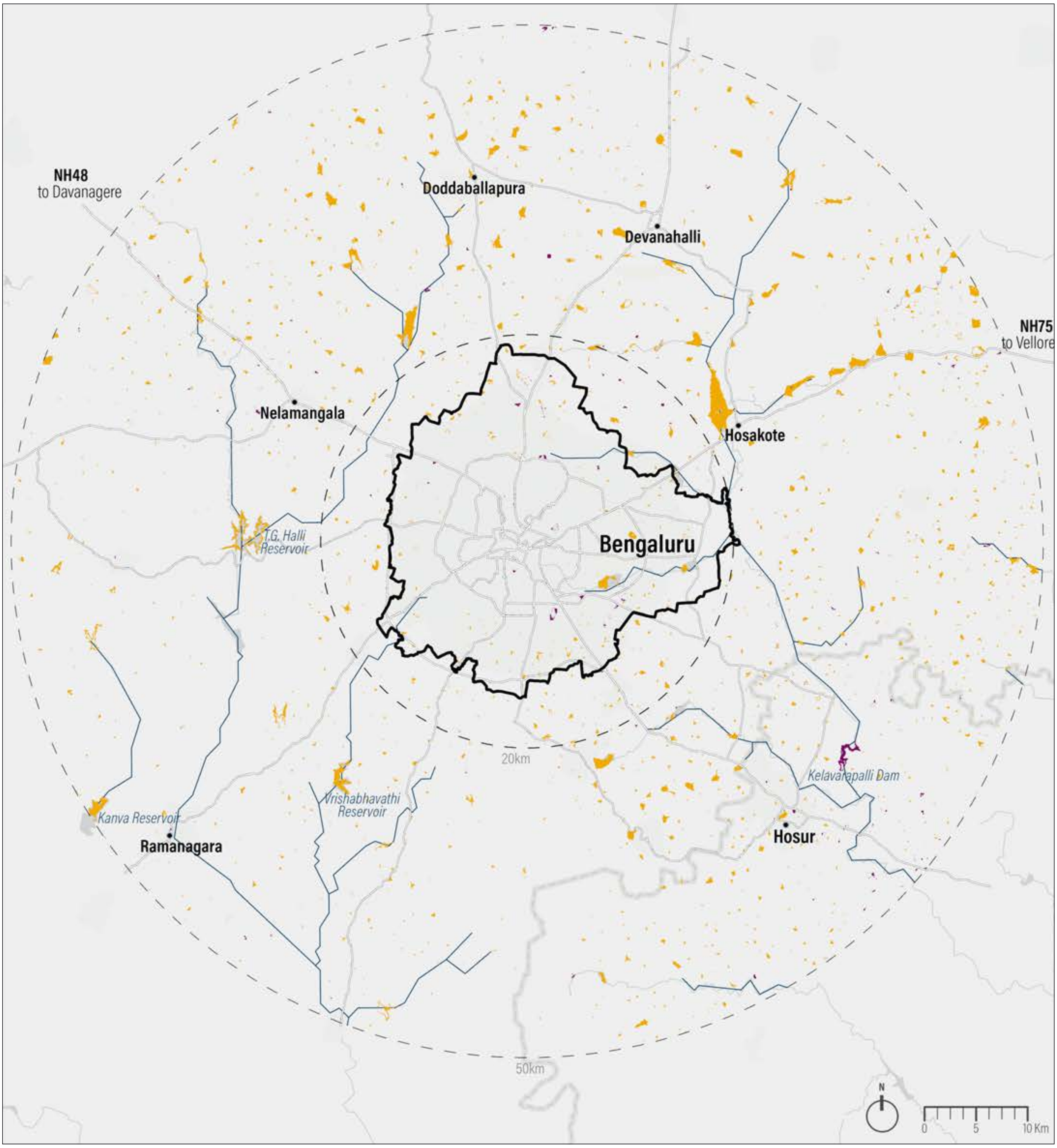
2- Lake Nr MHT Colony

3- Shah Hatim Talab

Notes: The comparisons are based on lake extents as described in Survey of India maps from 1975 and 1976.
Sources: Survey of India 1975a, 1975b, 1976a, 1976b; Google Earth Engine 2021.

Sources: a. Ramachandraiah 2008. b. Ramachandraiah and Prasad 2004, 16. c. Center for Science and Environment 2013. d. MoEFCC 2019. e. HMDA 2017. f. Krishna Chaitanya 2019. g. Jamwal et al. 2008.

Figure 6 | **Significant Loss of Surface Water Indicated by Conversion of Surface Water to Land in the Bengaluru Region between the Two Study Epochs (1998–2003 and 2013–2017)**



Municipal Boundary | Highways | Land to Surface Water Change
Distance from Core | River Network | Surface Water to Land Change

Notes: Only land-to-surface-water and surface-water-to-land changes are indicated in this map. Water bodies that show no change between the two study epochs are not shown here.
Sources: Surface Water Extent – USGS n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

C. Vegetation Change Trend

Undeveloped land typically has some vegetation except regions such as deserts, geological features such as massif rocky surfaces, and regions with subzero temperatures. Urban development leads to changes in the natural vegetated surface in and around cities. Vegetation change is not a linear trend (consistent reduction or consistent increase) across the entire urban region (Liu et al. 2015). Localized variations can impact the quantity and quality of green cover in urban areas, such as a shift from forest or woodlands (natural spaces) to agriculture or urbanized land. Changes in green cover have consequences for the quality and quantity of the ecosystem services provided by natural spaces. A reduction in green cover is corelated with increased stormwater runoff and flooding and reduced infiltration (Konrad 2003), along with an increase in urban heat island effects.

This study looks at the trend of vegetation change in the 10 study cities from 1997 to 2017,[14] correlating it with the transformation seen in the built-up area. The vegetation change trend map detects the change in green cover (observed as the green signature represented by the NDVI) over a period. The spatial analysis method adopted here does not directly detect individual trees and bushes or the type of green cover (farmlands, parks). Instead, only the change in the NDVI value per pixel over a period is observed. For instance a pixel with tropical forest might have an NDVI value of 0.6 to 0.8 (Weier and Herring 2000), and if the forest has been converted to urban land use, the NDVI value should drop to 0 or 0.1 (that is, a reduction of 0.5–0.8) (Ariadne Barbosa Gonçalves et al. 2018). Areas where no vegetation change (NDVI change) is detected are not captured in this analysis. Our study estimates and analyzes only areas with NDVI change to establish what type of loss or gain has occurred.

Losses and gains are classified across six categories, ranging from high loss to high gain.[15] This study looks at long-term trends (greening/browning) by collecting all Landsat images over a 20-year period for each study city and then filtering for cloud cover. Pixelwise linear regression is applied on the resultant images to look at long-term trends (see Appendix E).

Findings

The vegetation change trends in the 10 study cities between 1997 and 2017 indicate both negative and positive NDVI movement, indicating both loss and gain of green cover in the study region. The area with high gain or high loss in the NDVI change trend is very small, with about 0.2 sq. km being the change in both these categories across all the 10 cities. About 98 percent of the loss and gain is in the low-level loss and low-level gain categories. Loss and gain are unevenly distributed across the 0–20 and 20–50 km study intervals.

In the 0–20 km region for the study cities, although both loss and gain in vegetation change trend have occurred, in six cities (Bengaluru, Chennai, Delhi, Hyderabad, Jaipur, and Pune) the losses exceed the gains (see Figure 7). Across all the 10 cities, the 0–20 km region has 33 percent of the area with decreasing and 16 percent with increasing vegetation change trend.

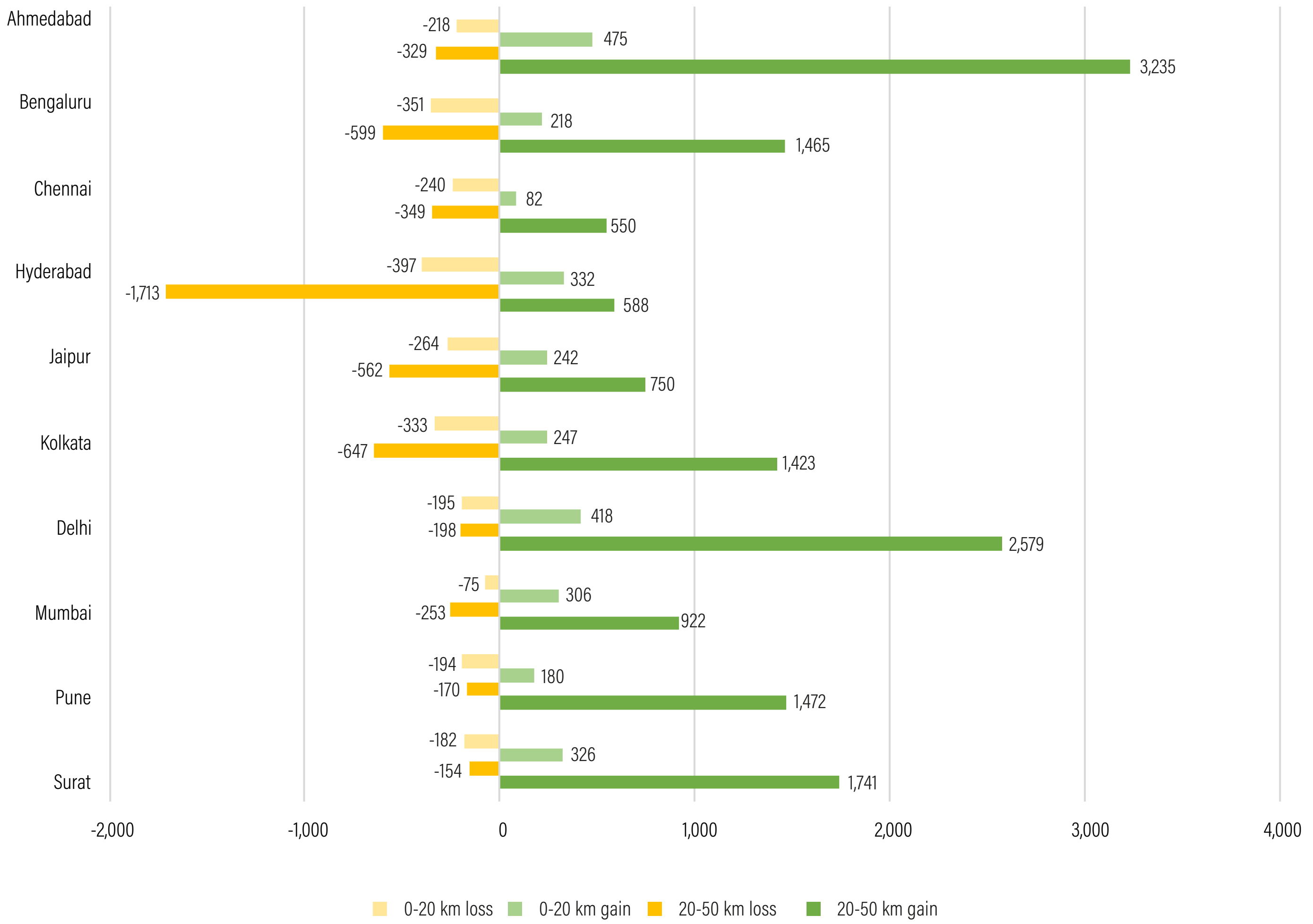
In the 20–50 km region, for all cities except for Delhi, areas with increasing vegetation change trend are more than areas with decreasing vegetation change trend (Figure 7). This finding runs counter to the stated hypothesis, as an increase in the built-up area has not led to a decline in green cover in this region. The spatial distribution of losses and gains is also higher in the 20–50 km region, with 67 percent of the decreasing and 84 percent of the increasing vegetation change trend occurring here.

Discussion

Increasing vegetation trend, indicated by an increase in the NDVI, must be very cautiously interpreted, as a range of influencing factors could be responsible. In urban and peri-urban areas, gains in green cover may indicate a shift in land use or land cover (e.g., from barren to cultivated land or from low-intensity to high-intensity farming) (see Box 4); increased water availability, year-round cultivation, and growth of trees; and due to improved urban forestry management and rooftop and individual gardens.

The low-level gain seen in the study cities could be due to a reduction in seasonal fluctuations in green cover over the study period. This study analyzes multiple images of each city over a 20-year period to derive the NDVI trend. A reduction in seasonal fluctuations (as seen in the early years of the study) to almost constant year-round green cover (in later years) indicates an increase in the NDVI. Seasonal fluctuations in green cover occur due to natural or managed water availability (rainfall or irrigation) and temperature changes throughout the year (Li et al. 2017). Seasonal variations may be disrupted if water becomes available for longer

Figure 7 | **Vegetation Change Trend between 1997 and 2017 for the 10 Study Cities**



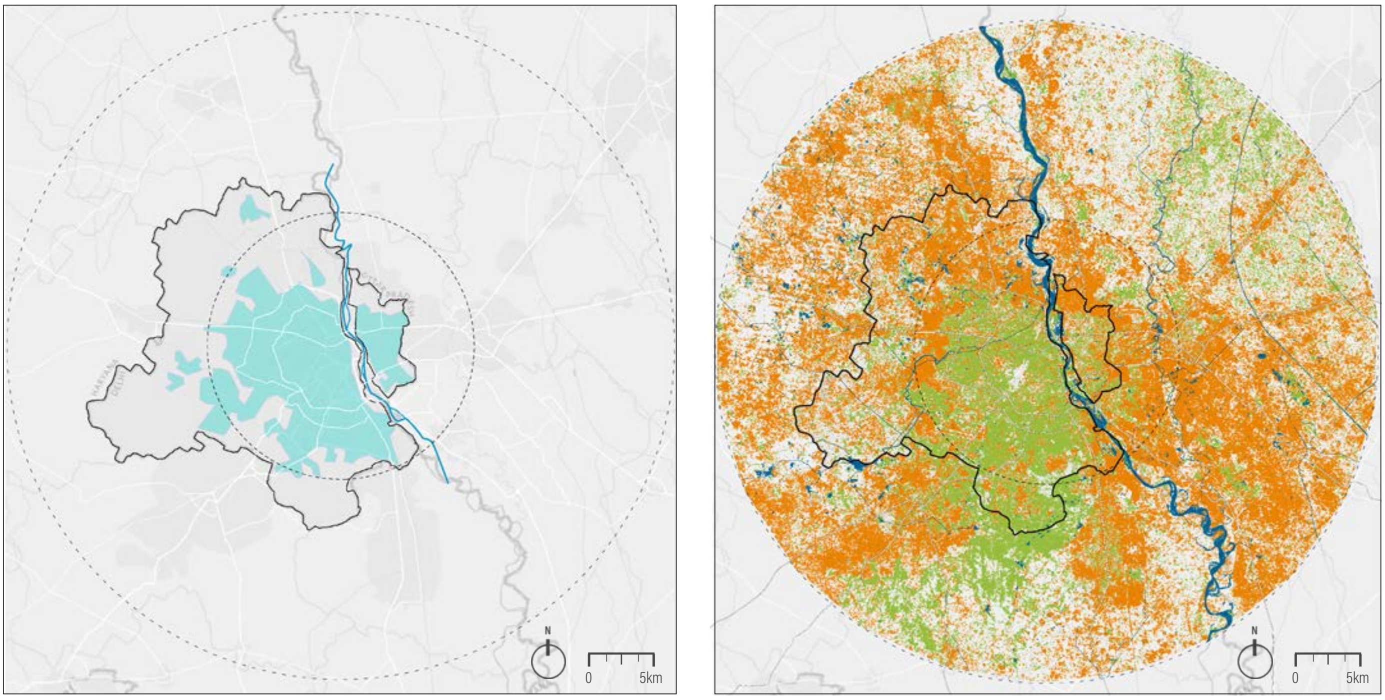
Notes: All figures are in square kilometers. All cities except Delhi show significant areas with an increasing vegetation trend in the 20-50 km region.
Sources: WRI authors.

periods or throughout the year because of irrigation practices (Johnson and Belitz 2012), other human actions (leakages from piped networks), or climatic factors (increased rainfall).

In the 0–20 km region of the study cities, the low-level increase in the NDVI indicates that green cover gains are distributed across core-city areas (on public properties and roads and private developments) and are not confined to locations such as parks or other designated green spaces.

This observation could be attributed to the increased and year-round water supply in core-city areas due to improved water supply, which reduces seasonal variations. Leakages from underground water supply and sewerage networks and increasing unsewered discharge of urban wastewater could also have contributed to the increase in green cover. Core-city areas are typically better serviced in terms of underground piped networks for both water supply and sewerage services, but these networks are also older and leak considerably, as evidenced by reports of unaccounted water (Shah 2016). This hypothesis is reinforced by a study of the available maps and visualizations of the underground water supply and sewerage networks in Delhi (see Figure 8). The improved water supply also encourages localized gardening efforts within private property, which is likely to flourish throughout the year.

Figure 8 | **Alignment between Areas of Green Cover Gain in Delhi and the Extents of the Sewerage Network**



Sources: Gosain 2014; Vegetation Trend - NASA n.d.; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

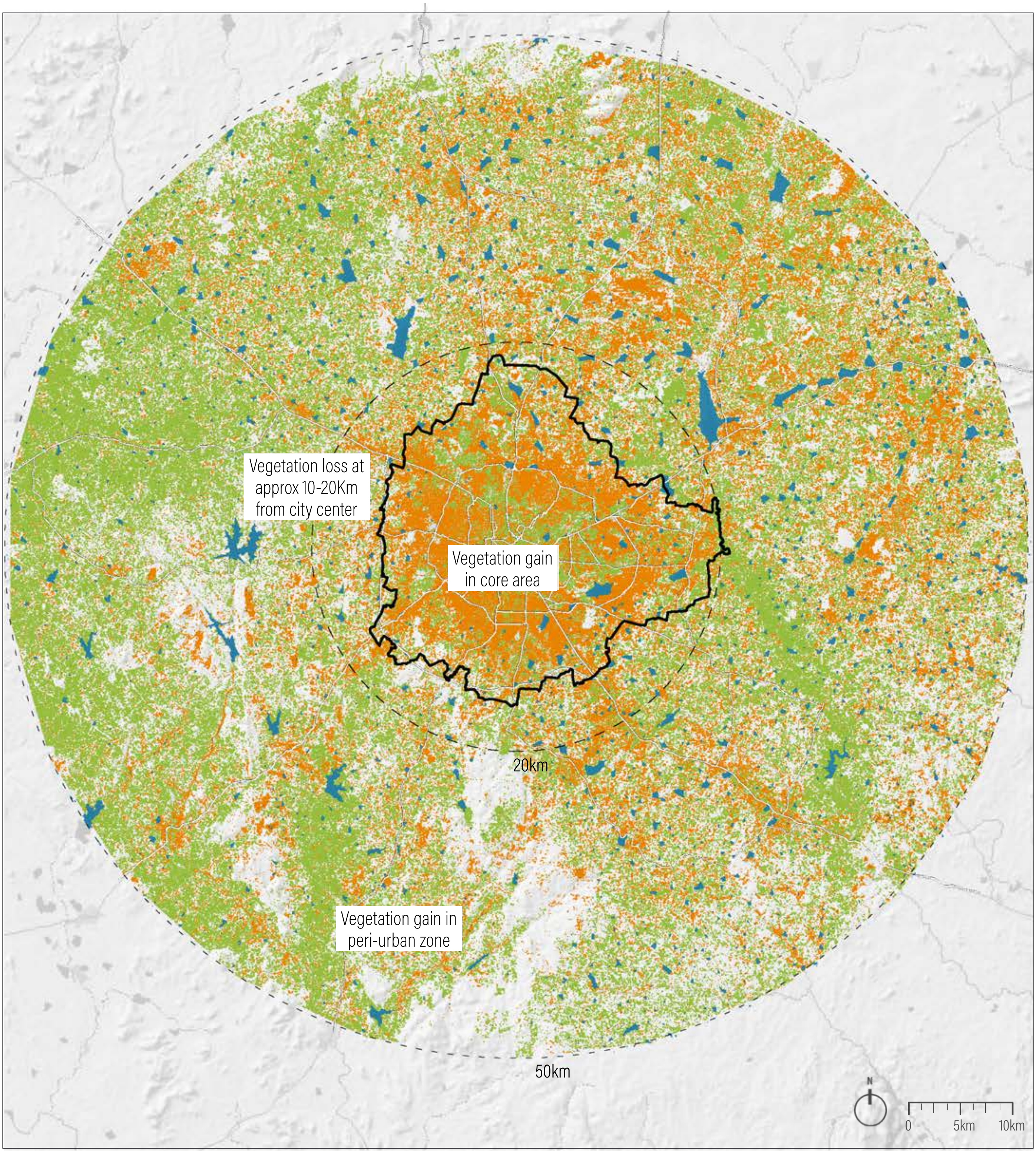
Inference

Although each study city has unique local characteristics, some commonalities are observed in the spatial distribution of vegetation change. Increasing green cover trends are seen to be most widespread in the core inner city area and in peri-urban areas (near the 50 km boundary). Increasing green cover trend dominate in the areas that are close to either the 20 km boundary or to the municipal boundary of each city (see Figure 9). Mumbai is the exception, with low-level green cover gain distributed almost evenly across the city within the municipal boundary.

Decreasing green cover trend is greatest in the peripheral areas of the city near the municipal boundary and the 20 km boundary; the core inner city and peri-urban areas experienced increasing green cover trend. The green cover loss, indicated by NDVI reduction, is found to spatially corelate with development and infrastructure activities, with low to moderate loss noted along road expansions, airport complexes, industrial clusters, ports, and other urban developments (see Figure 10). Also see Appendix L.

The low-level green cover gains observed could be due to the individual factors mentioned above or a combination of them. This study uses only remotely sensed data to understand the changes in green cover over the study period. This method does not distinguish the details of whether an increase in vegetation cover is due to an actual increase in tree cover, reduced seasonality of green cover, or increased agricultural activities. Similarly, the drivers of the green cover increase, whether due to increased piped water supply, access to groundwater, or increased rainfall, cannot be individually identified with this method. There is scope for future research to develop a detailed assessment of urban green cover combining remote sensing and on-ground validation, which can offer greater insights and lead to good practices. In this study, only a few possible reasons for the low-level gains have been explored.

Figure 9 | **Vegetation Change Trend in Bengaluru Indicates Losses Clustered at the Municipal Boundary and in the Northeast of the Study Region**



Municipal Boundary | Distance from core

Maximum Surface Water (1984–2018) | **Vegetation Trend:** Loss | Gain

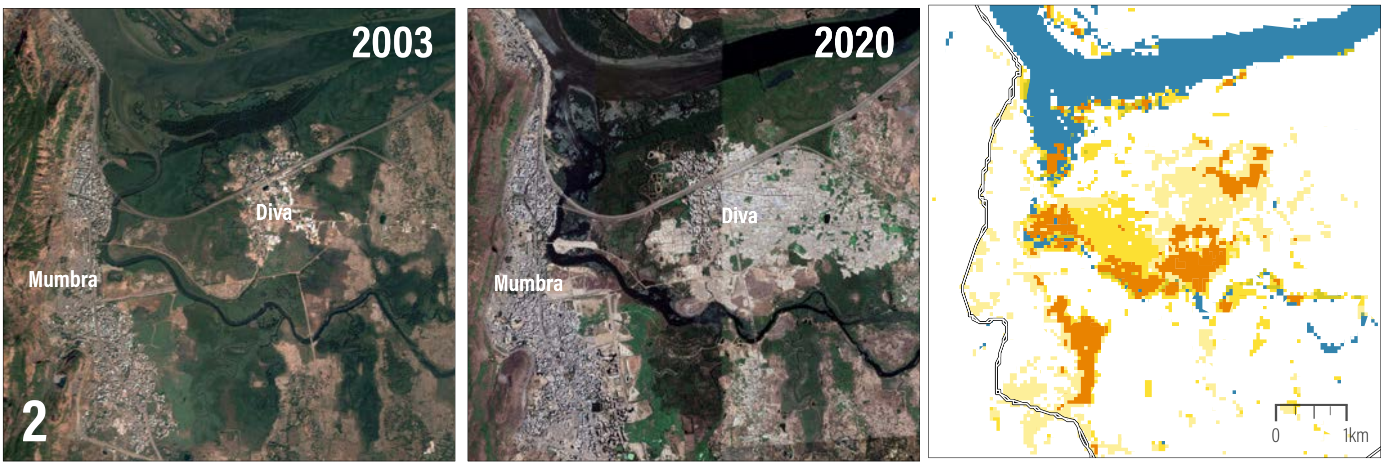
Notes: Gains are seen in core central areas of Bengaluru and in the 20–50 km peripheral region; significant loss has occurred near the municipal boundary. This vegetation change trend is similar in all the study cities except Delhi. Only vegetation change trend of loss or gain is indicated here; areas where changes are not detected are in white.

Sources: Vegetation Trend - NASA n.d.; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

Figure 10 | **Maps Showing Thematic Overlays for Mumbai in 1997-2017, Connecting Various Urban Activities to Changes in Green Cover**

Municipal Boundary
Distance from core
Highways
Built-Up Area
Maximum Surface Water (1984–2018)
Vegetation Loss Low Loss Moderate Loss High Loss

1. CST Airport has expanded operations that has led to incremental loss in vegetation.



2. High vegetation loss trend seen in Karipada Mangroves due to urban expansion of Mumbra and Diva.

3. Stone crushing quarry operating outside municipal limits has led to vegetation loss in Padeghar, Panvel

Sources: Built-up area - European Commission 2016; Vegetation Trend - NASA n.d.; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

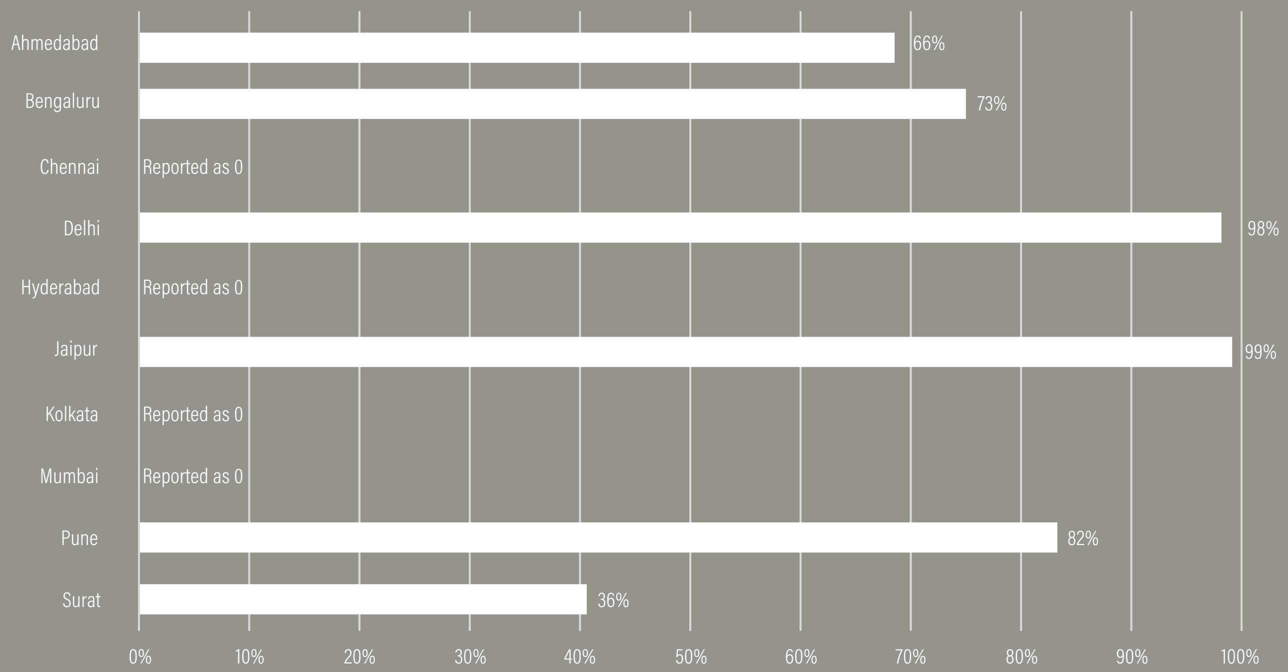
Box 4 | **Peri-urban Agriculture and Groundwater Stress**

The growth in urban demand for produce and the ability to tap into groundwater resources can support intensive agriculture practices in urban and peri-urban regions.[a] This might potentially be the case in the peri-urban regions (the zone between 20 and 50 km or between the municipal boundary and 50 km), where most of the agricultural activity is undertaken.

Peri-urban (and urban) agriculture can be an effective response to meeting the growing urban demand for fruit and vegetables and enable local production and consumption networks. Increasing urban and peri-urban agriculture in the Indian context poses water risks to the urban region. Unconstrained extraction and use of already depleted groundwater resources and unmonitored use of urban wastewater streams are leading to groundwater contamination.

The Food and Agriculturel Organization of the United Nations (FAO) provides district-wise data on the extents of irrigation-equipped areas categorized by source as fresh surface water and fresh groundwater withdrawal[b] on the AQUASTAT portal. These data (where reported) indicate that irrigated lands in the districts where study cities are located are highly dependent on groundwater (see Figure B4.1).

Figure B4.1. | **Proportion of Area Equipped with Groundwater Irrigation Facilities in Districts Where the Study Cities Are Located**



Notes: The percentages in the figure are derived from the areas estimated by the Food and Agriculturel Organization (FAO) of the United Nations. The data for India on area equipped for irrigation are compiled by FAO from the Net Irrigated Area statistics in reports and databases prepared by the Ministry of Agriculture from the Agricultural Census (2000-01), Input Survey (2000-01), and Minor Irrigation Census (2000-01).

The groundwater aquifers in most districts where the study cities are located are unsustainably managed. Surat's groundwater is classified as safe, and Ahmedabad and Pune are semi-critical; 5 of the remaining 7 districts[16] are overexploited according to the Central Ground Water Board.[c] The use of groundwater for increasing and intensifying peri-urban agriculture further stresses this resource in urban zones, but also may cause low-level green cover gain.

To relieve some of the pressure on groundwater aquifers and also support urban and peri-urban agriculture, the monitored use of treated domestic wastewater streams, which are the output from urban areas, could be explored. Such practices can promote a more circular approach for both water use and the agricultural produce generated.

Sources: a. Butsch and Heinkel 2020. b. FAO 2013. c. CGWB 2

D. Recharge Zones Converted to Built-Up Area

Groundwater is a critical resource across India that supports domestic, commercial, and industrial demand in urban areas. It is extensively extracted across the 10 study cities, leading to overextraction in most places (CGWB 2017), and yet continues to support individual and community water security efforts and economic development strategies (Mvandaba et al. 2019).

Groundwater aquifers are impacted by climate variability and a range of localized factors such as soil type, green cover, slope, and rainfall. The change from open space (permeable cover) to built-up area has major impacts on the volume of water that may be recharged into aquifers or flow away as surface runoff. Using only satellite-derived remote sensing data, we estimate the groundwater recharge potential as a function of the green cover (assessed from the NDVI) and slope of the ground surface (extracted from a DEM).

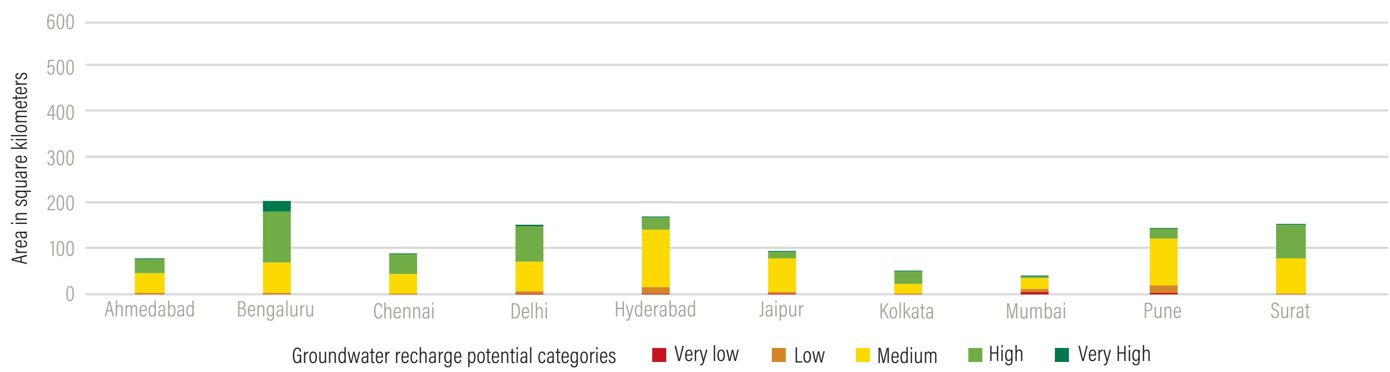
This study extrapolates the loss of various groundwater recharge potential zones in 2015 compared with 2000. To arrive at this estimation, we developed a groundwater recharge potential map for 2000 and overlaid on it all the new built-up areas added by 2015. This allowed us to assess where new construction is located with respect to the various classes of recharge potential zones. For details of the estimation methodology, see Appendix F.

The recharge potential is estimated across five classes: very low, low, medium, high, and very high. The very low recharge potential class corresponds to low green cover and steep slopes, and the very high recharge potential class corresponds to high green cover and low slopes.

Findings

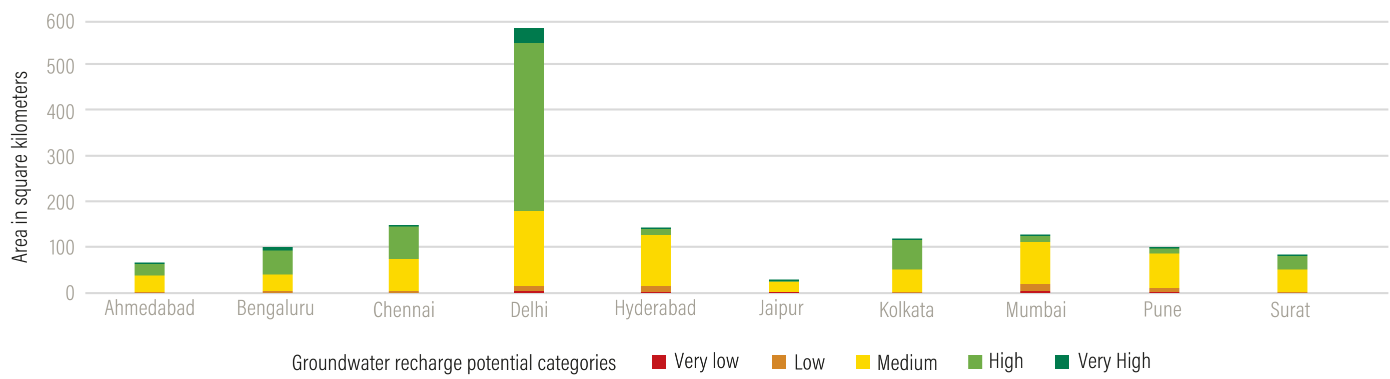
Development over the various classes of recharge potential zones for the 0–20 km and 20–50 km regions are shown in Figures 11 and 12. Across all the 10 study cities, new built-up area of 1,509 sq. km was added in the 20–50 km

Figure 11 | **Built-Up Area Developed between 2000 and 2015 over Various Classes of Areas with Groundwater Recharge Potential (0-20 km Region)**



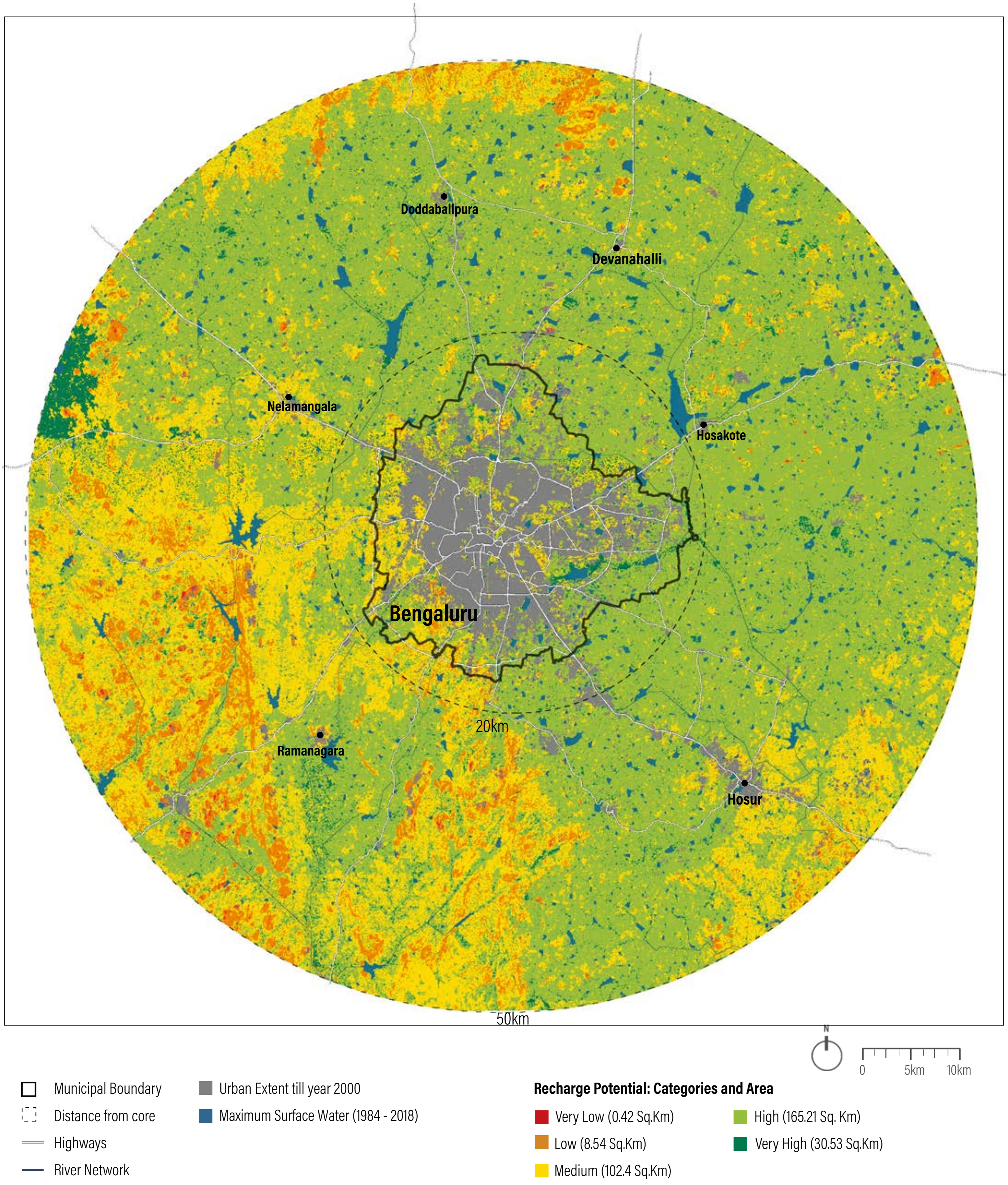
Notes: Bengaluru shows substantial new development in high and very high recharge potential zones in 0-20 km region.
Sources: WRI authors.

Figure 12 | **Built-Up Area Developed between 2000 and 2015 over Various Classes of Areas with Groundwater Recharge Potential (20-50 km Region)**

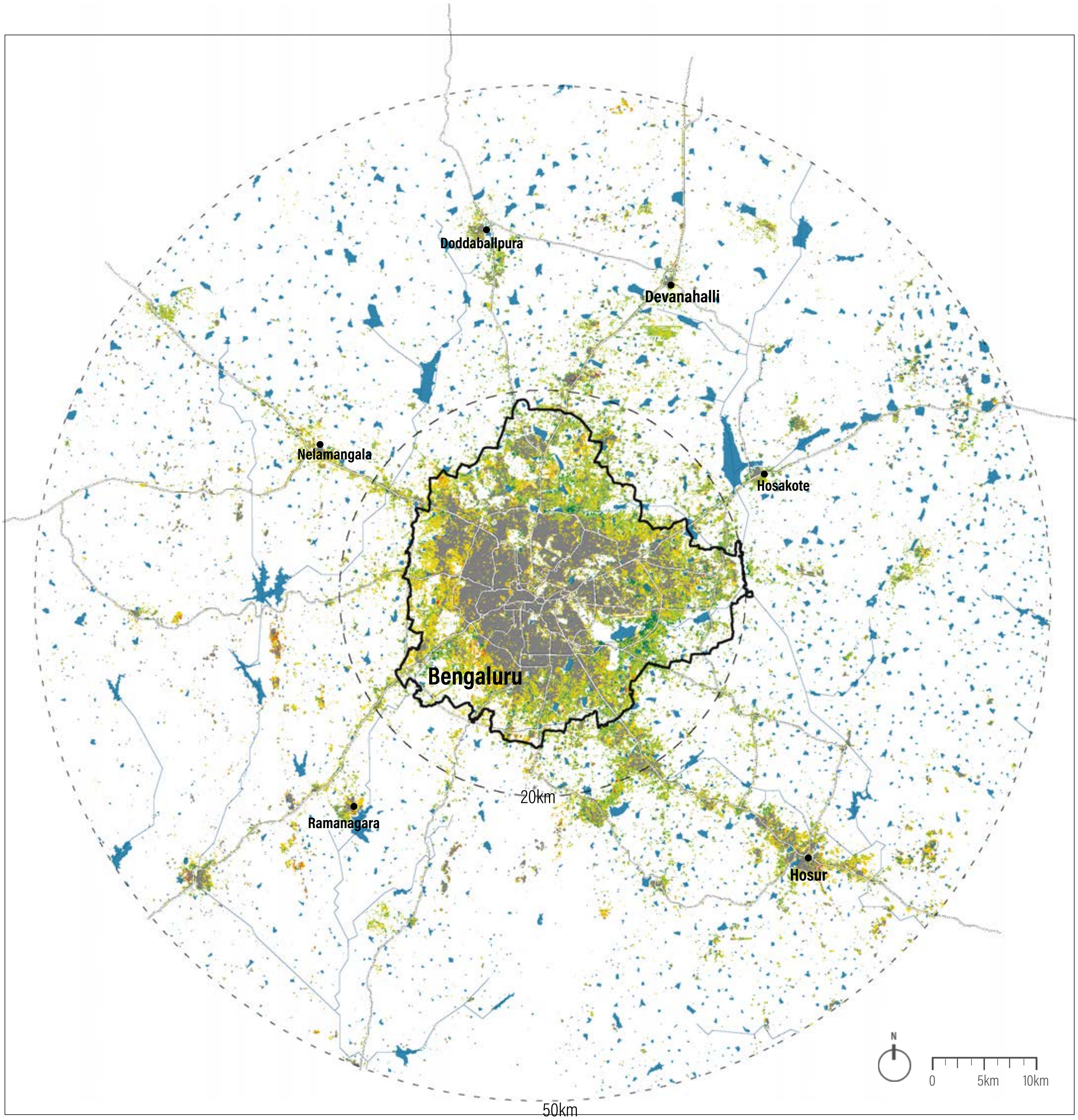


Notes: Delhi shows substantial new development in high and very high recharge potential zones in the 20-50 km region.
Sources: WRI authors.

Figure 13 | **Maps Showing Groundwater Recharge Potential in Bengaluru Indicating Substantial New Development Sited on High and Very High Recharge Potential Zones**



Notes: Urban development in the year 2000 overlaid over various recharge potential zones for areas not yet built up in the 0–50 km study region.
Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.



- Municipal Boundary
- Distance from Core
- Highways
- River Network
- Urban Extent till year 2000
- Maximum Surface Water (1984–2018)

Recharge Potential: Categories and Area

- Very Low
- Low
- Medium
- High
- Very High

Notes: Urban development of the year 2000 in gray, and new urban development overlaid over various recharge potential zones (areas where urban development has not taken place are not highlighted here).
Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

region compared with 1,182 sq. km added in the 0–20 sq. km region. However, the 20–50 km region is still less dense than the 0–20 km region, which corresponds to the city center.

Discussion

Although cities are facing increasing groundwater depletion (CGWB 2017), about 39 percent (462 sq. km) of the new built-up area added between 2000 and 2015 in the 0–20 km region has been in high and very high recharge potential zones (see Figure 11). Similarly, about 47 percent (714 sq. km) of the new built-up area added between 2000 and 2015 in the 20–50 km region has been in high and very high recharge potential zones (see Figure 12). As noted earlier, much of the urban expansion occurs along roads and other transportation networks; the maps of the groundwater recharge potential indicate that these infrastructure networks have also been placed in high and very high recharge potential zones (see Figure 13).

Urban expansion, especially in the 20–50 km region, could have been better managed to protect natural resources and infrastructure by using development restrictions to direct urban growth to areas with lower natural infrastructure. High and very high recharge zones are areas of high green cover and flatter, low-lying areas. These zones are likely to be more attractive to the real estate sector (for development) and to infrastructure providers (for roads). Given various factors such as the development pressures on these peri-urban lands, lax regulatory structure, and discounting of ecological risks, development since 2000 has been heavily concentrated on high-value natural infrastructure zones (see Figure 13). Regulation of groundwater remains limited, with only a few cities having implemented measures to restrict extraction. Various cities and states have implemented more proactive policies for rainwater harvesting (New Delhi, Bengaluru, and Chennai), but these primarily target new constructions (Center for Science and Environment n.d.), which limits the volume of water that could be diverted into aquifers as existing buildings are not integrated in these interventions. Also, not all rainwater harvesting techniques necessarily support aquifer recharge.

Groundwater remains a highly exploited resource across India's urban centers, but data on groundwater availability and realistic mapping of groundwater resource are lacking (Shah 2016). Thus, despite progressive measures (policies and practices) in various cities, there is no comprehensive measure of how rainwater harvesting techniques are impacting aquifer levels.

Inference

The predominance of new built-up area in these zones indicates loss of green cover and a higher likelihood of flooding in these areas.

Low-lying areas around the Durgam Cheruvu in Hyderabad and the surrounding regions of the lake were extensively urbanized between 2003 and 2019. The urban built-up area has consumed much of the low-lying floodplain and paved over natural open spaces, which indicates a reduction in groundwater recharge as well as an increased risk of flooding for habitations here (see Figure 14).[17]

E. Lost Groundwater Recharge Volume

Groundwater is a critical resource across India and has important social, environmental, and economic functions in urban areas (Mvandaba et al. 2019). Across India, groundwater serves as a major source of domestic supply for various urban regions, as public water supply agencies, private water providers, and individuals tap into this resource to meet water demand. Abstraction rates are extremely high, and as the world's largest groundwater user, India draws about 260 cubic kilometers per year (Asoka et al. 2017). Demand is constantly increasing, with only nominal efforts to regulate extraction (Cullet 2018) and improve the infiltration and recharge rates of this critical resource. The growth of built-up area over high-value recharge potential zones has significant impacts on the potential volume of aquifer recharge. Reductions in inflow into the aquifer alongside high abstraction rates stress groundwater resources, which is already visible in many of the study cities.

Findings

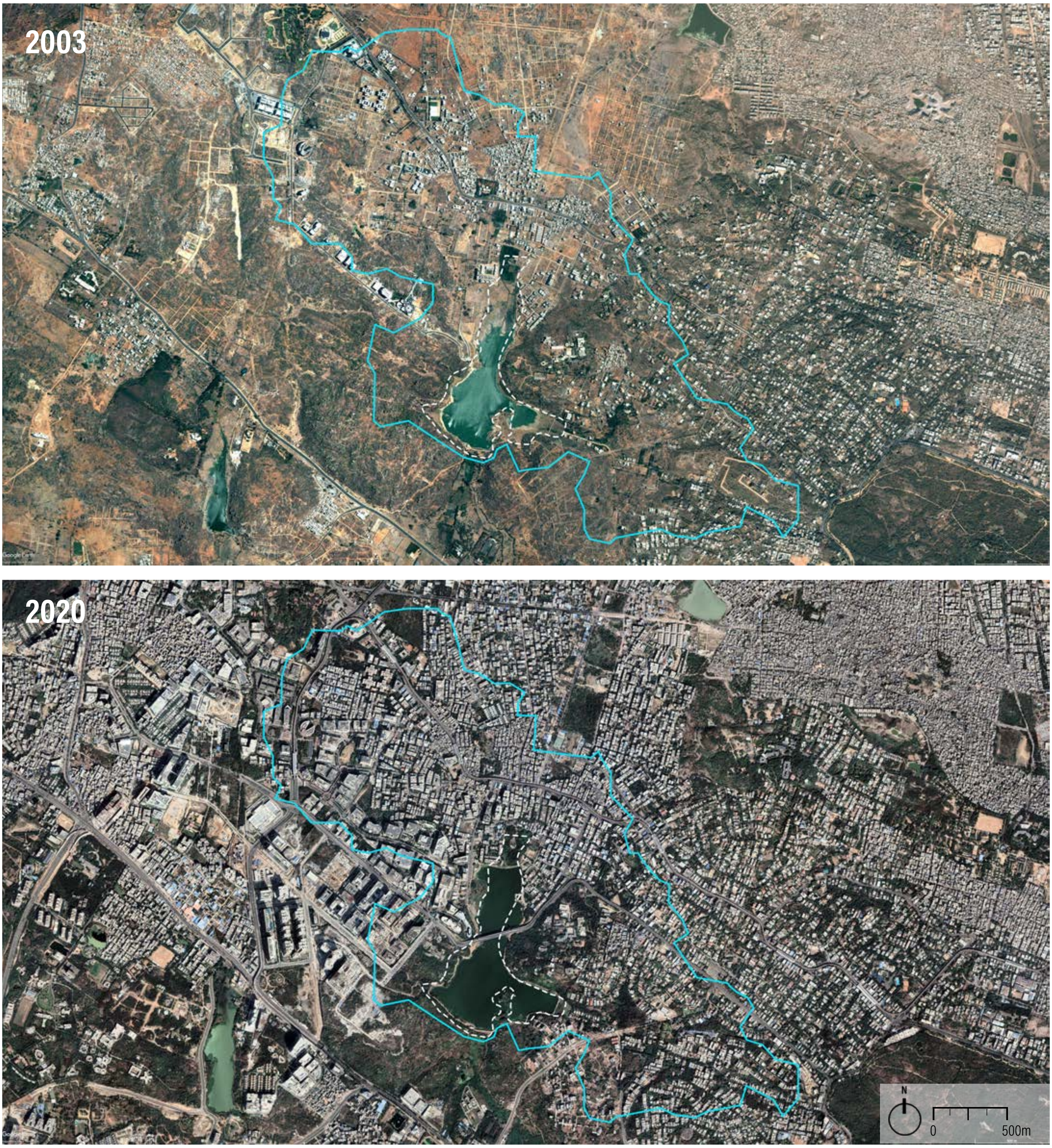
We estimate the volume of groundwater recharge potential lost in the 0–20 km and 20–50 km regions for the 10 study cities between 2000 and 2015. Establishing the volume of water diverted from aquifers provides a more useful measure (along with the area where the recharge potential has changed).

To estimate the lost recharge volume, each recharge potential class[18] is assigned a recharge coefficient. The volume is estimated (million liters per day) as the product of the area, rainfall, and recharge coefficient, less the infiltration into the built-up area. Using the values of the new built-up area added between 2000 and 2015 in various recharge potential zones, we conservatively estimate the potential recharge volume that has been lost as runoff and not infiltrated into groundwater aquifers (see Figure 15). See Appendix G.

Discussion

It is estimated that the total lost volume of recharge for the 10 cities is about 870 million liters per day in the 0–50 km region. The 10 cities have added a population of about 39 million between 2000 and 2015 in the 0–50 km region[19] ; at 100 lpcd water provision, the additional demand from this population is about 3,900 million liters per day (MLD). The lost volume of recharge, around 870 MLD, could potentially have met a fifth of the new demand (see Table 2).

Figure 14 | **Substantial Conversion of Natural Spaces into Urban Built-Up Area in the Durgam Cheruvu Catchment between 2003 and 2020**



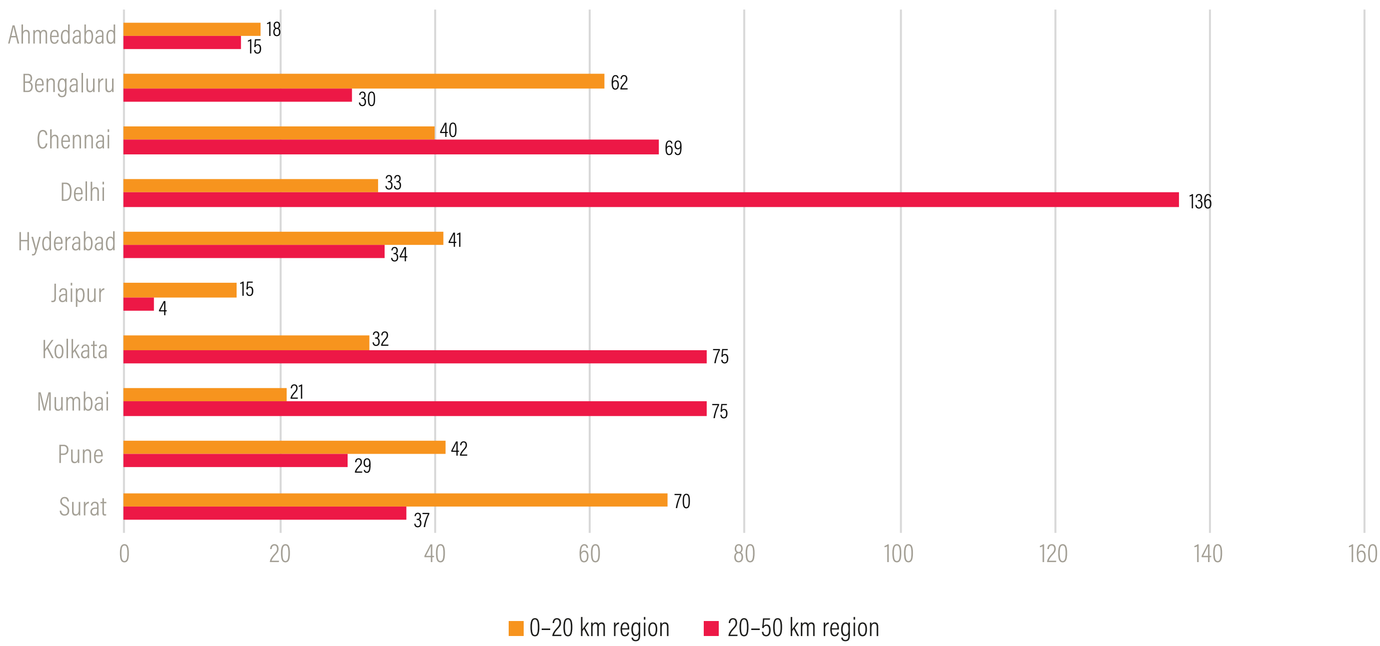
Notes: The conversion of natural spaces to urbanized area has significantly altered the surface water flow in the catchment (denoted in blue) of the Durgam Cheruvu (denoted in white).
Sources: Farr et al. 2007; Basemap: Google Earth Pro 2003; Google Earth Engine 2021.

Table 2 | **Lost Recharge Volume and Water Demand for Population Added in 2000–2015**

	ESTIMATED GROUNDWATER LOST (0–20 KM) DUE TO NEW DEVELOPMENT (IN MLD)	ESTIMATED GROUNDWATER LOST (20–50 KM) DUE TO NEW DEVELOPMENT (IN MLD)	POPULATION CHANGE (0–50 KM REGION)	WATER DEMAND OF THIS POPULATION AT 100 LPCD (IN MLD)	ESTIMATED GROUNDWATER LOST (0–50 KM) DUE TO NEW DEVELOPMENT (IN MLD)	PERCENTAGE OF DEMAND THE TOTAL GROUNDWATER LOST (0–50 KM) COULD HAVE MET (%)
Ahmedabad	18	15	2,063,765	206	33	16
Bengaluru	62	30	5,332,397	533	92	17
Chennai	40	69	2,609,740	261	109	42
Delhi	33	136	8,817,771	882	169	19
Hyderabad	41	34	2,541,134	254	75	30
Jaipur	15	4	1,675,839	168	19	11
Kolkata	32	75	3,056,104	306	107	35
Mumbai	21	75	7,724,045	772	97	12
Pune	42	29	2,647,241	265	71	27
Surat	70	37	2,761,622	276	107	39
Total	375	504	39,229,658	3,923	879	22

Notes: lpcd = liters per capita per day; MLD = million liters per day.
Sources: WRI Authors

Figure 15 | **Lost Recharge Volumes in 0–20 and 20–50 km Regions**



Notes: The volumes are the totals across all the five recharge potential classes (very low, low, medium, high, and very high) in million liters per day.
Sources: WRI authors.

India's extremely high groundwater dependence lies in overexploited or semi-critical aquifers, across 7 of the 10 study cities.[20] The Central Ground Water Board's (CGWB's) analysis (CGWB 2017) shows that 7 of the 10 study cities lie in overexploited or semi-critical aquifers, indicating that the abstraction rate is far higher than the annual recharge rate (see Table 3).

Inference

The high volume of lost recharge indicates the loss of a possible buffer against the climate shock of water scarcity, as it is completely wasted as runoff and does not recharge the aquifer. The indiscriminate growth of built-up area, especially when unsupported by policies and mechanisms for rainwater harvesting and aquifer recharge structures, leads tosignificant groundwater abstraction and depletion of aquifer levels (see Box 5).

The spatial mapping of recharge potential zones and assessment of potential recharge volumes can offer evidence-based guidance for future urban expansion plans (such as master plans) when mandating no/low development on areas with high recharge potential.

Table 3 | **Stage of Groundwater Development (from CGWB Website)**

	STATUS OF GROUNDWATER DEVELOPMENT
Ahmedabad	Semi-critical
Bengaluru	Overexploited
Chennai	Overexploited
Delhi	Overexploited
Hyderabad	Overexploited
Jaipur	Overexploited
Kolkata	Not available
Mumbai	Unsafe to consume
Pune	Semi-critical
Surat	Safe

Notes: CGWB = Central Ground Water Board.
Sources: CGWB 2015, 2017.

Box 5 | **India's Groundwater Overdependence**

India is a heavily groundwater-dependent country across its urban and rural areas. Globally, India is the highest groundwater extractor, withdrawing about 260 cubic kilometers per year from underground aquifers,[a] which is more than a quarter of the global total. Urban and peri-urban areas face multiple cascading issues due to this high dependence on groundwater. Multiple competing uses such as domestic, commercial, and industrial water demand place high stress on this (annually renewable) but limited resource. Furthermore, groundwater extraction is typically not monitored or regulated. It is only recently that groundwater acts are being deployed at the state level to regulate extraction, but withdrawal limits are typically mandated only for commercial and industrial use, and not for domestic use.[b]

One of the direct consequences of population increase is an increase in water demand,[21] but an increase in built-up area impacts the recharge potential of the region and inhibits the renewal of local aquifers. Water utilities try to meet the ever-growing demand by seeking to source water supply from larger (but typically more distant) surface water bodies such as reservoirs and rivers.[c] Meanwhile, supply shortfalls remain, and urban residents both inside and outside municipal boundaries depend on groundwater extraction and tanker water[d] to meet their daily requirement of water. This behavior in turn further stresses groundwater aquifers by increasing abstraction rates far higher than infiltration rates.

Sources: a. Asoka et al. 2017. b. Cullet 2018. c. IIHS 2014. d. Shastry et al. 2018.

Overexploitation of aquifers is indicated in most cities for the study period of 2000 to 2015, yet in recent years some of these cities have seen some improvement in groundwater levels. For instance, in Bengaluru, seven out of the nine assessed borewells in 2019–20 saw an increase in groundwater levels (CGWB 2020). These types of on-ground variations are not captured in the type of spatial analysis done in this study. This is precisely why cities must create a more granular picture of their aquifers for more detailed and accurate planning, by assessing a greater number of shallow and deep wells across the city.

F. Impacts on Urban Areas Due to Changes in Natural Infrastructure

Urbanization-driven negative impacts on natural infrastructure not only disrupt biophysical systems but also lower livability in urban areas. These are interlinked issues: biophysical disruptions such as increased surface runoff can lead to flooding, which impacts lives, livelihoods, and economic activity. Similarly, an increase in the impermeable built-up area can reduce groundwater infiltration, causing the decline of shallow aquifers and leading to water scarcity. Eventually, the far-reaching consequences of such natural infrastructure loss, such as access and equity concerns and economic costs, will have to be borne by urban residents and authorities.

The analyses in the preceding sections indicate that natural infrastructure such as blue cover and green cover have decreased where the urban built-up area has expanded in the 10 study cities. We highlight some of the impacts, such as decreased aquifer levels as reported by the CGWB (CGWB 2017), the loss of water bodies (in part or full) indicated by a comparison of historical and current spatial maps, and changes to green cover.

The loss of surface water between 2000 and 2015, estimated to be around 900 billion liters across the 10 study cities, could potentially have met around 60 percent of the new water demand generated by the growing populations in these cities. Instead, urban water utilities have to bear high economic and energy costs to procure increasing volumes of water from distant reservoirs[22] (IIHS 2014).

Utilities are also struggling to extend water and sanitation networks to the peripheries of expanding cities, and growing populations of urban residents across the economic divide remain without access to these necessary services. These populations, to cope with the lack of services, turn to alternative sources such as borewell or tanker water[23] to meet their water needs (Shastry et al. 2018), increasing the stress on the overexploited aquifers. If these alternatives are also not available, then households are forced to either manage with very little water or turn to low-quality water, which poses health risks due to reduced sanitation and hygiene.

At the same time, as dependence on groundwater has increased manifold in urban areas, the spaces to recharge aquifers are being rapidly depleted. This study estimates that new urban development between 2000 and 2015 has impacted recharge zones that could potentially have diverted 321 billion liters of rainwater per year into underground aquifers. This lost groundwater recharge is equal to 22 percent of the demand of the new population added to these cities in the 15-year study period.

THE FUTURE OF URBANIZATION AND NATURAL INFRASTRUCTURE IN INDIA

This spatial analysis links the growing urbanization in its current form in India to negative impacts on natural infrastructure, which in turn has affected the water security and resilience of urban communities. These challenges are made more complex by the multiple policies and institutions (at the national, state, and local levels) involved in managing land, development, and natural infrastructure. Often, the mandates of these institutions are at odds with one another, leading to conflicts between urban development and natural infrastructure management.

The findings and inferences from this study indicate two primary challenges associated with the current form of urbanization, which is depleting natural resources and infrastructure:

Challenge 1: Urban development disrupts hydrological connections

Any urbanization process disturbs the natural state of the environment and impacts natural hydrological flows and other natural systems. Natural spaces such as lakes and parklands have been consumed to make way for developed land, and have shrunk even where such spaces have been protected as heritage sites.

Challenge 2: Degradation of natural infrastructure impacts urban resilience

In India, planned and unplanned urban expansion has taken over natural spaces and ecosystems at a rapid pace. Natural spaces such as forests, woodlands, wetlands, and lakes provide services such as slowing down stormwater runoff, increasing infiltration, and reducing flooding; the loss of these spaces can increase these adverse events.

In regions in the Global South, urbanization is projected to continue to increase over the next few decades. Decisions around development plans and infrastructure taken today will impact these communities decades into the future. Can the state and municipal authorities shift the existing urbanization trajectories that degrade natural infrastructure? Can alternate pathways for urban growth preserve natural infrastructure and support adaptation and resilience in urban areas? We offer the following recommendations toward this end.

Recommendation 1: Develop maps using current and historical satellite imagery to assess the available natural infrastructure and changes to it

To understand the condition of natural infrastructure in urban regions, planning agencies can use satellite imagery to gather evidence on the available blue and green cover and changes to it, and the built-up area. This study uses available open-source satellite imagery and current analytical methods (see Appendices C–F) that can be replicated by interested city agencies. Agencies can further validate the findings from such spatial analysis exercises with ground truthing.

Recommendation 2: Integrate hydrogeological aspects with urban planning.

Urban agencies at present function in silos, and their expertise is narrow. Development agencies only organize land uses with no (or limited) hydrogeological inputs, with the result that natural infrastructure such as water bodies (*Deccan Chronicle* 2018; Shekar and Thirumurthy 2019), zones with high recharge potential, and forested upstream areas are not adequately protected. Hydrogeology must become an integral part of urban planning exercises. A few examples have now emerged in urban India (Delhi and Mumbai) where development authorities have explicitly included natural or blue-green infrastructure in city and regional development plans (Delhi Development Authority 2021; Mumbai Metropolitan Planning Committee 2021). The effects of these policies are yet to be seen on the ground as these plans are still in the draft phase and yet to be legally notified.

Recommendation 3: Restore and conserve degraded/deteriorated natural infrastructure

Urban agencies must seek to restore and conserve these degraded/deteriorated blue-green spaces so that the ecosystem services and livelihood opportunities provided by these spaces can be retained or further developed. Robust regulation and monitoring must be implemented to limit or prohibit development of urban built-up areas (including public infrastructure such as roads and government buildings) in zones with high recharge potential or ecologically sensitive areas.

Recommendation 4: Consider natural systems as green infrastructure assets and integrate them into urban infrastructure planning

Natural systems (parks and lakes) and built (gray) infrastructure (stormwater drains) are treated as separate urban assets managed by different departments or agencies. However, nature-based solutions can effectively supplement or replace conventional infrastructure and offer a greater range of co-benefits (Browder et al. 2019). To enable the incorporation of nature-based solutions, such practices will need to be recognized as legitimate infrastructure assets (Chan et al. 2018). Further, cities will need to move beyond pilot projects at single locations and pursue nature-based solutions at site, neighborhood, and city scale (such as blue-green streets and green roofs) to accumulate significant benefits.

Degradation of natural infrastructure impacts the resilience of entire urban regions. Disadvantaged groups are at higher risk as they are often located in high-risk zones (such as lake beds and flood plains) or locations with no natural infrastructure (such as green spaces) to alleviate stresses (heat stress). In 2014, about 30 percent of slums in Ahmedabad were identified to be near water bodies or the Sabarmati River (Centre for Research and Development Foundation 2014). The Delhi government in 2015 reported that about 17 percent of the slums in the National Capital Territory were close to streams (nullahs) or the river (Directorate of Economics and Statistics 2015). In Hyderabad too, slum communities are likely to be located near water bodies such as the Musi River (or streams flowing into it) and lakes (Nallathiga 2014).

This study has not deeply investigated the location of urban poor settlements in the 10 study cities and the impacts of natural infrastructure degradation on them. There is scope for future research to map the locations of such settlements and the populations in them, and overlay them on the thematic maps developed here. Such integrated analysis can help develop robust, evidence-based practices to mitigate the impacts of natural infrastructure loss faced by disadvantaged communities.

The most innovative, advanced, and expensive engineering solutions of the 20th century are no longer enough to meet the infrastructural needs of urban areas and protect against climate change driven extreme events. Fragmented decision-making due to policies enacted by multiple actors at the national, state, and local levels increases the conflict between urban development and natural infrastructure. Urban planning and infrastructure management, which continues to focus on conventional engineering solutions, must leapfrog into the 21st century. A paradigm shift to integrate natural infrastructure as a key component in urban assets is required to ensure that cities are able to hedge extreme risks. A shift to an urban blue-green approach that restores and conserves natural spaces, water bodies, aquifers, and other ecosystems can offer a slew of benefits such as ecosystem services, climate change mitigation benefits, water risk resilience benefits, and improved livability for all (see Figure 16).

Figure 16 | **Strategies for Urban Agencies to Chart a New Path for Future Urbanization with Nature-Based Solutions**

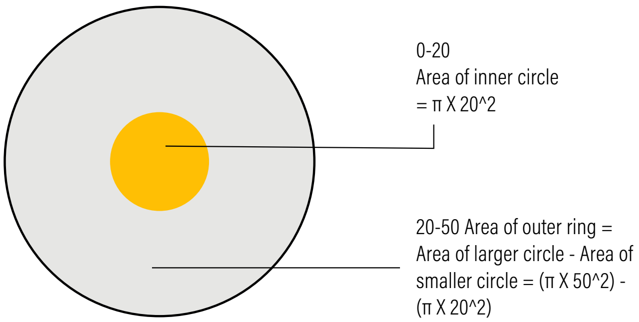
Challenges associated with current urbanization pattern	Shifting to ecologically sensitive urbanization
	Develop maps using current and historical satellite imagery to assess the available natural infrastructure and changes to it
	Integrate hydrogeological aspects with urban planning to conserve natural infrastructure as urbanization expands
Urban development disrupts hydrological connections	Restore and conserve degraded/ deteriorated natural infrastructure
Natural infrastructure degradation impacts urban resilience	Consider natural systems as green infrastructure assets and integrate them into urban planning infrastructure

Sources: WRI authors.

APPENDIX A STUDY AREA OF 10 CITIES

Methodology - For the 10 cities, data are extracted/ estimated at 10 km intervals within a 50-km-radius study zone. A further two sub-study zones are designated: the area within a radius of 20 km from the city center and the area between 20 and 50 km from the city center (see Figure A1).

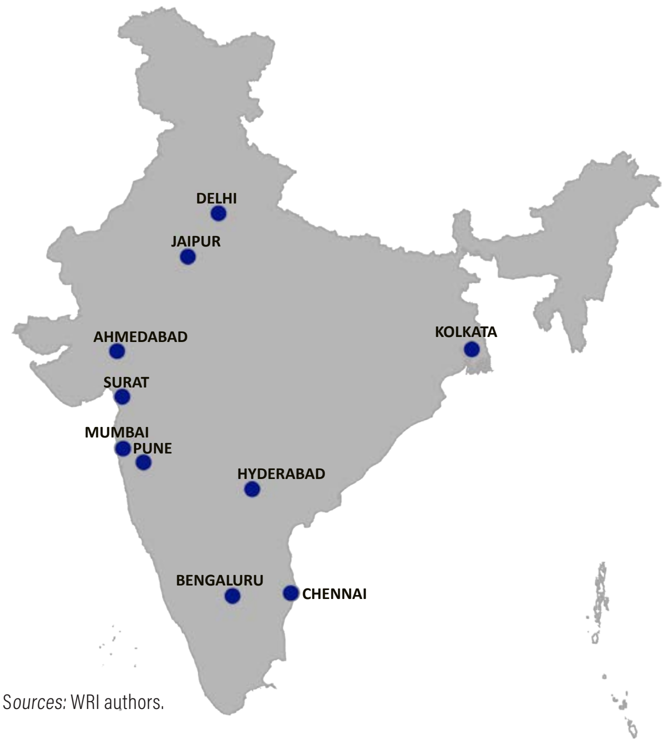
Figure A1 | Study Zone Areas for 0–20 km and 20–50 km Intervals



Sources: WRI authors.

The area of a study zone is calculated from the areas of the circle and of the ring within these distances, as shown in Figure A1. For Mumbai, Chennai, and Surat, the study areas are estimated in the same manner, but the ocean present in the vicinity is masked from the study area. The actual areas to be studied for these three cities are then extracted directly from the remote sensing software (see Figure A2 and Table A1).

Figure A2 | Map of India Indicating Locations of the 10 Study Cities



Sources: WRI authors.

Datasets

Table A1 | Area of Study Zones for the 10 Study Cities for 0–20 km and 20–50 km from City Center

CITY	AREA OF STUDY ZONE (0–20 KM) IN SQ. KM	AREA OF STUDY ZONE (20–50 KM) IN SQ. KM
Ahmedabad	1,256	6,596
Bengaluru	1,256	6,596
Chennai*	653	3,592
Delhi	1,256	6,596
Hyderabad	1,256	6,596
Jaipur	1,256	6,596
Kolkata*	1,256	6,502
Mumbai*	711	3,592
Pune	1,256	6,596
Surat*	1,222	4,122

Notes: * Areas of study zones directly extracted from ArcGIS.
Sources: Survey of India n.d.

APPENDIX B URBAN POPULATION ESTIMATES IN STUDY CITIES

Methodology - The urban population numbers used here are taken directly from the Global Human Settlements Layer. This is produced by the European Commission–Joint Research Centre (EC-JRC) (European Commission 2016), which collates data from various sources to provide population data and dense built-up cover for four years—1975, 1990, 2000, and 2014—by assessing the REGIO-OECD "degree of urbanization" model (OECD et al. 2021), using the population grid cells as input (Pesaresi et al. 2015).

Resolution - 30 m

Time stamp - 2000, 2015

APPENDIX C BUILT-UP AREA

Methodology - To extract the built-up area, this study considers the settlement layer as provided by the EC-JRC Global Human Settlements Layer's built-up grid. Each square kilometer grid cell has been generated by integrating the built-up areas produced from Landsat image and population data derived from the Center for International Earth Science Information Network Gridded Population of the World, Version 4 (CIESIN GPW v4). These data are divided into three discrete categories: urban centers, urban clusters, and rural areas. Urban centers, or high-density clusters, are defined as contiguous cells (4-connectivity, gap filling) with a density of at least 1,500 inhabitants/sq. km or a built-up density greater than 50 percent, and a minimum of 50,000 inhabitants per cluster. Urban clusters are lower-density clusters including towns and suburbs, defined as contiguous grid cells with a population of at least 300 inhabitants per sq. km or a built-up density greater than 50 percent and a minimum of 5,000 inhabitants (Pesaresi et al. 2015).

This layer is filtered for the study years (2000 and 2015), and settlement data for a 50 km radius from the city center for the 10 study cities are considered (settlement data of all other urban and rural areas are masked). The statistics for the built-up area were calculated separately for the areas at 0–20 km and 20–50 km intervals from the city center. The original resolution of the Global Human Settlement Layer (GHSL) Built-Up Grid layer (i.e., 30 m) is used (see Figure C1).

The permanent and seasonal water layers (for 2015) were taken from the JRC Yearly Water Classification History layer (Pekel et al. 2016) to indicate the spatial extents of blue cover (water bodies) in these cities. The JRC Yearly Water Classification History provides information on the seasonality of the water cover a 32-year period.

Datasets

- EC-JRC Global Human Settlements Layer, Built-up Grid
- JRC Yearly Water Classification History

Resolution - 30 m
Time stamp - 2000, 2015

Interpreting the map - Built-up areas represent the presence of structures such as buildings, concrete surfaces, and roads on land. These are indicated in the satellite imagery for two time periods in the maps: in 2000 and in 2015.

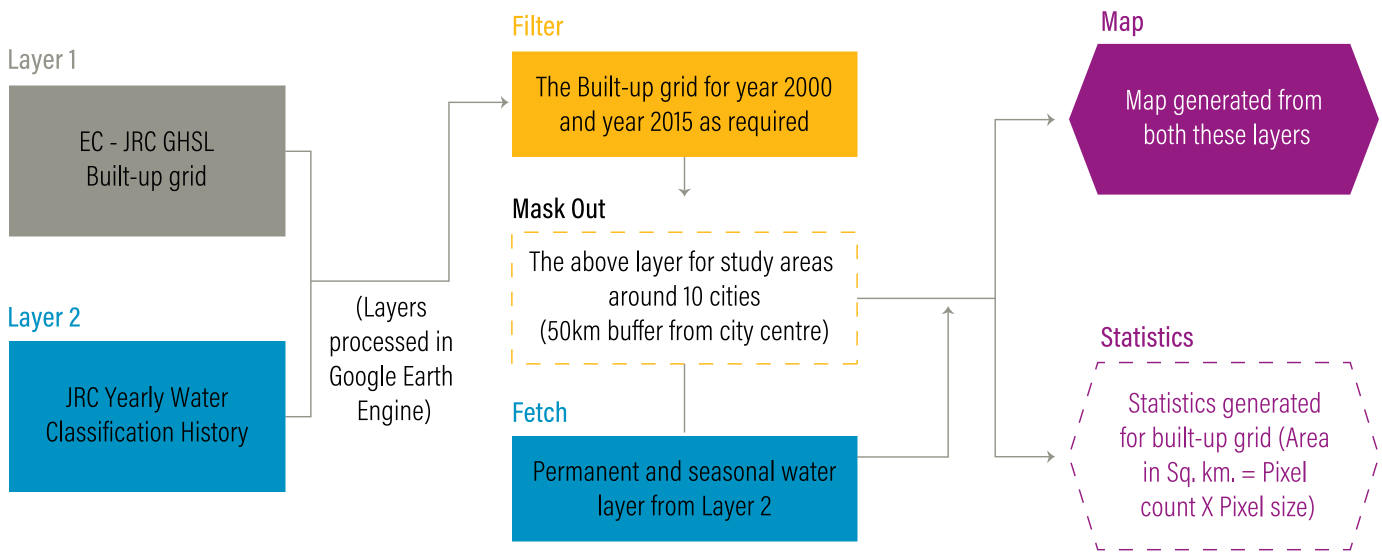
Legend - The map of the built-up cover (see Appendix H) shows the built-up area within the area of interest for the indicated time periods. The red color indicates built-up layers in 2015, and the gray color indicates built-up layers in 2000.

Limitations - The 30 m resolution of the EC-JRC Global Human Settlements Layer, Built-up Grid provides the settlement layer as a citywide built-up area layer. Plot-level characteristics in terms of permeable open space or unpaved areas are not captured.

APPENDIX D BLUE COVER

Methodology - The blue cover is estimated by calculating the Modified Normalized Difference Water Index (MNDWI) from the satellite imagery (Guo et al. 2017). For this study, a composite image is created from the NDWI collection of images for each city for the two study epochs (1998–2002 and 2013–2017). To create the composite image, the Landsat image collection (Jones 2019) is filtered for the epoch (years) and less than 5 percent cloud. Next, the NDWI is mapped (processed) on all the filtered images. We reduce the above collection at the end to obtain a composite image by calculating the maximum value of each pixel across the stack. Images with cloud cover are filtered out of the collection by

Figure C1 | Flowchart to Estimate Area of Impervious Cover from the EC-JRC Global Human Settlements Layer



Sources: WRI authors.

selecting the BQA band from the Landsat imagery.

Using the Canny Edge Detection algorithm, the sharp edges in the NDWI layer are isolated to identify water bodies. In the next step, the MNDWI is calculated. For Landsat 5, Band 2 and Band 5 are taken, whereas Band 3 and Band 6 are considered for Landsat 8 to generate the MNDWI. With this result, the pixels having values greater than 0.15 are clipped to define water clearly.

Generating blue cover using this method created errors in that random water pixels from farmlands were detected within it. To solve this problem, masking is carried out in two steps. First, unwanted pixels are eliminated using the connected pixel count method so that any isolated pixels identified as blue cover are removed.

The next step uses the water extent band of the JRC Global Surface Water Mapping Layer. This layer contains all the locations where water has ever been detected for the period 1984–2015. A focal mean of 50 m with circle as type was applied after performing five iterations of the focal mean, as required in the tool in ArcGIS, on the maximum water extent band. The focal mean function is used to create an extra buffer around the maximum surface water layer (factor of safety), enabling elimination of the results falling outside the JRC global surface water layer's focal mean result. To remove the errors, the water pixels from the MNDWI result were extracted from this newly created JRC global surface water layer's focal mean result. This clearly gives us the water detected throughout years within water bodies, wetlands, salt pans, and so on, avoiding farms and other temporary structures where water is present (see Figure D1).

The number of water pixels is counted to derive the final surface water area in square kilometers. In the maps, to indicate change to surface water areas, the areas with no change are removed. Only pixels where there is a difference between the two study epochs are indicated. Two categories are shown: land-to-surface-water change (gain) and surface-water-to-land change (loss).

Datasets

- USGS Landsat 5 TM Collection 1 Tier 1 TOA Reflectance
- USGS Landsat 8 Collection 1 Tier 1 TOA Reflectance

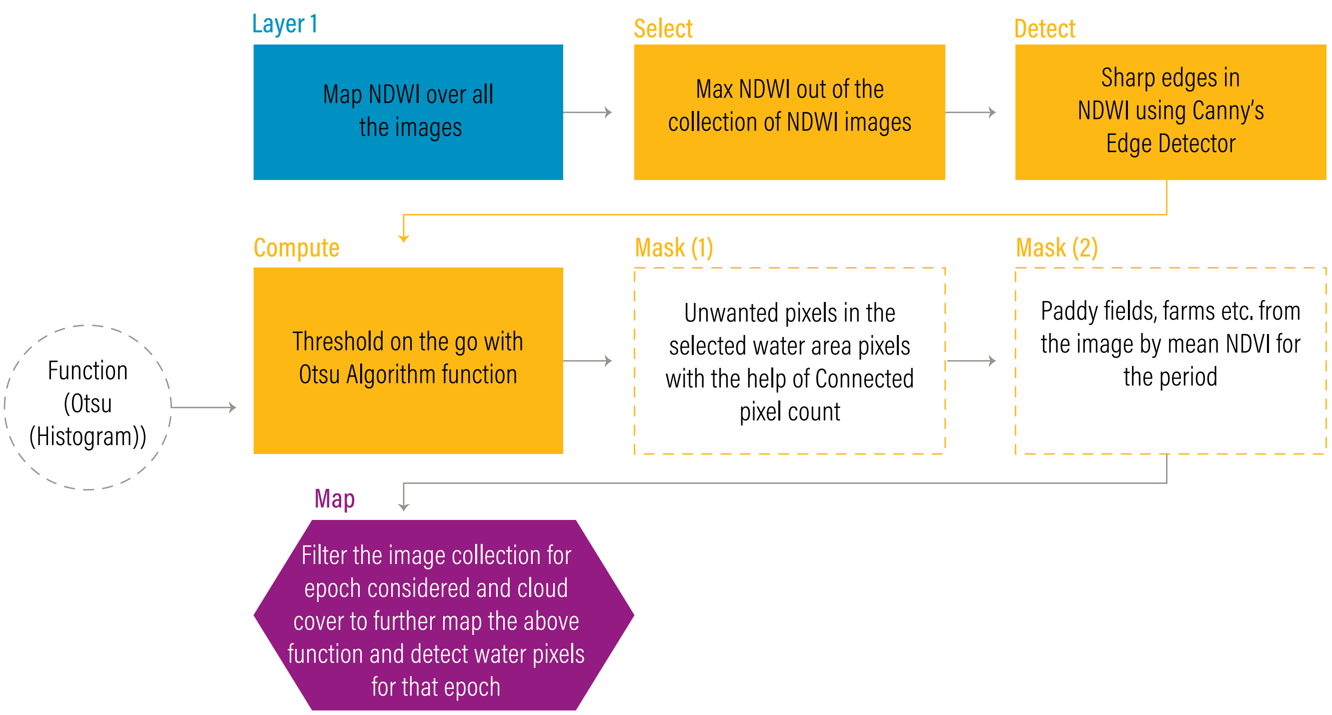
Resolution - 30 m

Time stamp - 1998–2002, 2013–2017 (epochs)

Interpreting the map - The maps indicate the change in blue cover in the study cities seen for Epoch 1 (1998–2002) and Epoch 2 (2013–2017).

Legend - The map of blue cover in the study cities (see Appendix I) represents the blue cover change in the area of interest for the indicated time periods. Area detected as land in Epoch 1(1998-2002) and water in the Epoch 2 (2013-2017) is described as land to surface water change and is represented in purple. Areas detected as water in

Figure D1 | **Flowchart to Estimate Blue Cover in Study Cities Using Landsat 5 and 8 Imagery and JRC Global Surface Water Mapping Layer**



Sources: WRI authors.

Epoch 1 and land in Epoch 2 is described as surface water to land change and is indicated in yellow.

Limitations - This study filters satellite imagery to access cloud-free images for the indicated period and thus uses only a limited set of appropriate images to assess the blue cover. Further, even if greater water extents may be present in many images, they may not be studied as the images were filtered to obtain consistent cloud-free imagery across all the 10 study cities.

APPENDIX E VEGETATION CHANGE TREND ANALYSIS

Methodology - The vegetation change trend map detects how much green cover (observed as the green signature represented by the Normalized Difference Vegetation Index [NDVI] value) of a pixel has changed over a period. This study does not directly detect individual trees, bushes, farmlands, and so on.

A pixelwise trend analysis is conducted using the linear regression method. Long-term satellite data from Landsat 5, 7, and 8 are stacked temporally and filtered for cloud cover and seasons. Using these data, a temporal NDVI stack is created using the following formula: NDVI = (NIR – R)/(NIR + R)

Linear regression is performed over the stack, where the NDVI is a dependent variable of the independent time variable. To find the equation of the straight line from the dependent and independent variable values, the least squares estimation method is used. The residual is the variation between the values of the dependent variable and of the predicted model. The ordinary least squares method attempts to reduce this variation, and the model with the least mean square error is selected as the linear model.

The eventual equation of the trend line is $y = mx + c$, in which m is the slope, and c is the offset. A significance test was performed to eliminate chances of randomly obtaining any trend (see Figure E1).
The above methodology (pixelwise linear regression trend) is a commonly used model in remote sensing for establishing long-term trends in vegetation data. Fensholt and Proud (2012) established a method for applying pixelwise trend analysis to the entire globe using Moderate Resolution Imaging Spectroradiometer (MODIS) data.

Datasets

- Landsat 5, 7, and 8

Resolution - 30 m

Time stamp - 1997–2017

Interpreting the map - The NDVI is a dimensionless index that describes the difference between the visible and near-infrared reflectance of green cover and can be used to estimate its density on an area of land (Weier and Herring 2000). Long-term (20-year) vegetation change trend analysis using time series composite NDVI data proved suitable for identifying areas of green cover change.

Areas showing positive and negative NDVI trends mostly coincided with areas of land cover class change, indicating an increase or a decrease in vegetation, respectively. Note that the change in green cover could be due to multiple reasons, one of which is the conversion of land to built-up areas.

Legend - The map of green cover (see Appendix J) represents the vegetation change trend in the area of interest for the indicated period. The change trend is classified into six categories: high loss (in purple), moderate loss (in red), low loss (in orange), low gain (in light green), moderate gain (in dark green), and high gain (in forest green).

Limitations

- Vegetation change is sensitive to a range of geographic, geological, and meteorological conditions and losses, and gains can also occur due to non-anthropogenic factors.

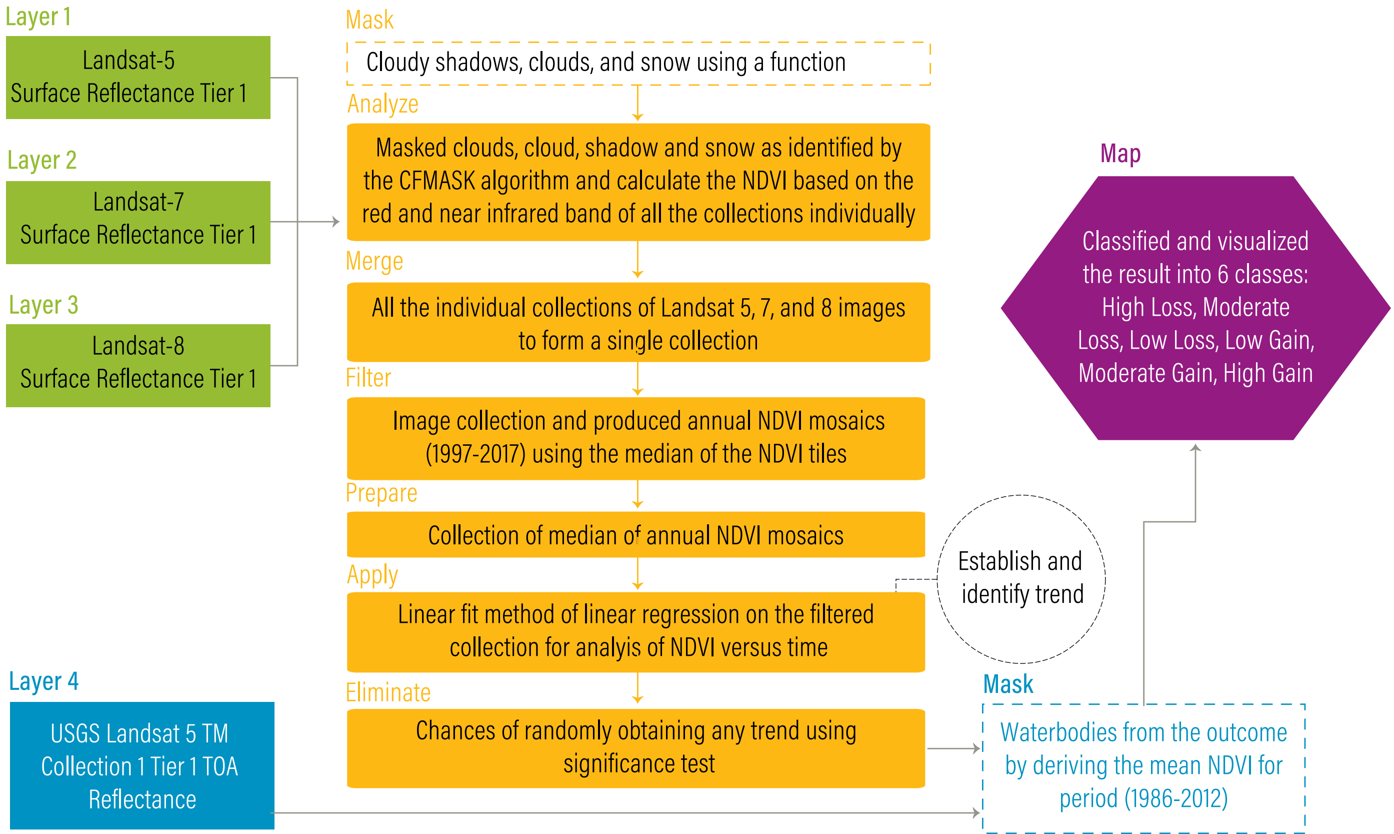
- This study attempts to arrive at a spatial correlation between the locations of urban expansion (increase in built-up area) and the impacts on green cover.

APPENDIX F GROUNDWATER RECHARGE POTENTIAL

Methodology - We estimate the groundwater recharge potential by adapting the method from the report "The Impact of Climate Change on Groundwater Availability" by Mvandaba et al. (2019), which uses the slope, Normalized Difference Vegetation Index (NDVI), and rainfall to assess the groundwater recharge potential. Various other studies use a range of parameters, such as the spatial distribution of soil types, soil permeability, and evapotranspiration rates, to estimate the groundwater recharge potential of a region (da Costa et al. 2019). These methods use a combination of satellite imagery (30 m Landsat pixel scale), geographical information systems (GIS), and on-ground survey data to derive the groundwater recharge potential.

The groundwater recharge potential is derived from the NDVI (Chen 1996) and slope of the land surface

Figure E1 | **Flowchart to Estimate Vegetation Change Trend in Study Cities Using Landsat 8 Imagery and JRC Global Surface Water Mapping Layer**



Sources: WRI authors.

(taken from the digital elevation model [DEM]). In the information derived from satellite imagery and its analysis, we have assigned 50 percent weightage to the slope and NDVI ((NDVI × 0.5) + (slope × 0.5)) in each pixel to generate a spatial visualization of the groundwater recharge potential across the 10 study cities in the 50 km study area around them. The groundwater recharge potential varies between 0.5 and 5, which is classified into five equal categories from very low to very high (see Figure F1).

The mapping of the groundwater recharge potential is overlaid with the built-up area layer from 2000 to eliminate all built-up spaces visible that year. Further, the built-up area added between 2000 and 2015 is again overlaid on the groundwater recharge potential map to estimate the areas of recharge potential converted to built-up area between 2000 and 2015.

Datasets

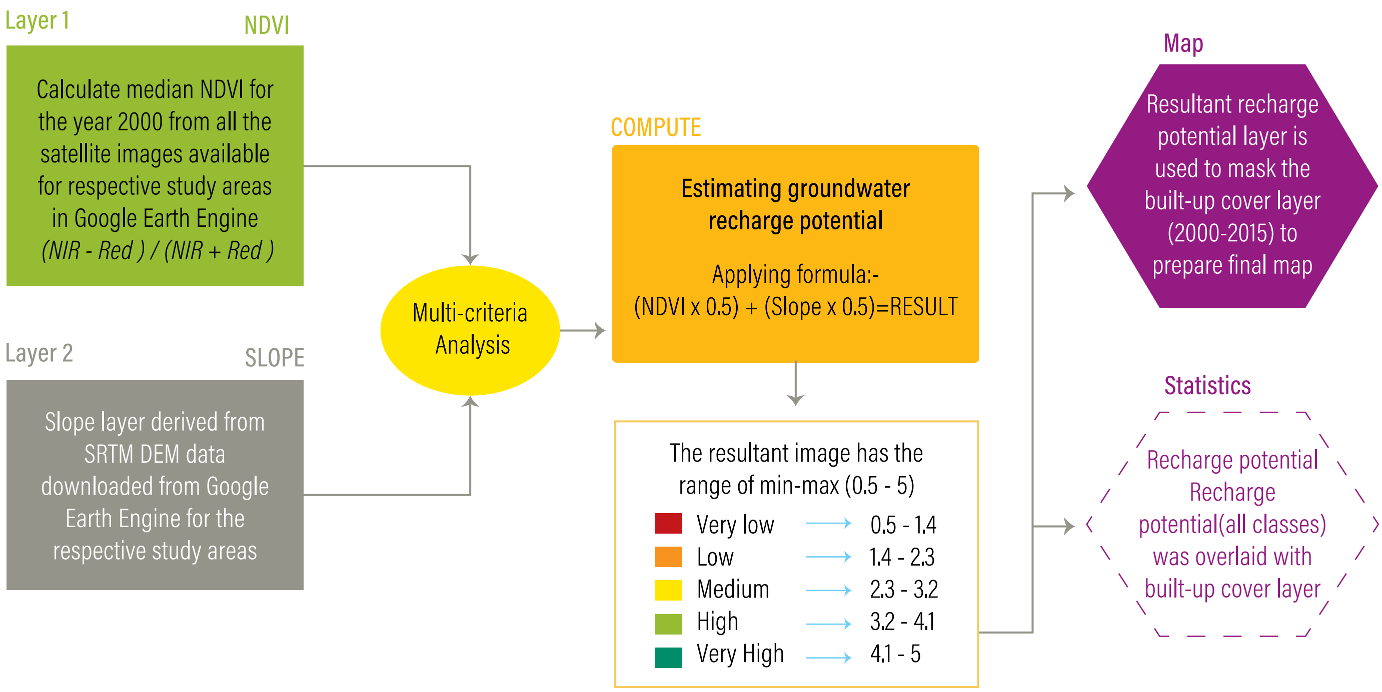
- EC-JRC Global Human Settlements Layer, Built-up Grid
- Landsat 5 TM Collection 1 Tier 1 32-Day NDVI Composite (1986–2012)

Table F1 | **Reclassification factors for recharge indicators**

RECHARGE INDICATOR	RECLASSIFICATION		WEIGHT
NDVI	<0	0	0.50
	0.0 - 0.2	1	
	0.2 - 0.4	2	
	0.4 - 0.5	3	
	0.5 - 0.6	4	
	> 0.6	5	
Slope (degrees)	0.0 - 2.5	5	0.50
	2.5 - 5.0	4	
	5.0 - 7.5	3	
	7.5 - 10.0	2	
	> 10.0	1	

The mapping of the groundwater recharge potential is overlaid with the built-up area layer from 2000 to eliminate all built-up spaces visible that year. Further, the built-up area added between 2000 and 2015 is again overlaid on the groundwater recharge potential map to estimate the areas of recharge potential converted to built-up area between 2000 and 2015.

Figure F1 | **Method to Estimate the Recharge Potential for Each City**



Sources: Adapted from Mvandaba et al. 2019.

- JRC Global Surface Water Mapping Layers, v1.0
- USGS Landsat 5 TM Collection 1 Tier 1 TOA Reflectance

Resolution - 30 m

Time stamp - 2000, 2015

Interpreting the map - The maps (see Appendix K) indicate the area of the new built-up layer (between 2000 and 2015) added over five classes of recharge zones as detected in 2000.

Legend - Red indicates very low recharge potential zones
Yellow indicates low recharge potential zones
Orange indicates medium recharge potential zones
Dark green indicates high recharge potential zones
Dark blue indicates very high recharge potential zones

Limitations

- We limited ourselves to the use of satellite imagery and other open-source remote sensing information. This study does not include, for example, soil maps with detailed infiltration coefficients or evapotranspiration rates derived from on-ground studies.
- We use only the NDVI and slope as factors to estimate the groundwater recharge potential.
- The built-up area in 2000 is excluded from the groundwater recharge potential study as it is already developed and assumed to have zero recharge capacity.

APPENDIX G LOST GROUNDWATER RECHARGE VOLUME

Methodology - To estimate the lost volume of recharge, each recharge potential class (the five classes are very low, low, medium, high, and very high) is given a recharge coefficient. The volume is estimated (million liters) as the product of the area, rainfall, and recharge coefficient, less the infiltration into the built-up area at the rate of 5 percent (see Figure G1).

Limitations - The recharge coefficient is the ratio of recharge to rainfall in a certain area expressed as a percentage. However, the amount of recharge depends on a range of variables such as the soil type, soil moisture, aquifer type, slope, and evapotranspiration. The recharge coefficient for the same region can vary between years

Figure G1 | **Formula to Estimate Total Recharge Volume Lost**

Total recharge volume lost = [Potential recharge in area] – [Recharge into built-up area]
Potential recharge in area = Area × Rainfall × Recharge coefficient
Recharge in built-up zones = Area of built-up area × Rainfall × Recharge coefficient

Sources: WRI authors.

Datasets

Table G1 | **Recharge Coefficient Assigned to Areas with Varying Recharge Potential**

RECHARGE POTENTIAL	RECHARGE COEFFICIENT (%)
Built-up area	2
Very low	5
Low	10
Medium	15
High	20
Very high	25

Sources: WRI Authors

Table G2 | **Rainfall Volume (80 percent of Average Rainfall) Considered to Estimate the Total Lost Recharge Volume per City**

CITY	80% OF AVERAGE RAINFALL (1989-2018)	AVERAGE RAINFALL 1989-2018
Ahmedabad	568.08	710.1
Bengaluru	660.72	825.9
Chennai	1,082.16	1,352.7
Delhi	508.184	635.23
Hyderabad	661.76	827.2
Jaipur	419.44	524.3
Kolkata	1,481.84	1,852.3
Mumbai	1,716.88	2,146.1
Pune	814.56	1,018.2
Surat	1,073.6	1,342

Notes: The average rainfall for 1989–2018 was used to better capture recent rainfall trends.

Sources: Extracted from website of the Indian Meteorological Department, Ministry of Earth Sciences (IMD 2018).

depending on the existing soil moisture (Pirastru and Niedda 2013). Further, the study cities are located on varying aquifer and soil types (CGWB 2017). Moreover, qualitative characteristics such as high or low ascribed to the recharge coefficient depend on various characteristics. For Ogun State, Nigeria, a recharge coefficient of 11 percent is classified as low recharge (Adeleke et al. 2015), whereas for a sand and gravel aquifer in Ireland, a 30 percent recharge coefficient is considered low (Misstear et al. 2009).

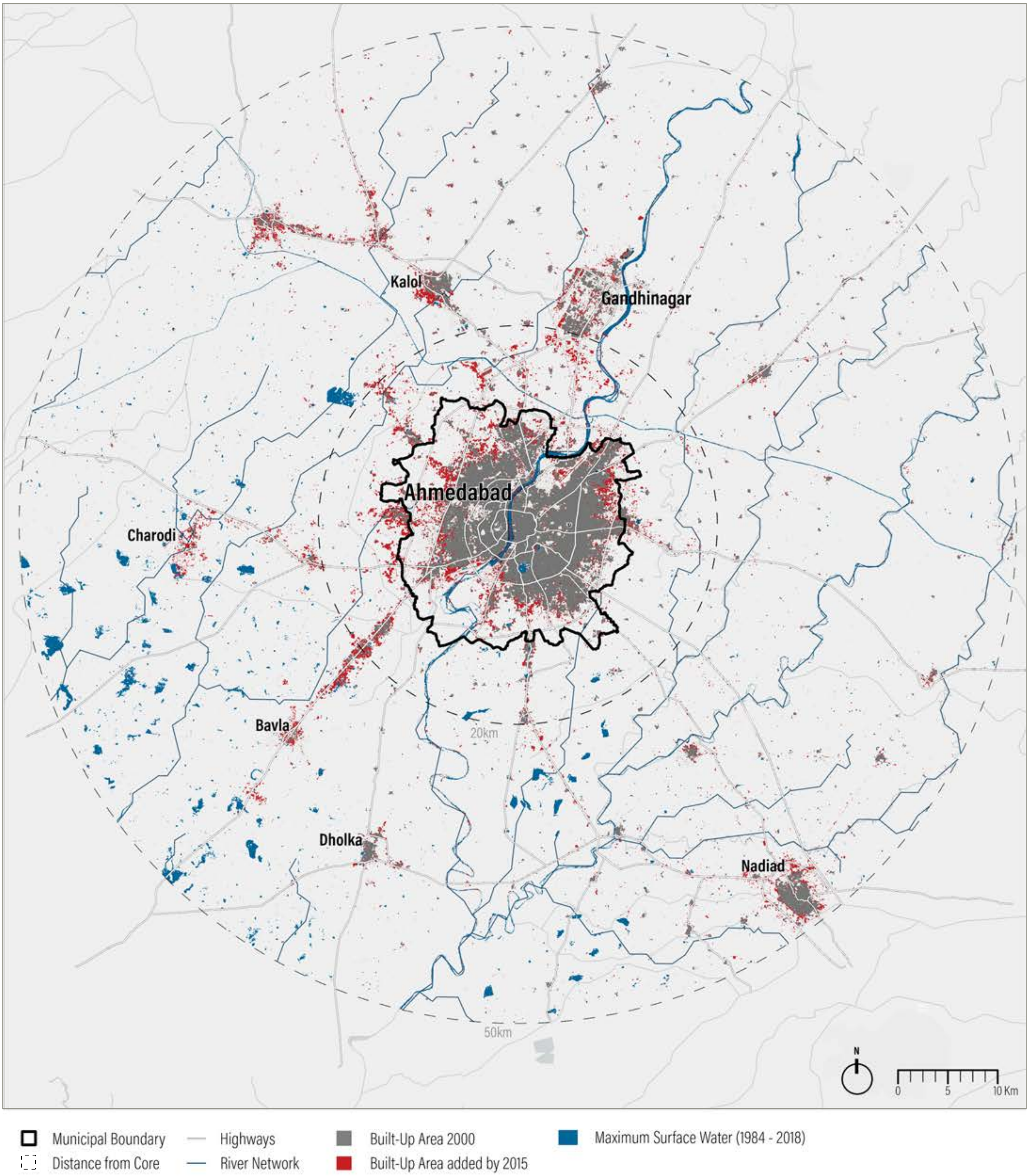
Similarly, the natural recharge rate is also determined by the lithological profile. In the case of Bengaluru, Subhash Chandra and Hegde (2014) state that a layer of clay in the Dakshina Pinakini zone prevents natural recharge beyond 6 m. They argue that the natural recharge rate for Bengaluru city as a whole is between 3 percent and 8 percent, and Muddu et al. argue it is closer to 15 percent (2017).

In this study, factors such as the on-ground characteristics of soil types are not considered. We limit the variables to slope and vegetation (as assessed by the NDVI). We assume recharge coefficients conservatively as only two variables are considered, and to account for the variations in soil type and aquifer type across the study cities, we use a range from very low (5 percent) to very high (25 percent); built-up area is also assigned a 2 percent recharge coefficient rate (see Table G1). The ascribed recharge rates are similar to the recharge rates assigned to various soil types by the Central Ground Water Board.

The rainfall number used is 80 percent of the annual average for 1989–2018 for each city. All cities except Chennai get most (about 80 percent) of their annual rainfall in the pre-monsoon and monsoon seasons. In Chennai, the 80 percent rate corresponds to the monsoon and return monsoon rainfall numbers (see Table G2).

APPENDIX H BUILT-UP AREA MAPS

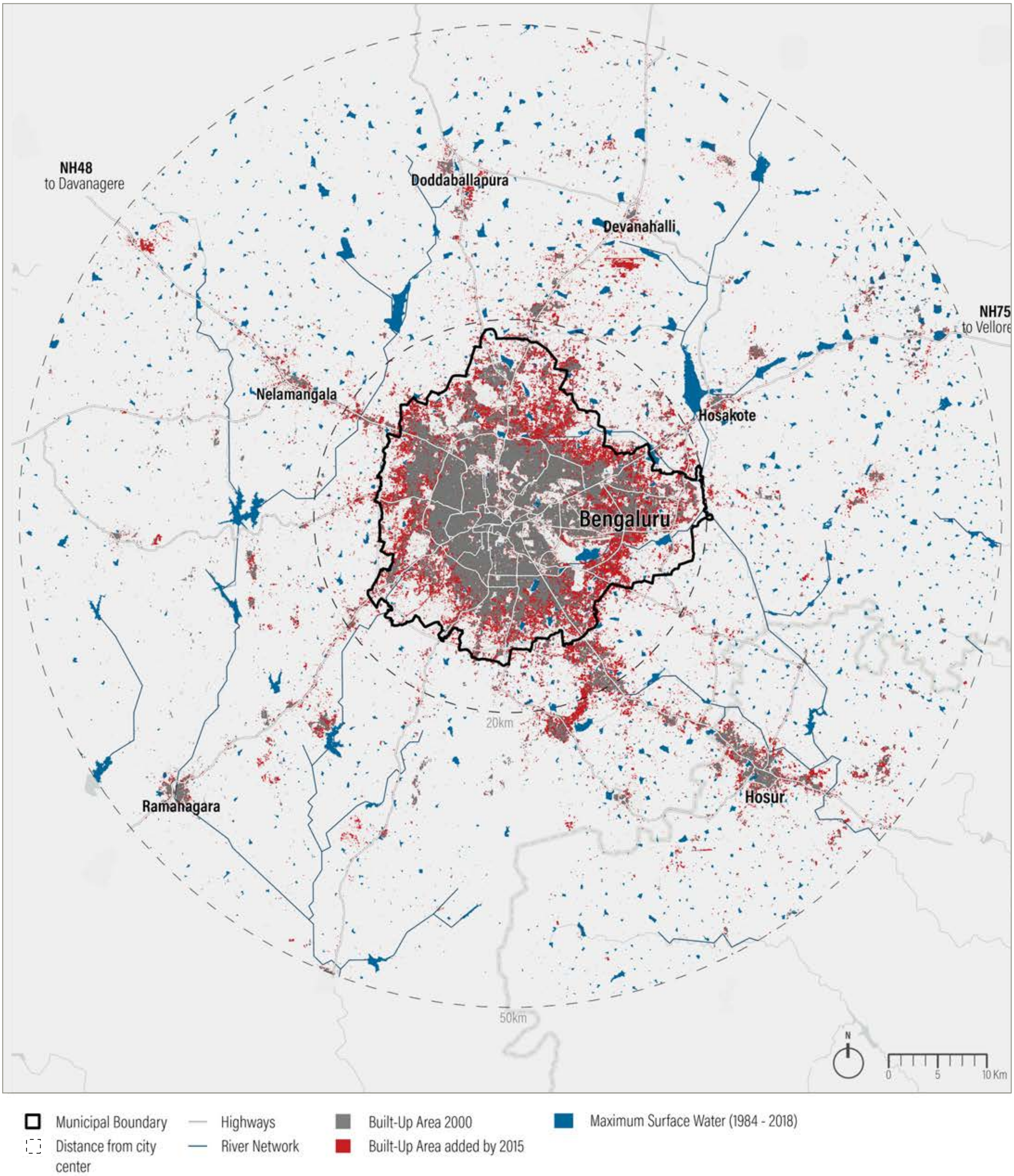
Figure H1 | **Built-Up Area in Ahmedabad Increased by 46% in the 0–50 km Region between 2000 and 2015**



Notes: Higher proportion of new development is distributed in core areas with 54 percent of new development in the 0–20 km region as compared to 43 percent in the 20–50 km region.

Sources: Built-up area – European Commission 2016; Maximum Surface Water – EC-JRC/Google n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

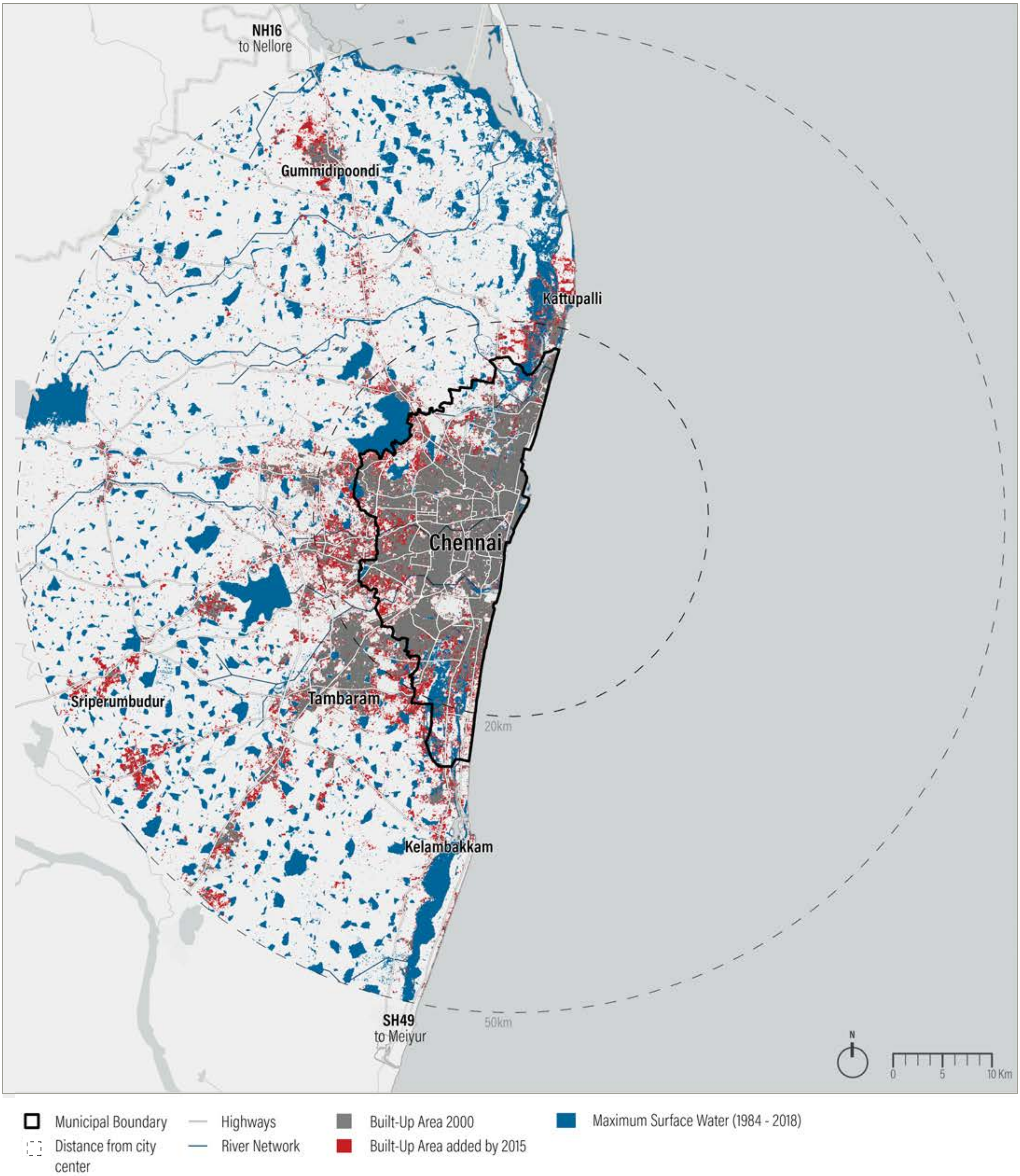
Figure H2 | **Built-Up Area in Bengaluru Increased by 76% in the 0–50 km Region between 2000 and 2015**



Notes: Around 200 sq. km of built-up area has been added in the core area (0–20 km); in peripheral areas development is clustered along road networks.

Sources: Built-up area – European Commission 2016; Maximum Surface Water – EC-JRC/Google n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

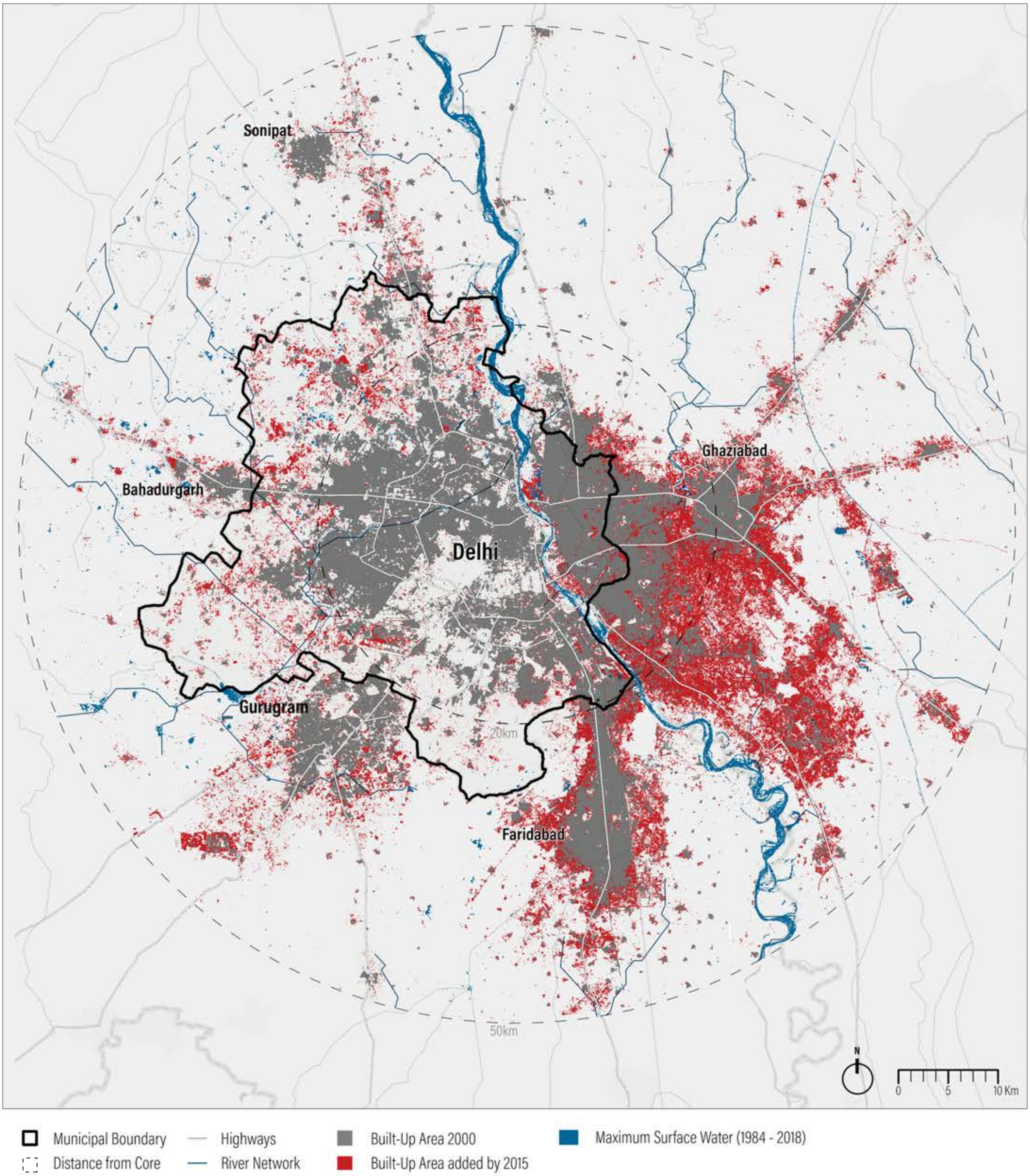
Figure H3 | **Built-Up Area in Chennai Increased by 61% in the 0–50 km Region between 2000 and 2015**



Notes: Two-thirds of the development added between 2000 and 2015 is in the peripheral zone.

Sources: Built-up area – European Commission 2016; Maximum Surface Water – EC-JRC/Google n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

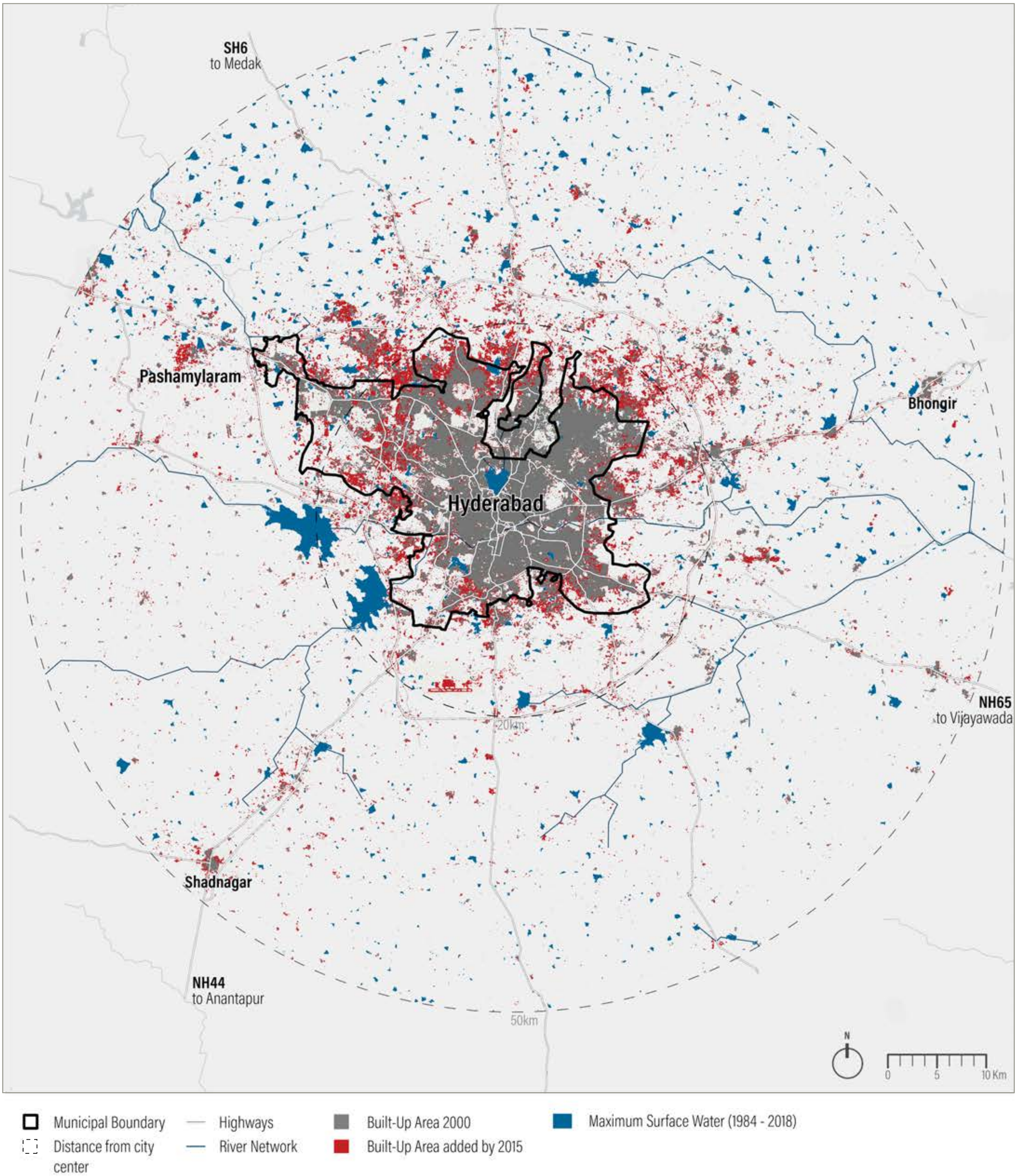
Figure H4 | **Built-Up Area in Delhi Increased by 61% in the 0–50 km Region between 2000 and 2015**



Notes: 80% of new development in Delhi is in the peripheral (20–50 km) region with a significant portion to the east of Yamuna River.

Sources: Built-up area – European Commission 2016; Maximum Surface Water – EC-JRC/Google n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

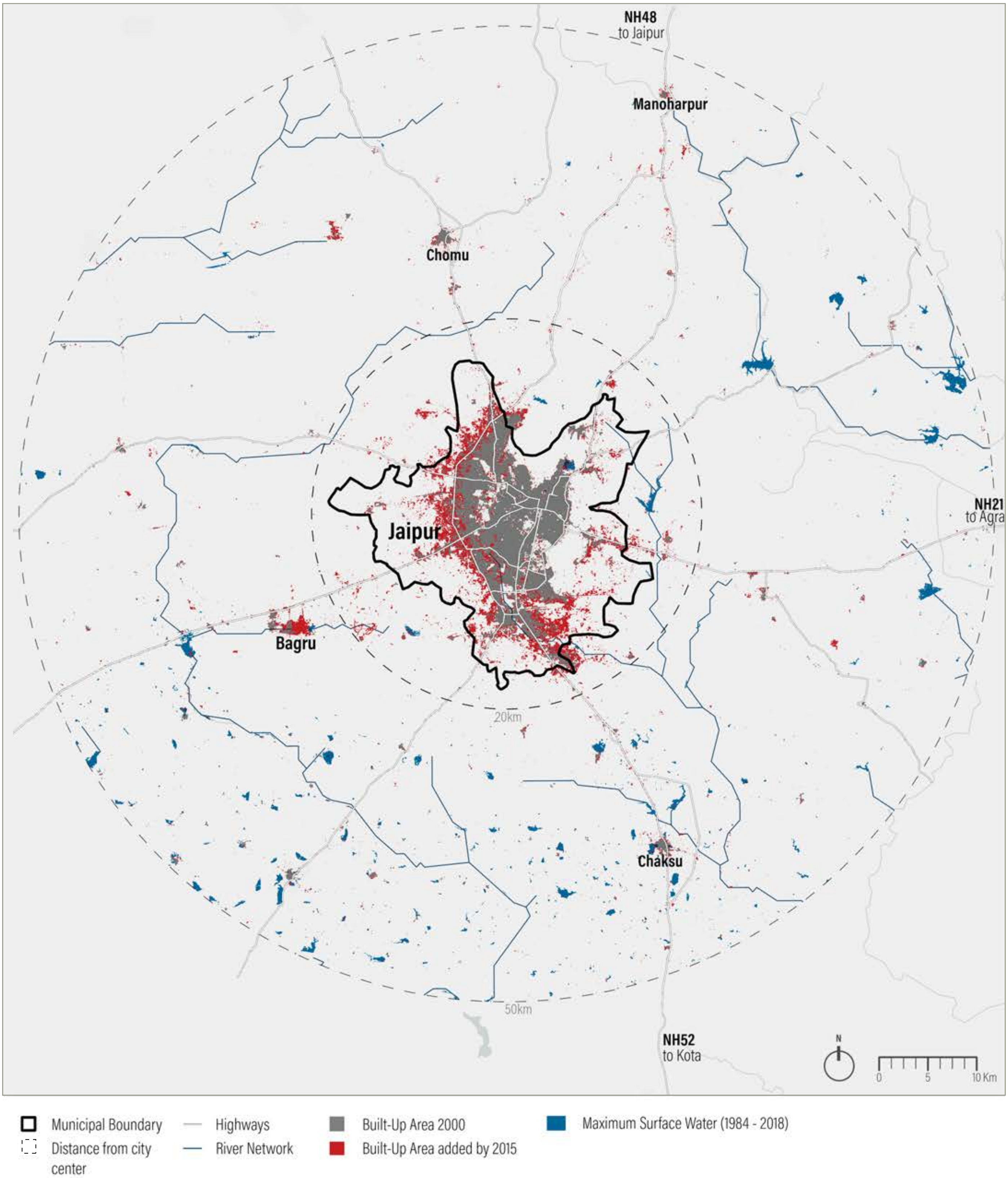
Figure H5 | **Built-Up Area in Hyderabad Increased by 60% in the 0–50 km Region between 2000 and 2015**



Notes: About 150 sq. km of built-up area has been added in the 20–50 km region; this is a 129 percent increase in the 15-year study period.

Sources: Built-up area – European Commission 2016; Maximum Surface Water – EC-JRC/Google n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

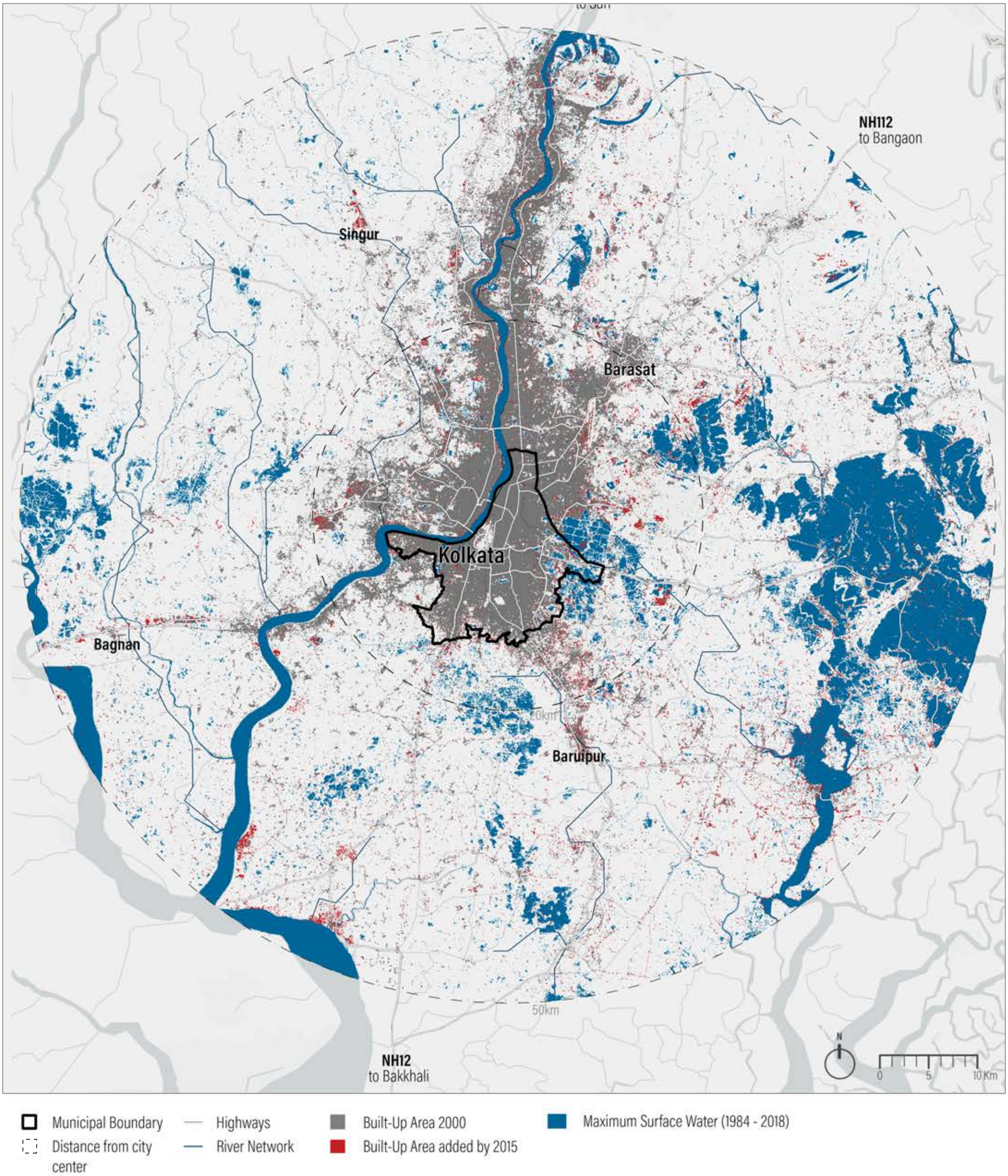
Figure H6 | **Built-Up Area in Jaipur Increased by 61% in the 0–50 km Region between 2000 and 2015**



Notes: Almost 80 percent of new built-up area is in the 0–20 km region for Jaipur.

Sources: Built-up area – European Commission 2016; Maximum Surface Water – EC-JRC/Google n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

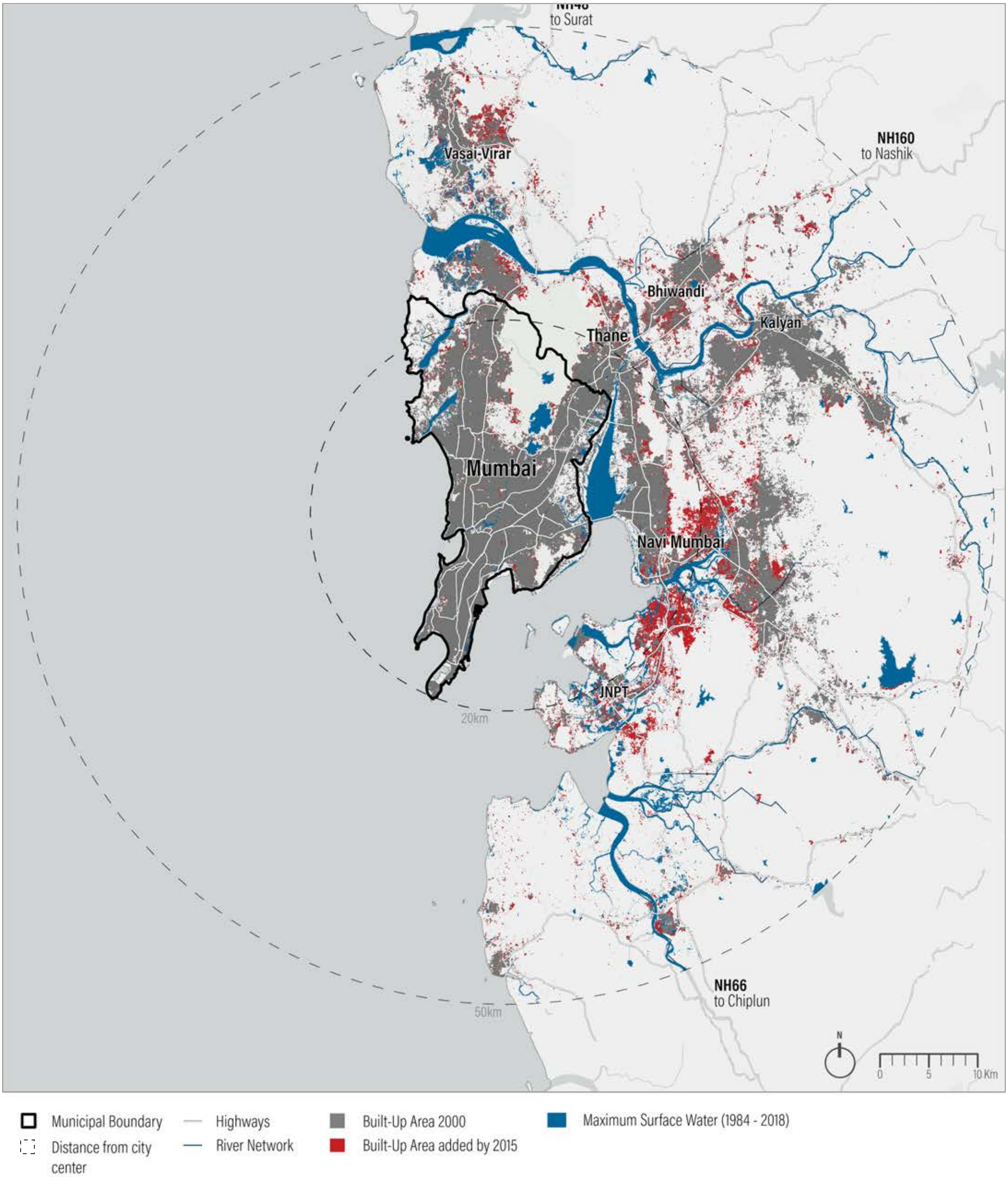
Figure H7 | **Built-Up Area in Kolkata Increased by 19% in the 0–50 km Region between 2000 and 2015**



Notes: Kolkata has added 50 sq. km and 118 sq. km in the 0–20 km and 20–50 km regions accounting for a 10 percent and 30 percent increase in the respective regions.

Sources: Built-up area – European Commission 2016; Maximum Surface Water – EC-JRC/Google n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

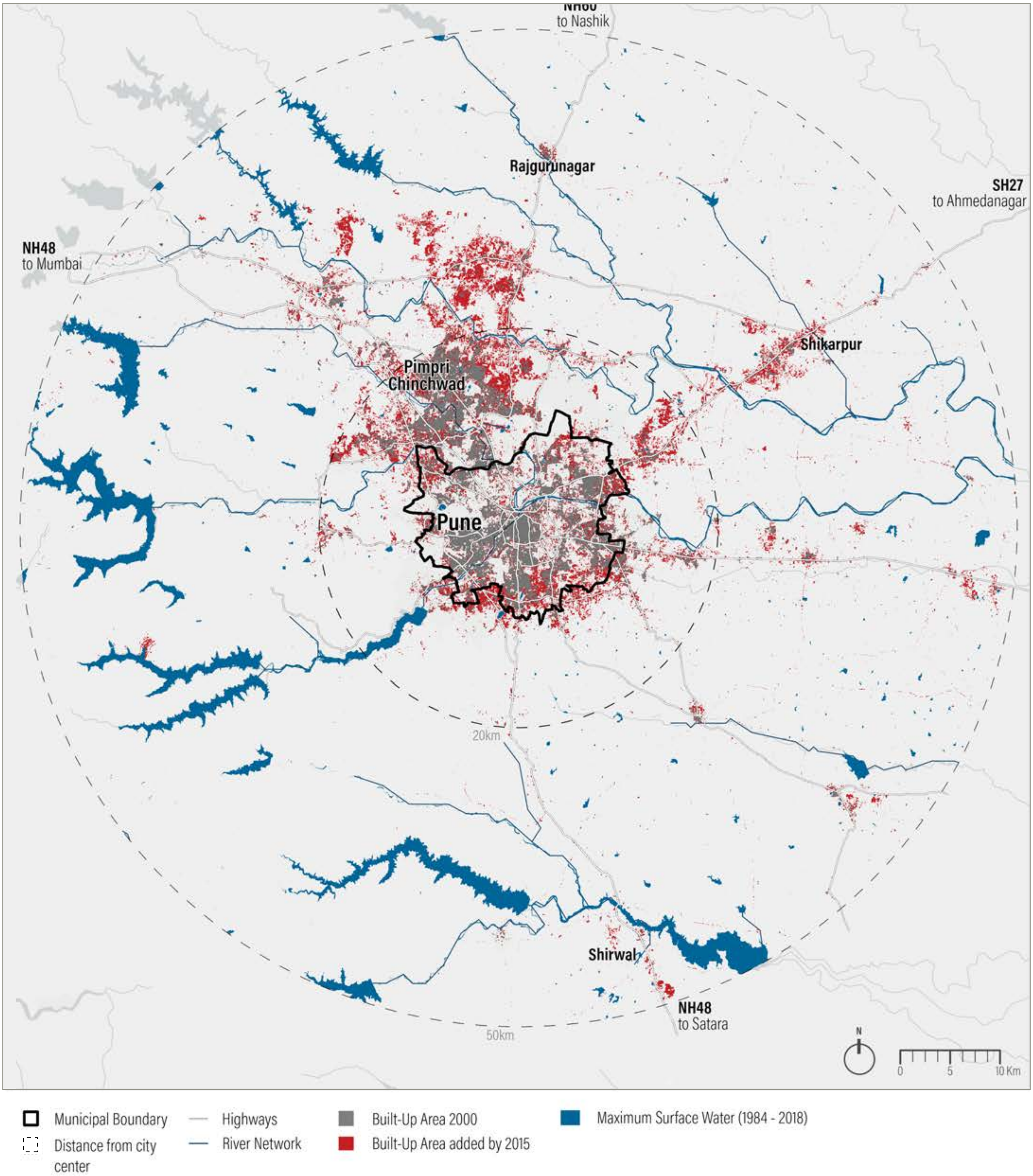
Figure H8 | **Built-Up Area in Mumbai Increased by 20% in the 0–50 km Region between 2000 and 2015**



Notes: Around 75 percent of new development in Mumbai has been added in the 20–50 km region.

Sources: Built-up area – European Commission 2016; Maximum Surface Water – EC-JRC/Google n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

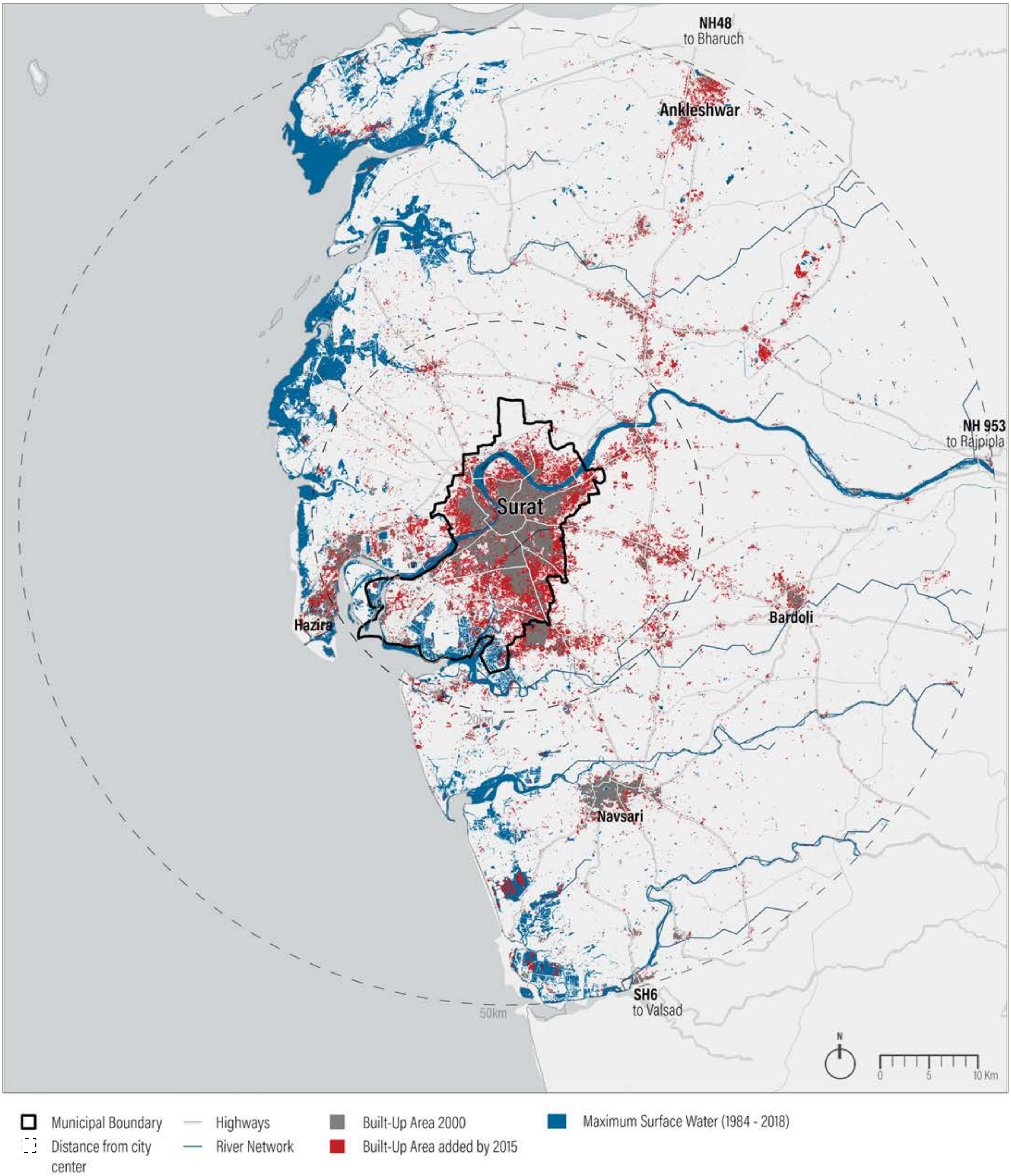
Figure H9 | **Built-Up Area in Pune Increased by 118% in the 0–50 km Region between 2000 and 2015**



Notes: Pune increased from 25 sq. km to 126 sq. km in the 20–50 km region which is a 412 percent increase in built-up area.

Sources: Built-up area – European Commission 2016; Maximum Surface Water – EC-JRC/Google n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

Figure H10 | **Built-Up Area in Surat Increased by 139% in the 0–50 km Region between 2000 and 2015**

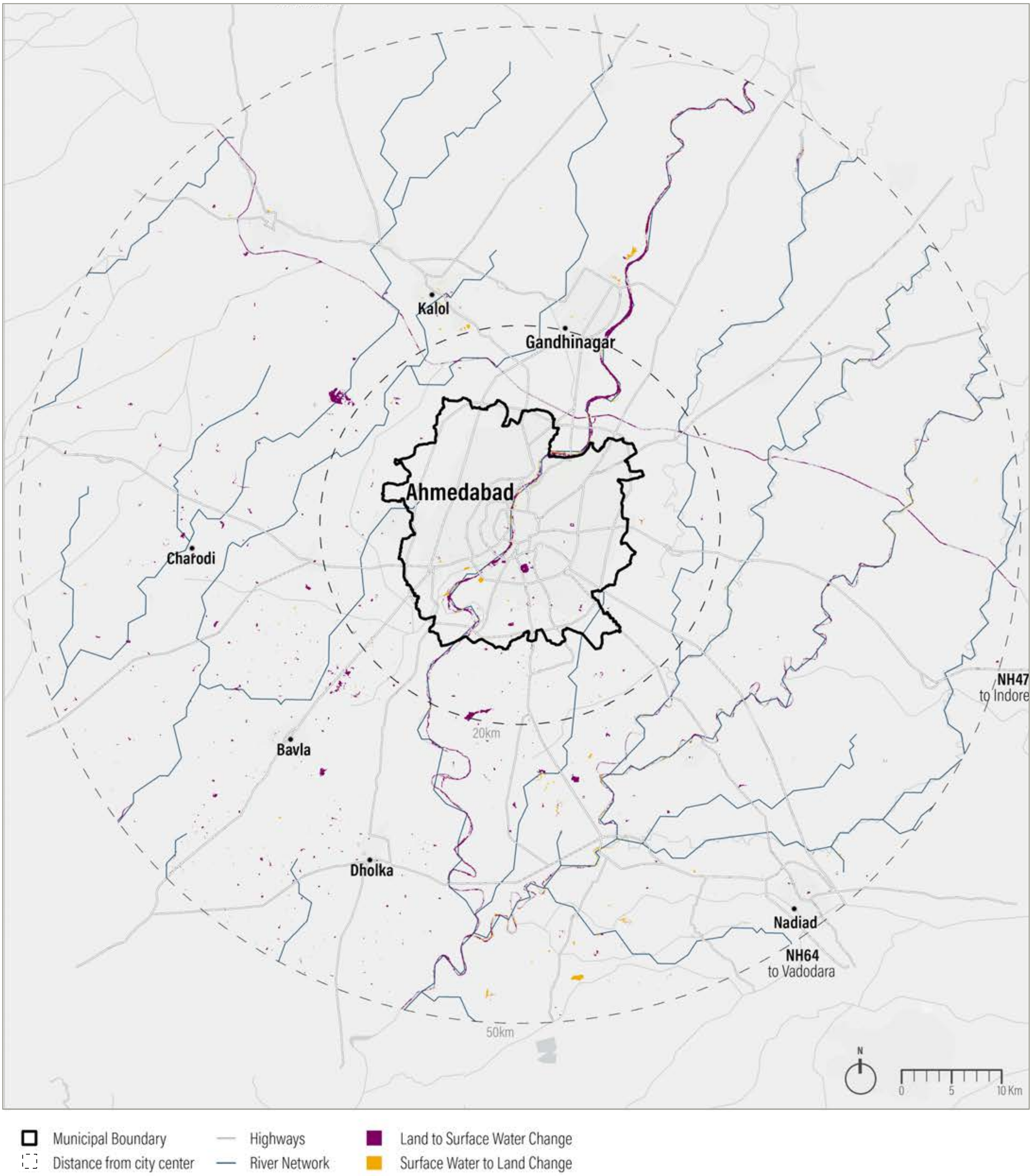


Notes: In Surat, 64 percent of new development is sited in the 0–20 km region.

Sources: Built-up area – European Commission 2016; Maximum Surface Water – EC-JRC/Google n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

APPENDIX I BLUE COVER CHANGE MAPS

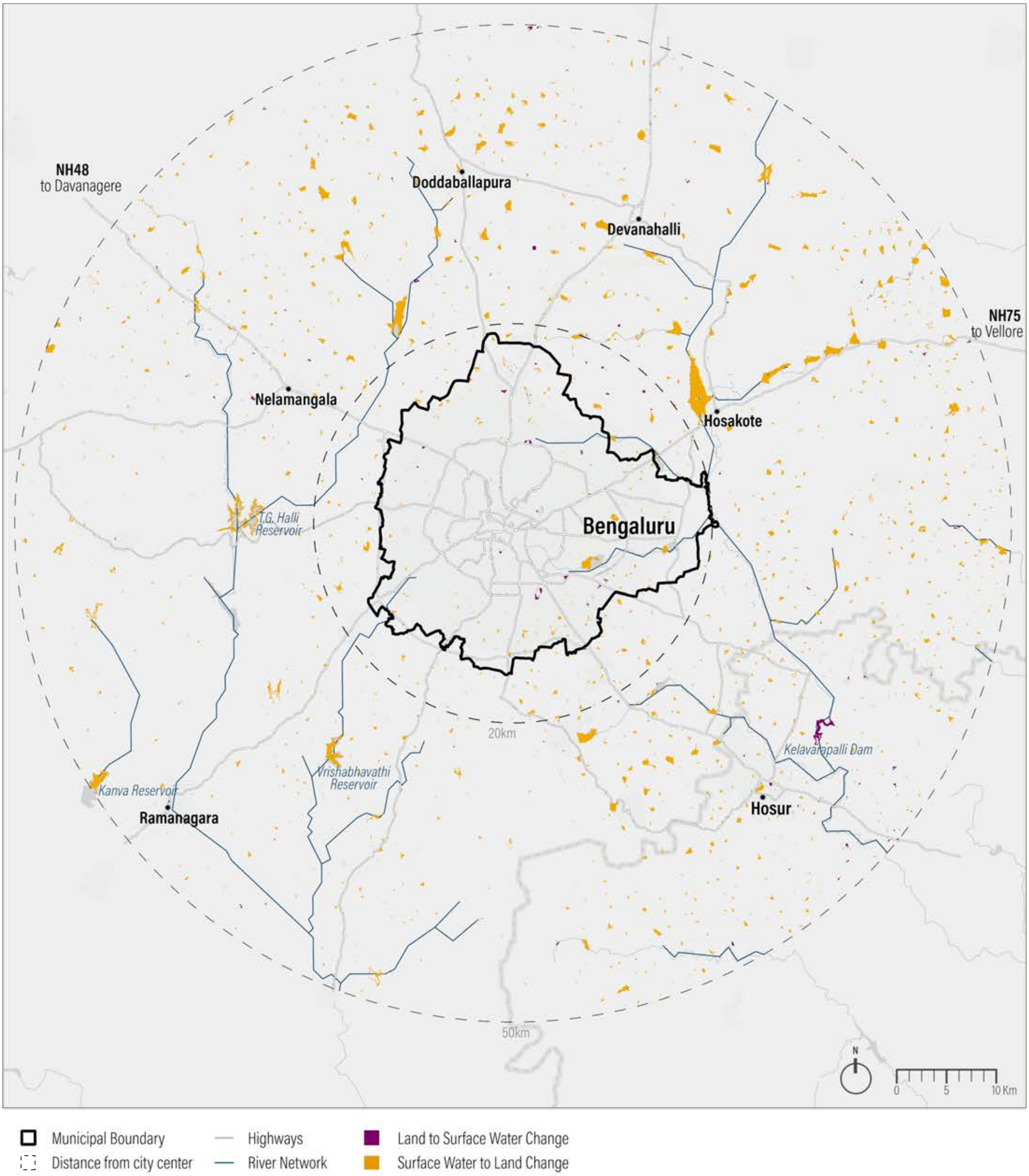
Figure I1 | **Blue Cover Increased by 143% in Ahmedabad in the 0–50 km Region between 2000 and 2015**



Notes: Only land-to-surface-water and surface-water-to-land changes are indicated in this map. Water bodies that show no change between the two study epochs are not shown here.

Sources: Surface Water Extent – USGS n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

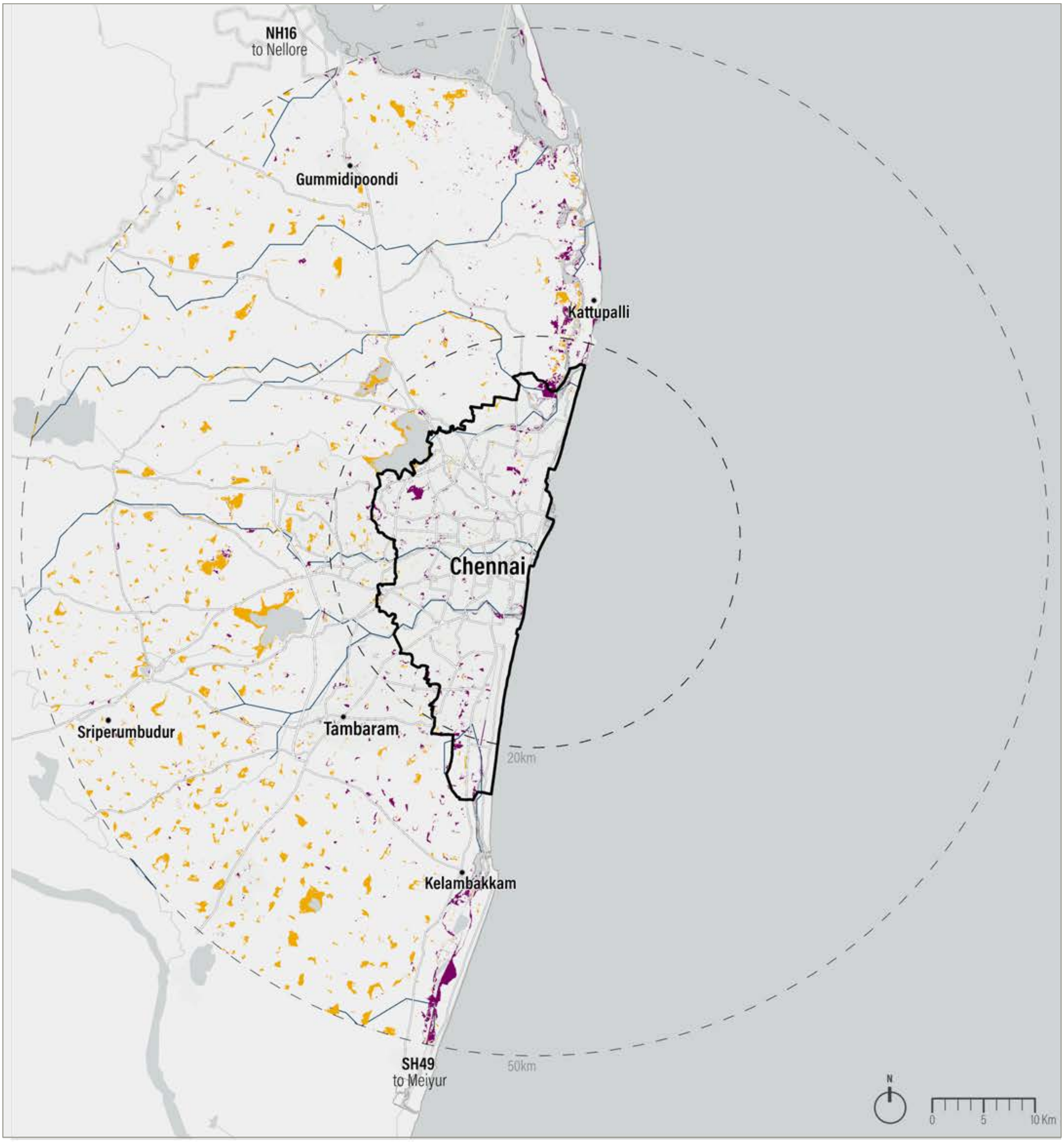
Figure I2 | **Blue Cover Decreased by 74% in Bengaluru in the 0–50 km Region between 2000 and 2015**



Notes: Only land-to-surface-water and surface-water-to-land changes are indicated in this map. Water bodies that show no change between the two study epochs are not shown here.

Sources: Surface Water Extent – USGS n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

Figure I3 | **Blue Cover Decreased by 26% in Chennai in the 0–50 km Region between 2000 and 2015**

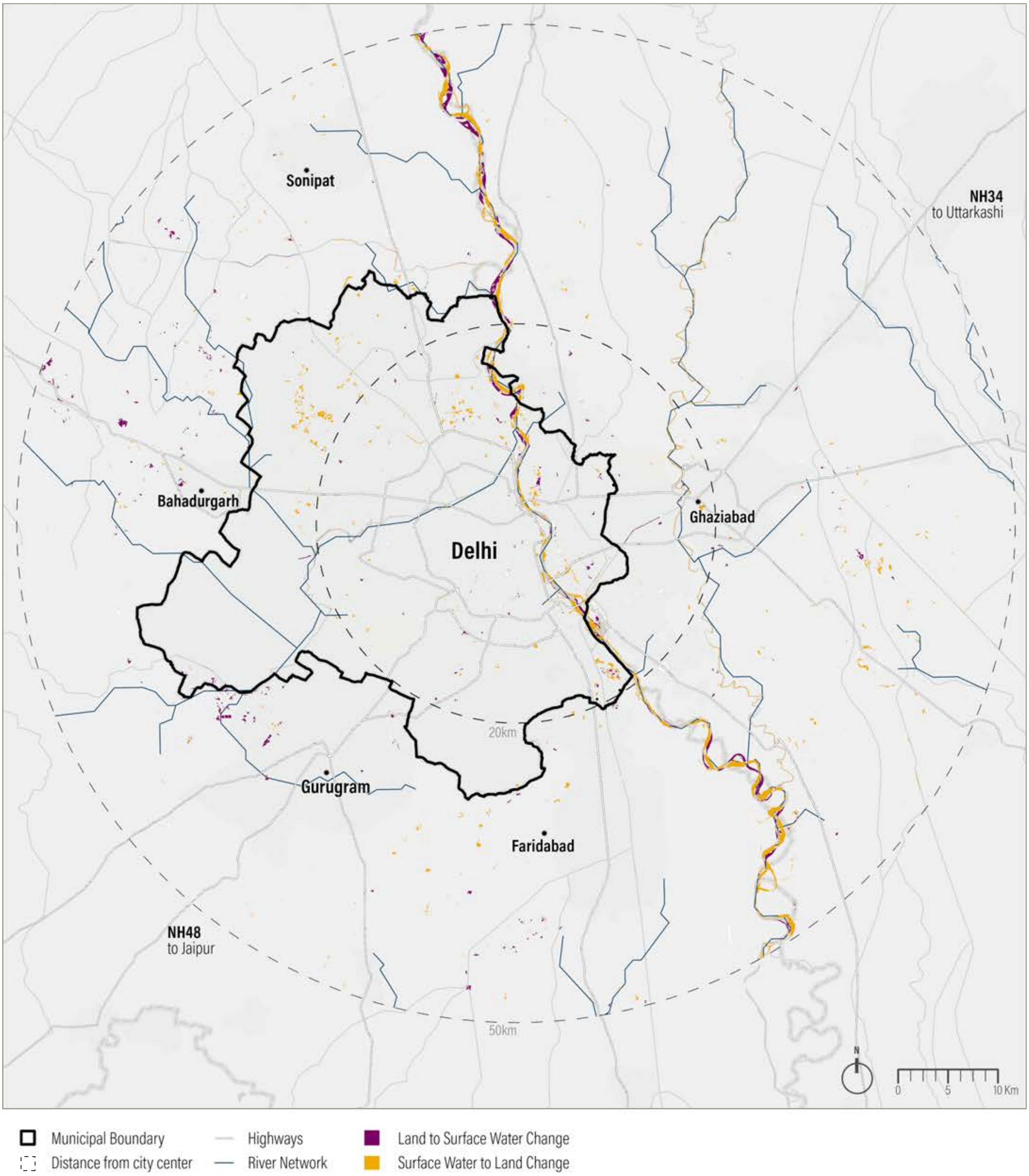


Municipal Boundary
Distance from city center
Highways
River Network
Land to Surface Water Change
Surface Water to Land Change

Notes: Only land-to-surface-water and surface-water-to-land changes are indicated in this map. Water bodies that show no change between the two study epochs are not shown here.

Sources: Surface Water Extent – USGS n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

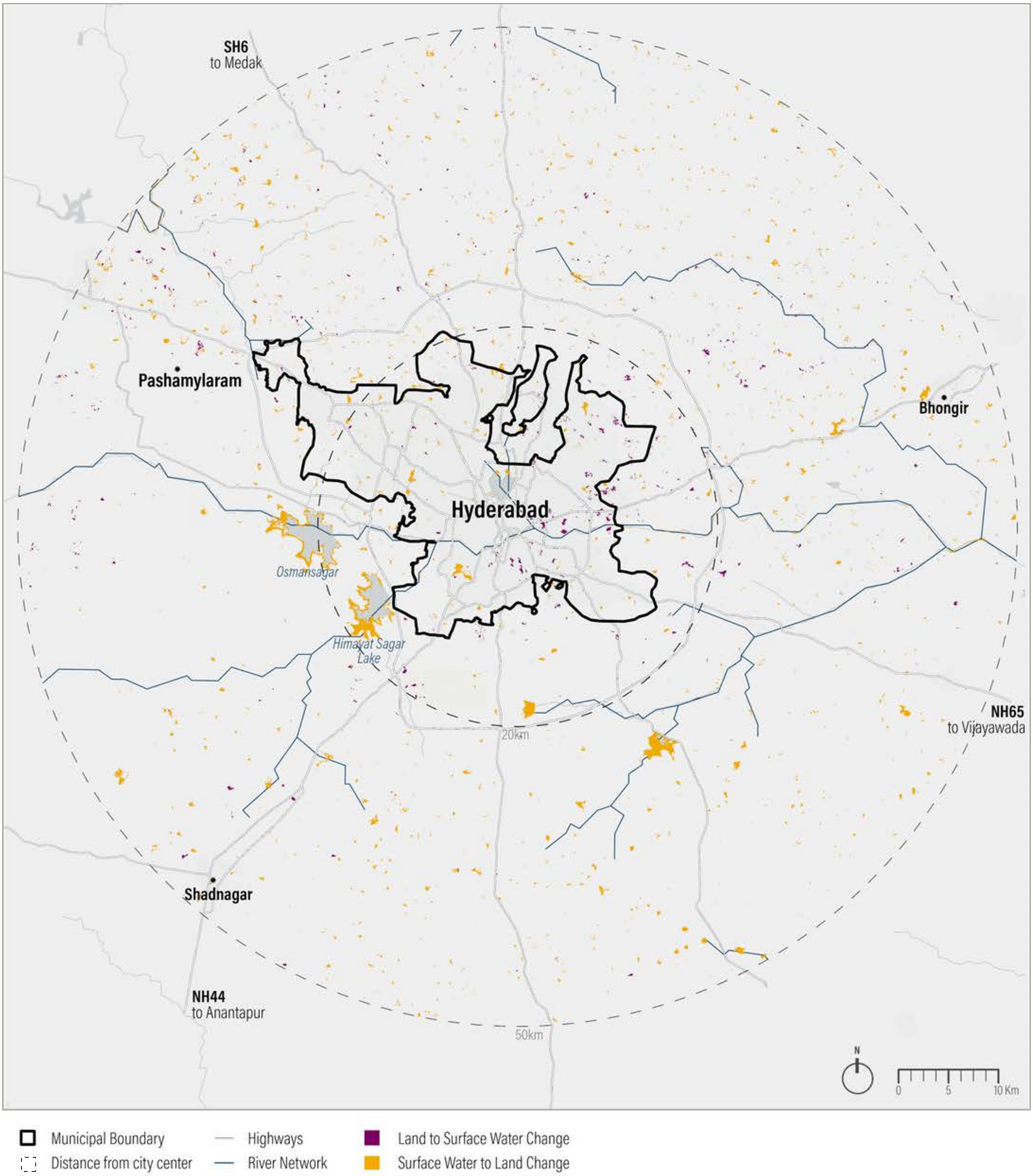
Figure I4 | **Blue Cover Decreased by 36% in Delhi in the 0–50 km Region between 2000 and 2015**



Notes: Only land-to-surface-water and surface-water-to-land changes are indicated in this map. Water bodies that show no change between the two study epochs are not shown here.

Sources: Surface Water Extent – USGS n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

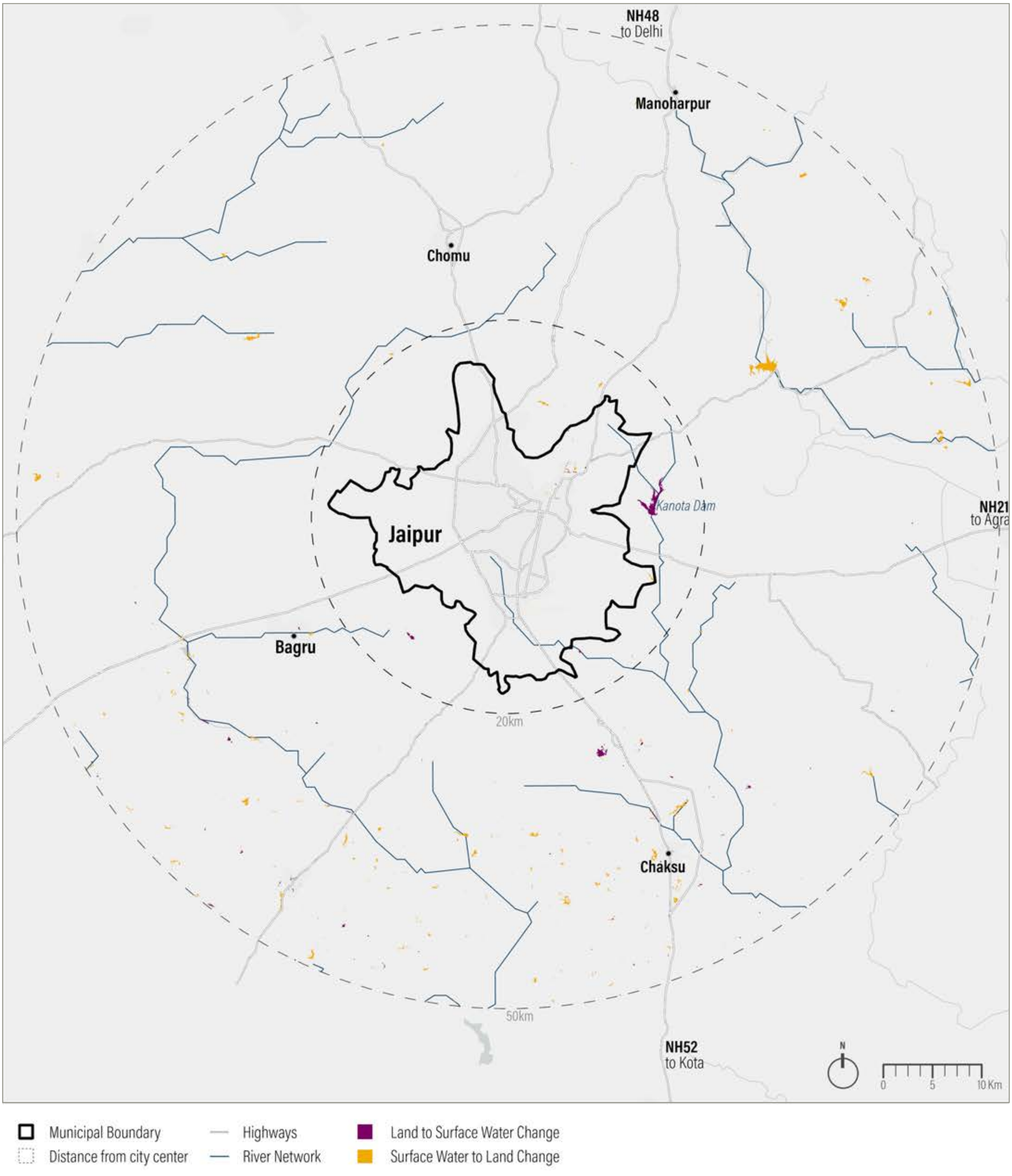
Figure I5 | **Blue Cover Decreased by 37% in Hyderabad in the 0–50 km Region between 2000 and 2015**



Notes: Only land-to-surface-water and surface-water-to-land changes are indicated in this map. Water bodies that show no change between the two study epochs are not shown here..

Sources: Surface Water Extent – USGS n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

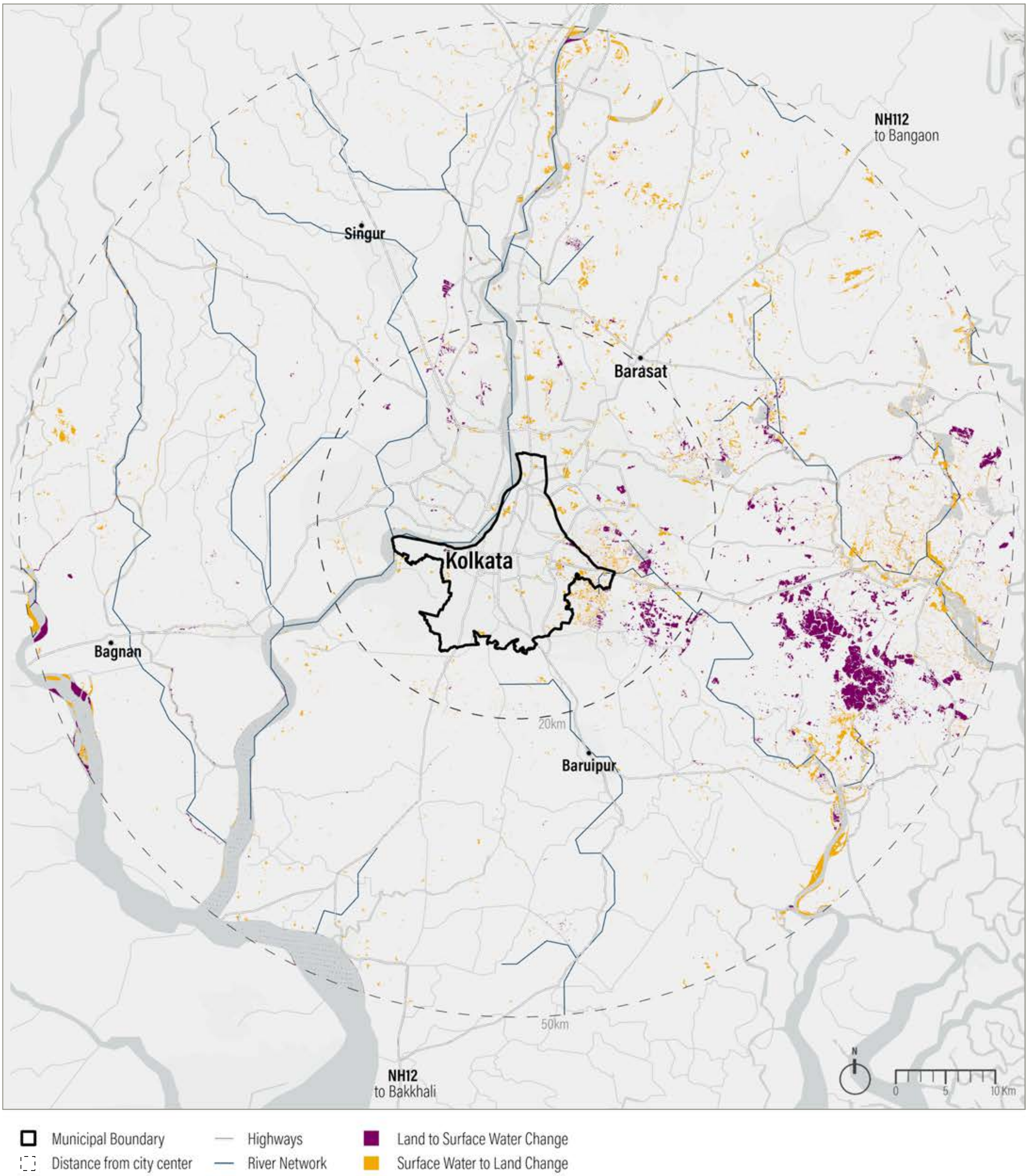
Figure I6 | **Blue Cover Decreased by 46% in Jaipur in the 0–50 km Region between 2000 and 2015**



Notes: Only land-to-surface-water and surface-water-to-land changes are indicated in this map. Water bodies that show no change between the two study epochs are not shown here.

Sources: Surface Water Extent – USGS n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

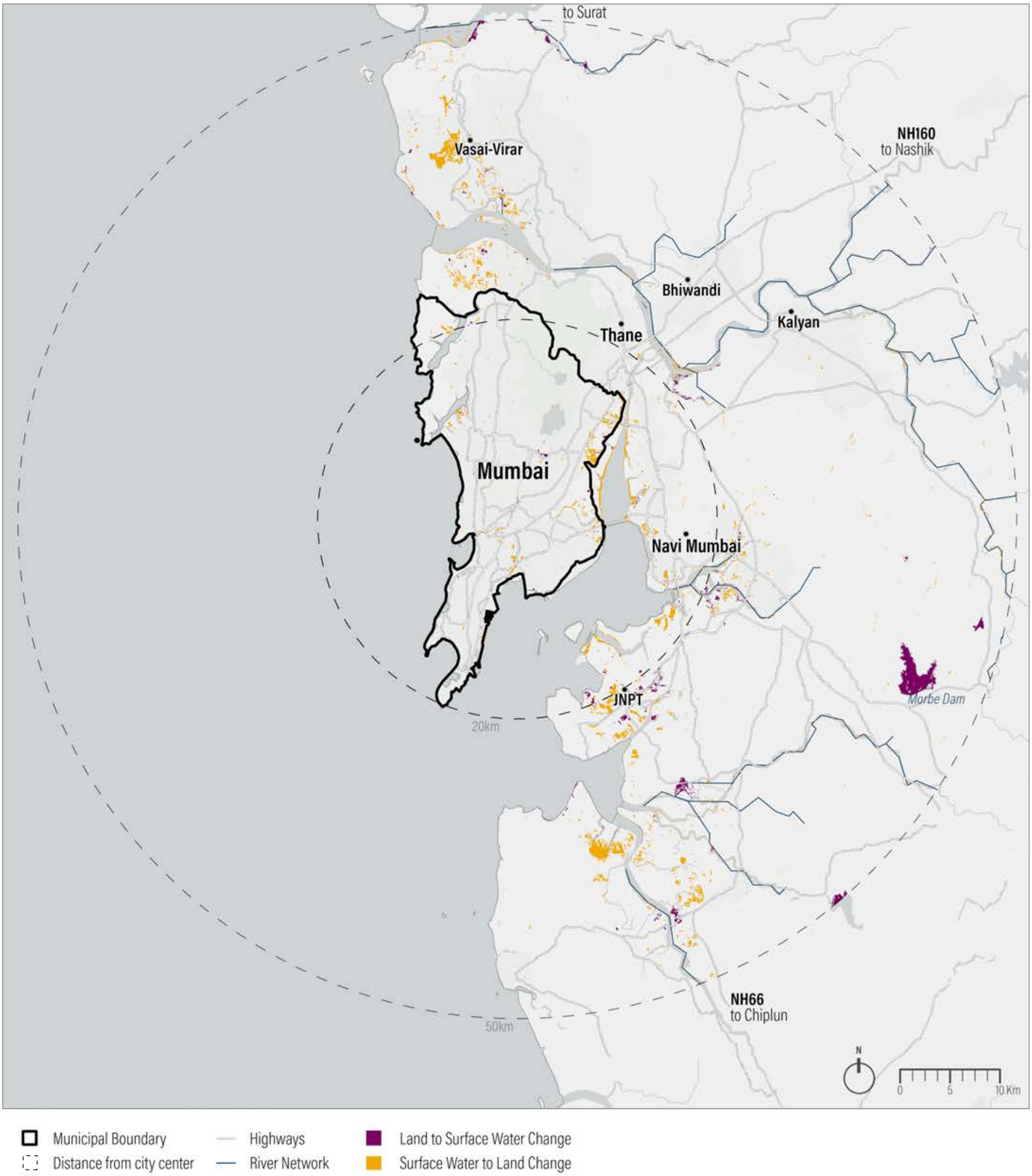
Figure I7 | **Blue Cover Decreased by 5% in Kolkata in the 0–50 km Region between 2000 and 2015**



Notes: Only land-to-surface-water and surface-water-to-land changes are indicated in this map. Water bodies that show no change between the two study epochs are not shown here.

Sources: Surface Water Extent – USGS n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

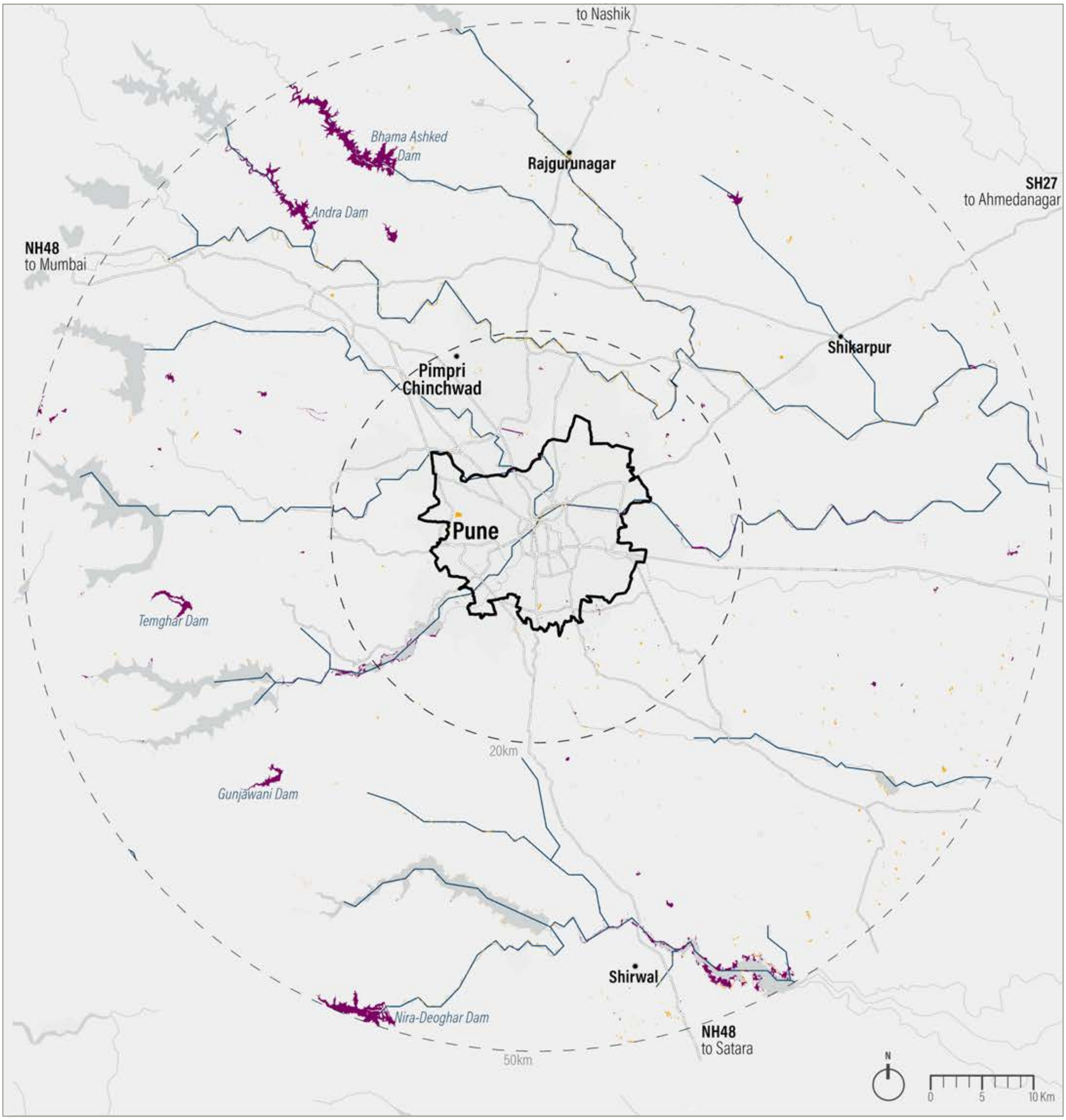
Figure I8 | **Blue Cover Decreased by 19% in Mumbai in the 0–50 km Region between 2000 and 2015**



Notes: Only land-to-surface-water and surface-water-to-land changes are indicated in this map. Water bodies that show no change between the two study epochs are not shown here.

Sources: Surface Water Extent – USGS n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

Figure I9 | **Blue Cover Increased by 16% in Pune in the 0–50 km Region between 2000 and 2015**

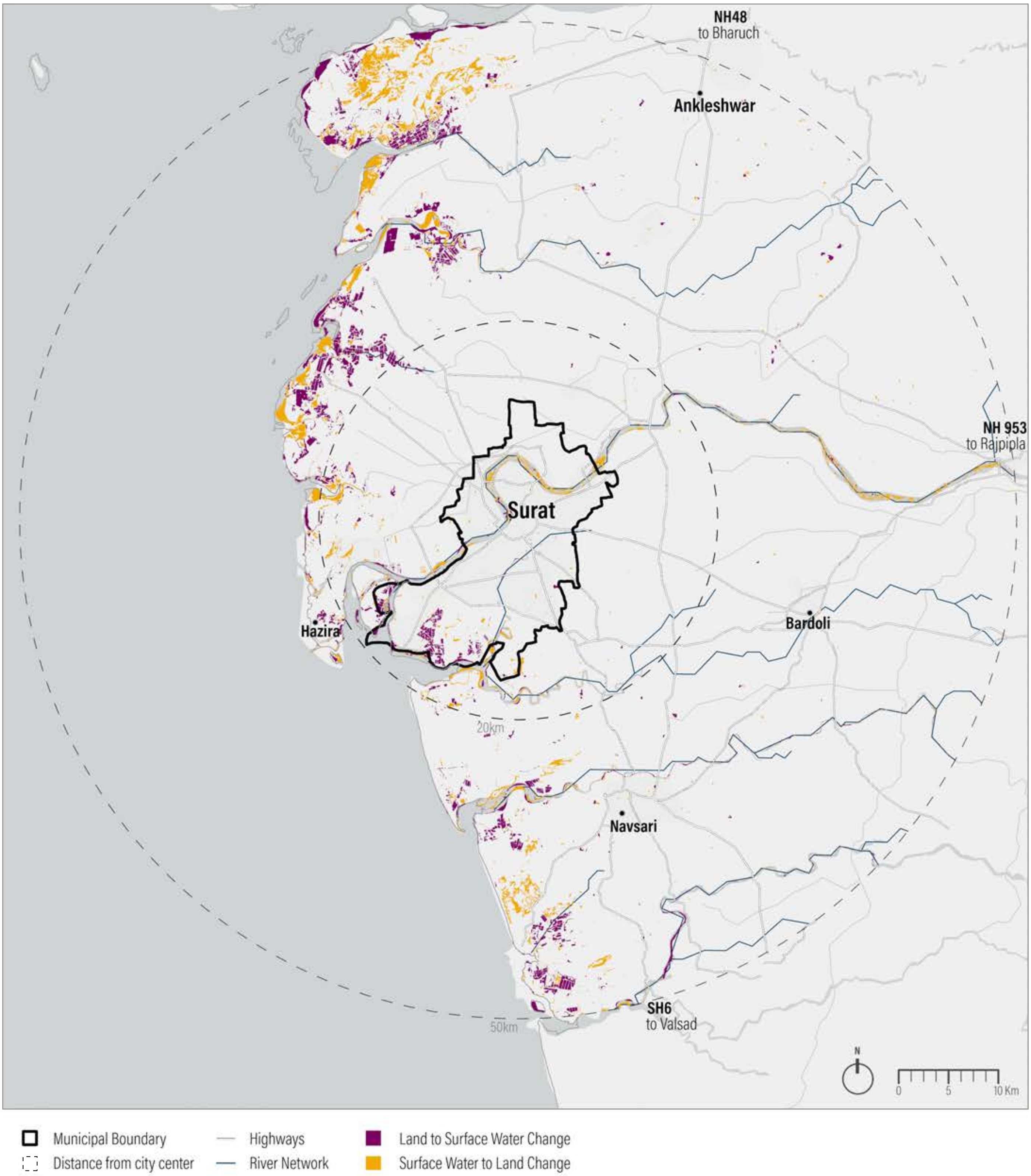


Municipal Boundary
Distance from city center
Highways
River Network
Land to Surface Water Change
Surface Water to Land Change

Notes: Only land-to-surface-water and surface-water-to-land changes are indicated in this map. Water bodies that show no change between the two study epochs are not shown here.

Sources: Surface Water Extent – USGS n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

Figure I10 | **Blue Cover Decreased by 1% in Surat in the 0–50 km Region between 2000 and 2015**

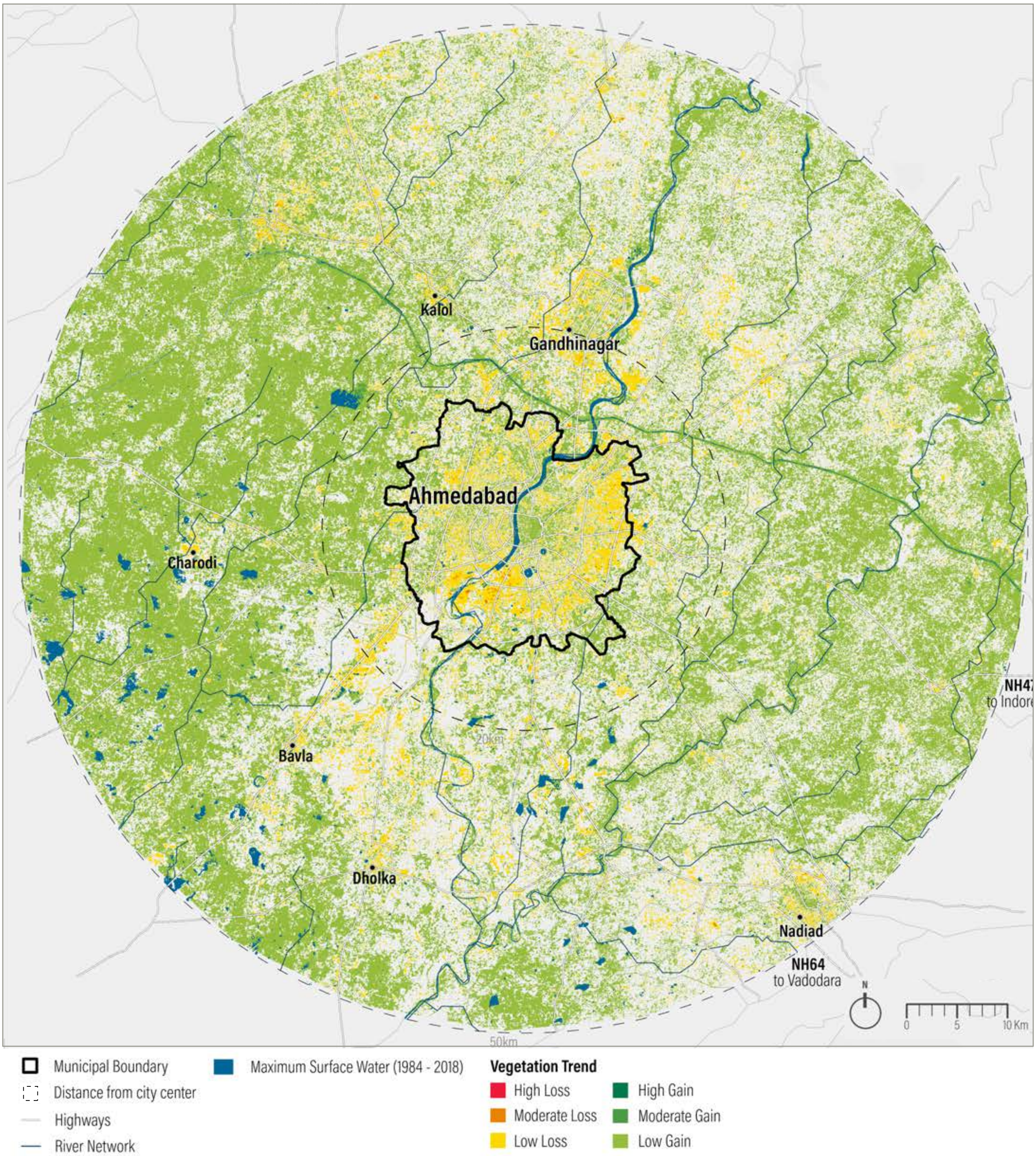


Notes: Only land-to-surface-water and surface-water-to-land changes are indicated in this map. Water bodies that show no change between the two study epochs are not shown here.

Sources: Surface Water Extent – USGS n.d.; River Network – FAO n.d.; Basemap – Esri, DeLorme, HERE, MapmyIndia.

APPENDIX J VEGETATION TREND MAPS

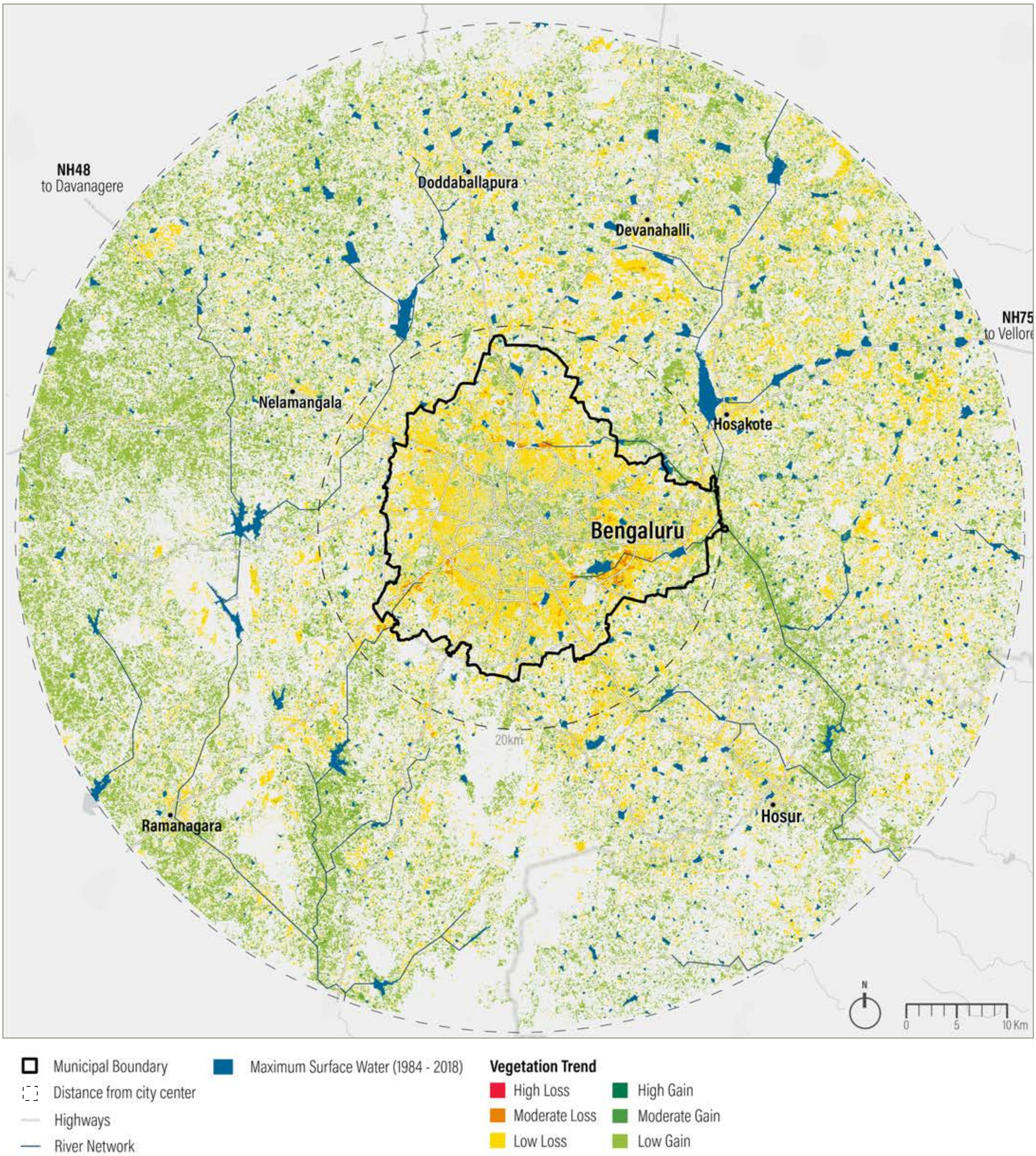
Figure J1 | **Ahmedabad Has a Net Positive Vegetation Trend of 3,163 sq. km in the 0-50 km Region between 2000 and 2015**



Notes: Only areas with vegetation change trends are indicated in color; areas in the study region where no change is detected is left blank.
In the Ahmedabad region, green cover has declined in 7 percent, increased in 47 percent and has no change in 46 percent of the total study area.

Sources: Vegetation Trend - NASA n.d.; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

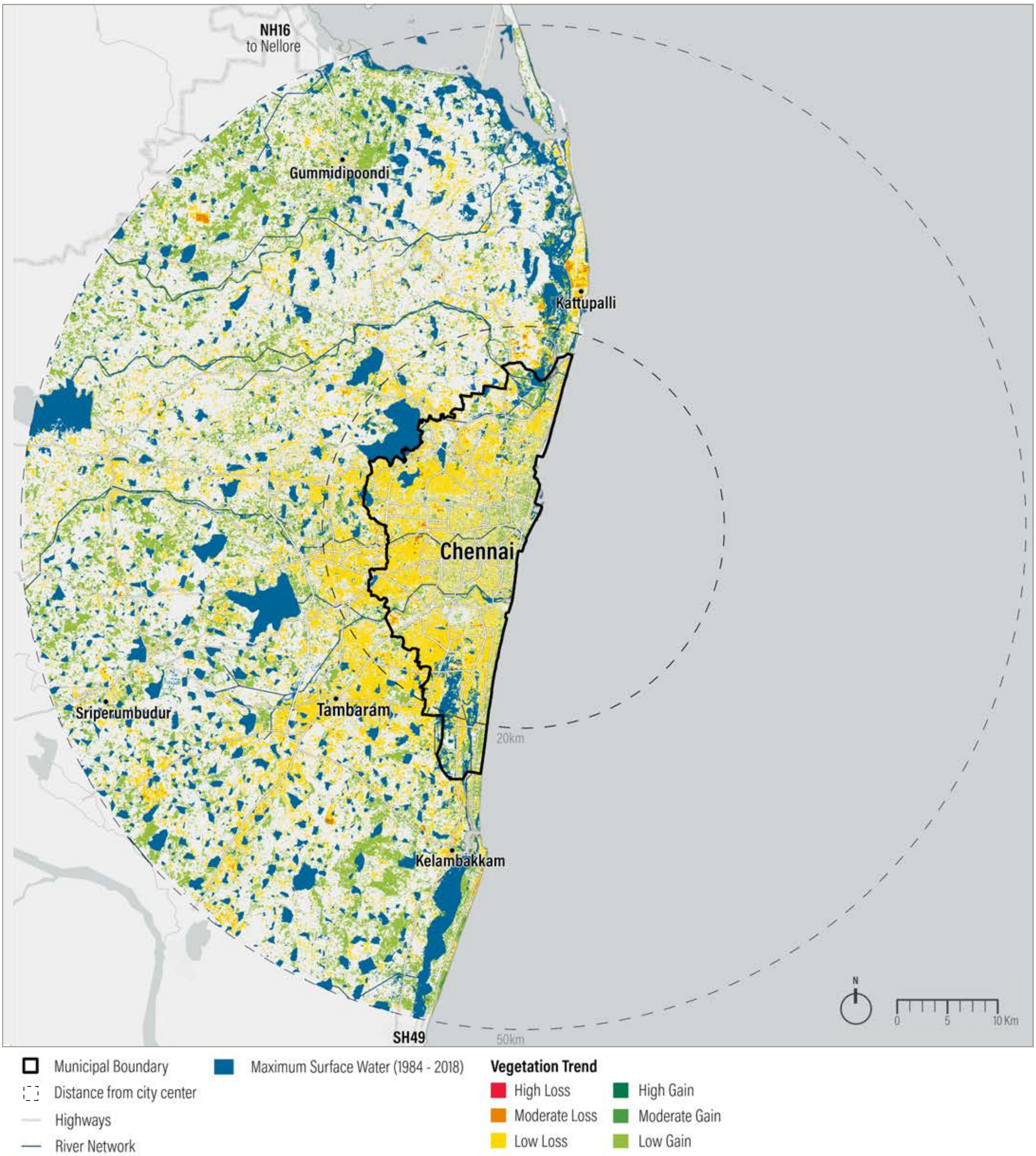
Figure J2 | **Bengaluru Has a Net Positive Vegetation Trend of 733 sq. km in the 0-50 km Region between 2000 and 2015**



Notes: Only areas with vegetation change trends are indicated in color; areas in the study region where no change is detected is left blank.
Bengaluru has net negative vegetation trend of 133 sq. km in the 0-20 km region and a net positive vegetation trend of 866 sq. km in the 20-50 km region.

Sources: Vegetation Trend - NASA n.d.; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

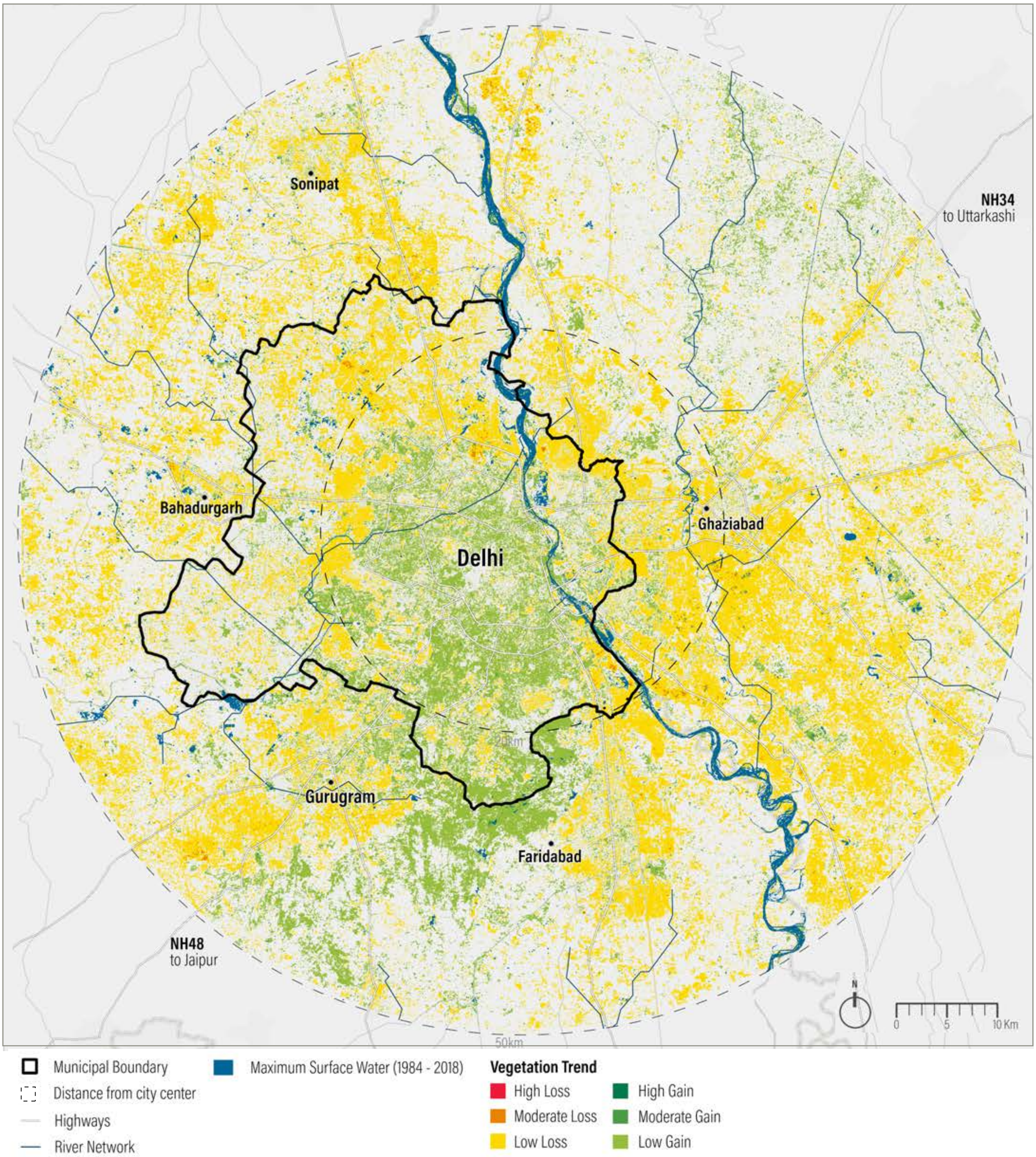
Figure J3 | **Chennai Has a Net Positive Vegetation Trend of 43 sq. km in the 0-50 km Region between 2000 and 2015**



Notes: Only areas with vegetation change trends are indicated in color; areas in the study region where no change is detected is left blank. About 70 percent of the study area around Chennai has seen no change in green cover.

Sources: Vegetation Trend - NASA n.d.; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

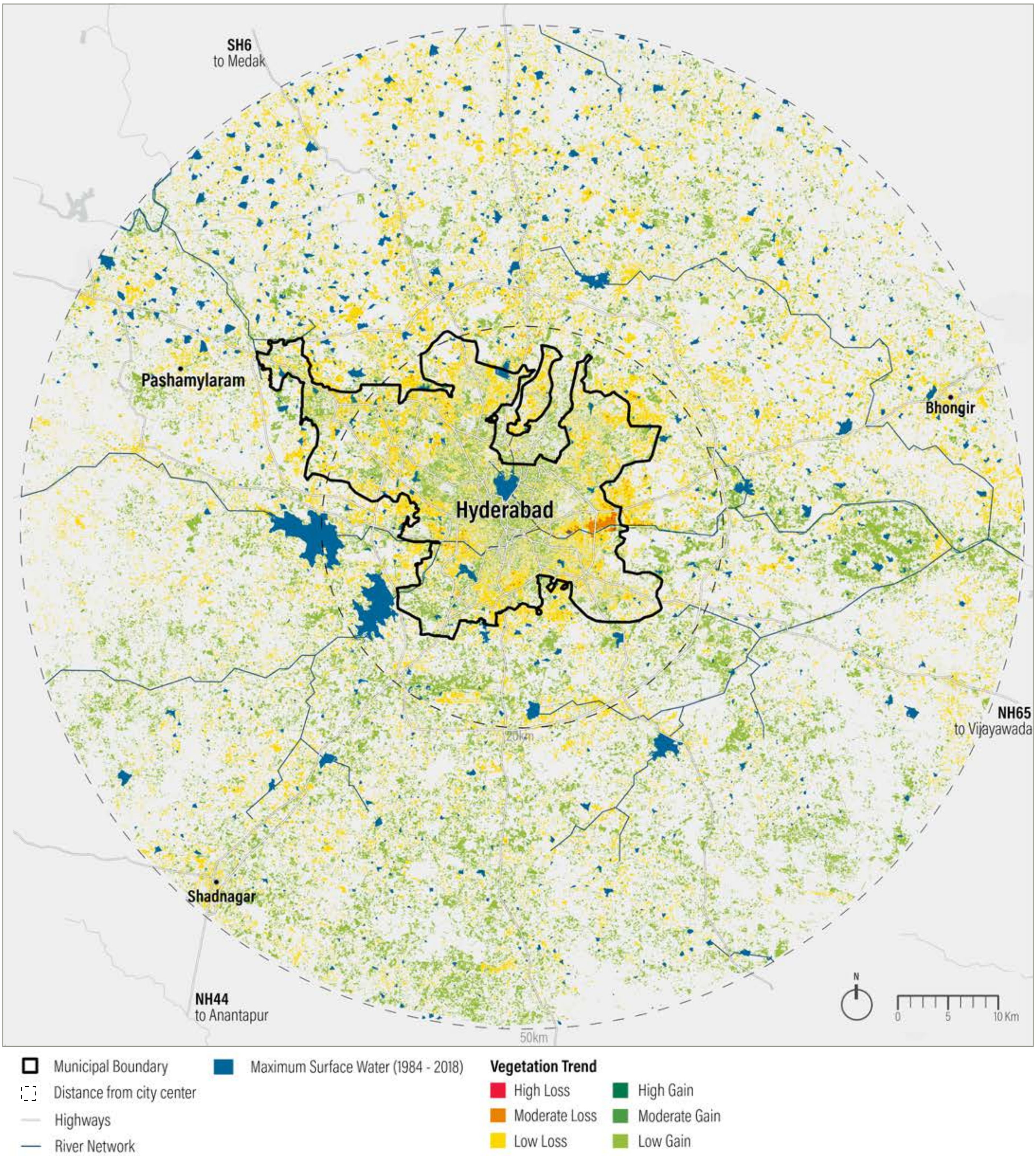
Figure J4 | **Delhi Has a Net Negative Vegetation Trend of 1,191 sq. km in the 0-50 km Region between 2000 and 2015**



Notes: Only areas with vegetation change trends are indicated in color; areas in the study region where no change is detected is left blank.
In Delhi the 1,200 sq. km with net negative vegetation trend is about a quarter of the 0-50 km study region.

Sources: Vegetation Trend - NASA n.d.; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

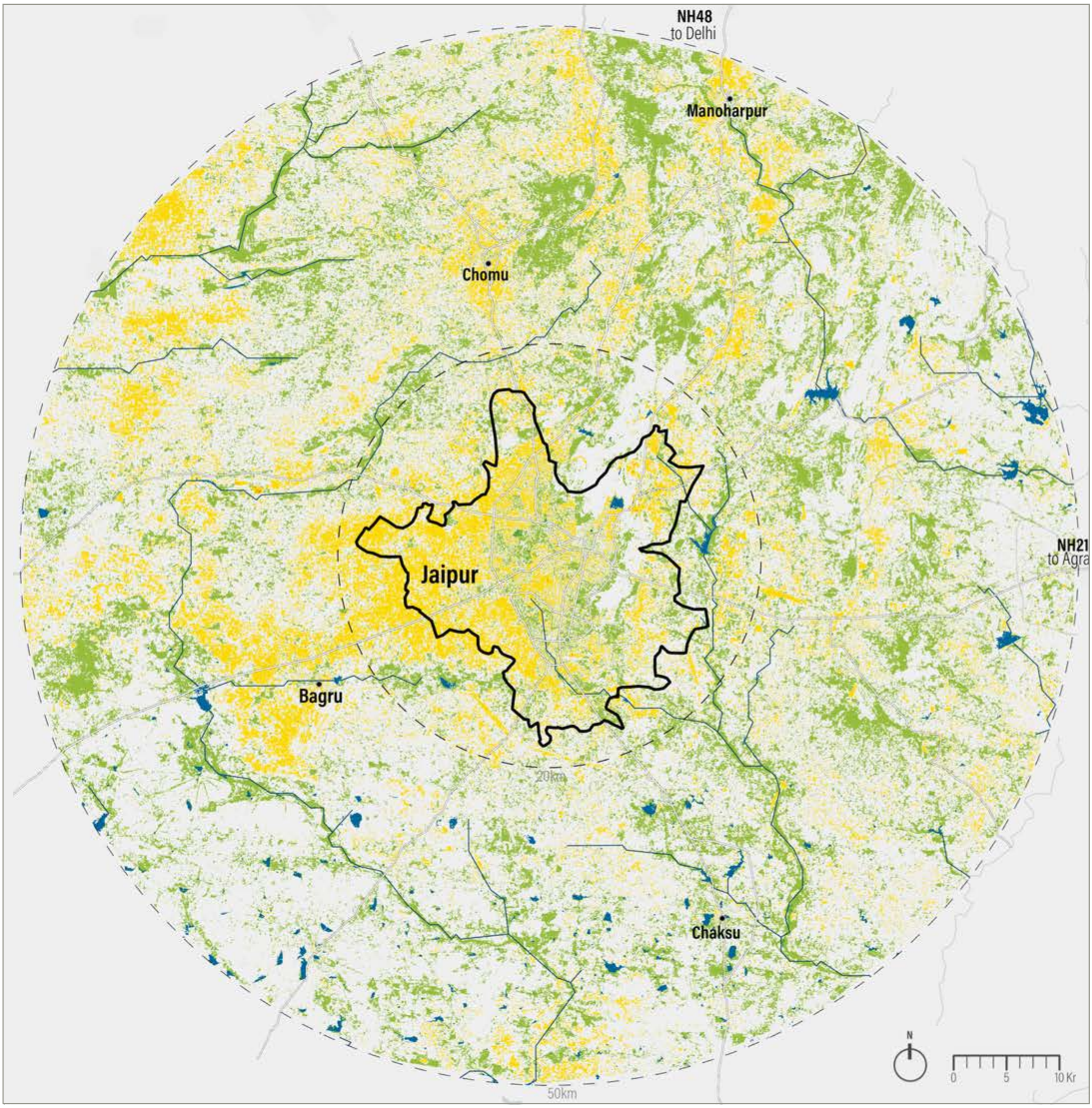
Figure J5 | **Hyderabad Has a Net Positive Vegetation Trend of 166 sq. km in the 0-50 km Region between 2000 and 2015**



Notes: Only areas with vegetation change trends are indicated in color; areas in the study region where no change is detected is left blank.
About 70 percent of the area with declining vegetation trend in Hyderabad is in the 20-50 km region.

Sources: Vegetation Trend - NASA n.d.; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

Figure J6 | **Jaipur Has a Net Positive Vegetation Trend of 690 sq. km in the 0-50 km Region between 2000 and 2015**



Municipal Boundary
Distance from city center
Highways
River Network
Maximum Surface Water (1984 - 2018)

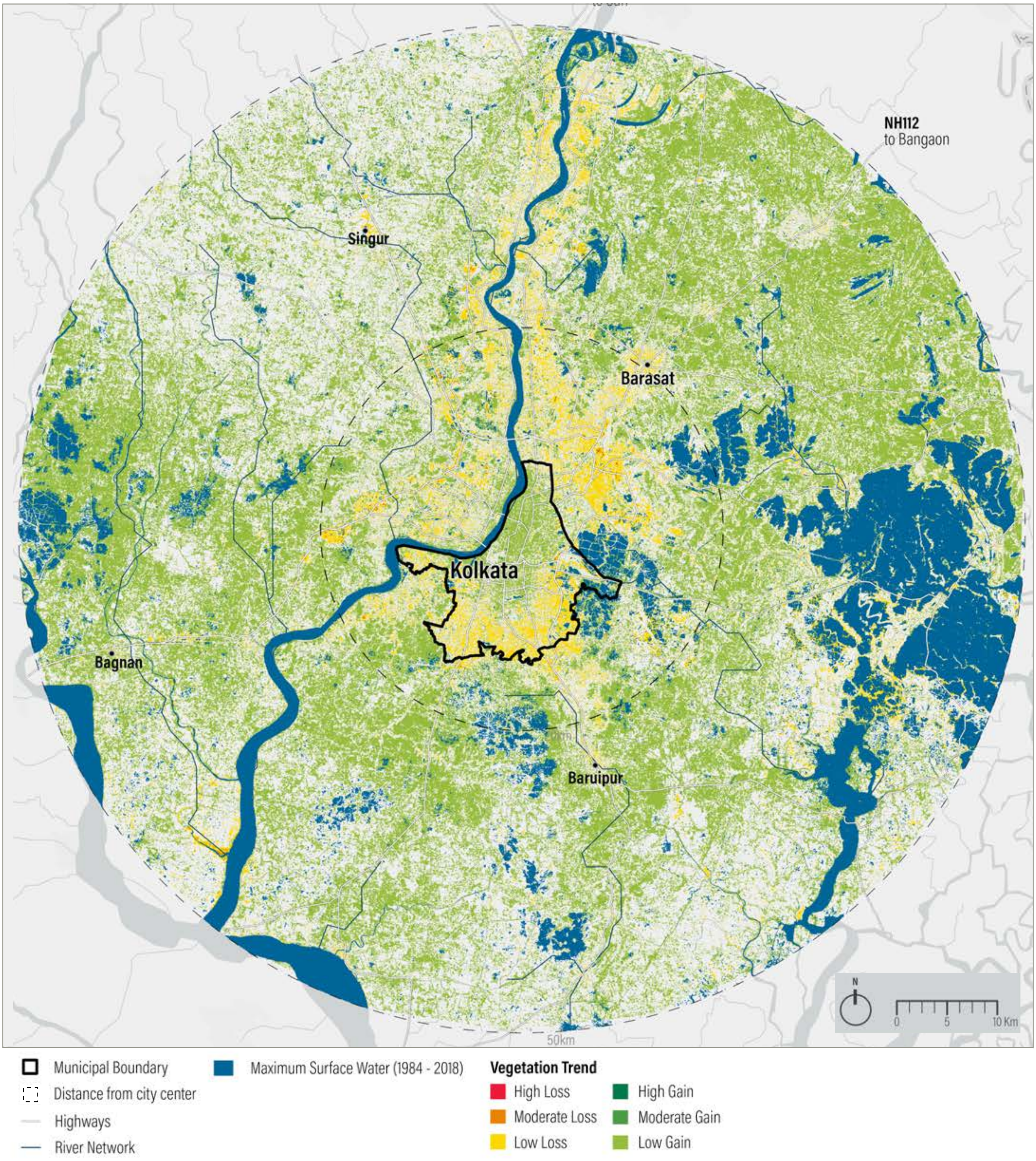
Vegetation Trend

High Loss
Moderate Loss
Low Loss
High Gain
Moderate Gain
Low Gain

Notes: Only areas with vegetation change trends are indicated in color; areas in the study region where no change is detected is left blank.
Area with increasing vegetation trend is two times the area with decreasing vegetation trend in the study region for Jaipur.

Sources: Vegetation Trend - NASA n.d.; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

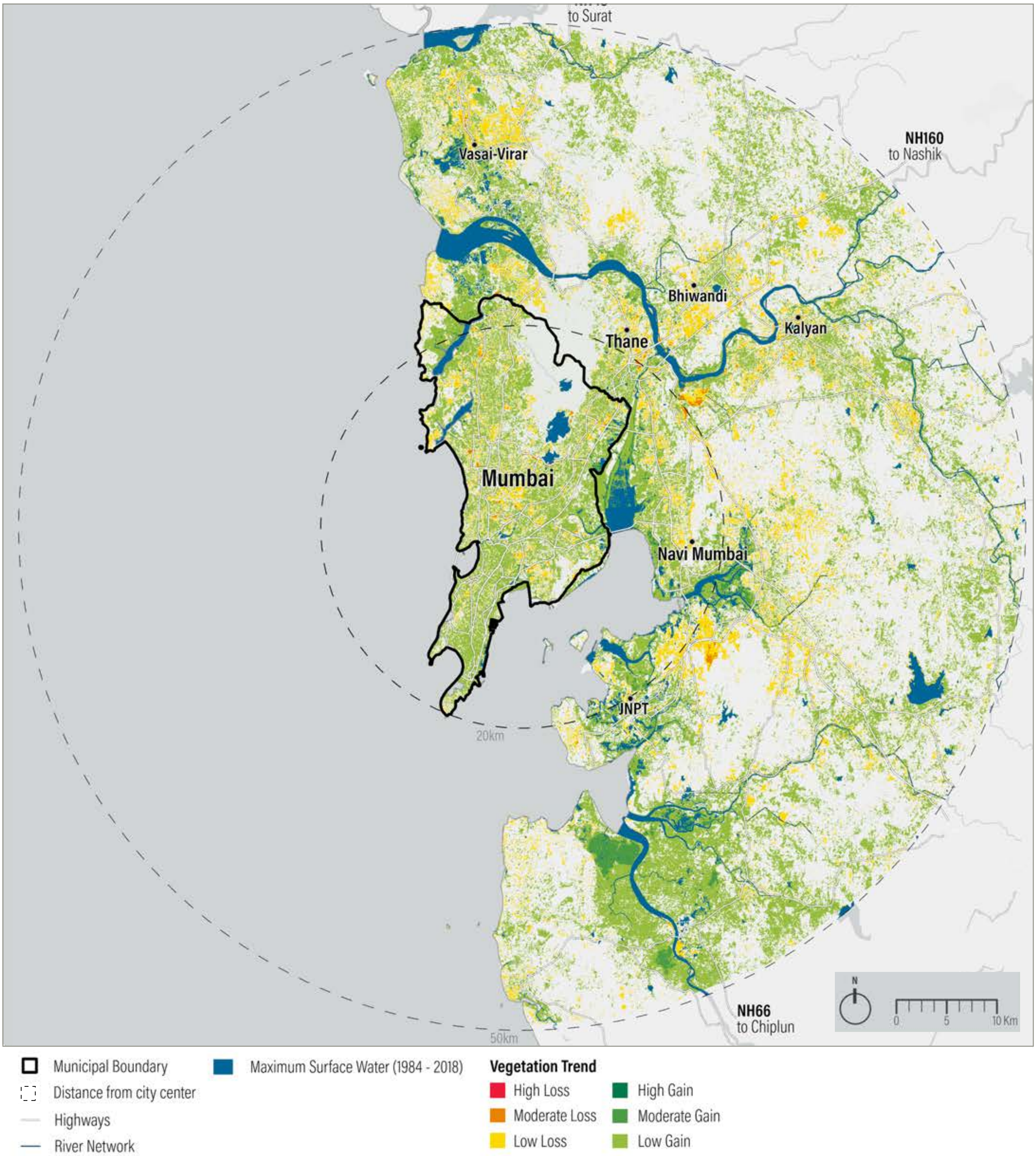
Figure J7 | **Kolkata Has a Net Positive Vegetation Trend of 2,604 sq. km in the 0-50 km Region between 2000 and 2015**



Notes: Only areas with vegetation change trends are indicated in color; areas in the study region where no change is detected is left blank.
Five percent of the study region around Kolkata has seen green cover losses, which are primarily sited along the Ganga River north of the city boundary.

Sources: Vegetation Trend - NASA n.d.; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

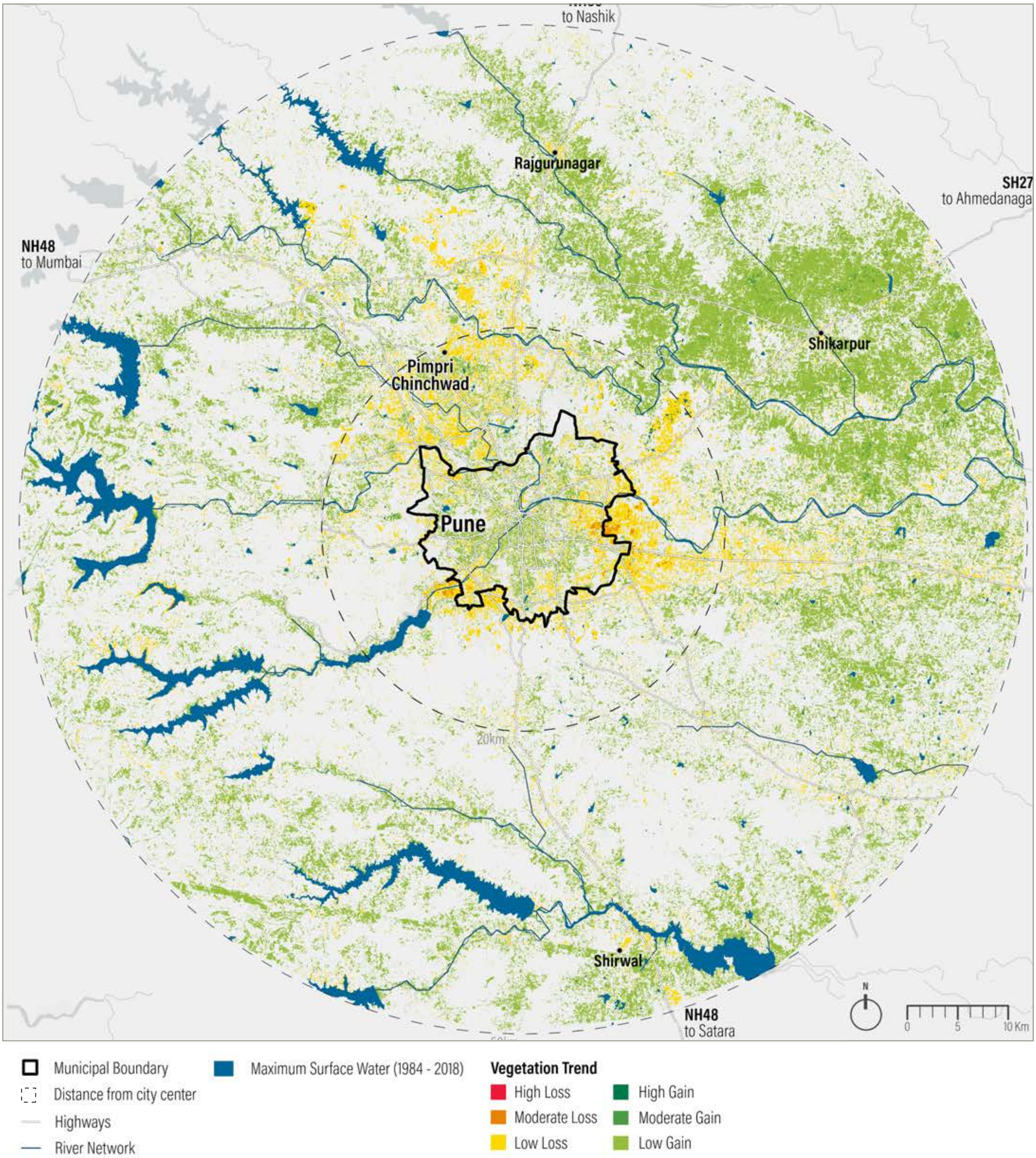
Figure J8 | **Mumbai Has a Net Positive Vegetation Trend of 901 sq. km in the 0-50 km Region between 2000 and 2015**



Notes: Only areas with vegetation change trends are indicated in color; areas in the study region where no change is detected is left blank.
Area with increasing vegetation trend is around 4 times the area with decreasing vegetation trend in the study region around Mumbai.

Sources: Vegetation Trend - NASA n.d.; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

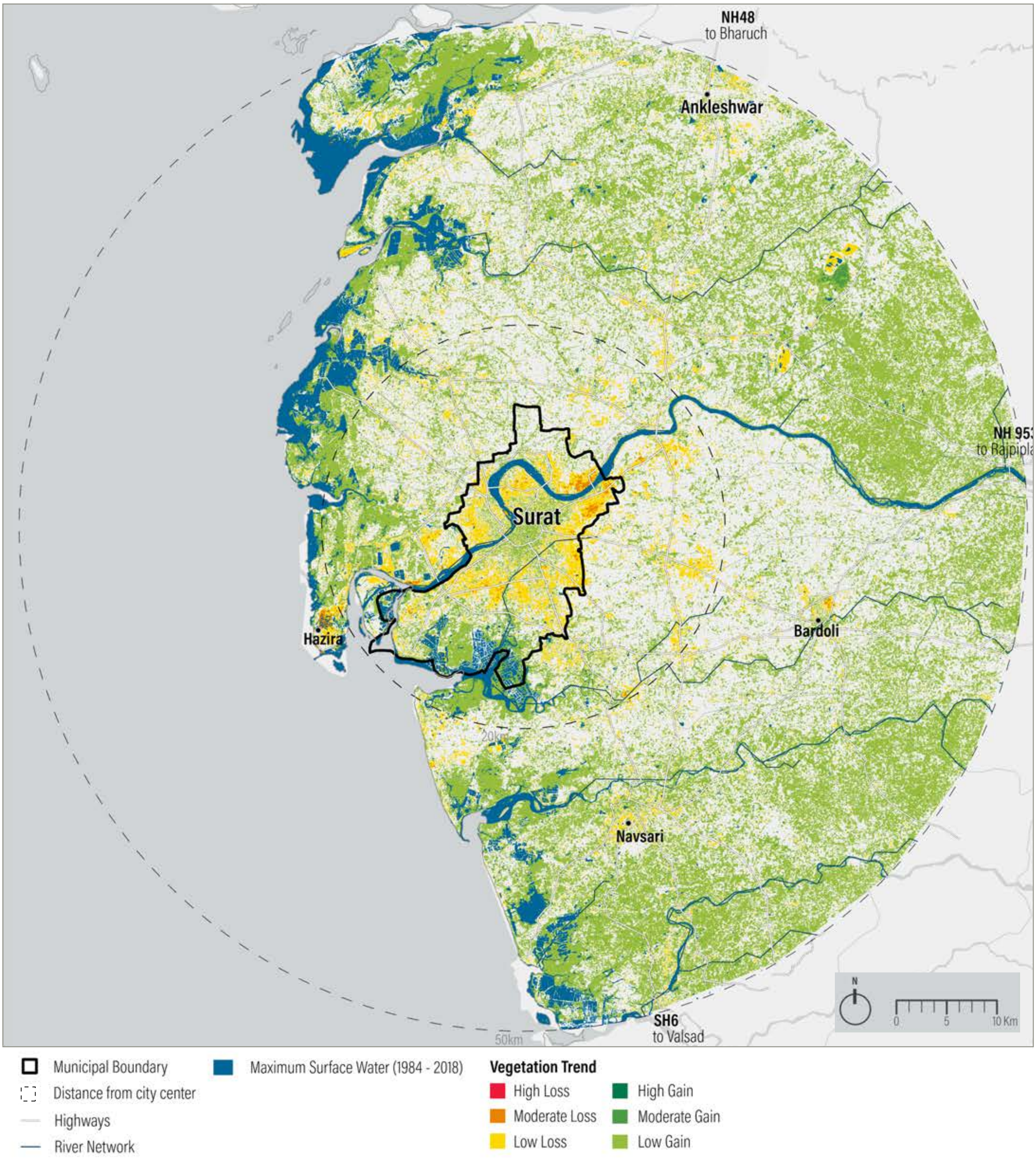
Figure J9 | **Pune Has a Net Positive Vegetation Trend of 1,288 sq. km in the 0-50 km Region between 2000 and 2015**



Notes: Only areas with vegetation change trends are indicated in color; areas in the study region where no change is detected is left blank. Eighty-nine percent of the increasing vegetation trend in Pune has been in the 20–50 km region primarily to the northeast of the city.

Sources: Vegetation Trend - NASA n.d.; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

Figure J10 | **Surat Has a Net Positive Vegetation Trend of 1,731 sq. km in the 0-50 km Region between 2000 and 2015**

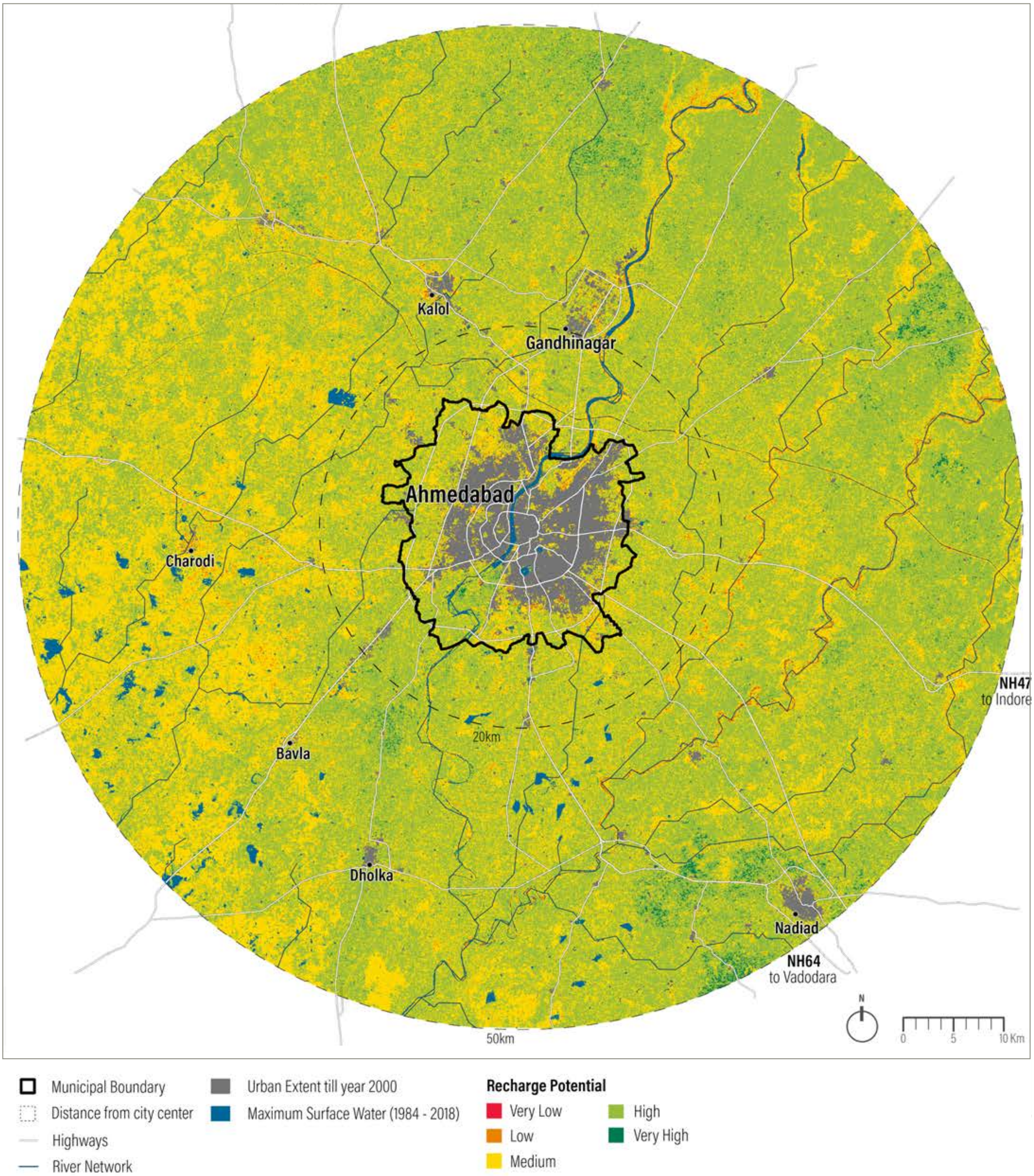


Notes: Only areas with vegetation change trends are indicated in color; areas in the study region where no change is detected is left blank.
Fifteen percent of the area in the 0-20 km region has a decrease in vegetation trend as compared to 4 percent in the 20-50 km region.

Sources: Vegetation Trend - NASA n.d.; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

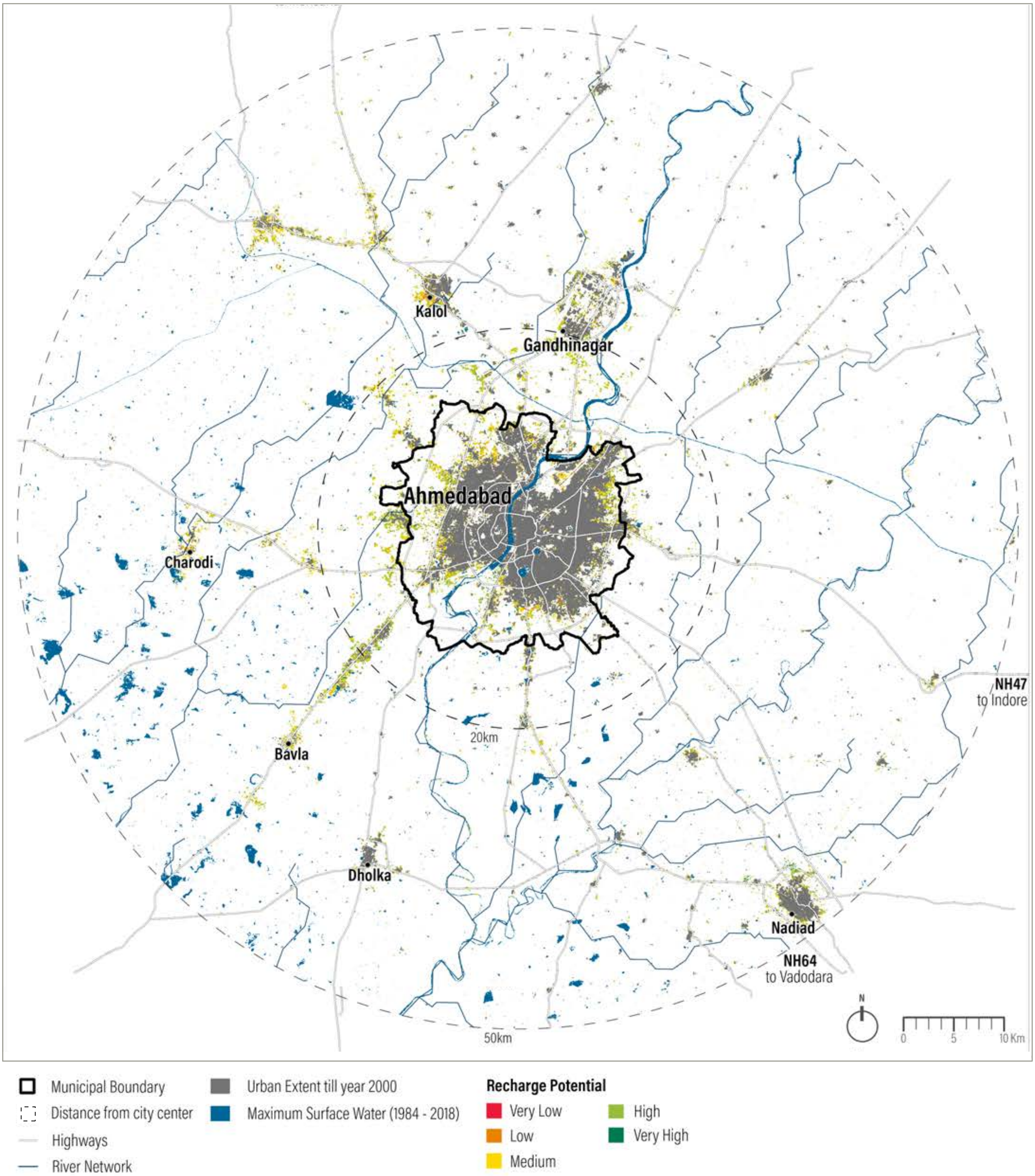
APPENDIX K GROUNDWATER RECHARGE POTENTIAL ZONE MAPS

Figure K1 | **41% of New Development in Ahmedabad Is Sited on High and Very High Recharge Potential Zones**



Notes: Urban development in the year 2000 overlaid over various recharge potential zones for areas not yet built up in the 0–50 km study region.

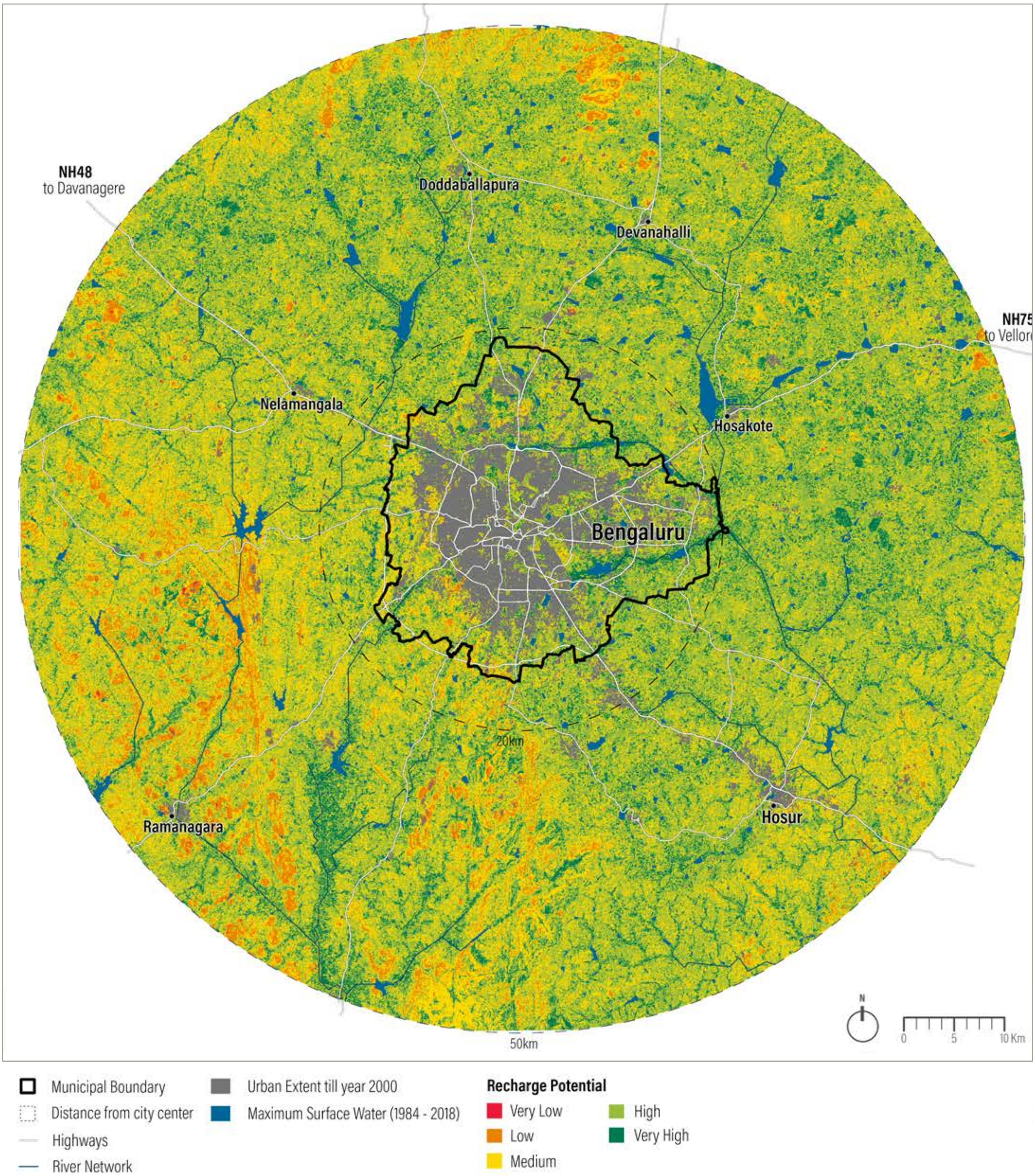
Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.



Notes: Urban development of the year 2000 in gray, and new urban development overlaid over various recharge potential zones (areas where urban development has not taken place are not highlighted here).

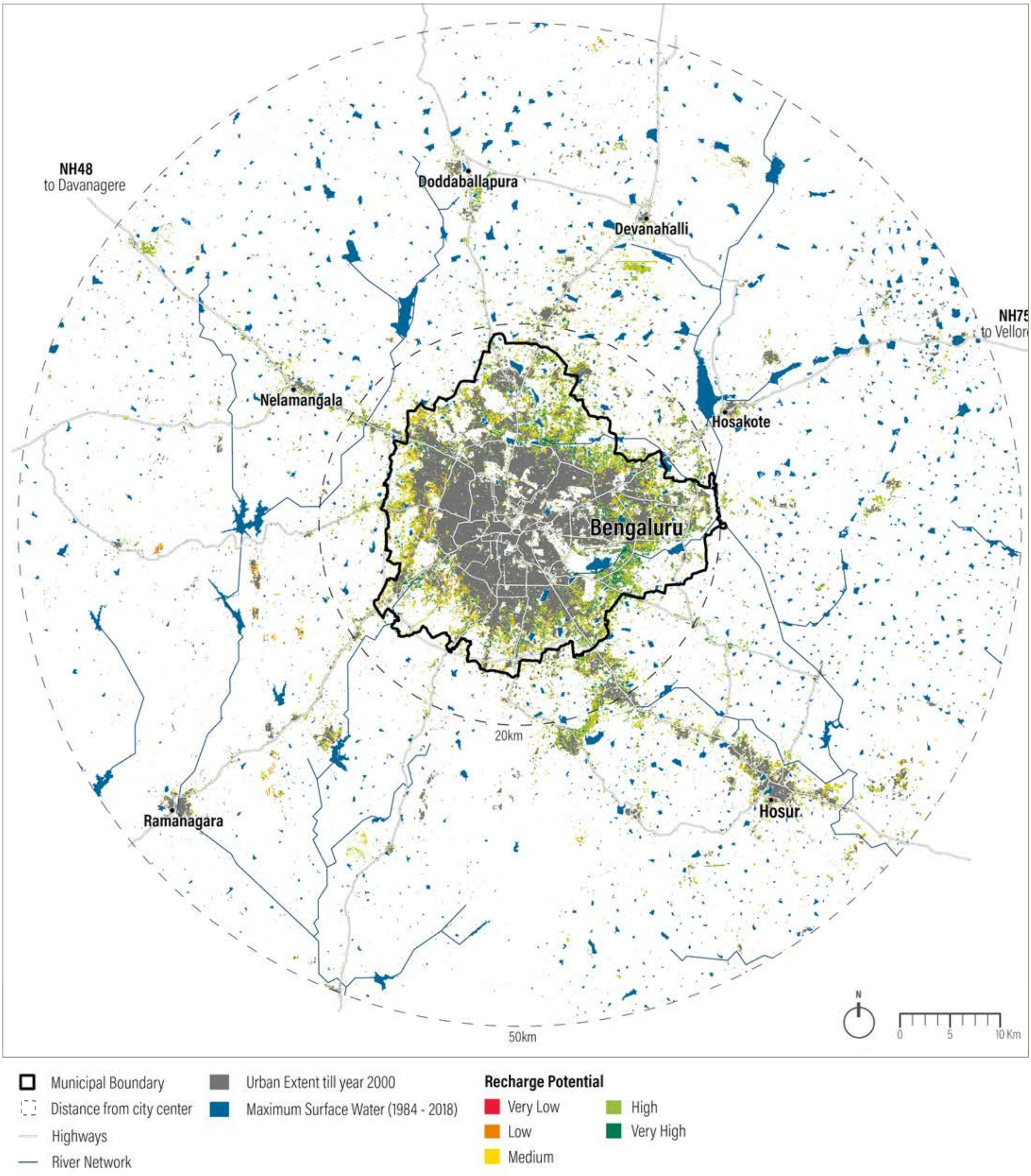
Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

Figure K2 | **64% of New Development in Bengaluru Is Sited on High and Very High Recharge Potential Zones**



Notes: Urban development in the year 2000 overlaid over various recharge potential zones for areas not yet built up in the 0–50 km study region.

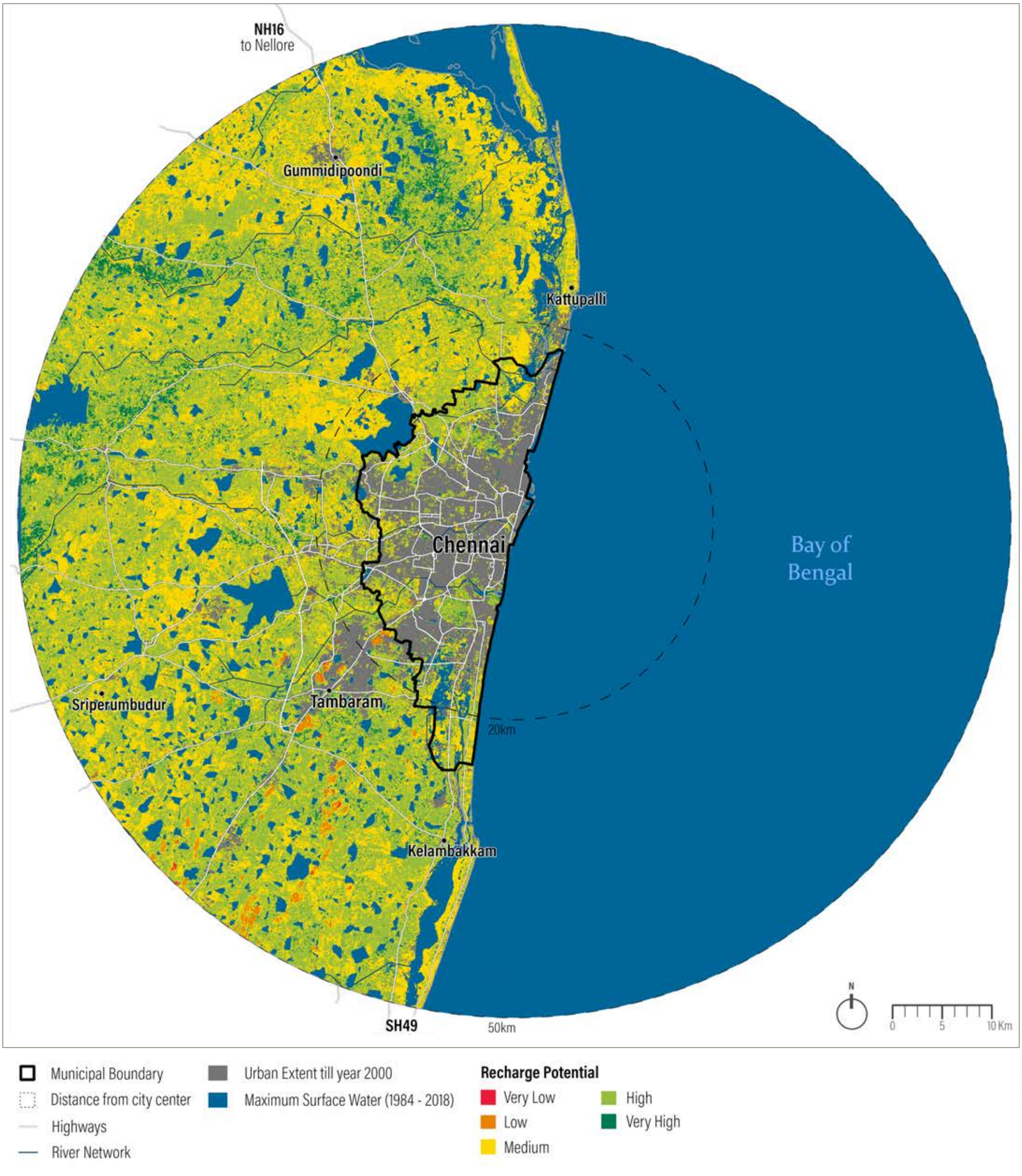
Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.



Notes: Urban development of the year 2000 in gray, and new urban development overlaid over various recharge potential zones (areas where urban development has not taken place are not highlighted here).

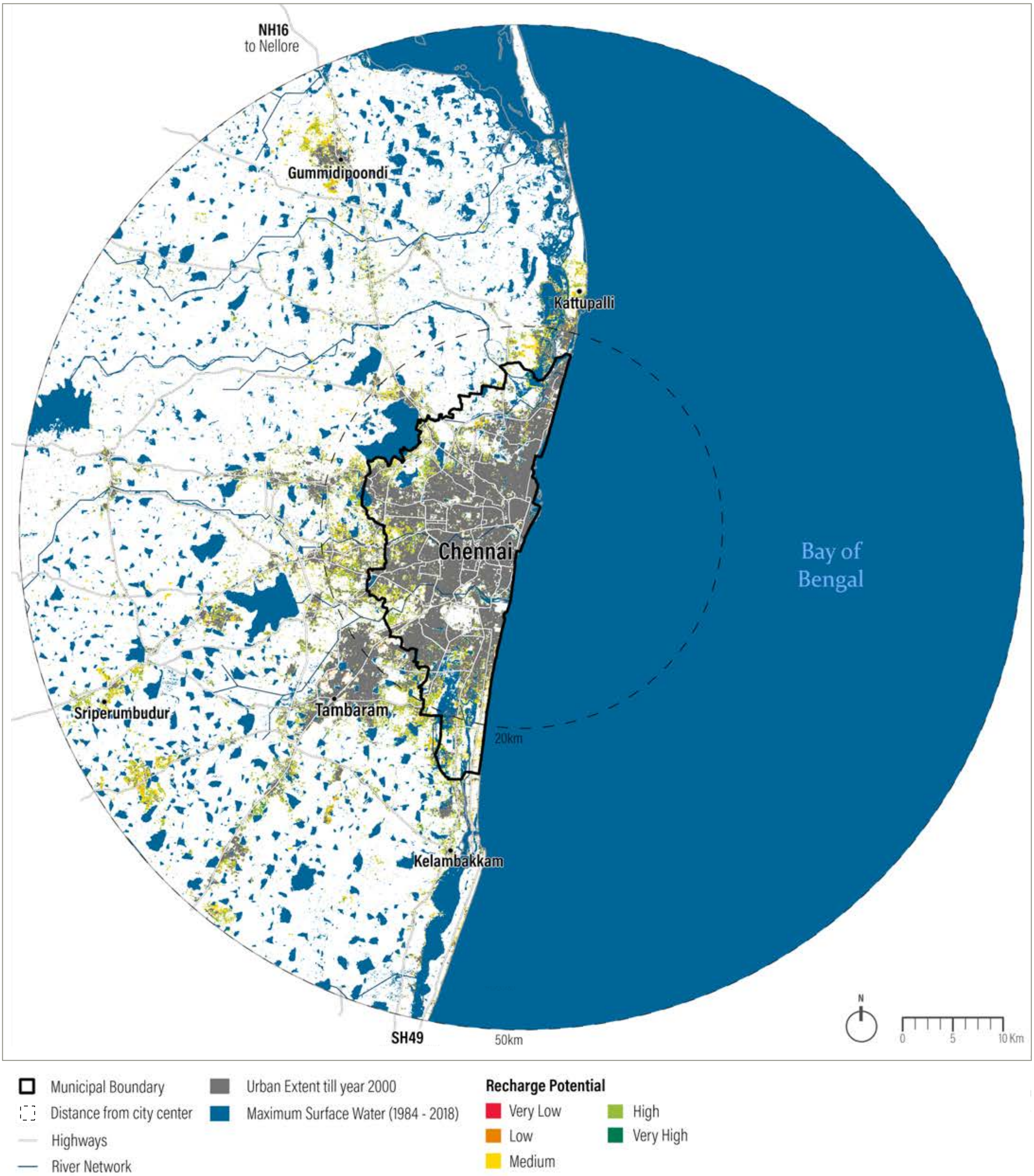
Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

Figure K3 | **49% of New Development in Chennai Is Sited on High and Very High Recharge Potential Zones**



Notes: Urban development in the year 2000 overlaid over various recharge potential zones for areas not yet built up in the 0–50 km study region.

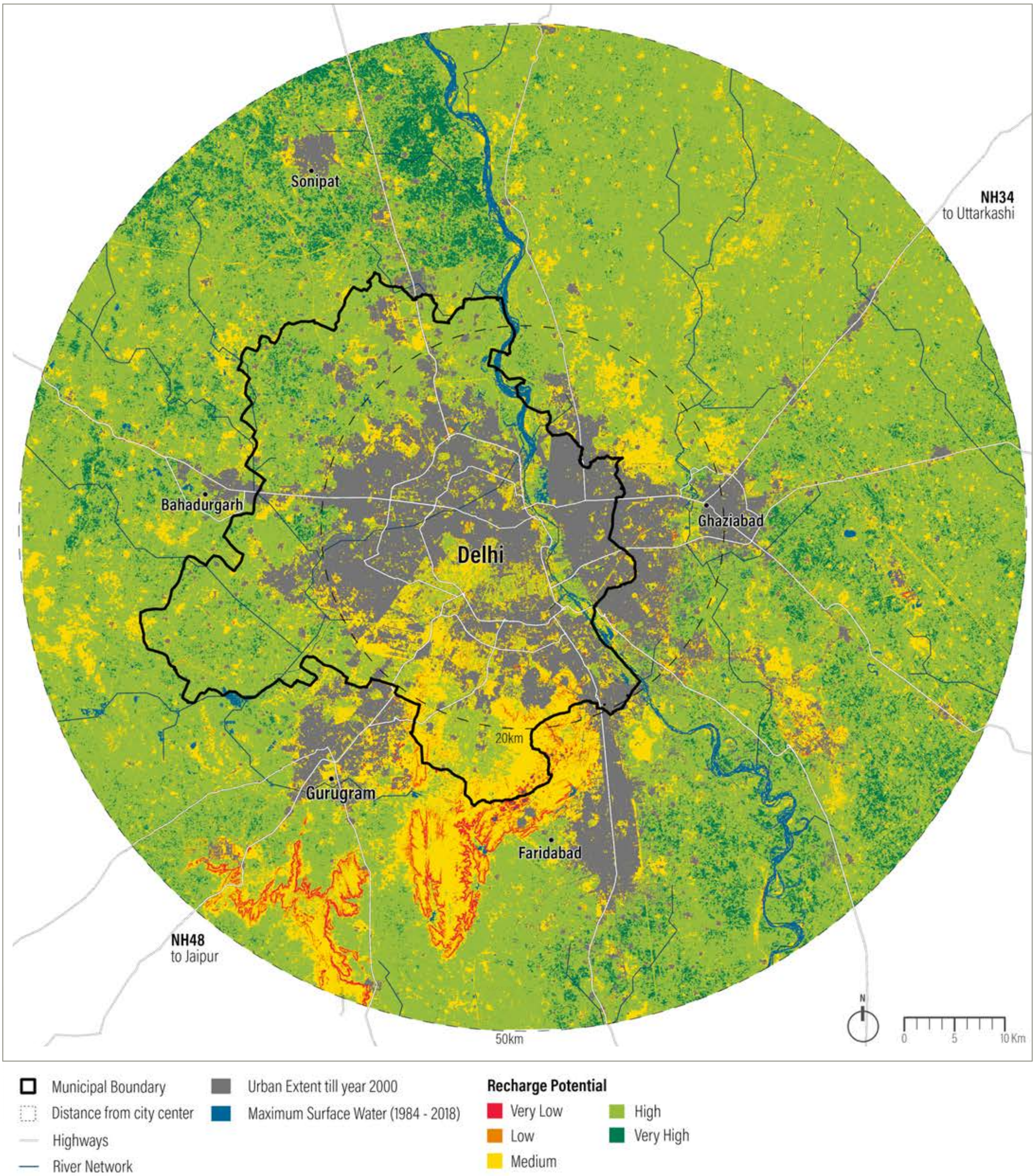
Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.



Notes: Urban development of the year 2000 in gray, and new urban development overlaid over various recharge potential zones (areas where urban development has not taken place are not highlighted here).

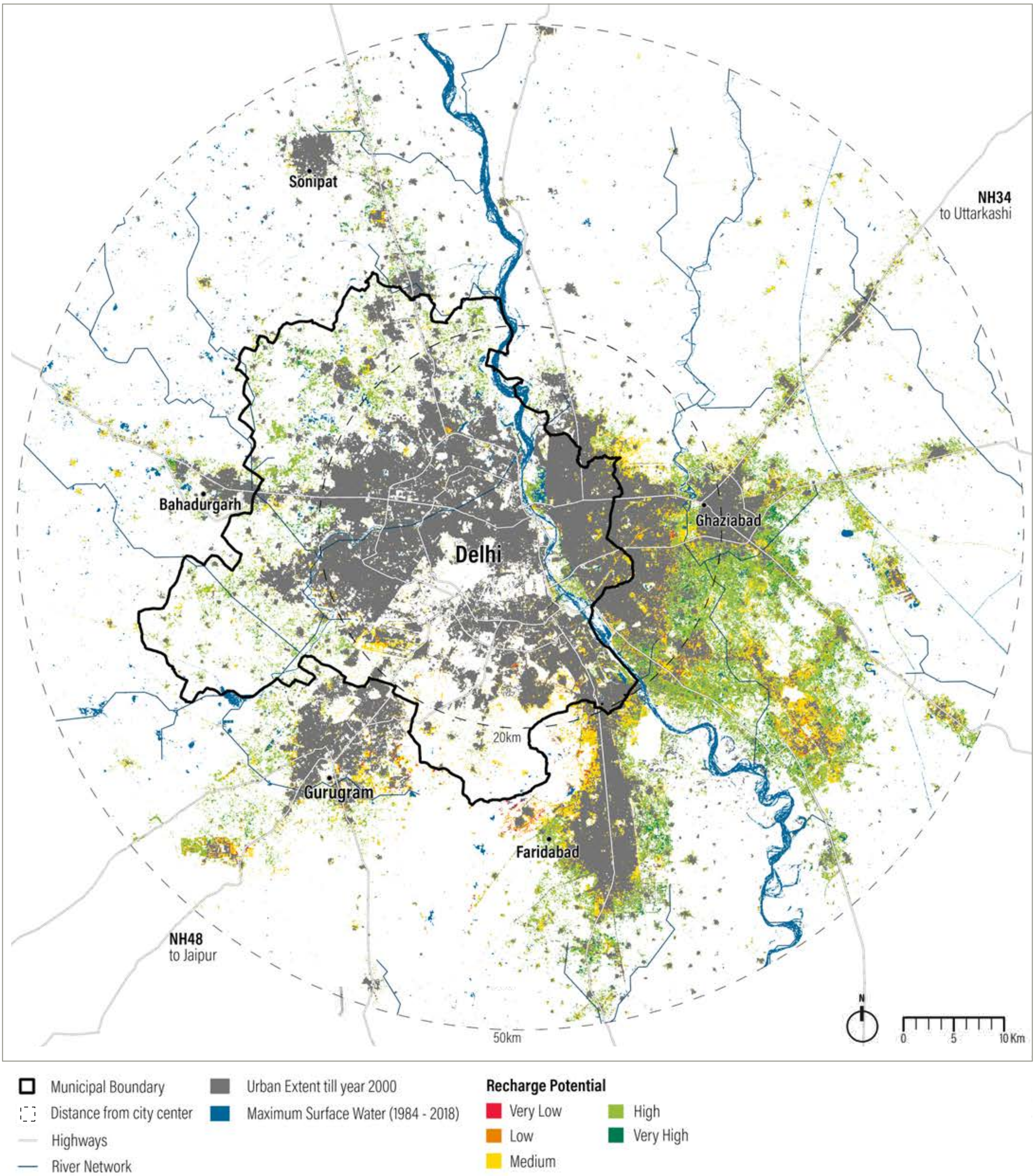
Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

Figure K4 | **66% of New Development in Delhi Is Sited on High and Very High Recharge Potential Zones**



Notes: Urban development in the year 2000 overlaid over various recharge potential zones for areas not yet built up in the 0–50 km study region.

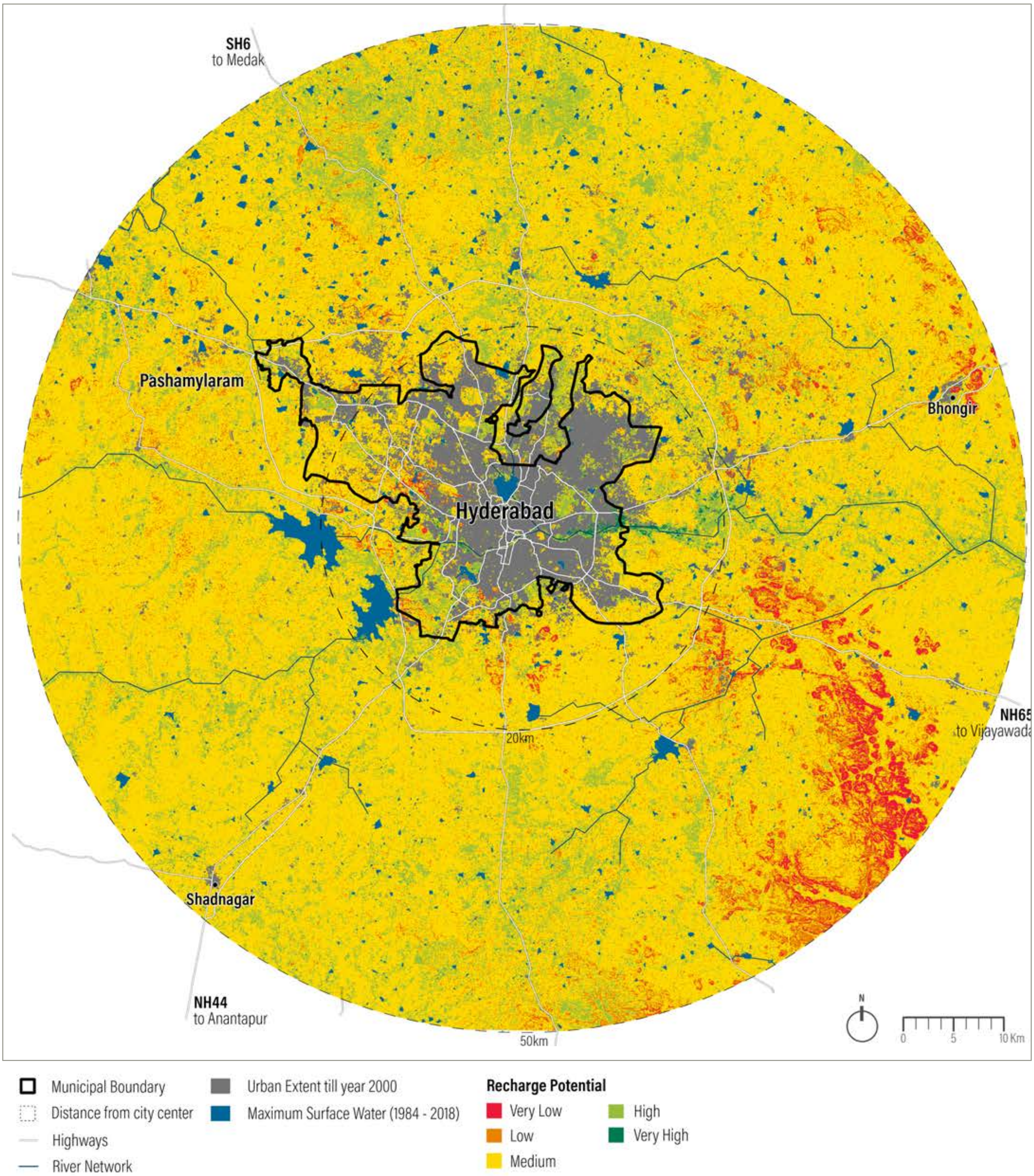
Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.



Notes: Urban development of the year 2000 in gray, and new urban development overlaid over various recharge potential zones (areas where urban development has not taken place are not highlighted here).

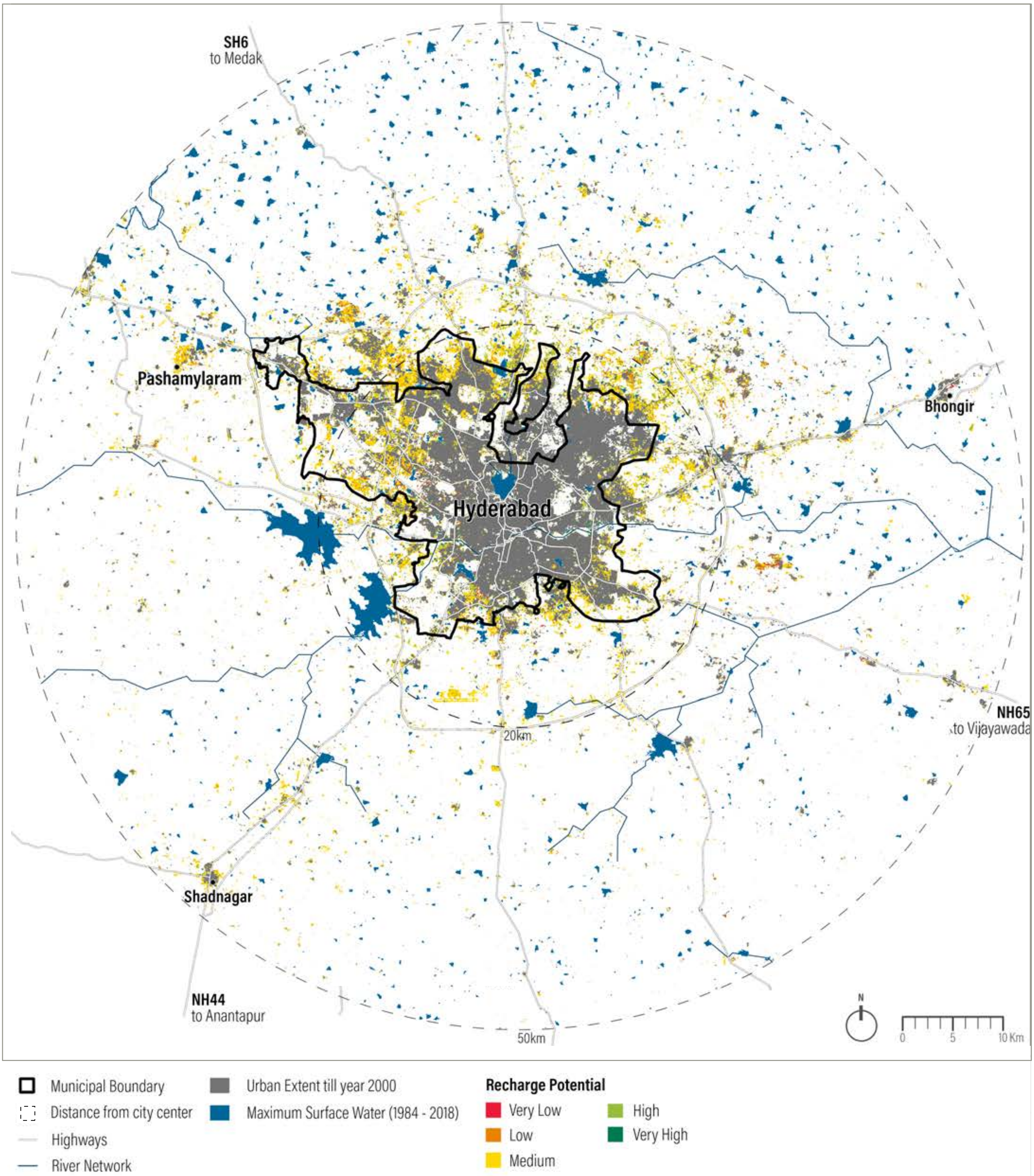
Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

Figure K5 | **14% of New Development in Hyderabad Is Sited on High and Very High Recharge Potential Zones**



Notes: Urban development in the year 2000 overlaid over various recharge potential zones for areas not yet built up in the 0–50 km study region.

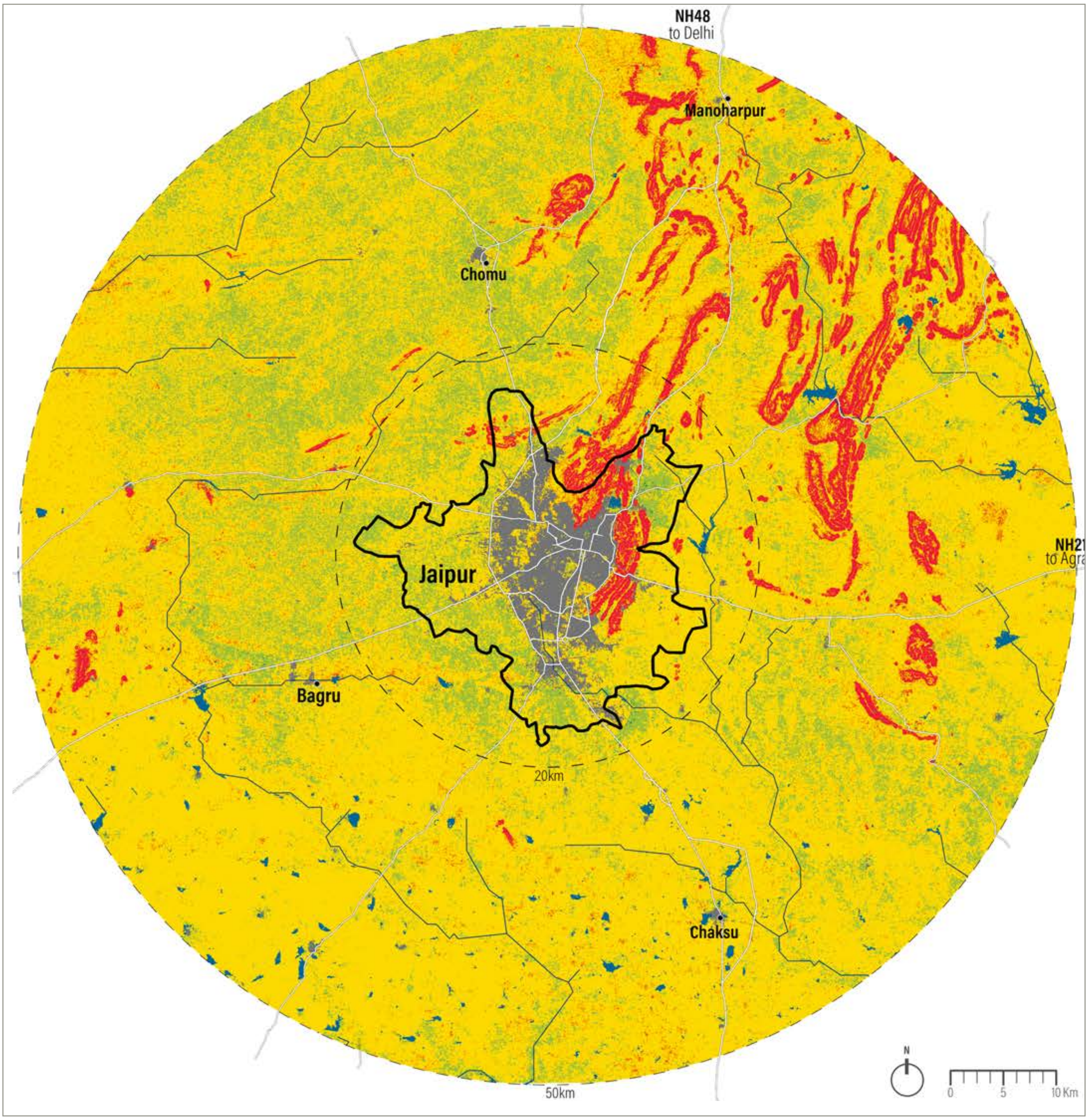
Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.



Notes: Urban development of the year 2000 in gray, and new urban development overlaid over various recharge potential zones (areas where urban development has not taken place are not highlighted here).

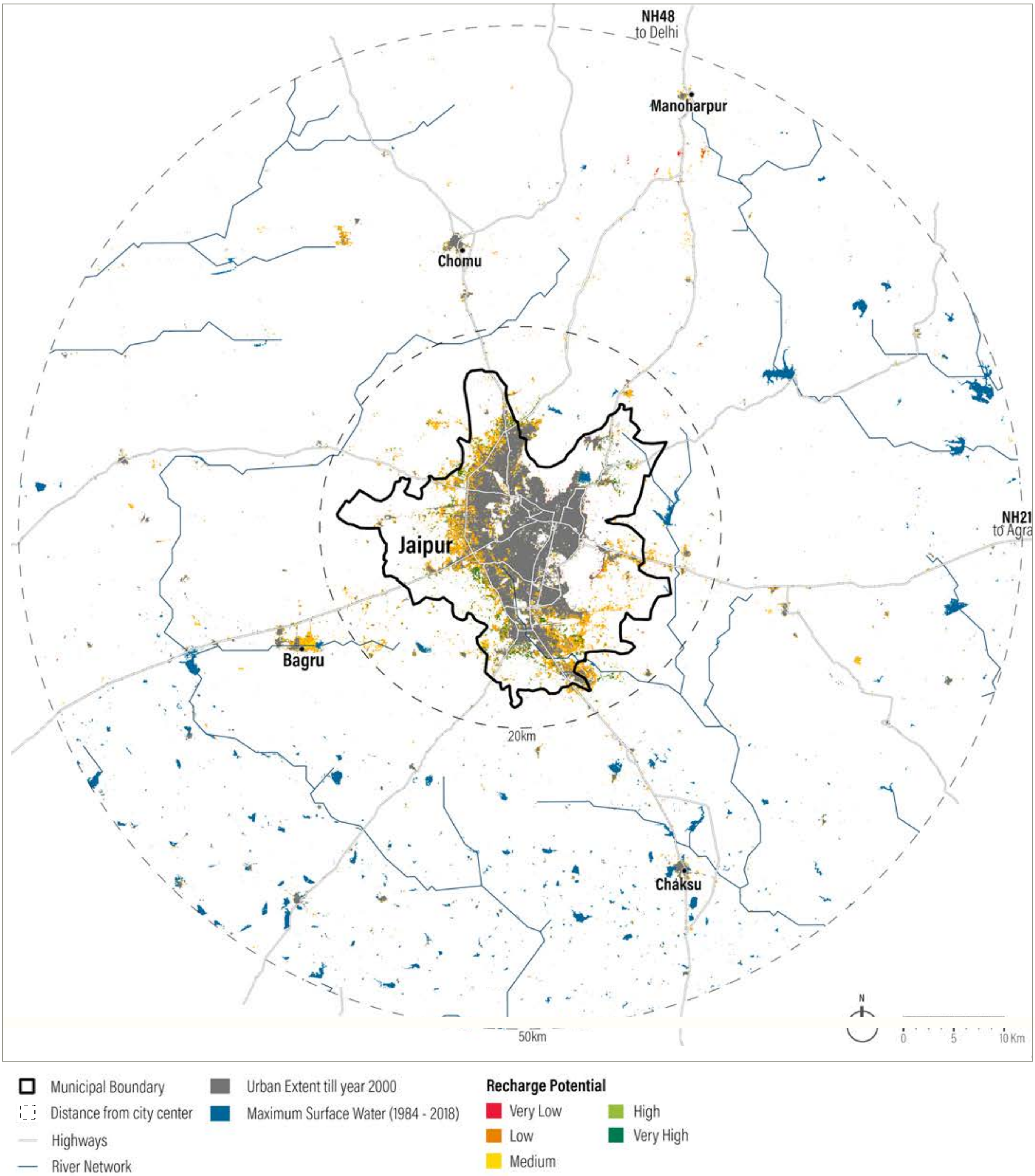
Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

Figure K6 | **15% of New Development in Jaipur Is Sited on High and Very High Recharge Potential Zones**



Notes: Urban development in the year 2000 overlaid over various recharge potential zones for areas not yet built up in the 0–50 km study region.

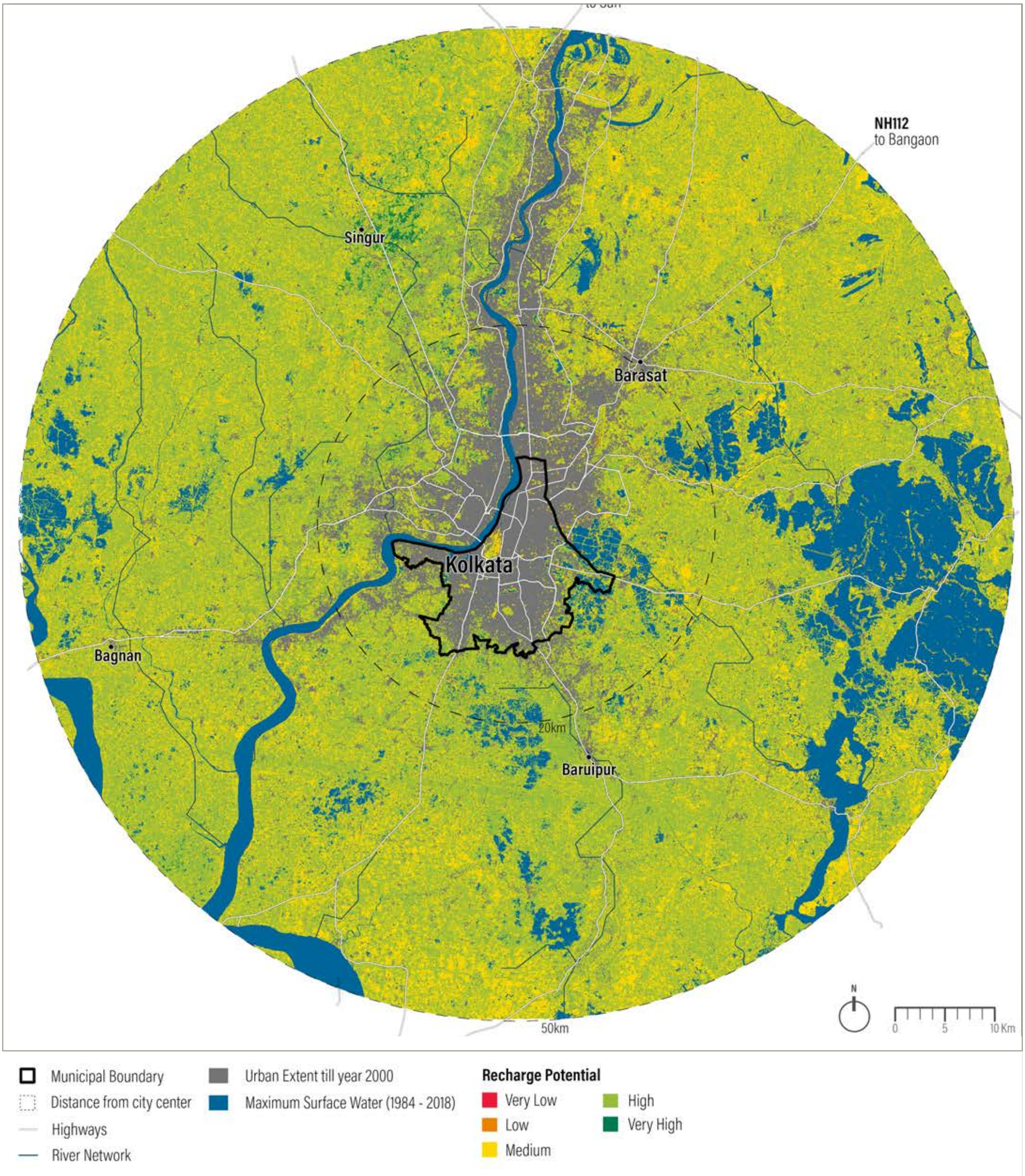
Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.



Notes: Urban development of the year 2000 in gray, and new urban development overlaid over various recharge potential zones (areas where urban development has not taken place are not highlighted here).

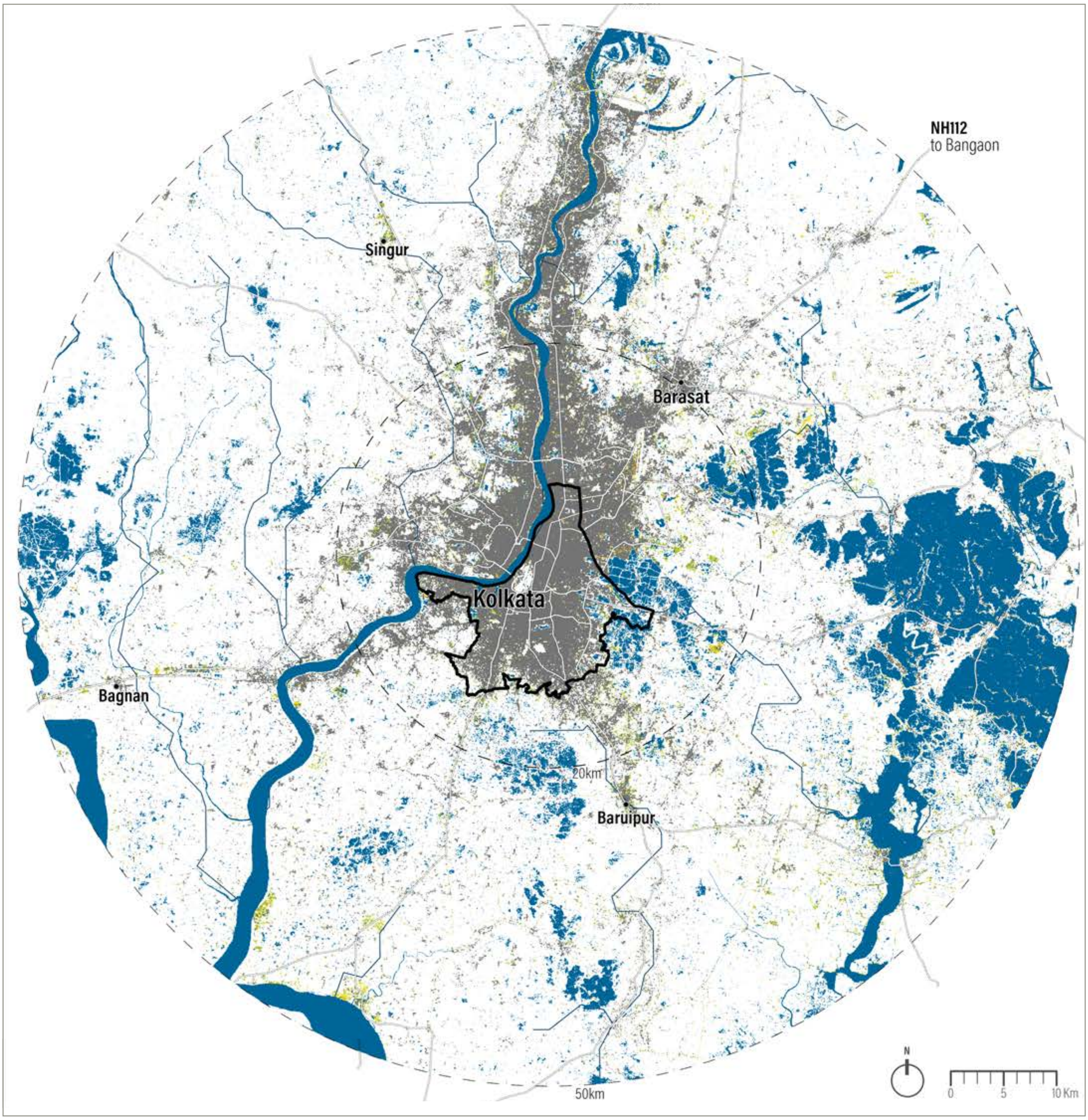
Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

Figure K7 | **54% of New Development in Kolkata Is Sited on High and Very High Recharge Potential Zones**



Notes: Urban development in the year 2000 overlaid over various recharge potential zones for areas not yet built up in the 0–50 km study region.

Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.



- Municipal Boundary
- Distance from city center
- Highways
- River Network
- Urban Extent till year 2000
- Maximum Surface Water (1984 - 2018)

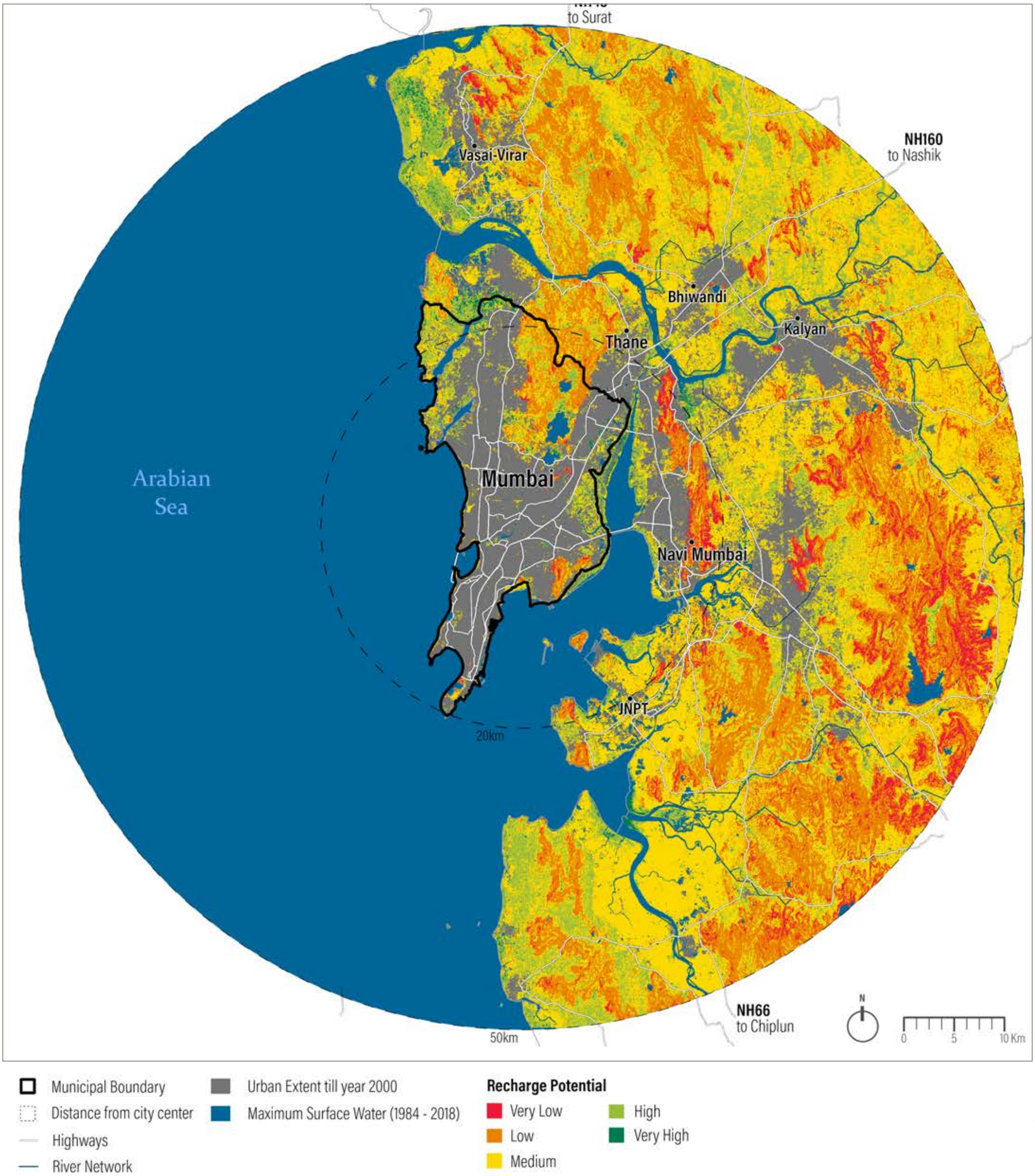
Recharge Potential

- Very Low
- Low
- Medium
- High
- Very High

Notes: Urban development of the year 2000 in gray, and new urban development overlaid over various recharge potential zones (areas where urban development has not taken place are not highlighted here).

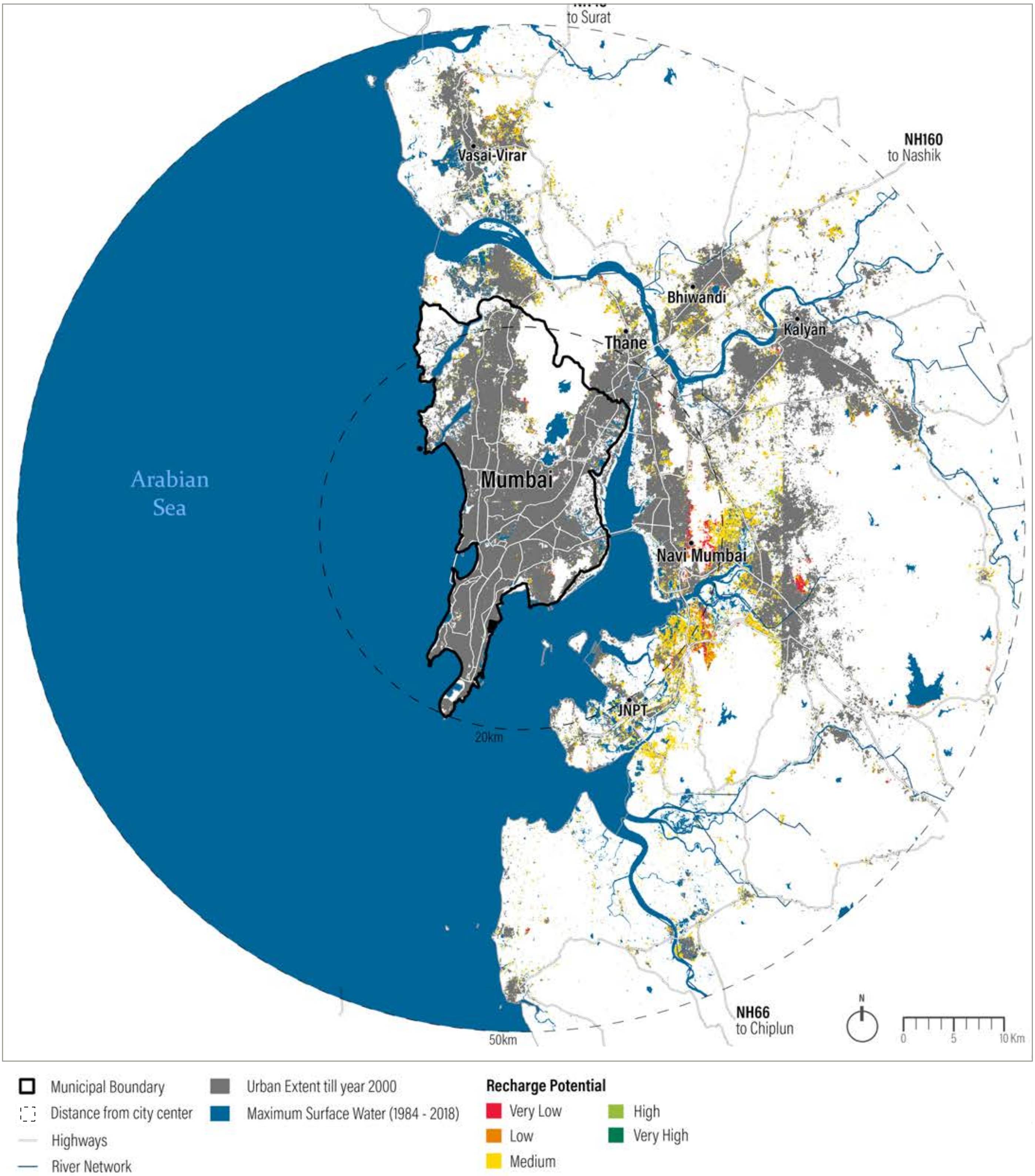
Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

Figure K8 | **11% of New Development in Mumbai Is Sited on High and Very High Recharge Potential Zones**



Notes: Urban development in the year 2000 overlaid over various recharge potential zones for areas not yet built up in the 0–50 km study region.

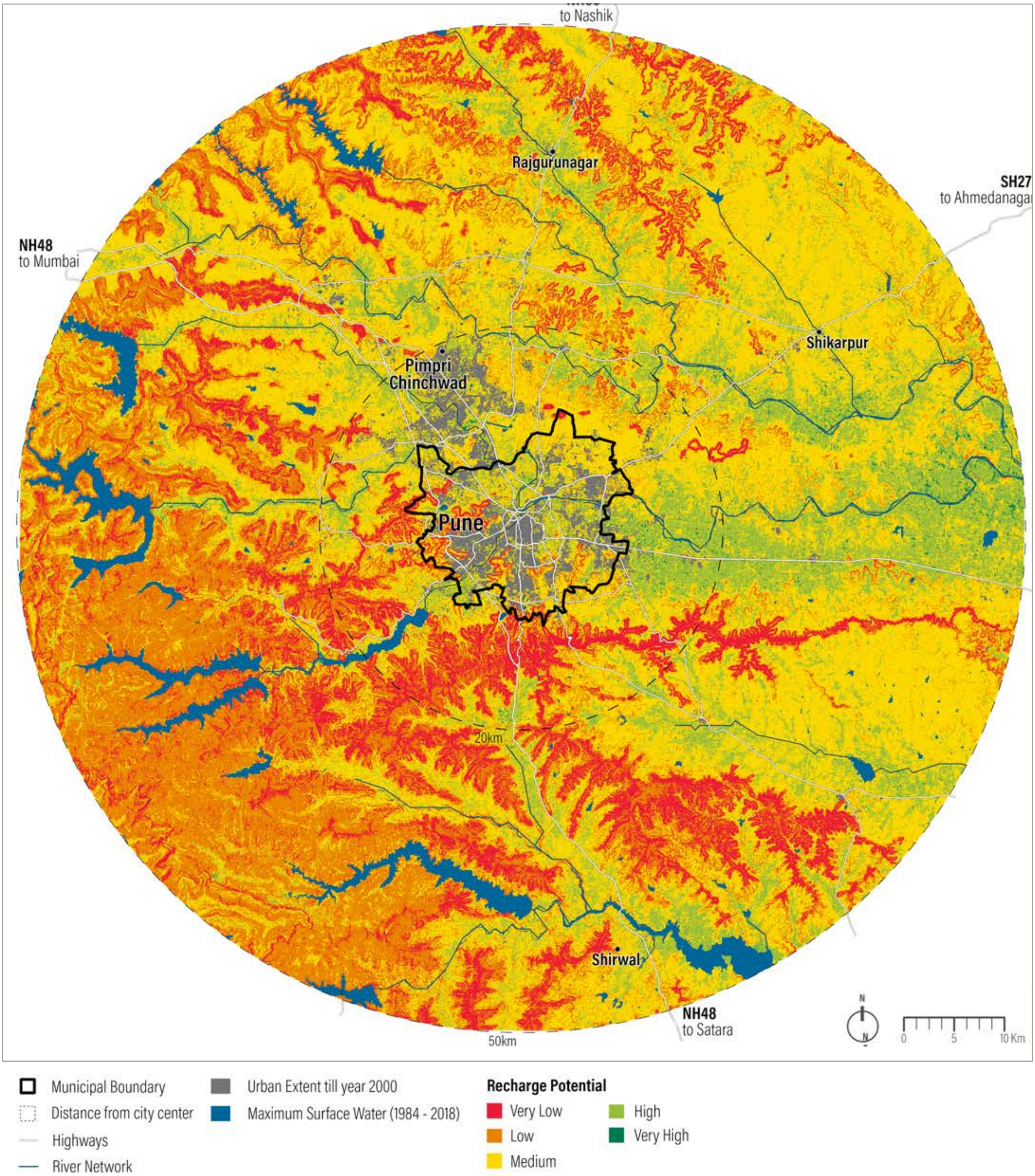
Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.



Notes: Urban development of the year 2000 in gray, and new urban development overlaid over various recharge potential zones (areas where urban development has not taken place are not highlighted here).

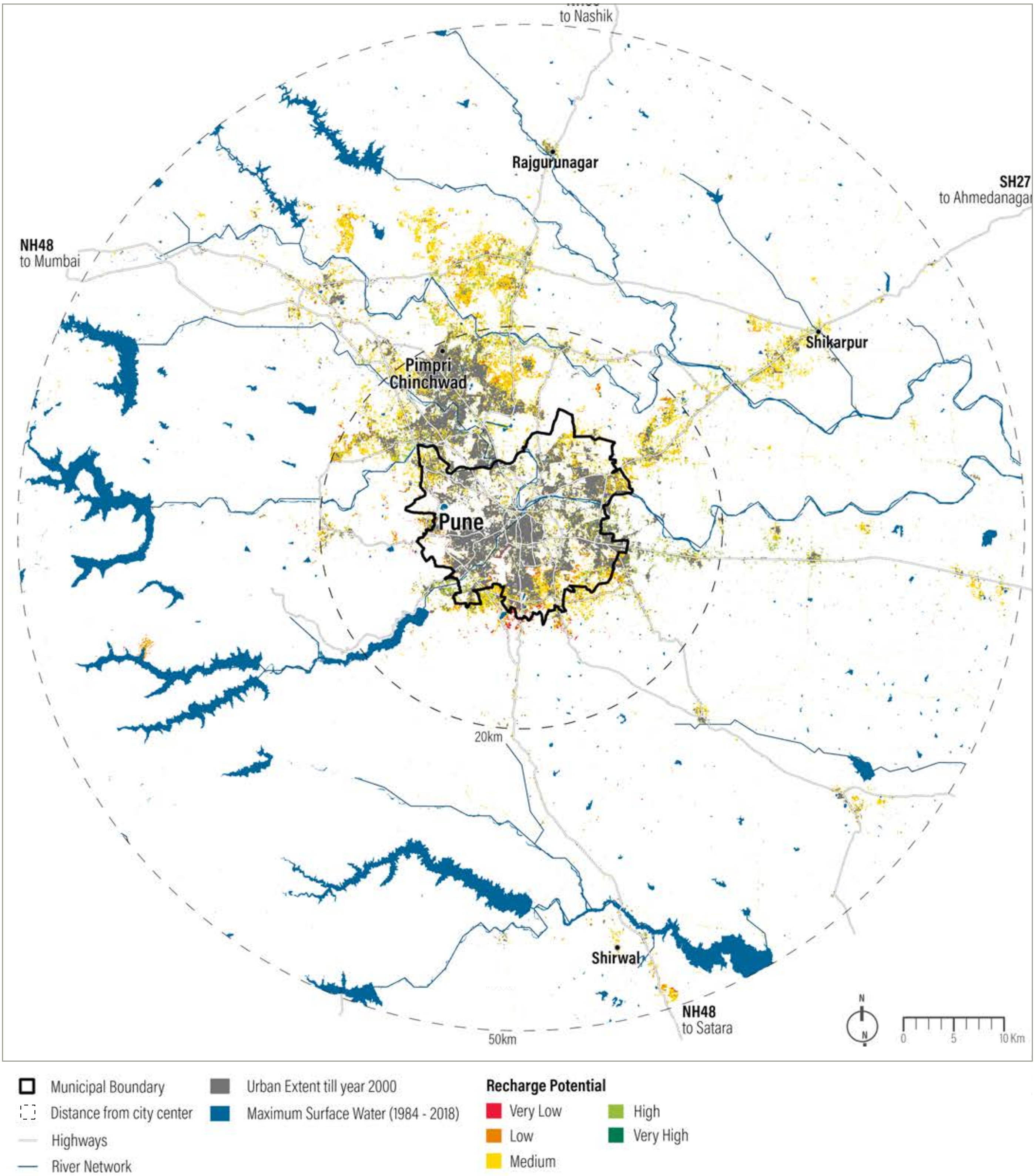
Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

Figure K9 | **14% of New Development in Pune Is Sited on High and Very High Recharge Potential Zones**



Notes: Urban development in the year 2000 overlaid over various recharge potential zones for areas not yet built up in the 0–50 km study region.

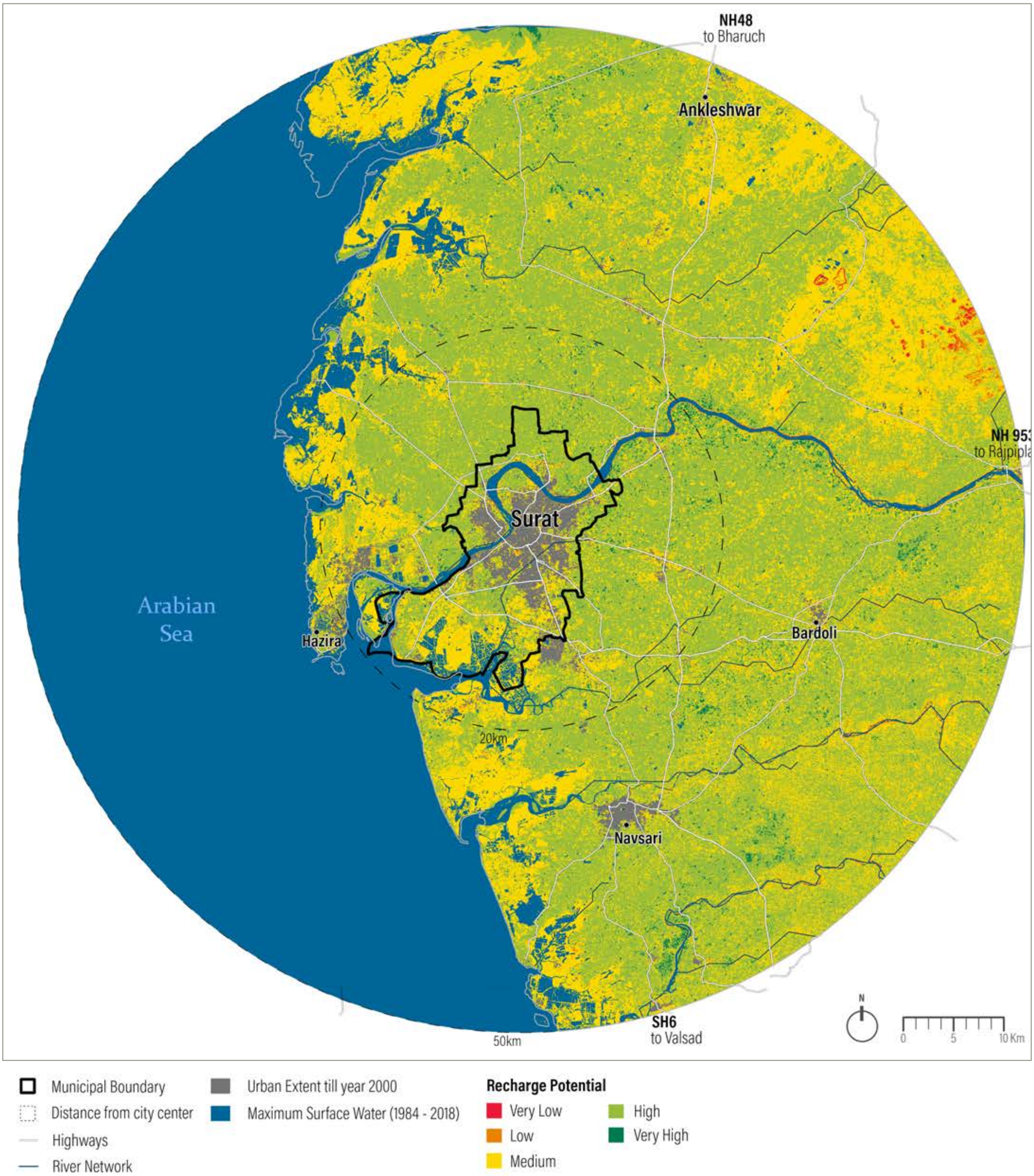
Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.



Notes: Urban development of the year 2000 in gray, and new urban development overlaid over various recharge potential zones (areas where urban development has not taken place are not highlighted here).

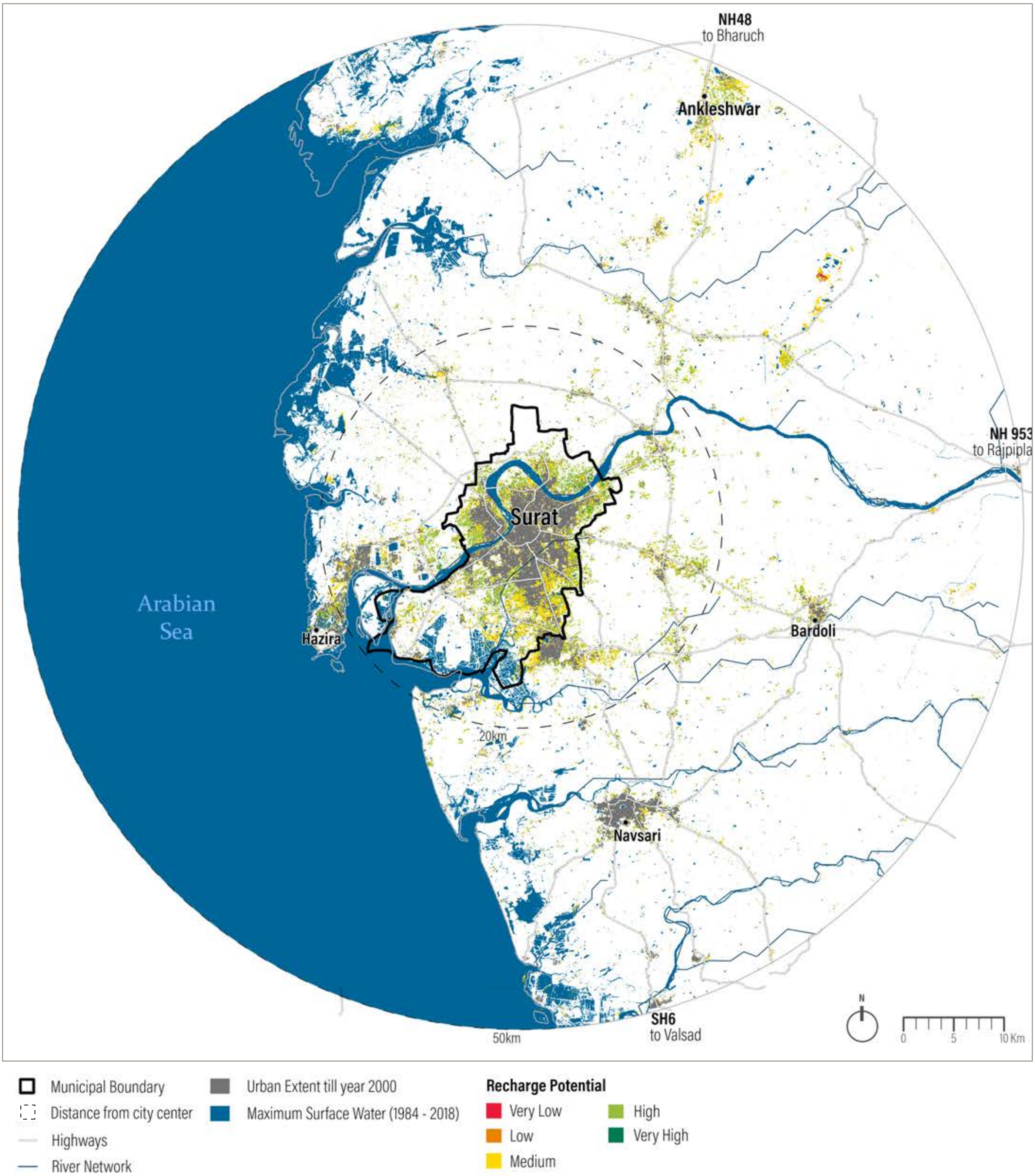
Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

Figure K10 | **45% of New Development in Surat Is Sited on High and Very High Recharge Potential Zones**



Notes: Urban development in the year 2000 overlaid over various recharge potential zones for areas not yet built up in the 0–50 km study region.

Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

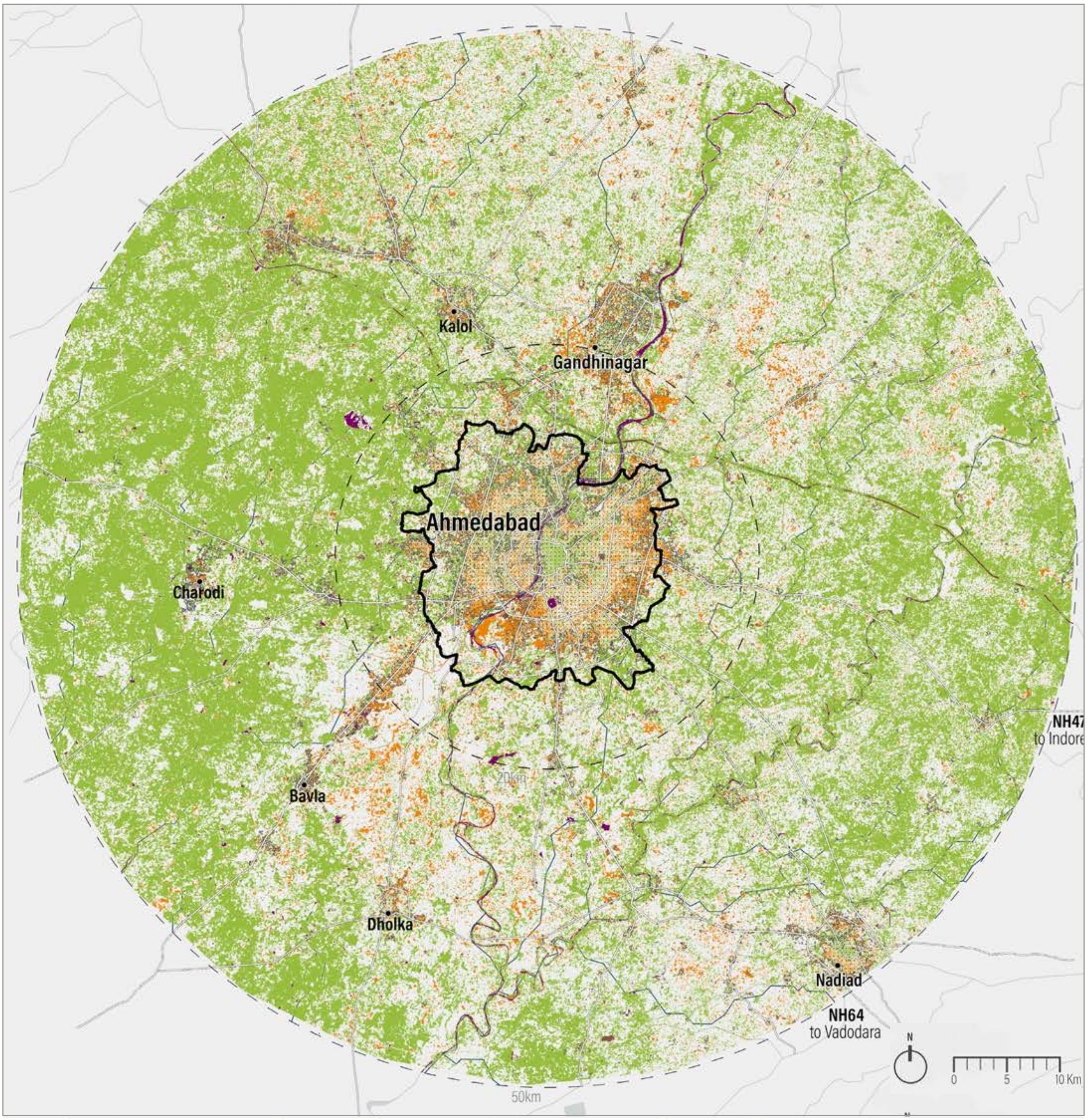


Notes: Urban development of the year 2000 in gray, and new urban development overlaid over various recharge potential zones (areas where urban development has not taken place are not highlighted here).

Sources: Recharge potential - Farr 2007, NASA n.d.; Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

APPENDIX L THEMATIC OVERLAY MAPS

Figure L1 | **Built-Up Area and Vegetation Loss Overlap Significantly in Ahmedabad**

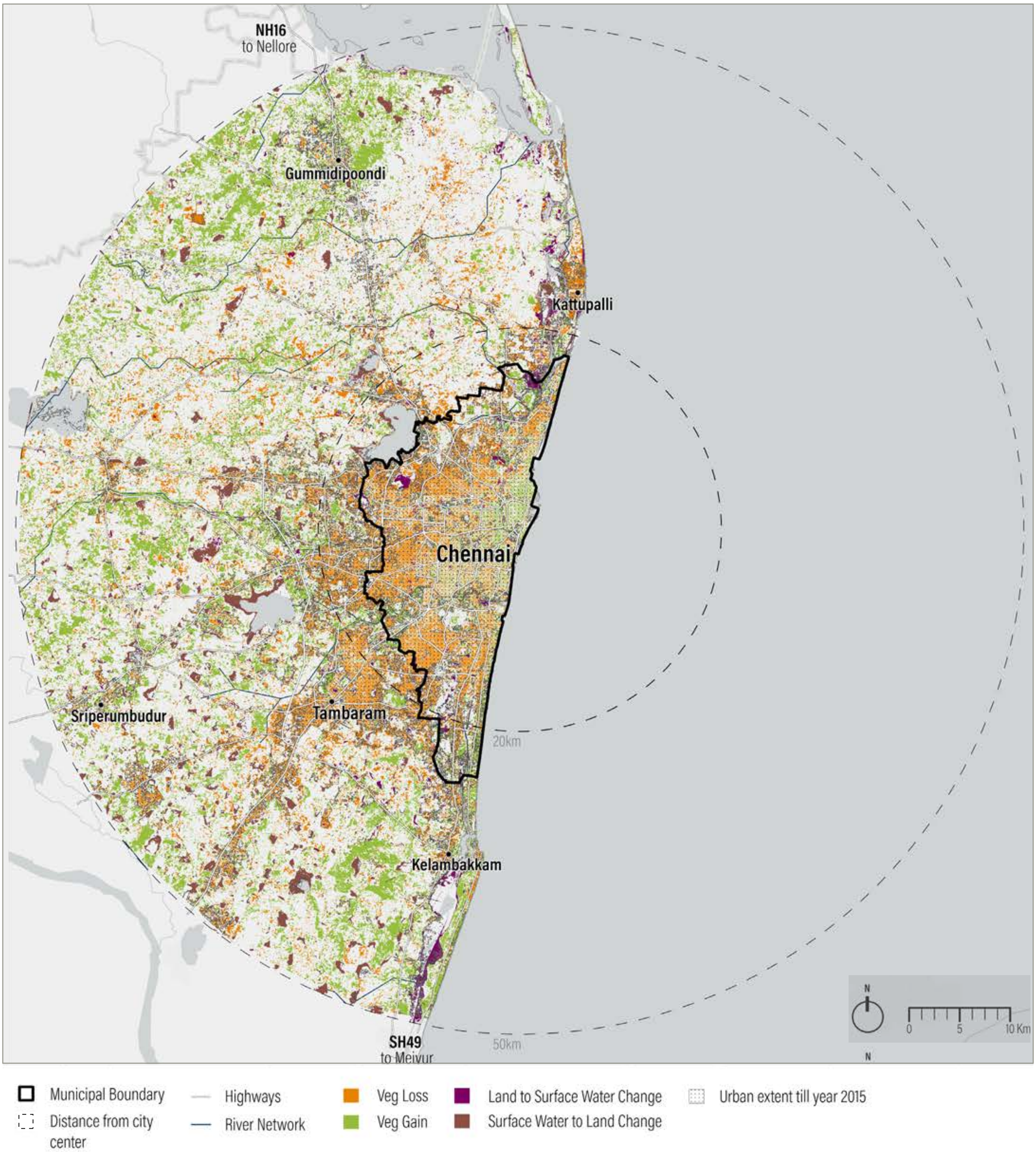


Sources: Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; Vegetation loss - NASA n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

Figure L2 | **Built-Up Area and Vegetation Loss Overlap Significantly in Bengaluru and Vegetation Gains Are Distinctly Visible along Two Rivers Flowing Out of the City to the South**

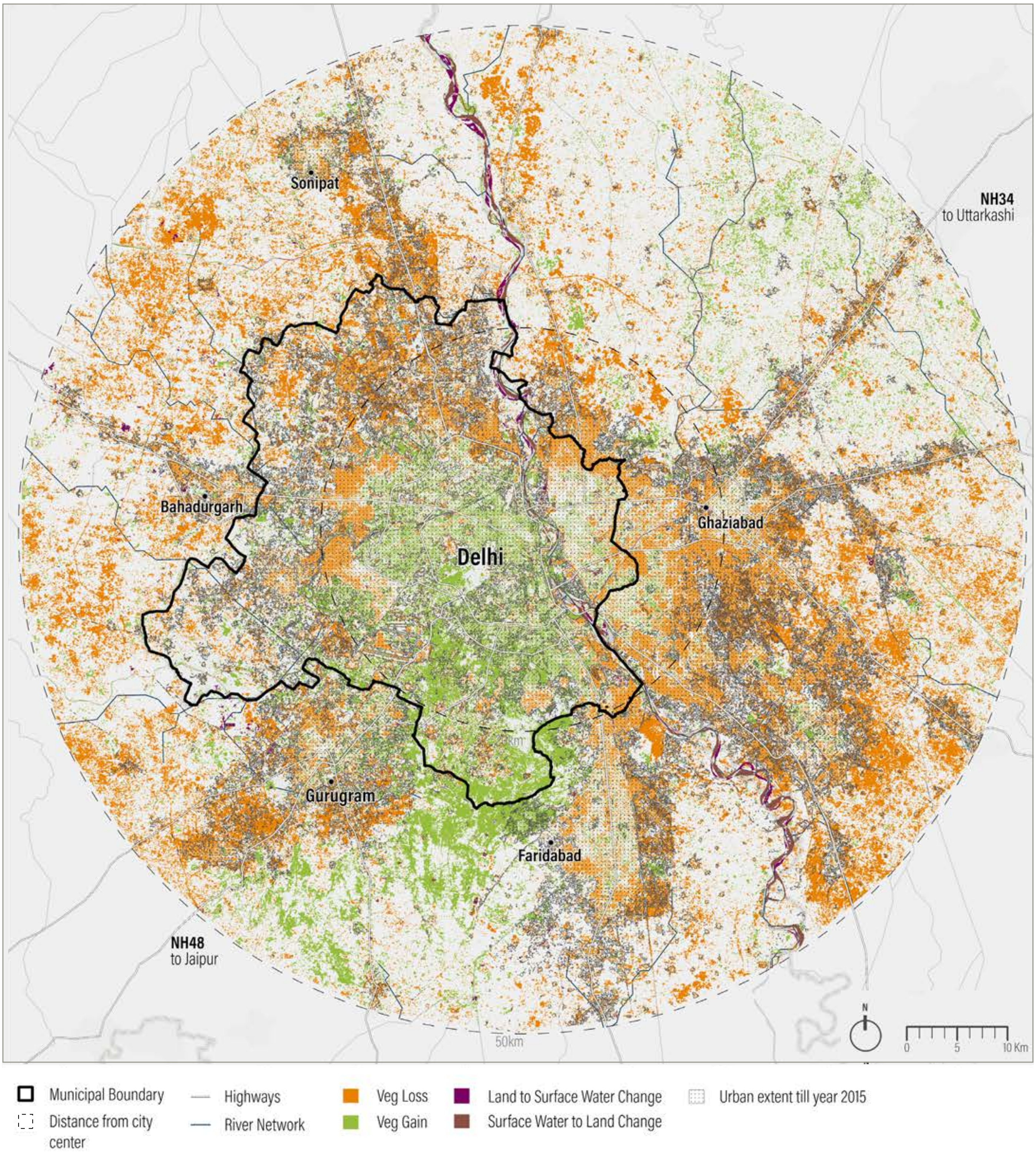
Sources: Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; Vegetation loss - NASA n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

Figure L3 | **Vegetation Loss Overlaps with Built-Up Area Especially along Roadways in Chennai**



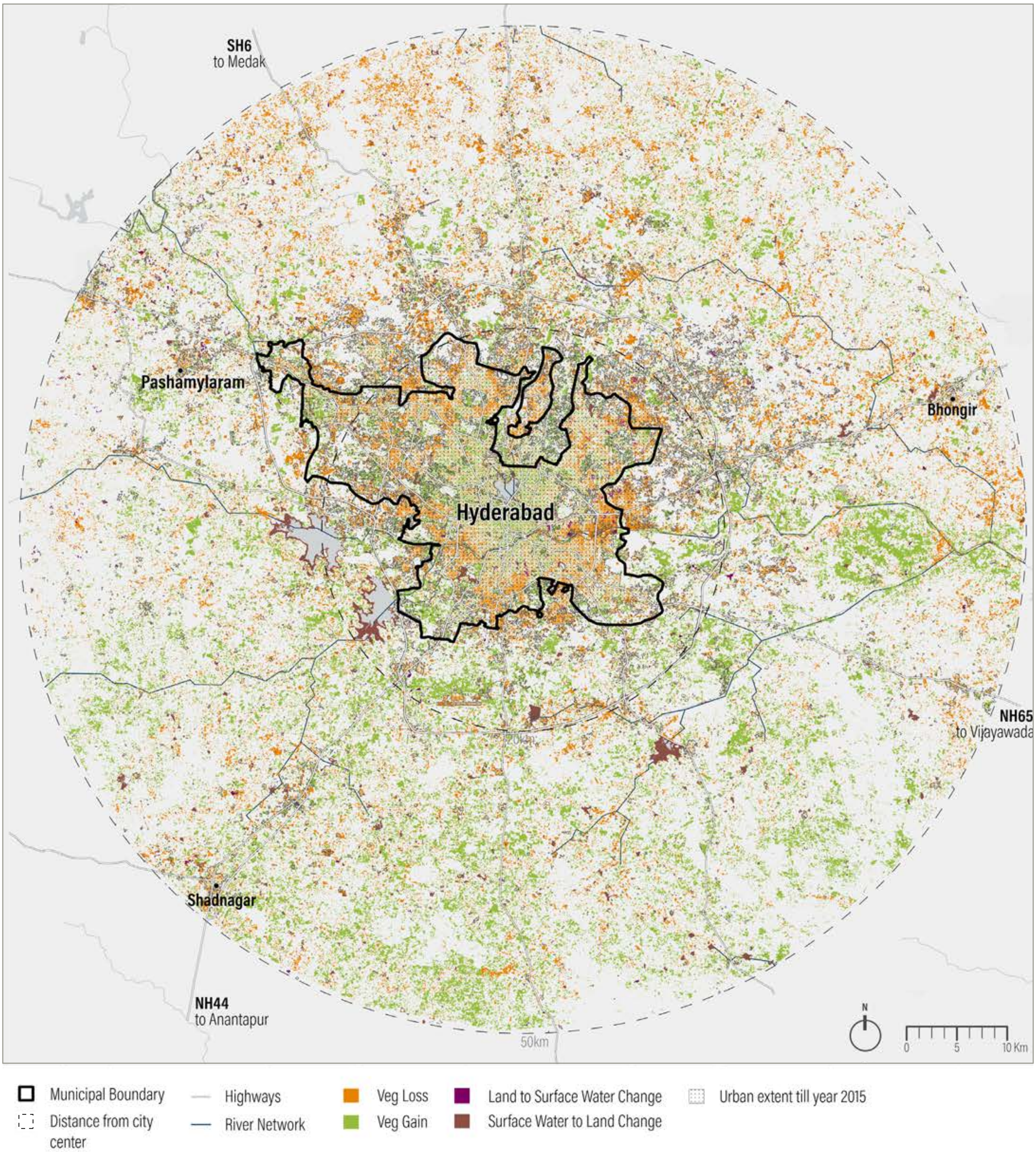
Sources: Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; Vegetation loss - NASA n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

Figure L4 | **Built-Up Area and Vegetation Loss Overlap Significantly in Peripheral Areas in Delhi**



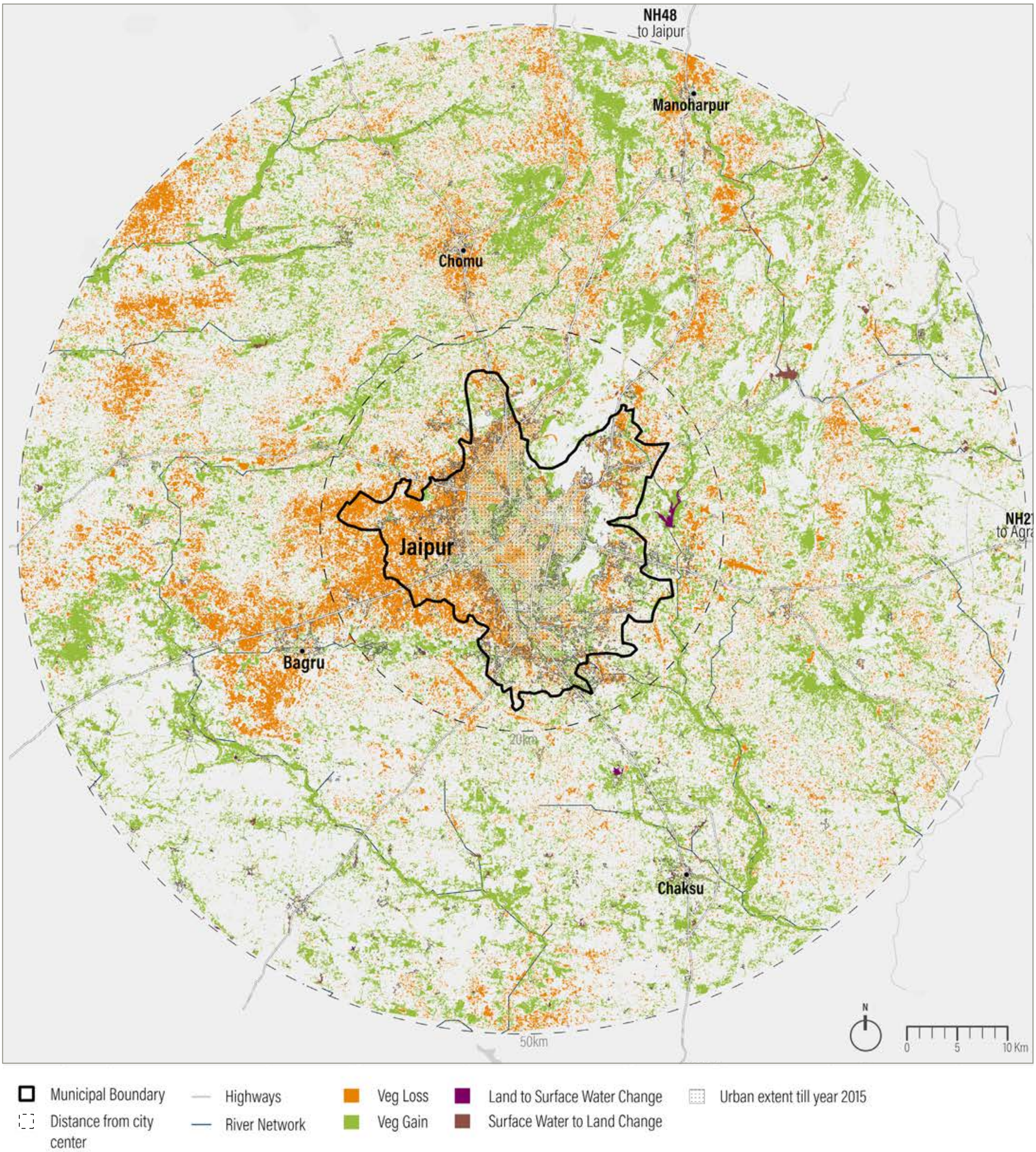
Sources: Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; Vegetation loss - NASA n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

Figure L5 | **Vegetation Loss Is Distributed Close to Hyderabad's Municipal Boundary and to the North of the Study Area**



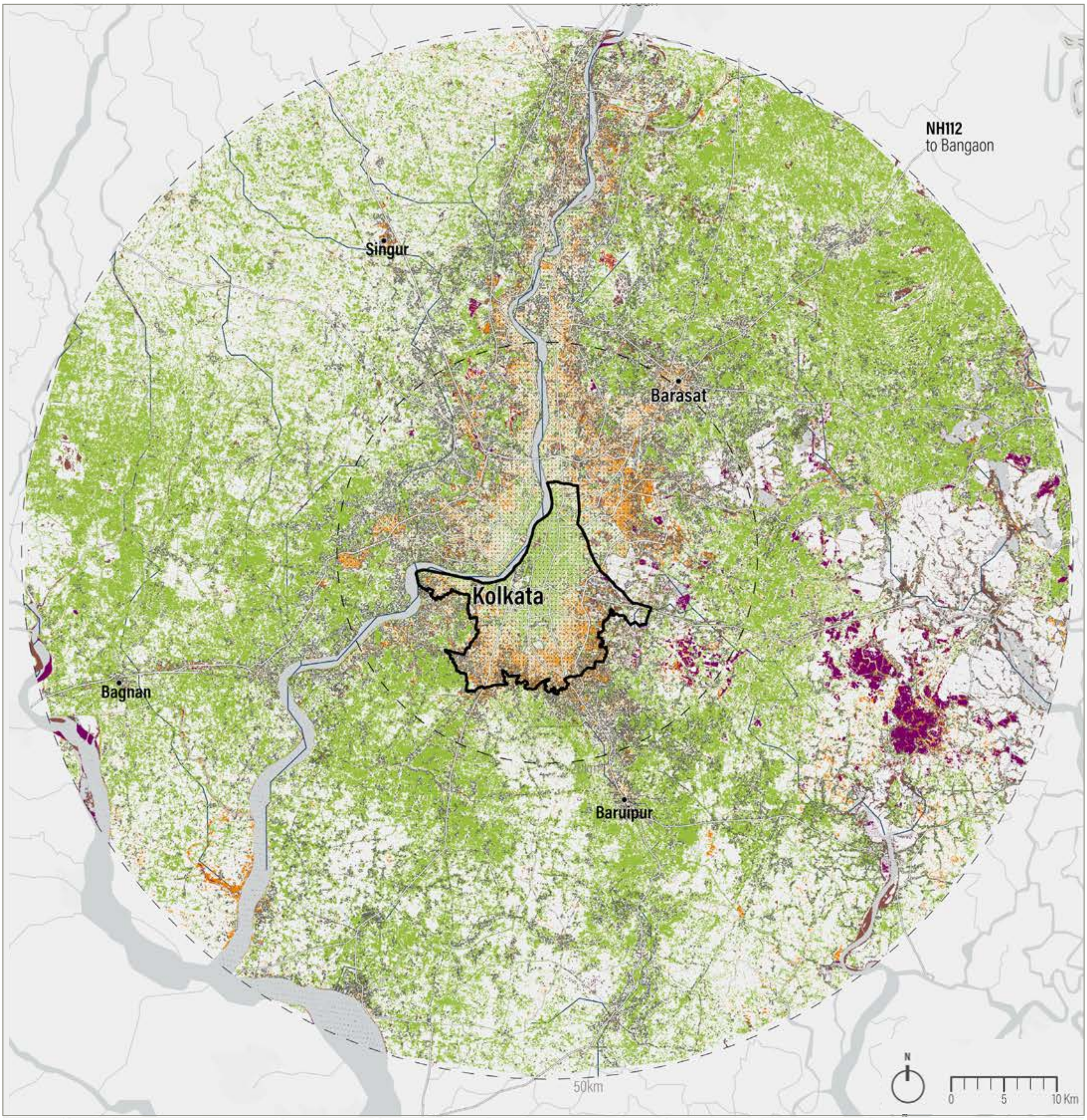
Sources: Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; Vegetation loss - NASA n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

Figure L6 | **Vegetation Loss Is Significant to the West of Jaipur and Vegetation Gains Align with Streams and Rivers**



Sources: Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; Vegetation loss - NASA n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

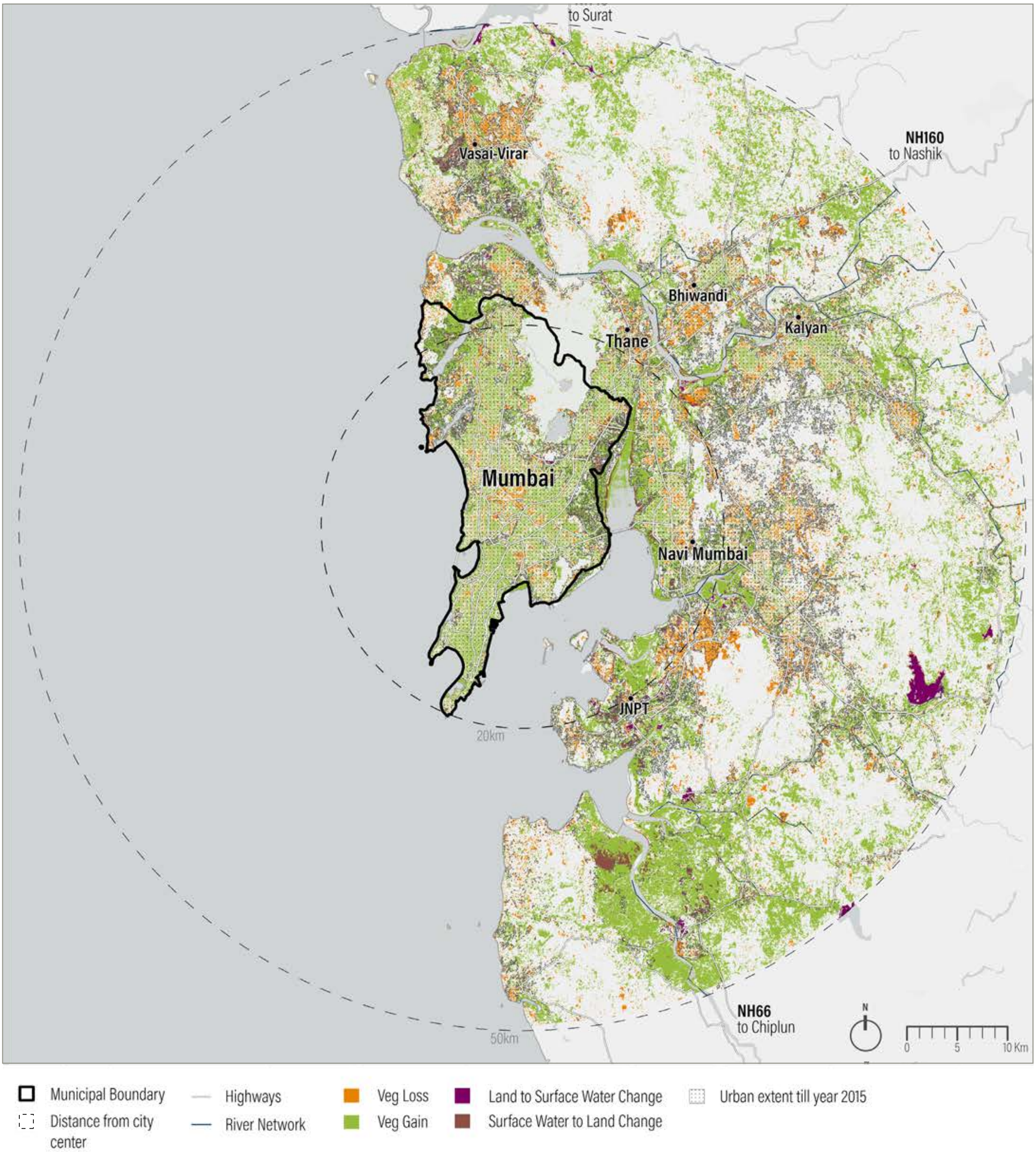
Figure L7 | **Vegetation Loss Overlaps Closely with Built-Up Area in Kolkata**



Municipal Boundary
Distance from city center
Highways
River Network
Veg Loss
Veg Gain
Land to Surface Water Change
Surface Water to Land Change
Urban extent till year 2015

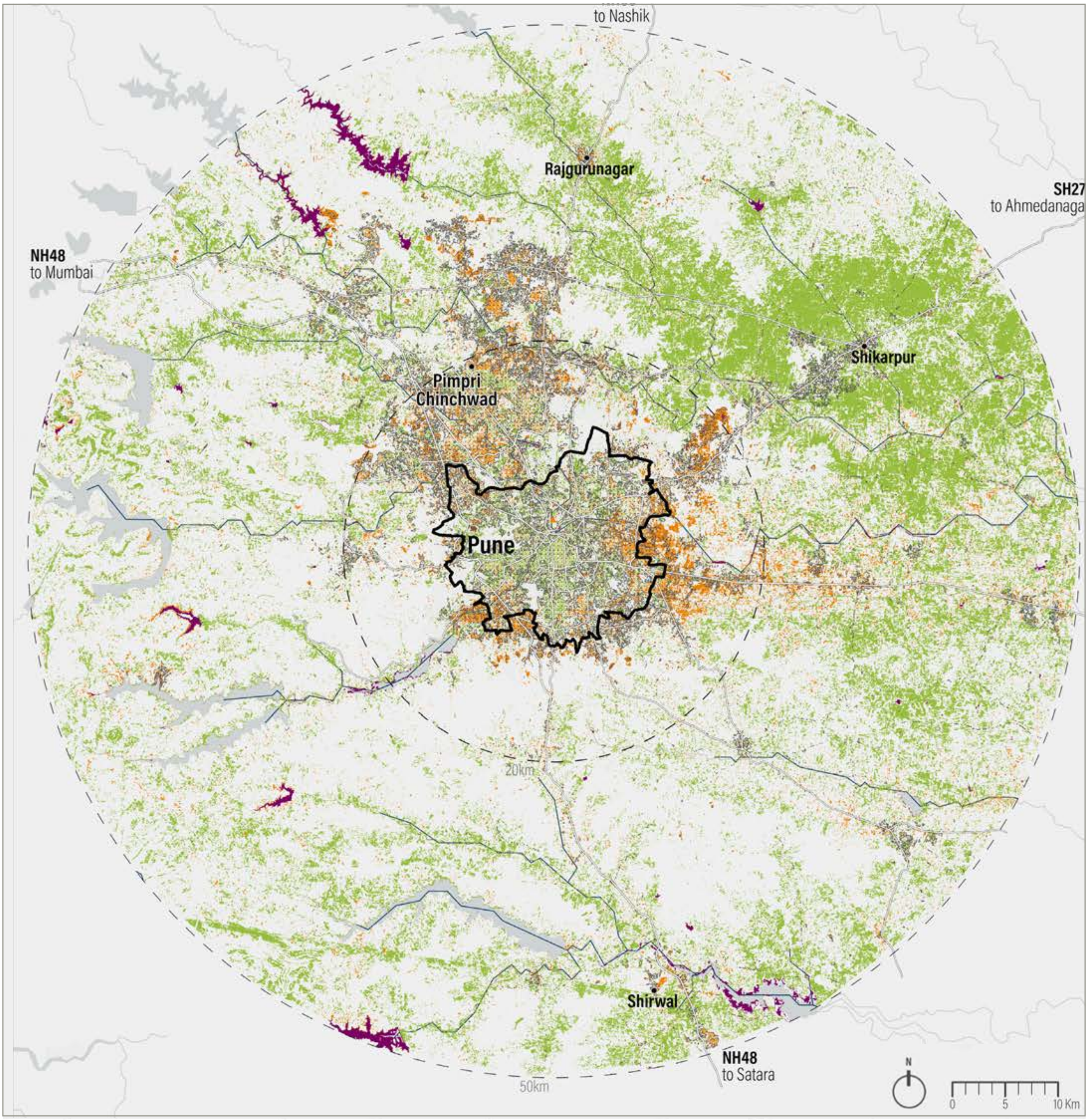
Sources: Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; Vegetation loss - NASA n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

Figure L8 | **Built-Up Area Overlaps with Both Vegetation Loss and Gain in Mumbai**



Sources: Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; Vegetation loss - NASA n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

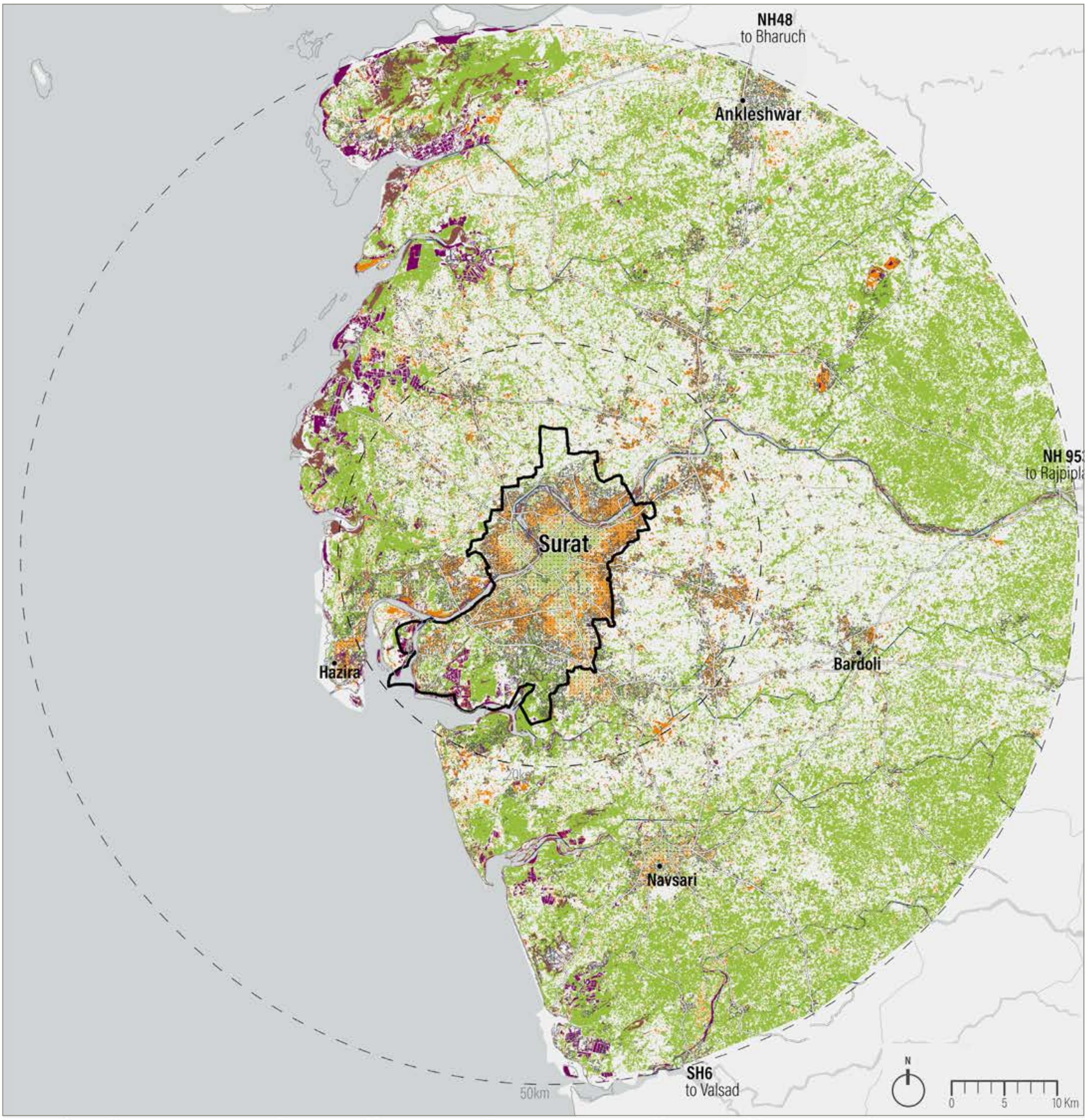
Figure L9 | **Vegetation Loss Overlaps with Built-Up Area Especially along Roadways in Pune**



Municipal Boundary
Distance from city center
Highways
River Network
Veg Loss
Veg Gain
Land to Surface Water Change
Surface Water to Land Change
Urban extent till year 2015

Sources: Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; Vegetation loss - NASA n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

Figure L10 | **Vegetation Loss Overlaps Significantly with Built-Up Area Close to the Municipal Boundary of Surat**



Municipal Boundary
Distance from city center
Highways
River Network
Veg Loss
Veg Gain
Land to Surface Water Change
Surface Water to Land Change
Urban extent till year 2015

Sources: Built-up Area - European Commission 2016; Maximum surface water- EC JRC/Google n.d.; Vegetation loss - NASA n.d.; River Network - FAO n.d.; Basemap - Esri, DeLorme, HERE, MapmyIndia.

LIST OF ABBREVIATIONS

CGWB: Central Ground Water Board
FAO: Food and Agriculture Organization of the United Nations
GDP: Gross Domestic Product
lpcd: Liters Per Capita Per Day
MLD: Million Liters Per Day
MNDWI: Modified Normalized Difference Water Index
MODIS: Moderate Resolution Imaging Spectroradiometer
NBS: Nature-Based Solution
NDVI: Normalized Difference Vegetation Index
NDWI: Normalized Difference Water Index
SDG: Sustainable Development Goals
UN: United Nations

GLOSSARY

Blue cover refers to all surface water bodies (seasonal and perennial) such as lakes, reservoirs, ponds, rivers, and streams.

Blue-green infrastructure refers to natural or constructed systems such as a streams, lakes, wetlands, treatment facilities, trees, parks, and woodlands that provide services such as stormwater absorption and conveyance, stormwater management, and flood mitigation. Natural infrastructure (defined below) is considered a type of blue-green infrastructure.

Built-up area refers to the presence of structures such as buildings, concretized surfaces, and tar roads on natural land surface, which, by virtue of their design and construction material, drastically alter the natural infrastructure characteristics of an area/region by modifying/destroying natural hydrological patterns, reducing infiltration into the ground and increasing the surface runoff during rain events.

Ecosystem services encompass a group of provisioning, regulating, habitat-supporting, and cultural services that natural ecosystems provide that are of value to the natural world and to humans. These include provisioning of food, raw materials, water, regulating micro and global climate, flood control, and carbon sequestration (TEEB n.d.)

Open/green permeable space refers to all the areas not covered by anthropogenic, built, less permeable areas such as paving and concrete. Open green permeable space comprises blue cover, green spaces such as forests, and vegetated and non-vegetated natural lands, barren grasslands, and agricultural lands.

Modified Normalized Difference Water Index (MNDWI) is a spectral index used to enhance open water features while efficiently suppressing and even removing built-up land noise as well as vegetation and soil noise in satellite imagery.

Moderate Resolution Imaging Spectroradiometer (MODIS) is a key instrument onboard the Terra (originally known as EOS AM-1) and Aqua (originally known as EOS PM-1) satellites.

Natural infrastructure refers to naturally occurring physical systems (water bodies, permeable open spaces) that provide essential services such as clean and abundant water supply, flood control, and groundwater recharge. We consider blue spaces and permeable open spaces as examples of natural infrastructure. Natural infrastructure is a subset of blue-green infrastructure, which encompasses both naturally occurring and engineered systems.

Net vegetation change trend for a study region is a sum of all the estimated areas with increasing and decreasing vegetation changes. A net positive vegetation change trend indicates that areas with increasing vegetation trends are more than areas where vegetation is declining. Conversely, a net negative vegetation change trend indicates that decrease is occurring in a larger area.

Normalized Difference Water Index (NDVI) is a dimensionless index that describes the difference between visible and near-infrared reflectance of vegetation cover and can be used to estimate the density of green cover on an area of land.

ENDNOTES

1 Affluent residents and business and commercial properties may also be located in high-risk zones, but their financial and technical resources enable these groups to better protect themselves from, adapt to, and recover from climate shocks (Mahendra and Seto 2019).

2 The Guidelines for National Lake Conservation Plan developed by the Ministry of Environment and Forests defines lakes as water bodies with a minimum depth of 3 m (MoEF 2008).

3 The population increased by 39 million between 2000 and 2015 in the 0–50 km region of the 10 cities (population estimates from the Global Human Settlements Layer produced by the European Commission–Joint Research Centre (EC-JRC 2016). Considering a demand of 100 lpcd (liters per person [capita] per day), the additional annual demand is about 1,400 billion liters.

4 Unplanned urban development alludes to the haphazard nature of development due to restrictive, obsolete, inadequate, and/or unenforced development control and zoning regulations that lead to the creation of informal settlements (Ellis and Roberts 2016) and communities that are cut off from transportation and economic networks (Beard et al. 2016).

5 Unmanaged urban development refers to the unregulated expansion of urban land area into surrounding agricultural lands and natural areas (Mahendra and Seto 2019); this expansion is inadequately managed, causing higher environmental and economic risk as well as deepening urban inequalities (Du and Mahendra 2019).

6 Unregulated, unplanned, and unmanaged urban expansion, typically seen in Global South cities, is due to weak governance and institutions that are unable to control or moderate the pressures on land (Chu et al. 2019).

7 In this study, the city center is identified by the central or oldest railway station in the city, which corresponds to the geographic center as well. Mumbai is the exception, and the 50 km study area for Mumbai is described as the minimum bounding circle that encompasses the Urban Agglomeration (as defined in the 2011 Census of India).

8 The 10 study cities are quite different in their urban footprint, and the spatial distinction between core-city and peripheral areas is an approximation made by the authors. For almost all the cities (except Delhi), the municipal boundary (describing the zone with building regulations) lies at or within a circle of radius 20 km.

9 Sensors and instruments aboard satellites have varying capacities, and technological advances often make it challenging to compare observations from different satellite sources. Spatial resolution, spectral bands, and revisit times dictate the quality and quantum of information that is available from each satellite source.

10 The epochs considered for blue cover estimation were 1998–2002 and 2013–2017.

11 The 1997–2017 timeline is considered to provide a 20-year study period, which allows a substantial number of images to be used for the trend analysis and also aligns the timeline as closely as possible with the study period for blue cover, whose epochs are 1998–2002 and 2013–2017.

12 Volume of water (in billion liters) in a 307 sq. km area reservoir = Area of the reservoir × Depth of water; 1 sq. km = 1,000 × 1,000 sq. m; 1 cubic meter = 1,000 liters.

13 Water demand estimation (assuming 100 liters per capita per day): Population (in millions) × Per capita per day demand = Total water demand (in million liters per day).

14 The 1997–2017 timeline (i.e., a 20-year study period) enables a substantial number of images to be used for trend analysis and also closely aligns with the study period for blue cover, whose epochs are 1998–2002 and 2013–2017.

15 The six classifications of vegetation change—high loss, moderate loss, low loss, low gain, moderate gain, and high gain—indicate a change in the NDVI value. For the classification, an NDVI reduction between 0 and 0.3 is considered low loss, between 0.3 to 0.6 moderate loss, and greater than 0.6 high loss. Similarly, an increase in the NDVI value between 0 and 0.3 is low gain, between 0.3 and 0.6 moderate gain, and greater than 0.6 high gain. The ranges used in the classifications are derived for this study from the range of results.

16 Data for Kolkata is not reported in the Central Ground Water Board report published in 2017.

17 In addition to changes in groundwater recharge and flooding events, another impact of increased urbanization in the watershed could be a change in inflow into the lake. This impact would require a separate study and is not considered in the current research.

18 Five classes: very low, low, medium, high, and very high.

19 Urban populations are extracted from the Global Human Settlement Population Grid, which provides population estimates for 1975, 1990, 2000, and 2015 (EC-JRC n.d.).

20 Only Surat is classified as safe from the standpoint of the groundwater abstraction rate (CGWB 2017, p. 82). The CGWB recommends that groundwater not be used for drinking in Mumbai , and the municipal corporation in Mumbai issues warnings against the use of groundwater for drinking in this city; although the water is potable, contamination from sewage and industrial affluents makes it unsafe (CGWB 2010). Kolkata's stage of groundwater development has not been updated in the 2017 report.

21 Using a conservative estimate of 100 lpcd water supply requirement, the overall water demand for the population within 0–20 km of the city center for the 10 study cities rose from 7,683 MLD in 2000 to 9,800 MLD in 2015. According to guidelines issued by the Government of India, water in metropolitan cities should be supplied at 150 lpcd.

22 Water for Delhi is procured from the Tehri Dam, which is located 320 km from the city (IIHS 2014).

23 Tanker water supply depends predominantly on groundwater extracted from private borewells (Ranganathan 2014), and this service fills the gaps that arise due to inadequate public water supply. Areas not connected to public utility networks are greatly dependent on tanker water supply. There is high demand for this service during water-scarce times (the summer months) when supply may be disrupted even to areas connected to public water supply networks. Tanker water supply is a critical service that offers households an alternative source, but it is a highly unregulated sector with no price control (Ranganathan 2014) or checks on water quality (Joseph and Sibi 2020).

REFERENCES

Adeleke, O.O., V. Makinde, A.O. Eruola, O.F. Dada, A.O. Ojo, and T.J. Aluko. 2015. "Estimation of Groundwater Recharges Using Empirical Formulae in Odeda Local Government Area, Ogun State, Nigeria." *Challenges* 6: 271–81.

Asoka, A., T. Gleeson, Y. Wada, and V. Mishra. 2017. "Relative Contribution of Monsoon Precipitation and Pumping to Changes in Groundwater Storage in India." *Nature Geoscience* 10: 109–17.

Beard, V.A, A. Mahendra, and M.I. Westphal. 2016. "Towards a More Equal City: Framing the Challenges and Opportunities." Working Paper. World Resources Report, Washington, DC.: World Resources Institute.

Blum, A.G., P.J. Ferraro, S.A. Archfield, and K.R. Ryberg. 2020. "Causal Effect of Impervious Cover on Annual Flood Magnitude for the United States." *Geophysical Research Letters* (Wiley Online Library) 47 (5).

Browder, G., S. Ozment, I. R. Bescos, T. Gartner, and G. M. Lange. 2019. "Integrating Green and Gray: Creating Next Generation Infrastructure." Washington, DC.: World Resources Institute and World Bank.

Butsch, C., and S.B. Heinkel. 2020. "Periurban Transformations in the Global South and Their Impact on Water-Based Livelihoods." *Water* 12 (2): 458.

Center for Science and Environment. n.d. "Rainwater Harvesting: Laws and Policy." https://www.cseindia.org/laws-and-policy--1161. Accessed September 10, 2021.

Center for Science and Environment. 2013. "Legal, Institutional and Technical Framework for Lake/Wetland Protection." Briefing Paper. New Delhi: Center for Science and Environment.

Centre for Research and Development Foundation. 2014. "Ahmedabad Slum Free City Action Plan." Action Plan. Ahmedabad: CEPT University.

CGWB (Central Ground Water Board). 2010. "Ground Water Information – Greater Mumbai District." Nagpur: CGWB. http://cgwb.gov.in/District_Profile/Maharashtra/Greater%20Mumbai.pdf.

CGWB. 2015. "Frequently Asked Questions." http://cgwb.gov.in/faq.html. Accessed November 15, 2020.

CGWB. 2017. *National Compilation on Dynamic Ground Water Resources of India, 2017*. Faridabad: CGWB. http://cgwb.gov.in/GW-Assessment/GWRA-2017-National-Compilation.pdf.

CGWB. 2020. *Groundwater Yearbook of Karnataka State (2019-2020)*. Yearbook. Bangalore: CGWB.

Chan, F.K.S., J.A. Griffiths, D. Higgitt, S. Xu, F. Zhu, Y.-T. Tang, Y. Xu, et al. 2018. "'Sponge City' in China—a Breakthrough of Planning and Flood Risk Management in the Urban Context." *Land Use Policy* 76: 772–78.

Chen, J.M. 1996. "Evaluation of Vegetation Indices and a Modified Simple Ratio for Boreal Applications." *Canadian Journal of Remote Sensing* 22 (3): 229–42.

Chu, E., A. Brown, K. Michael, J. Du, S. Lwasa, and A. Mahendra. 2019. "Unlocking the Potential for Transformative Climate Adaptation in Cities." Background Paper prepared for the Global Commission on Adaptation. World Resources Institute: Washington, DC., and Rotterdam.

Cullet, P. 2018. "Model Groundwater (Sustainable Management) Bill, 2017: A New Paradigm for Groundwater Regulation." *Indian Law Review* 2 (3).

Cunniff, S. E. 2019. "Scaling Protection and Restoration of Natural Infrastructure to Reduce Flood Impacts and Enhance Resilience." *Shore & Beach* 87 (4).

da Costa, A.M., H.H.C. de Salis, J.H.M. Viana, and F.A. Leal Pacheco. 2019. "Groundwater Recharge Potential for Sustainable Water Use in Urban Areas of the Jequitiba River Basin, Brazil." *Sustainability* 11 (10) : 2955.

Deccan Chronicle. 2018. "Hyderabad: Over 3,000 Water Bodies Disappear in 2 Decades." May 5, 2018.

Delhi Development Authority. 2021. "Draft Master Plan for Delhi-2041." https://dda.org.in/MPD_2041.aspx#. Accessed October 20, 2021.

Desai, D. 2020. "From 630 to 122: Where Did Ahmedabad's Lakes Disappear?" *Citizen Matters*, October 19.

Directorate of Economics and Statistics. 2015. *Urban Slums in Delhi. Sample Survey Report*. New Delhi: Directorate of Economics and Statistics.

DNA. 2014. "Ahmedabad: Developed Lakes Reflect Authorities' Apathy." February 2.

Donchyts, G., F. Baart, H. Winsemius, N. Gorelick, J. Kwadijk, and N. van de Giesen. 2016. "Earth's Surface Water Change over the Past 30 Years." *Nature Climate Change* 6 (9) : 810–13.

Du, J., and A. Mahendra. 2019. "Too Many Cities Are Growing Out Rather than Up. Three Reasons That's a Problem." *The City Fix*. Blog, January 31. https://thecityfix.com/blog/many-cities-growing-rather-3-reasons-thats-problem-jillian-du-anjali-mahendra/.

EC-JRC (European Commission–Joint Research Centre). 2016. "GHSL – Global Human Settlement Layer." https://ghsl.jrc.ec.europa.eu/ghs_pop2019.php.

EC-JRC/Google. n.d. "Global Surface Water – Data Access." https://developers.google.com/earth-engine/datasets/catalog/JRC_GSW1_3_GlobalSurfaceWater. Accessed March 23, 2020.

Ellis, P., and M. Roberts. 2016. *Leveraging Urbanization in South Asia: Managing Spatial Transformation for Prosperity and Livability*. Washington, DC.: World Bank.

European Commission. 2016. GHS Settlement Grid Following the REGIO Model 2014 in Application to GHSL Landsat and CIESIN GPW v4-Multitemporal (1975-1990-2000-2015). Dataset, European Commission, Joint Research Centre (JRC) (Dataset). https://ghsl.jrc.ec.europa.eu/ghs_smod.php . Accessed April 10, 2020.

FAO (Food and Agriculture Organization). n.d. "Rivers of South and East Asia." FAO Map Catalog. https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/metadata/dc2a5121-0b32-482b-bd9b-64f7a414fa0d. Accessed April 15, 2020.

FAO. 2013. "AQUASTAT - FAO's Global Information System on Water and Agriculture: India." http://www.fao.org/aquastat/en/geospatial-information/global-maps-irrigated-areas/irrigation-by-country/country/IND. Accessed October 15, 2021.

Farr, T.G., P.A. Rosen, E. Caro, R. Crippen, R. Duren, S. Hensley, M. Kobrick, et al. 2007. "The Shuttle Radar Topography Mission." *Reviews of Geophysics* 45 (2) : RG2004. https://doi.org/10.1029/2005RG000183.

Fensholt, R., and S.R. Proud. 2012. "Evaluation of Earth Observation Based Global Long Term Vegetation Trends — Comparing GIMMS and MODIS Global NDVI Time Series." *Remote Sensing of Environment* 119: 131–47.

Frazer, L. 2005. "Paving Paradise: The Peril of Impervious Surfaces." *Environmental Health Perspectives* 113 (7).

Friedman, Uri. 2014. "'70% of India Has Yet to Be Built' Can the Government Turn Slums into the World's Greenest Cities?" *The Atlantic*, June 29.

Gonçalves, A.B., Ariadne Barbosa , R. de Faria Godoi, A.C. Paranhos Filho, M.T. Folhes, and H. Pistori. 2018. "Urban Phytophysiognomy Characterization Using NDVI from Satellites Images and Free Software." *Anuário do Instituto de Geociências* 41 (3): 24–36.

Google Earth Engine 2021. Contains modified Copernicus Sentinel data 2020, processed by the European Space Agency (ESA).

Google Earth Pro 2003. Contains Landsat and Copernicus images, Maxar Technologies.

Gosain, A.K. 2014. *Conversation on Swacch Delhi: A Sampoorna Approach*. ICRIER. India Habitat Center. New Delhi.

Güneralp, B., M. Reba, B.U. Hales, E.A. Wentz, and K.C. Seto. 2020. "Trends in Urban Land Expansion, Density, and Land Transitions from 1970 to 2010: A Global Synthesis." *Environmental Research Letters* 15 (4): 044015.

Guo, Q., R. Pu, J. Li, and J. Cheng. 2017. "A Weighted Normalized Difference Water Index for Water Extraction Using Landsat Imagery." *International Journal of Remote Sensing* 38 (19): 5430–45.

Hallegatte, S., A. Vogt-Schilb, J. Rozenberg, M. Bangalore, and C. Beaudet. 2020. "From Poverty to Disaster and Back: A Review of the Literature." *Economics of Disasters and Climate Change* 4 (1): 223–47.

HMDA (Hyderabad Metropolitan Development Authority). 2017. "Notification of Full Tank Level Boundaries and Buffer Zones of Lakes/ Water Bodies in Hyderabad Metropolitan Region," October 18.

IIHS (Indian Institute of Human Settlements). 2014. "Urban Water Supply and Sanitation in India." Bangalore: IIHS. https://iihs.co.in/knowledge-gateway/wp-content/uploads/2017/11/RF-WATSAN_reduced_sized.pdf.

IMD (India Meteorological Department). 2018. "Observed Rainfall Variability and Changes over Different States." https://internal.imd.gov.in/press_release/20200330_pr_778.pdf

Jamwal, P., A.K. Mittal, and J. Mouchel. 2008. "Effects of Urbanisation on the Quality of the Urban Runoff for Delhi Watershed." *Urban Water Journal* 5 (3) :247–57.

Johnson, T.D., and K. Belitz. 2012. "A Remote Sensing Approach for Estimating the Location and Rate of Urban Irrigation in Semi-arid Climates." *Journal of Hydrology* 414–415 : 86–98.

Jones, J.W., 2019. "Improved Automated Detection of Subpixel-Scale Inundation—Revised Dynamic Surface Water Extent (DSWE) Partial Surface Water Tests." *Remote Sensing* 11 (4): 374. https://doi.org/10.3390/rs11040374.

Joseph, J., and G. Sibi. 2020. "Physicochemical and Microbiological Quality of Tanker Waters in Bengaluru Urban for Safe Water Supply." *International Journal of Clinical Microbiology and Biochemical Technology* 3 (1): 21–25.

Konrad, C.P. 2003. "Effects of Urban Development on Floods." Fact Sheet FS-076-03. Tacoma, Washington: U.S. Geological Survey.

Krishna Chaitanya, S.V. 2019. "In a Surprise Move, TN Proposes 'Zero' Buffer Zone around Pulicat Bird Sanctuary." *The New Indian Express*, August 18.

Kulkarni, A., T.P. Sabin, and J.S. Chowdary. 2020. "Precipitation Changes in India." In *Assessment of Climate Change over the Indian Region*, edited by R. Krishnan, J. Sanjay, C. Gnanaseelan, M. Mujumdar, A. Kulkarni, and S. Chakraborty. Singapore: Springer.

Kundu, A. 2003. "Urbanisation and Urban Governance: Search for a Perspective Beyond Neo-Liberalism." *Economic and Political Weekly* 38 (29): 3079–87.

Li, F., G. Song, Z. Liujun, Z. Yanan, and L. Di. 2017. "Urban Vegetation Phenology Analysis Using High Spatio-Temporal NDVI Timeseries." *Urban Forestry & Urban Greening* 25: 43–57.

Liu, Y., Y. Wang, J. Peng, Y. Du, X. Liu, S. Li, and D. Zhang. 2015. "Correlations between Urbanization and Vegetation Degradation across the World's Metropolises Using DMSP/OLS Nighttime Light Data." *Remote Sensing* 7 (2) :2067–88.

Mahendra, A., and K.C. Seto. 2019. "Upward and Outward Growth: Managing Urban Expansion for More Equitable Cities in the Global South." Working Paper. Washington, DC: World Resources Institute.

Misstear, B.D.R, L. Brown, and P.M. Johnston. 2009. "Estimation of Groundwater Recharge in a Major Sand and Gravel Aquifer in Ireland Using Multiple Approaches." *Hydrogeology Journal* 17 (3): 693–706.

MoEF (Ministry of Environment and Forests). 2008. *Guidelines for National Lake Conservation Plan*. New Delhi: MoEF.

MoEFCC (Ministry of Environment, Forest and Climate Change). 2019. *National Plan for Conservation of Aquatic Ecosystems (NPCA) Guidelines.* New Delhi: MoEFCC.

Muddu, S., S. K. Tomer, S. Thiyaku, P. Giriraj, S. Murthy, and V. K. Mehta. 2017. "Groundwater Level Dynamics in Bengaluru City, India." *Sustainability* 10 (1): 26.

Mumbai Metropolitan Planning Committee. 2021. Final Regional Plan for Mumbai Metropolitan Region. Master Plan. Mumbai: Mumbai Metropolitan Region Development Authority.

Mvandaba, V., J.M. Kahinda, P. Nzuza, and P. Hobbs. 2019. *Green Book – The Impact of Climate Change on Groundwater Availability.* Technical Report, Pretoria: Council for Scientific and Industrial Research (CSIR).

Nallathiga, R. 2014. "Strategizing Poverty Reduction at City Level: The Approach of Hyderabad." *Indian Journal of Inclusive Growth* 1 (2): 187–92.

NASA (National Aeronautics and Space Administration). n.d. MODIS Vegetation Index Products (NDVI and EVI). Washington, DC: NASA. https://modis.gsfc.nasa.gov/data/dataprod/mod13.php. Accessed March 27, 2020.

OECD (Organisation for Economic Co-operation and Development), European Commission, FAO, UN-Habitat, ILO (International Labour

Organization), and World Bank. 2021. *Applying the Degree of Urbanisation: A Methodological Manual to Define Cities, Towns and Rural Areas for International Comparisons.* OECD Regional Development Studies. Paris/European Union, Brussels: OECD Publishing. https://doi.org/10.1787/4bc1c502-en.

Parmar, J. 2021. "70 Of City's Lakes Gone, AMC Wakes Up to Loss, Decides to Revive 142." *Ahmedabad Mirror,* September 19.

Pekel, J. F., A. Cottam, N. Gorelick, and A. S. Belward. 2016. "High-Resolution Mapping of Global Surface Water and Its Long-Term Changes." *Nature* 540 (7633): 418–22.

Pesaresi, M., D. Ehrlich, A. Florczyk, S. Freire, A. Julea, T. Kemper, P. Soille, and V. Syrris. 2015. "GHS-BUILT R2015B—GHS Built-Up Grid, Derived from Landsat, Multitemporal (1975, 1990, 2000, 2014)." European Commission–Joint Research Centre (JRC) [Dataset]. https://data.europa.eu/data/datasets/jrc-ghsl-ghs_built_ldsmtcnfd_globe_r2015b?locale=en. Accessed April 5, 2020.

Pirastru, M., and M. Niedda. 2013. "Evaluation of the Soil Water Balance in an Alluvial Flood Plain with a Shallow Groundwater Table." *Hydrological Sciences Journal* 58 (4): 898–911.

Ramachandraiah, C. 2008. "Urban Growth, Loss of Water Bodies and Flooding in Indian Cities." In *Water and Urban Development Paradigms: Towards an Integration of Engineering, Design and Management Approaches,* edited by Jan Feyen, Kelly Shannon, and Matthew Neville, 121–25. London: Taylor and Francis.

Ramachandraiah, C., and S. Prasad. 2004. *Impact of Urban Growth on Water Bodies: The Case of Hyderabad.* Hyderabad: Centre for Economic and Social Studies.

Ranganathan, M. 2014. "'Mafias' in the Waterscape: Urban Informality and Everyday Public Authority in Bangalore." *Water Alternatives* 7 (1): 89–105.

Shah, M. 2016. "Urban Water Systems in India: A Way Forward." Working Paper. New Delhi: Indian Council for Research on International Economic Relations (ICRIER).

Shailesh R. Shah vs. State of Gujarat. 2002. Special Civil Application No. 10621 of 2000 (Gujarat High Court, Ahmedabad, August 2).

Shastry, S., S. Goswami, A. Markandya, A. Sagar, I. Roy, Z. Aziz, S. Paul, M. Pai, A. Tagat, and A. Chatterjee. 2018. "Towards Smarter Service Provision for Smart Cities: Accounting for the Social Costs of Urban Service Provision." Working Paper. Bangalore: WRI India.

Shekar, A., and P. Thirumurthy. 2019. "Tamil Nadu Government – Largest Encroacher of Water Bodies in the State?" *The News Minute*, July 20.

Sridhar, M.B., and R. Sathyanathan. 2020. "Assessing the Spatial Impact of Urbanization on Surface Water Bodies using Remote Sensing and GIS." In *IOP Conference Series: Materials Science and Engineering* 912 (6): 062069. IOP Publishing.

Subhash Chandra, K. C., and G. V. Hegde. 2014. "Occurrence of Groundwater in the Ponnaiyar River Catchment Covering Eastern Parts of Bangalore City." *Current Science* 106 (10) : 1353–56.

Survey of India. n.d. "Downloads." International Boundary Vector Format. Department of Science and Technology. https://surveyofindia.gov.in/pages/downloads. Accessed, April 25 2020.

Survey of India. 1975a. Hyderabad and Nalgonda Districts, Andhra Pradesh [map]. 1st Edition. 1: 50, 000. 56K11. New Delhi: Survey of India.

Survey of India. 1975b. Chengalpatta and Madras Districts, Tamil Nadu [map]. 1st Edition. 1: 50, 000. 66D1&D5. New Delhi: Survey of India.

Survey of India. 1976a. Chengalpattu and Madras Districts, Tamil Nadu [map]. 1st Edition. 1: 50, 000. 66C4. New Delhi: Survey of India.

Survey of India. 1976b. Chengalpatta and Madras Districts, Tamil Nadu [map]. 1st Edition. 1: 50, 000. 66C8. New Delhi: Survey of India.

Survey of India. 1978a. Bangalore District, Karnataka [map]. 1st Edition. 1: 50, 000. 57G12. New Delhi: Survey of India.

Survey of India. 1978b. Hyderabad and Medak Districts, Andhra Pradesh [map]. 1st Edition. 1: 50, 000. 56K7. New Delhi: Survey of India.

TEEB (The Economics of Ecosystems and Biodiversity). n.d. "Ecosystem Services." http://teebweb.org/our-work/nca/understanding-nca/faqs/. Accessed October 25, 2020.

The Nature Conservancy. 2018. Nature in the Urban Century. Arlington, Virginia, United States: The Nature Conservancy. https://www.nature.org/content/dam/tnc/nature/en/documents/TNC_NatureintheUrbanCentury_FullReport.pdf.

United Nations. 2019. World Urbanization Prospects: The 2018 Revision. New York: United Nations: Department of Economic and Social Affairs, Population Division.

USGS (U.S. Geological Survey). 2003. "Ground-Water Depletion across the Nation." https://pubs.usgs.gov/fs/fs-103-03/. Accessed September 18, 2021.

USGS. n.d. "Landsat Collection 1 Level 3 and Collection 2 Level 3 Dynamic Surface Water Extent (DSWE) Science Products courtesy of the U.S. Geological Survey." Landsat Dynamic Surface Water Extent Science Products.. "https://www.usgs.gov/landsat-missions/landsat-dynamic-surface-water-extent-science-products. Accessed May 25, 2020.

Weier, J., and D. Herring. 2000. "Measuring Vegetation (NDVI & EVI)." Washington, DC: NASA Earth Observatory.

Whitford, V., A.R. Ennos, and J.F. Handley. 2001. "'City Form and Natural Process'—Indicators for the Ecological Performance of Urban Areas and Their Application to Merseyside, UK." *Landscape and Urban Planning* 67 (2) : 91–103.

World Bank. 2013. Urbanization beyond Municipal Boundaries: Nurturing Metropolitan Economies and Connecting Peri-urban Areas in India. Directions in Development. Washington DC: World Bank.

Wu, S., Z. Liang, and S. Li. 2019. "Relationships between Urban Development Level and Urban Vegetation States: A Global Perspective." *Urban Forestry & Urban Greening* 38: 215–22.

Zhu, J., Q. Zhang, and Z. Tong. 2015. "Impact Analysis of Lakefront Land Use Changes on Lake Area in Wuhan, China." *Water* 7 (9): 4869–86.

Zipperer, W.C., R. Northrop, and M. Andreu. 2020. "Urban Development and Environmental Degradation." From *Oxford Research Encyclopedia of Environmental Science* (https://oxfordre.com/environmentalscience). https://www.srs.fs.usda.gov/pubs/ja/2020/ja_2020_zipperer_004.pdf.

ACKNOWLEDGMENTS

We thank Vishwanath S. (Biome Environmental Trust), Victor Shinde (National Institute of Urban Affairs), and Vaishali Nandan (Deutsche Gesellschaft für Internationale Zusammenarbeit [GIZ] GmbH) for their insightful reviews of the publication and their time.

We are also grateful to the colleagues at WRI, Anjali Mahendra, Robin King, Eric Mackres, and Prerna Mehta for their critical inputs to the publication and their time. A special note of thanks to Abhinand Gopal for developing the cartographic guide for all the maps in this publication.

We extend our thanks to Shahana Chattaraj, Gregory Taff, Emilia Suarez, and Renee Pineda from the Research, Data, and Innovation (RDI) team at WRI. We thank Santhosh Matthew Paul for the copyediting support along with Garima Jain and Neeraja Dhorde for design support. We thank Romain Warnault for coordinating the final production review.

ABOUT THE AUTHORS

Sahana Goswami is Senior Program Manager with Urban Water Resilience at WRI India.

Samrat Basak is Director of Urban Water Resilience at World Resources Institute India.

Aakash Malik is Senior Program Associate with Urban Water Resilience at World Resources Institute India.

Raj Bhagat Palanichamy works as a Senior Program Manager, Geo Analytics for Sustainable Cities & Transport program at WRI India.

ABOUT WRI INDIA

WRI India is a research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

Our Challenge

Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach

COUNT IT

We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT

We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure that our outcomes will be bold and enduring.

SCALE IT

We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.

Maps are for illustrative purposes and do not imply the expression of any opinion on the part of WRI, concerning the legal status of any country or territory or concerning the delimitation of frontiers or boundaries.

Copyright 2022 World Resources Institute. This work is licensed under the Creative Commons Attribution 4.0 International License.
To view a copy of the license, visit http://creativecommons.org/licenses/by/4.0/.