DELINEATION OF BHOPAL METROPOLITAN REGION

A THESIS REPORT

Submitted in partial fulfillment of the requirements of the

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Of

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In

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By

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(Sch no. 24209011122)

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I hereby certify that the work which is being presented in the thesis entitled "**Delineation of Bhopal Metropolitan Region"** in partial fulfillment of the requirements for the award of the Master of Planning (Urban Planning) and submitted in the Department of Architecture and Planning of the Maulana Azad National Institute of Technology, Bhopal is an authentic record of my own work carried out during the period from January 2026 to July 2026 under the supervision of **Dr. Anuj Jaiswal,** Associate Professor, Department of Architecture and Planning, Maulana Azad National Institute of Technology, Bhopal.

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ABSTRACT

The 74th Constitutional Amendment Act (1992) mandates a Metropolitan Planning Committee for every urban agglomeration exceeding ten lakh population under Article 243ZE, yet Bhopal — with a Census 2011 Urban Agglomeration population of 24.06 lakh — remains without a notified Metropolitan Region boundary. This dissertation delineates the Bhopal Metropolitan Region (BMR) through a seven-phase empirical framework integrating gravity modelling, network accessibility analysis, LULC classification, CA-Markov urban growth projection, night-time light remote sensing, OECD Functional Urban Area delineation, and Metropolitan Influence Index computation across five districts (Bhopal, Sehore, Raisen, Vidisha, and Rajgarh). Reilly's (1931) breaking point model, calibrated from Census B-28 migration data (γ = 2.027, Spearman ρ = 0.900, p = 0.037), identified 953 in-zone villages of 6,142 analysed. Following village revenue boundary alignment, the final BMR covers 11,422.32 sq km with 2,185 villages and 18.22 lakh rural population. LULC classification (OA = 97.08%, Kappa = 0.9585) reveals 76.9% built-up expansion between 2011 and 2024. CA-Markov modelling (FOM = 39.86%) projects built-up area reaching 18,523 sq km by 2041. Night-time light analysis independently confirms 119.1% radiance growth (2014–2025). The boundary deviates by only 5.59% from the Bhopal Development Authority's independently proposed extent of 12,098 sq km (April 2026), while the calibrated model achieves 99.1% accuracy on the Nagpur Metropolitan Region, confirming transferability. Eight strategic planning proposals — spanning governance, land use, agricultural protection, transport, environment, economic clustering, housing, and phased implementation — are advanced per URDPFI (2014) guidelines. This dissertation provides the first empirically calibrated, cross-validated scientific basis for BMR notification and a replicable delineation framework for Indian second-tier metropolitan regions.

सारांश

74वाँ सं वधान संशोधन अ धनियम (1992), अनुच्छेद 243ZE के अंतर्गत, दस लाख से अ धक जनसंख्या वाले प्रत्येक नगरीय समूह (Urban Agglomeration) के लए महानगर योजना स मति (Metropolitan Planning Committee) के गठन को अनिवार्य करता है, फर भी भोपाल — जिसकी जनगणना 2011 के अनुसार नगरीय समूह जनसंख्या 24.06 लाख है — आज तक अ धसू चत महानगरीय क्षेत्र सीमा से वं चत है। यह शोध-प्रबंध भोपाल महानगरीय क्षेत्र (Bhopal Metropolitan Region – BMR) का परिसीमन एक सात-चरणीय आनुभ वक ढाँचे (seven-phase empirical framework) के माध्यम से करता है, जिसमें गुरुत्व मॉड लंग (Gravity Modelling), नेटवर्क अ भगम्यता वश्लेषण (Network Accessibility Analysis), भू म उपयोग/भू म आवरण वर्गीकरण (LULC Classification), CA-Markov नगरीय वकास प्रक्षेपण, रात्रिकालीन प्रकाश सुदूर संवेदन (Night-time Light Remote Sensing), OECD कार्यात्मक नगरीय क्षेत्र (Functional Urban Area) परिसीमन तथा महानगरीय प्रभाव सूचकांक (Metropolitan Influence Index) की गणना का समेकन पाँच जिलों — भोपाल, सीहोर, रायसेन, वदिशा और राजगढ़ — में कया गया है।

रेली (Reilly, 1931) के वभाजन बिंदु मॉडल (Breaking Point Model) को जनगणना B-28 प्रवासन आँकड़ों से अंशां कत (calibrated) कया गया ($\gamma = 2.027$, स्पीयरमैन $\rho = 0.900$, $p = 0.037$), जिसके आधार पर वश्ले षत 6,142 ग्रामों में से 953 ग्राम प्रभाव-क्षेत्र (in-zone) के भीतर चह्नित कए गए। ग्राम राजस्व सीमाओं के संरेखण (village revenue boundary alignment) के पश्चात्, अंतिम BMR का वस्तार 11,422.32 वर्ग कमी है, जिसमें 2,185 ग्राम तथा 18.22 लाख ग्रामीण जनसंख्या सम्मि लत है। LULC वर्गीकरण (समग्र शुद्धता OA = 97.08%, कप्पा गुणांक = 0.9585) 2011 से 2024 के मध्य नि र्मत क्षेत्र (built-up area) में 76.9% वस्तार दर्शाता है। CA-Markov मॉड लंग (FOM = 39.86%) के अनुसार नि र्मत क्षेत्र 2041 तक 18,523 वर्ग

कमी तक पहुँचने का प्रक्षेपण है। रात्रिकालीन प्रकाश वश्लेषण स्वतंत्र रूप से 2014–2025 के मध्य 119.1% व करण वृद् ध (radiance growth) की पुष्टि करता है। यह सीमा भोपाल वकास प्रा धकरण (BDA) द्वारा स्वतंत्र रूप से प्रस्ता वत 12,098 वर्ग कमी वस्तार (अप्रैल 2026) से मात्र 5.59% का वचलन दर्शाती है, जब क अंशां कत मॉडल नागपुर महानगरीय क्षेत्र पर 99.1% शुद्धता प्राप्त करता है, जो इसकी हस्तांतरणीयता (transferability) की पुष्टि करता है।

URDPFI (2014) दिशानिर्देशों के अनुरूप आठ रणनीतिक नियोजन प्रस्ताव प्रस्तुत कए गए हैं — जो शासन (governance), भू म उपयोग, कृ ष संरक्षण, परिवहन, पर्यावरण, आ र्थक समूहन (economic clustering), आवास तथा चरणबद्ध क्रयान्वयन को समाहित करते हैं। यह शोध-प्रबंध BMR की अ धसूचना हेतु प्रथम आनुभ वक रूप से अंशां कत, पारस्परिक रूप से सत्या पत (cross-validated) वैज्ञानिक आधार प्रदान करता है, साथ ही भारत के द् वतीय-श्रेणी महानगरीय क्षेत्रों के लए एक पुनरावर्तनीय (replicable) परिसीमन ढाँचा प्रस्तुत करता है।

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1 INTRODUCTION

1.1 Background of study



Figure 1 News regarding declaration of Bhopal metropolitan region (source: Dainik Bhaskar)

Urbanization is a complex, dynamic process driven by a confluence of socio-economic, political, and environmental factors, leading to the physical expansion of cities and the transformation of peripheral areas (Chaudhuri & Clarke, 2019). This global phenomenon is particularly pronounced in developing nations like India, which are projected to contribute significantly to the world's urban population by 2050 (Karmarkar et al., 2024). This rapid urban growth often results in sprawling metropolitan regions, presenting unique challenges for sustainable development and requiring precise delineation for effective regional planning (Bhatia et al., 2023).

Metropolitan area is a large urban settlement, which has population from 10 lakh and above. The aerial extent of such settlements is huge and often spread across multiple districts. India has 53 metropolitan cities per Census, 2011. Many of these cities have already been covered by metropolitan planning or development authorities, such as Mumbai, Kolkata, Chennai, Bangalore, Hyderabad, Ahmedabad and Guwahati.

Formulation of Metropolitans Authorities was conceived with the idea of initiating the integrated planning and development of the major cities and their surrounding areas. Constitution requires the States to constitute Metropolitan Planning Committees through State legislature. Various States- West Bengal, Maharashtra, Andhra Pradesh have issued procedures for formulation of Metropolitan Planning Committee (MPC) and metropolitan areas like Kolkata, Mumbai, Nagpur, Pune have MPCs. However, only Kolkata MPC has prepared a Metropolitan Development Plan (MDP). This has been referred as a lesson to guide the MPC formulation and integration in the existing scenario (Urdpfi guidelines, 2014). The delineation of such regions necessitates a thorough understanding of historical growth patterns and the application of appropriate projection models to anticipate future expansion (Sharma et al., 2025) (Chaturvedi et al., 2022). Metropolitan regions represent spatially and functionally integrated urban systems that extend beyond the jurisdictional boundaries of a single city. They emerge through the continuous expansion of urban activities, labour markets, service catchments, transportation networks, and economic interactions (Hall & Pain, 2006). A metropolitan region typically includes a primary core city and multiple surrounding settlements that maintain strong functional linkages with the core, particularly in terms of commuting, trade, and socio-economic interdependencies (OECD, 2020; Dijkstra, Poelman, & Veneri, 2019).

Modern urbanization processes—characterized by polycentricism, peri-urbanization, and metropolitan restructuring—have made the traditional municipal boundary insufficient to capture the dynamic nature of urban systems (UN-Habitat, 2024). As globalization and technological connectivity increase, metropolitan regions function as strategic nodes in national and global economies, often contributing disproportionately to national GDP and innovation (WorldBank, 2015).

In the Indian context, the 74th Constitutional Amendment Act (1992) recognizes metropolitan areas as urban agglomerations with populations exceeding one million and mandates the creation of Metropolitan Planning Committees (MPCs) to enable integrated regional planning (Government of India, 1992). The URDPFI Guidelines (2014) further emphasize identifying metropolitan regions based on functional criteria such as commuting flows, built-up continuity, economic linkages, and service areas, rather than administrative boundaries alone (MoUD, 2014).This dissertation aims to delineate the Bhopal Metropolitan Region by analyzing its current planning area, historical growth trajectories, and employing suitable urban growth projection models,

thereby providing a robust framework for future urban planning and policy formulation. Specifically, the research will leverage Geographic Information System integration of land cover with night-time lights data to spatio-temporally evaluate urban expansion, building upon methodologies applied in similar urban growth studies (Singh et al., 2023). This approach will involve creating decadal land use/land cover maps, performing areal analysis, and assessing accuracy to generate comprehensive urban growth pattern maps, including the direction of expansion (Sharma et al., 2023). This comprehensive analysis will facilitate the identification of diverse indicators crucial for metropolitan region delineation, ensuring a nuanced understanding of Bhopal's evolving urban landscape (Singh et al., 2023). This will enable the selection of the most suitable projection model for precise metropolitan region delineation, particularly given Bhopal's status as a rapidly expanding urban agglomeration in India (Singh et al., 2023) (Galland & Stead, 2022). Given its position as one of the world's fastest-growing urban centers, the continuous development as a state capital further accelerates Bhopal's population growth and subsequent spatial expansion (Singh et al., 2023). This rapid expansion necessitates a detailed examination of its metropolitan boundaries to accommodate sustainable growth and mitigate the challenges associated with unplanned urbanization, an area where research in developing countries like India remains limited (Bhatia et al., 2023). This study will address this gap by focusing on Bhopal, a medium-sized Indian city experiencing accelerated urban growth due to the saturation of larger cities, making it an ideal case for analyzing urban sprawl and its implications for regional planning (Chettry, 2022). The study will therefore utilize remote sensing data, which offers advanced capabilities for monitoring urbanization processes and quantifying urban growth over time, to provide a comprehensive understanding of Bhopal's evolving urban landscape (Singh et al., 2023) (Bhatia et al., 2023). This comprehensive analysis will facilitate the identification of diverse indicators crucial for metropolitan region delineation, ensuring a nuanced understanding of Bhopal's evolving urban landscape. This methodological approach is crucial for selecting the most suitable projection model for precise metropolitan region delineation, particularly given Bhopal's status as a rapidly expanding urban agglomeration in India. The planning area of Bhopal, spanning 1016 km², significantly exceeds the Bhopal Municipal Corporation area of 418 km², providing a comprehensive scope for analyzing diverse urban development patterns and spatio-temporal aspects of growth (Singh et al., 2023). This disparity underscores the importance of a regional

perspective in urban planning, moving beyond administrative boundaries to encompass the functional urban area (Shah & Patel, 2020). Such comprehensive analysis is crucial for developing countries like India, where urban growth often outpaces planning efforts and demands timely, updated datasets to monitor urban sprawl and ensure sustainable development (Bhatia et al., 2023) (Amin & Fazal, 2012). This study also aims to identify the crucial indicators for metropolitan region delineation, ensuring a holistic approach to understanding Bhopal's urban dynamics (Das & Praharaj, 2022). This work will therefore bridge existing knowledge gaps by integrating remote sensing and GIS techniques to effectively map and analyze the spatio-temporal dynamics of urban growth in Bhopal (Kantakumar et al., 2015). This approach is particularly valuable for understanding the horizontal expansion into peripheral areas often observed in medium-sized cities, which are prone to uncontrolled growth outside delimited municipal boundaries (Sharma et al., 2023) (Chettry, 2022). The use of multi-temporal datasets in conjunction with geospatial analyses offers a robust framework for understanding the complexities of urban sprawl typologies, such as ribbon and scatter development, which are prevalent in rapidly developing regions (Chettry, 2022). The application of remote sensing and GIS allows for efficient and cost-effective monitoring of these dynamics, providing crucial insights into land-use changes and the rate and intensity of urban expansion (Anees et al., 2020) (Jarag et al., 2023). These advanced techniques are superior to traditional methods because they enable researchers to effectively capture and analyze the ill-effects of urban sprawl, which is a complicated phenomenon in developing nations due to uncontrolled population growth and haphazard urbanization (Krishnaveni & Anilkumar, 2020). Moreover, the limited focus on medium-sized cities in urban sprawl assessment within India underscores the necessity of this research, as most studies have historically concentrated on larger metropolitan areas (Chettry, 2022). This study, therefore, aims to bridge this analytical gap by focusing on Bhopal, utilizing advanced geospatial measurement techniques to accurately assess urban sprawl and its underlying drivers (Chettry, 2022).

1.2 Concept of region and delineation methods

A Region according to dictionary may mean: (i) Any considerable and connected part of a space or surface; specifically, a tract of land or sea of considerable but indefinite extent; a country; a district; in a broad sense, a place without special reference to location or extent but viewed as an entity for geographical, social or cultural reasons.

(ii) An administrative sub-division of a city, a territory, a country or the European Union. (iii) A place in or a part of the body in anyway indicated. (iv) Place, rank, station, dignity. So, the term 'Region' has a wide usage. It has been used for a variety of purpose satisfying both popular and scientific handling. A common man finds a Region as an area having some characteristics which suit some kind of entrepreneurship or administration. But to a scientist or a geographer in particular, 'a Region is an area which is homogeneous in respect of some particular set of associated conditions, whether of land or of the people, such as industry, farming, the distribution of population, commerce, or the general sphere of influence of a city' (urdpfi guidelines, 2014)

1.2.1 Techniques for delineation

The criteria mentioned above are to be analysed by the following suggested
Techniques for area delineation:

1. Weighted Index Number Method: This method helps to determine a homogeneous region within certain variations/ deviation limits. For example, delineation of a region based on literacy rate may be limited within the area having specific mean literacy rate with not more than one a standard deviation. The approach used in this method is:

i. Identification of the criteria such as literacy rate, unemployment rate, watershed, contours etc.

ii. Determination of weights to the respective criteria

iii. Determination of homogeneity limits such as standard deviation.

2. Flow Analysis: The flow analysis identifies the direction and intensity of flows and builds up functional relationship between the dominant centre and the surrounding satellite towns. The flows show decreasing intensity as it becomes more distant from the main centre, hence identifying the sphere of influence of the main centre. The flows can be plotted on linear graphs from which following information can be obtained:

i. Most intense (Primary) and less intense (Secondary) flows into and out of each centre

ii. Hierarchy of nodes providing the form and extent of functional relationships within an area.

The flow analysis involves grouping together of local units which displays a considerable degree of inter dependence.

3. Gravitational Analysis: This technique identifies the potential flows between centres rather than the actual flows. This model suggests that the interaction between the two

centres is directly proportional to the ‘mass’ of the centres and inversely proportional to the ‘distance’between the centres. The variables used to measure ‘mass’ and ‘distance’ depend upon the problem and data availability. The ‘mass’ can be represented by variables such as population,employment, income, expenditure etc. and ‘distance’ can be represented by distance in physical terms i.e. km, time, price etc. Mathematically this can be represented as:

Tij = [pipj / d2ij]

Where Tijis the gravitational force between towns i and j and Pi and Pj are the masses of the two centres and dijis the distance between them. By calculating the potential for the centres in a study area, contour lines of equal potential can be plotted on a map, illustrating the relative attractiveness and sphere of influence of various centres. (urdpfi guidelines, 2014)

R.P. Misra (2002) has classified four types of Planning Regions in India considering both the physical and economic factors. The typology has been intended to give due attention to the ‘dual economic’ character of the national economy. Dual economy has a technical connotation explained by Ray Chaudhuri (2001) as existence of a slow

1.2.2 Hierarchy of planning region:

While delimiting regions for the purpose of planning, the most commonly faced problem is related to the size of the region i.e. how big a region should be to make the plan economically viable so that the scale of the intended development can be achieved within the convenient administrative framework. The planners have to work at different spatial levels in order to address the problems, needs and necessities of the region. For example, our country has a vast stretch by virtue of which differ greatly having different geographical scopes. An area (such as a village) may be located in a humid climatic regime while another may experience extreme aridity; some may have continental location while others enjoy maritime climate – so, each one is unique in its own way and individually form a micro-region. Since the problems and prospects of the micro-regions diverge from each other, prescriptions would obviously vary for its development. Furthermore, these micro-regions may coalesce to form a larger area having integrated planning vision. The success of regional planning therefore partly depends on the formulation of the objectives and policies at the respective spatial levels and thereby integrating them to have a holistic approach. According to Misra, Sundaram and Prakasa Rao (1974), it is possible to visualize three major area levels of

operation: Macro, Meso and Micro. On this basis, it would be possible to derive planning regions on various taxonomic ranks by grouping areas according to the purpose and scale of development. This is also referred to as hierarchy of Planning Regions.

(a) Macro Regions: This level calls for a comprehensive development decision involving progress related to hydrographic resources (such as river basins and irrigation system), food self-sufficiency, power supply, supply of industrial fuels, location of industries having national importance, infrastructure development(transport system etc.) and the like. Since the scale of these problems may involve areas covering more than one state, the planning unit may bother state and local government jurisdictions.

The Macro regions should not only address to the requirements in particular but also should possess a complex matrix of all the resources necessary for the integrated development. For an instance, power resources of any region remain responsible for the development of the economic profile of the same which in turn help in attaining a balanced regional growth. So, "each macro region should have at least one major existing or potential industrial nucleus rooted in a strong power base" (Misra, Sundaram and Prakasa Rao, 1974: 79). This industrial nucleus would become the pivotal point of development, which will have its linkages in a hierarchy of urban industrial development. So, the emergence of a higher order central place in each macro-region has been visualized in the materialization of the planning regions. Nevertheless, with the appearance of the higher order central place in a macro region, the metropolises continues to remain as foci of innovation, large scale industries, financial entrepreneurship, trade etc.

Macro regions are desirable to have "economic unity". There should be areas within which a high degree of mutual dependency persists. In other words, each macro-region should be characterized with a high level of internal cohesion, forming an economic system by itself and having an ability to generate exchanges between other regions of the country. This denotes economic specialization; complementarity of resources and also the growth of ancillary economic activities within each macro region.

"The macro regions should possess high degree of self-sufficiency in matters such as food, level of employment and potential ability to produce goods and services which can be exchanged with other areas in order to meet the tertiary needs of both rural and urban life" (Misra, Sundaram and Prakasa Rao, 1974: 80). This refers to the concept of self sufficiency of the macro regions, whereby they would put up the objective of

getting developed intra regionally so that they would enable themselves to draw up inter regional balances of production and distribution of commodities. This concept does not imply isolation of region rather envisages a balance through intra-regional and inter-regional development that targets overall progress of the country.

A prevalent belief was that planning regions of macro scale would possess 'ecological balance'. But later, it was said that it must be heterogeneous in character rather than being homogeneous having 'unity in diversity' up to a certain degree to strike an ecological balance. Therefore, macro regions are suitable units for resource investigation and analysis. They are conceived for regional development. They have the objective to meet the requirements of rational planning and calls for inter-regional coordination (especially for infrastructure building entailing irrigation, power, transport development etc.) towards the all round development of the country at large.

(b) Meso Regions: Meso Regions are the sub divisions of the macro regions. In other words, macro regions can be sub divided into several secondary regions to form the Meso regions. They are also known as the regions of second order. The meso regions are actually the primary economic units delineated for the purpose of planning; several of the districts administratively comprise the meso regions. The aim of delimiting the meso region is to identify the economically viable areas for the proper exploitation, conservation and utilization of resources. The economic viability of the meso regions indicate that these regions have adequate resource potential to create a production pattern which is capable of meeting the employment needs over a period of time and simultaneously can produce enough food or offer goods which can be exchanged for subsistence, meeting the consumption needs of the people of those areas. Economic viability of the meso regions can be tested by examining the indicators like per capita income of the component units or districts, per capita usable land, productivity index and manufacturing potential. The resource pattern of the meso region can be developed in such a manner that it leads to specialization of some means of production and even by grouping together areas having similar resource base or linking areas having complementary resource characteristics by intra-areal activities or flows. For example, the coastal plain of Kerala can be combined with the sub-montane plantation districts as then ir resources would supplement and complement each other. Similarly, the Telengana area can be linked with the Krishna-Godavari coastal plain to give more stability to the Telengana area.

(c) Micro Regions: The Micro region is usually smaller than the conventional Planning

Regions. Micro region looks after more particular issues compared to that of the former two. They are focused or oriented towards a common goal and also cater to amalgamated problems addressing common interest. The micro regions should avoid conflicting interests emanating within them. Its population should share in common certain qualities like attitudes, values, needs and desires.

1.2.3 Criteria for Delineation of Region

Regions can be classified based on many criteria but while delineating region for Planning purpose the forward and backward linkages of the parameters must be kept in mind and relevant parameters be selected for the delineation process. Some criteria for delineating the Planning Regions are presented below but list can be expanded based on requirements on planning approach and region's specifications: It is recommended that the planning region should have a nodal point, either developed or developable to satisfy the organisational needs of the region. The homogeneous region identified should be adjusted to the nearest administrative boundary, such as village boundary, taluka or district (urdpfi guidelines, 2014)

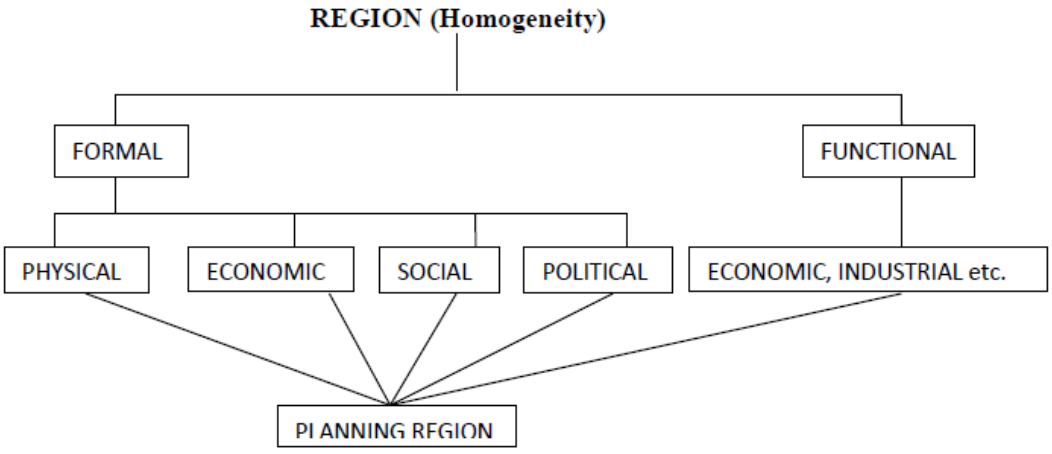


Figure 2 concept of region (source: regional planning in India by RP Mishra)

1.3 Aim

- To delineate Bhopal metropolitan Region.

1.4 Objectives

- To Review delineation frameworks (URDPFI, EU-OECD FUA, Gravity Model etc.)
- To Evaluate and select appropriate urban growth projection model
- To identify the functional sphere of influence of Bhopal city by using gravity model analysis & assess the spatial accessibility of settlements to Bhopal.
- To quantify inter-settlement migration intensity as an indicator of functional metropolitan integration
- To classify Land Use Land Cover (LULC) for four temporal years (2011, 2017, 2021, and 2024) and simulate future urban growth scenarios for the years 2031 and 2041 using a Cellular Automata–Markov (CA-Markov)
- To Formulate of Urban Growth Boundary and delineate Bhopal metropolitan region.

1.5 Scope & Limitations

1.5.1 Scope

- The study examines the Bhopal Metropolitan Region (BMR) across five revenue districts—Bhopal, Sehore, Raisen, Vidisha, and Rajgarh—covering 31,062 km² and 6,142 villages.
- Metropolitan boundary delineation is performed at the village level using gravity model analysis, road network accessibility, and Metropolitan Influence Index (MII) scoring.
- The research provides a comprehensive spatial assessment to identify the functional extent of Bhopal's metropolitan influence.
- The study adopts a seven-phase integrated methodology combining Reilly's Gravity Model, OSMnx accessibility analysis, Random Forest LULC classification, CA-Markov modelling, VIIRS night-time light analysis, OECD Functional Urban Area approach, and Metropolitan Influence Index.
- All analyses are based on secondary datasets obtained from publicly available sources, with no primary data collection.

- The framework integrates geospatial, demographic, and remote sensing techniques for objective metropolitan boundary delineation.
- The historical analysis covers 2011–2024, with Census 2011 as the demographic baseline and multi-temporal LULC assessment across four epochs.
- Night-time light analysis spans 2014–2025, while urban growth projections extend to 2041 using CA-Markov modelling.

1.5.2 Limitations

- All demographic analyses rely on Census 2011 data, as Census 2021 has not been released, resulting in a significant temporal lag.
- Recent demographic changes, peri-urban expansion, and industrial growth after 2011 may not be fully reflected, potentially underestimating metropolitan influence in rapidly developing areas.
- India lacks village-level origin–destination commuting datasets; therefore, Census B-28 work migration data is used as a proxy for functional connectivity.
- This approach captures migration rather than daily commuting and may underestimate actual travel-to-work interactions in the metropolitan region.
- The CA-Markov model projects future urban growth under a business-as-usual scenario based on historical land-use transitions from 2011–2024.
- It does not account for future policy interventions, and projections should be
- Narmadapuram district was excluded because it lies beyond the identified gravitational influence threshold despite its inclusion in the proposed BDA boundary.
- Village alignment is based on available revenue boundary data, as complete cadastral datasets were not accessible during the study.
- Authoritative digital environmental datasets for forests, wildlife sanctuaries, and water bodies were unavailable and were approximated using secondary spatial sources.
- OpenStreetMap road network gaps in remote rural areas required Euclidean distance corrections, which may slightly affect accessibility estimates.

1.6 Assumption & Expected Outcome

1.6.1 Assumption

- Historical census data (1971–2011) provides a reliable basis for applying multiple growth projection models.
- Existing administrative boundaries and datasets from BDPs and MP TCP Act notifications sufficiently represent the planning baseline.
- GIS-based land-use, built-up, and transport datasets remain accurate after preprocessing and ground verification.
- Morphological and functional indicators (density gradients, connectivity, economic linkages) can be used as valid proxies for metropolitan influence.
- Spatial expansion trends observed in past and draft BDPs reflect consistent urbanization patterns useful for metropolitan delineation.

1.6.2 Expected Outcome

- A scientifically delineated Bhopal Metropolitan Region integrating demographic, morphological, and functional criteria, cross-validated against an independent administrative proposal.
- Identification of major growth corridors and peripheral urbanisation zones — particularly along the NH-12 and NH-46 axes — that are driving regional expansion into Raisen and Vidisha districts.
- Selection and empirical validation of the most suitable urban growth projection model for forecasting Bhopal's built-up expansion to 2041.
- A GIS-based methodological framework for metropolitan delineation, demonstrated as transferable to other Indian second-tier metropolitan regions beyond Madhya Pradesh.

1.7 Need for the study

Delineation of a functional urban area (FUA) provides the planning canvas: it identifies the urban core (morphology) and commuting-based market (function) that together define the metropolitan extent. The EU-OECD method—widely adopted

internationally—uses a population-grid approach to identify dense urban cores and then applies a commuting threshold to include adjacent administrative units in the commuting zone (Dijkstra et al., 2019). This people-based definition improves cross-country comparability and is particularly useful where administrative boundaries do not reflect real economic linkages.

Once a defensible boundary is established, planners require tools to forecast where urbanisation will occur under alternative demand and policy scenarios. SLEUTH (a well-known cellular automaton model introduced by Clarke, Hoppen & Gaydos, 1997) operationalizes urban growth processes (diffusion, breed, spread, slope-resistance, road-gravity) using multi-temporal inputs and a staged calibration protocol (Clarke et al., 1997; Chaudhuri & Clarke, 2019).

• Lack of a Scientifically Defined Metropolitan Boundary for Bhopal

Bhopal's urban expansion has long surpassed its statutory municipal boundary, extending into Raisen and Sehore districts (Town and Country Planning Department, Government of Madhya Pradesh, 2018). However, the absence of an officially notified Bhopal Metropolitan Region (BMR) hampers coordinated land-use and infrastructure planning, leading to fragmented governance and inefficient resource allocation. According to OECD (2019), delineating Functional Urban Areas (FUAs) based on population density, commuting flows, and accessibility offers an internationally accepted, replicable method to define such regions. Hence, a data-driven functional boundary is required to form the institutional and analytical foundation for integrated metropolitan planning.

• Absence of Predictive Modelling for Spatial Growth Management

Current planning documents, such as Bhopal Development Plan–2031, provide zoning and density controls but lack a dynamic model to project spatial growth under alternative development scenarios. Growth Projection models offers a proven method for simulating urban expansion using parameters like diffusion, breed, spread, slope, and road gravity, which capture both natural and human-driven growth factors (Clarke, Hoppen, & Gaydos, 1997; Chaudhuri & Clarke, 2019).

• Alignment with National Urban Policies and Sustainable Development Goals

India's 74th Constitutional Amendment, National Urban Policy Framework (NIUA, 2018), and AMRUT 2.0 collectively promote metropolitan governance and data-driven planning. Sustainable Development Goal (SDG) 11 calls for 'inclusive, safe, resilient,

and sustainable cities,' emphasizing spatial monitoring and evidence-based regional planning. Integrating functional delineation (Phase 1) and urban growth simulation (Phase 2) supports these frameworks by enabling spatial equity, infrastructure efficiency, and resilience at the metropolitan scale.

Table 1: Policy act and keywords regarding metropolitan area planning (source: Author)

Level	**Document**	**Year**	**Main Provisions**	**Relevance to BMR**	**Keywords**
State	MP Town and Country Planning Act	1973	Legal basis for planning/metropolitan areas, development plans, authorities.	Statutory foundation for BMR.	Planning area, Regional plan,
City	Bhopal Development Plan 2005	1991	Defines historic planning area and land use.	Baseline for growth comparison.	Master Plan 2005, land use
City	Draft Bhopal Development Plan 2031	2023	Defines 1016 sq km planning area, projections, zoning.	Administrative baseline for BMR.	DP-2031, zoning, projections
Metropolitan	BMR RFP & announcement	2025	Proposal for metropolitan region planning.	Policy justification for delineation.	BMR, regional Integration
National	URDPFI Guidelines	2014	Criteria for region/metropolitan delineation.	Primary criteria source.	Regional planning, metropolitan Region
National	AMRUT GIS Master Plan Standards	2015	GIS data requirements for planning.	Technical basis for GIS methodology.	GIS layers, remote sensing

1.8 Research questions

- What are the key concepts, methods, and indicators used in the delineation of metropolitan regions in India and globally?
- How has Bhopal's urban area evolved over time, and what are the main factors influencing its spatial growth?
- Which urban growth projection models are most suitable for forecasting future expansion in Bhopal's regional context?
- What boundary can be proposed for the Bhopal Metropolitan Region based on projected urban expansion and validated spatial indicators?

2 STUDY AREA PROFILE AND SELECTION JUSTIFICATION

The study area for this dissertation encompasses five revenue districts of Madhya Pradesh — Bhopal, Sehore, Raisen, Vidisha, and Rajgarh — covering a total area of approximately 31,062 square kilometres in the central Indian plateau. The study area is bounded approximately by 22.5 degrees North to 24.3 degrees North latitude and 76.8 degrees East to 79.2 degrees East longitude, lying entirely within the WGS 1984 UTM Zone 43N coordinate reference system (EPSG:32643). The five-district study area was delineated based on three criteria: (a) administrative adjacency to Bhopal district; (b) presence of competing urban centres identified in the gravity model analysis (Sehore, Raisen, Vidisha, Rajgarh); and (c) coverage of the territorial extent within which Bhopal's gravitational metropolitan influence is hypothesised to extend, based on preliminary breaking point estimates ranging from 25 to 100 kilometres.

Bhopal city (21.1663 degrees North, 77.4114 degrees East) constitutes the metropolitan core of the study area, serving as the capital of Madhya Pradesh, India's geographically largest state by area. The five-district study area recorded a combined Census 2011 population of 6,269,789 persons across 6,687 revenue villages and 86 urban settlements, encompassing diverse land cover types ranging from dense urban fabric in Bhopal city to rain-fed agricultural land in Rajgarh district and forested terrain in parts of Raisen and Sehore.

2.1 Administrative Profile

2.1.1 District Overview

The five districts constituting the study area exhibit significant variation in size, population density, urbanisation level, and economic character, reflecting the heterogeneous nature of metropolitan hinterlands in Indian second-tier cities. Bhopal district, the smallest by area at 2,772 square kilometres, is by far the most urbanised (75.8% urban population) and densely populated (855 persons per sq km). The surrounding districts — Sehore, Raisen, Vidisha, and Rajgarh — are predominantly rural, with urbanisation levels ranging from 9.5% (Rajgarh) to 19.0% (Vidisha) and population densities ranging from 168 to 252 persons per sq km.

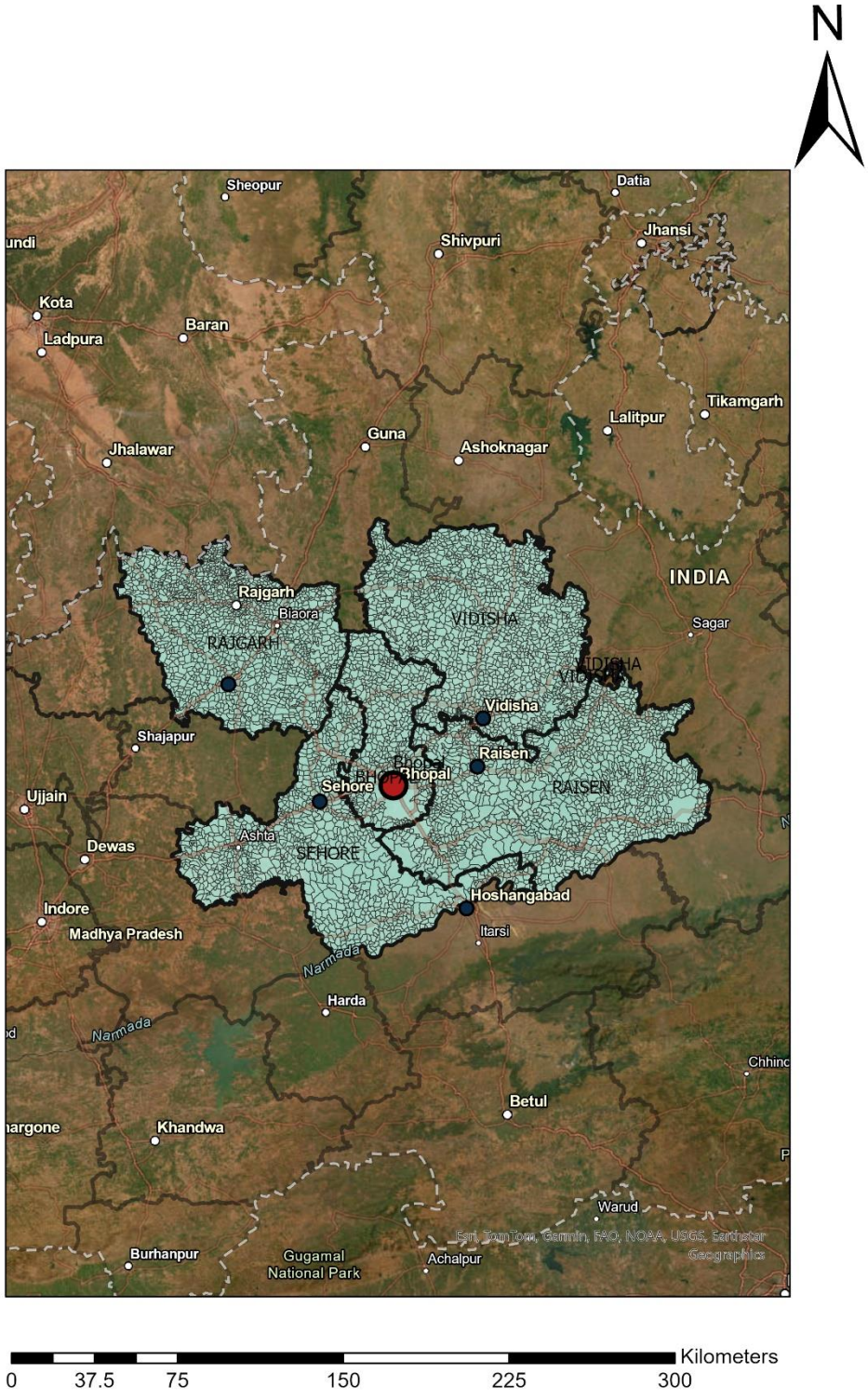


Figure 3 Study Area Profile (Source: Author)

Table 2: Administrative and demographic profile of the five-district study area. Source: Census of India (2011).

District	Area (sq km)	Population (2011)	Pop Density (/sq km)	Urban Pop (%)	Tehsils	Revenue Villages
Bhopal	2,772	2,371,061	855	75.8%	7	481
Sehore	6,578	1,311,028	199	16.2%	8	1,038
Raisen	8,395	1,331,597	159	13.9%	8	1,395
Vidisha	7,371	1,458,875	198	19.0%	8	1,539
Rajgarh	6,154	1,545,814	252	17.9%	6	1,689
STUDY AREA TOTAL	31,062	8,018,375	257	16.8% (excl. Bhopal)	37	6,142

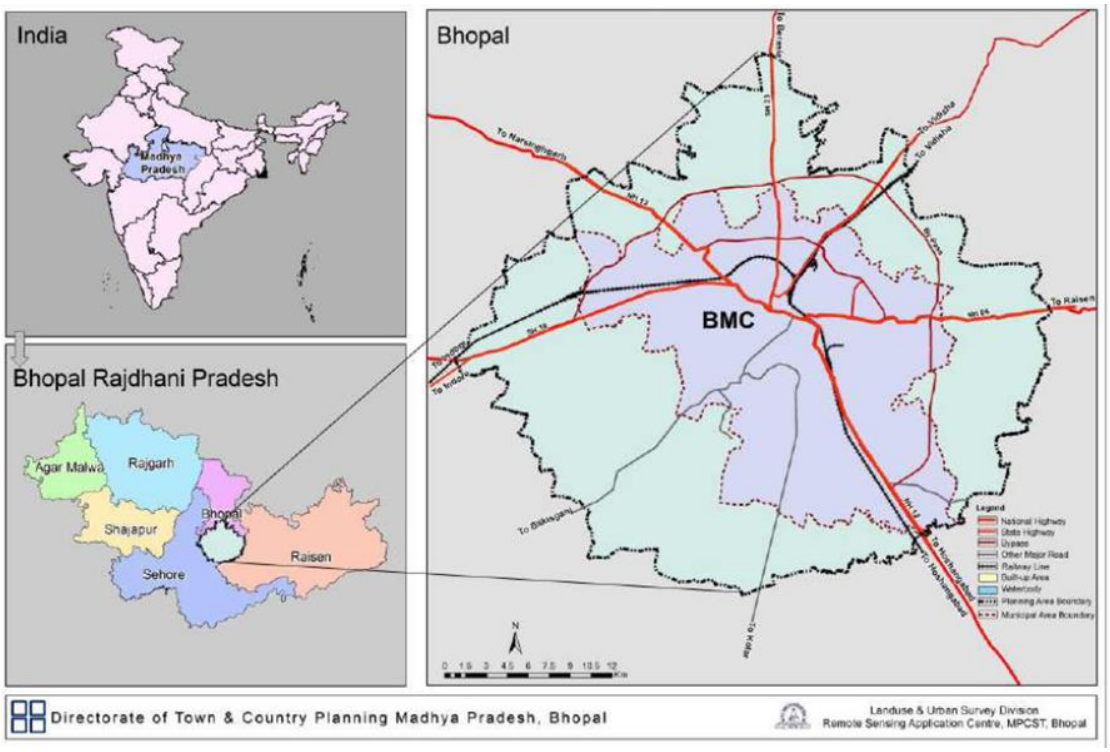


Figure 4 Administrative and Geographic Setting (Source: Draft BDP 2031)

2.1.2 Sub-District Units

Each district is sub-divided into tehsils (sub-districts), which serve as the primary administrative and revenue units for village-level data collection. The study

area contains 37 tehsils in total: 7 in Bhopal, 8 each in Sehore, Raisen, and Vidisha, and 6 in Rajgarh. Tehsil headquarters serve as local service centres for surrounding villages, providing access to government offices, secondary education, primary healthcare, agricultural markets, and banking services. The distance from a village to its tehsil headquarters — available in the Census Village Directory — serves as a proxy for local service accessibility in the Metropolitan Influence Index computation.

2.2 Physical Geography

2.2.1 Physiography and Topography

The study area lies on the Malwa Plateau and the Vindhya Range, forming part of the central Indian upland zone that constitutes India's geological watershed between the north-flowing Gangetic river system and the south-flowing Deccan river system. Elevations range from approximately 300 metres above mean sea level (AMSL) in the Narmada valley in the southern portions of the study area (Raisen district) to 650 metres AMSL on the Vindhyan plateau in the northern portions (Rajgarh district). Bhopal city is situated at a mean elevation of approximately 523 metres AMSL on a dissected plateau surface characterised by rocky outcrops, shallow seasonal streams, and the twin lake system of Upper and Lower Bhoj (Bhopal) Lake.

The topographic profile of the study area has significant implications for metropolitan growth patterns. The Vindhyan plateau surface provides a relatively flat terrain conducive to urban expansion in the Bhopal-Sehore and Bhopal-Vidisha corridors, while the deeply incised Narmada valley in the south (Raisen district boundary) constitutes a significant natural barrier to southward metropolitan expansion. The rocky, lateritic soils of the Rajgarh plateau limit agricultural productivity and infrastructure development, explaining the relatively low population density and urbanisation in this district despite its large area.

2.2.2 Hydrology

The study area's hydrology is dominated by three major river systems: the Betwa river system (draining Vidisha district northeastward into the Yamuna), the Narmada river system (draining Raisen and southern portions of Bhopal district southward to the Arabian Sea), and the Parvati river system (draining Rajgarh district northward into the Chambal). The watershed divide between these three systems runs

approximately through Bhopal city, giving the metropolitan area a distinctive multi-watershed character with significant implications for regional water resource management.

The Bhopal lakes — Upper Lake (Bada Talab, approximately 31 sq km) and Lower Lake (Chhota Talab, approximately 1.3 sq km) — are the most significant water bodies in the metropolitan core. The Upper Lake, created by the 11th-century Paramara king Raja Bhoj by damming the Kolans River, is one of India's largest artificial lakes and serves as the primary drinking water source for Bhopal city, supplying approximately 40% of the municipal water demand. The Halali reservoir (Vidisha district), Kerwa dam (Bhopal district), Kaliasot dam (Bhopal district), and Shahpura Lake provide additional water supply and recreational amenities for the metropolitan area. The Narmada River, flowing approximately 68 kilometres south of Bhopal city at Narmadapuram/Narmadapuram, constitutes the southern hydrological boundary of the metropolitan functional region.

2.2.3 Climate

The study area experiences a tropical monsoonal climate (Koppen classification Aw/BSh) characterised by three distinct seasons: a hot dry summer (March-June), a monsoon season (July-October), and a cool dry winter (November-February). Mean annual rainfall ranges from 900 mm in Rajgarh district (rain shadow effect of the Vindhyan escarpment) to 1,350 mm in Raisen district (orographic enhancement from the Satpura foothills). Bhopal city receives approximately 1,150 mm mean annual rainfall, predominantly during the southwest monsoon months of July-September.

Mean maximum temperatures range from 44 degrees Celsius in May-June to 18 degrees Celsius in January, with mean minimum temperatures ranging from 32 degrees Celsius (summer) to 10 degrees Celsius (winter). The climate supports rain-fed agriculture (primarily wheat, soybean, and gram) in Raisen, Vidisha, Sehore, and Rajgarh districts, with a single dominant agricultural season centred on the Rabi (winter) crop. Climate variability — particularly drought years and irregular monsoon onset — significantly affects peri-urban agricultural livelihoods in the metropolitan hinterland, contributing to rural-urban migration flows that are captured in the gravity model's Census B-28 data.

2.2.4 Vegetation and Land Cover

Natural vegetation in the study area is predominantly tropical dry deciduous forest (Champion & Seth, 1968 classification 5A), dominated by teak (Tectona grandis), sal (Shorea robusta), tendu (Diospyros melanoxylon), and associated species. Forest cover is most extensive in the Raisen district (the Ratapani Wildlife Sanctuary covers approximately 890 sq km in the eastern portion of the district) and in the Pachmarhi Biosphere Reserve foothills that extend into the southeastern portion of the study area. Bhopal district's Van Vihar National Park (4.45 sq km) provides green space within the metropolitan core. Agricultural land dominates in Vidisha, Sehore, and Rajgarh districts, where conversion from agricultural to built-up use in the metropolitan fringe constitutes one of the primary LULC change processes documented in this dissertation.

2.3 Bhopal: The Metropolitan Core

Bhopal's development as a planned administrative capital represents a significant departure from the organic growth pattern of most Indian cities. The city's origins lie in the early 18th century, when the Afghan soldier Dost Mohammad Khan founded the Bhopal State in 1709, establishing a provincial capital that grew under the succession of rulers — predominantly female Begums who governed Bhopal from 1819 to 1926 and left a distinctive architectural legacy of mosques, palaces, and civic structures. The most celebrated ruler, Qudsia Begum, constructed the Upper Lake embankment and much of the old city's urban fabric in the mid-19th century.

The post-independence transformation of Bhopal into the capital of Madhya Pradesh following the States Reorganisation Act of 1956 was the decisive event in the city's modern urban growth trajectory. The selection of Bhopal over the competing claims of larger cities (Jabalpur, Gwalior, and Indore) reflected its central location within the new state and the availability of large undeveloped land in the eastern portions of the princely state's territory. Rapid government employment growth, educational institution establishment, and planned residential development drove population expansion from approximately 102,000 in 1951 to 671,018 in 1981.

The Union Carbide gas tragedy of December 1984 — in which a methyl isocyanate leak from the Union Carbide India Limited pesticide plant killed an estimated 15,000-20,000 people — profoundly shaped Bhopal's subsequent

development. The industrial disaster prompted massive post-disaster reconstruction investment, the closure and decontamination of the industrial zone in the northern city, the development of new residential areas (particularly Berasia Road and Karond), and the establishment of specialised medical facilities (ICMR-NICHHH) focused on disaster-related health conditions. The tragedy also reinforced the city's institutional character — with government administration, hospitals, and universities replacing industry as dominant economic activities.

2.3.1 Administrative Governance

Bhopal Municipal Corporation (BMC), established under the Madhya Pradesh Municipal Corporation Act 1956, governs the urban core of Bhopal. The BMC area covers approximately 462 square kilometres and is divided into 85 wards. The Bhopal Development Authority (BDA), established under the Madhya Pradesh Nagar Tatha Gram Nivesh Adhiniyam 1973, exercises planning jurisdiction over a territory extending beyond the BMC boundary to encompass rapidly urbanising peri-urban

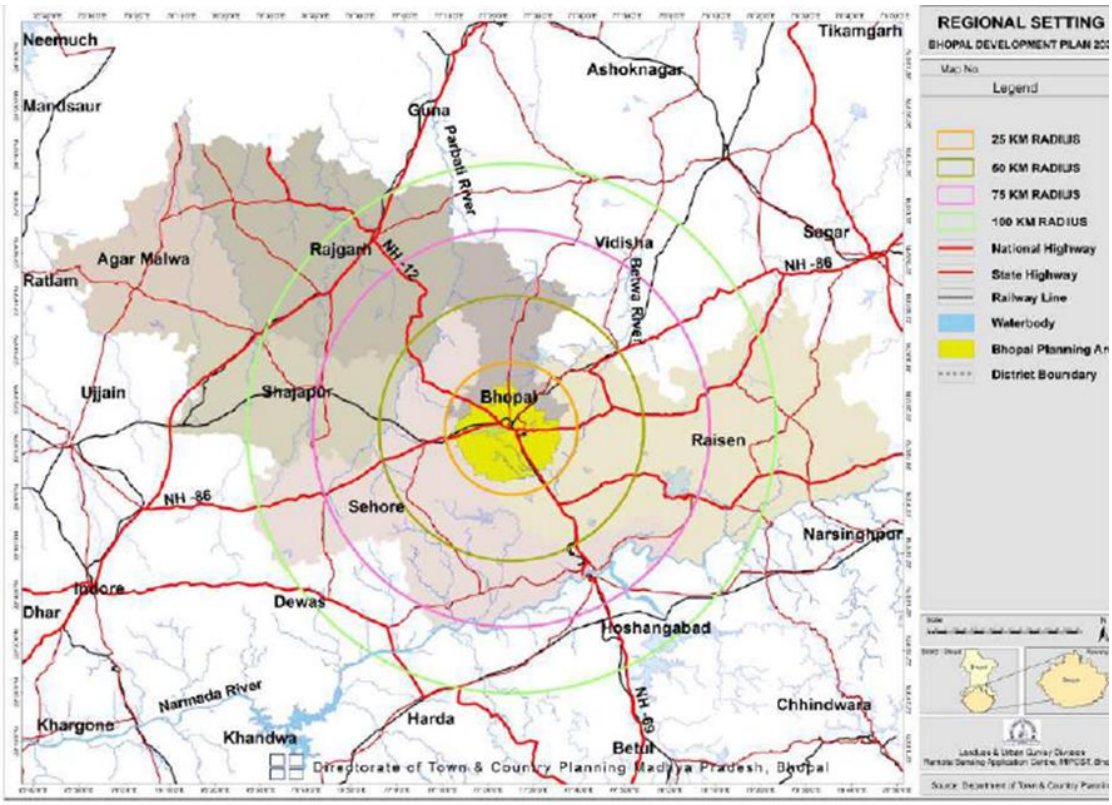


Figure 5 Regional influence zone (Source: Draft BDP 2031)

areas. The BDA's development plan area, as of the most recent draft plan, covers approximately 1,470 square kilometres — encompassing the BMC area plus portions of the surrounding rural fringe.

The Bhopal Smart City Limited (BSCL), a special purpose vehicle established under the Government of India's Smart Cities Mission (2016), has implemented approximately Rs. 2,200 crore of urban infrastructure investment in Bhopal's selected area-based development zone (ABDZ) and pan-city solutions. Key investments include the Intelligent Traffic Management System (ITMS), LED street lighting across the BMC area, smart water management, the Bhopal Metro Rail project (Phase 1 covering approximately 27 km), and the BRTS (Bus Rapid Transit System) on key corridors.

2.3.2 Economic Profile

Bhopal's economy is dominated by the public sector (state government administration, central government institutions, and public sector undertakings) and the service sector (education, healthcare, retail, information technology). Major employers include the Government of Madhya Pradesh secretariat and associated departments (approximately 80,000 government employees in Bhopal), Bharat Heavy Electricals Limited (BHEL), with its main plant at Piplani employing approximately 8,000 workers; the Indian Ordnance Factory at Itarsi (approximately 50 km south); and a growing information technology sector in the Maharana Pratap Nagar IT Park area.

Educational institutions constitute a major component of the metropolitan economy. Key institutions include the Maulana Azad National Institute of Technology (MANIT), Rajiv Gandhi Proudyogiki Vishwavidyalaya (RGPV), Barkatullah University, All India Institute of Medical Sciences (AIIMS Bhopal, established 2012), Indian Institute of Science Education and Research (IISER Bhopal, established 2008), National Law Institute University (NLIU), and the Indian Forest Research Institute. These institutions collectively enroll approximately 200,000 students from across Madhya Pradesh and neighbouring states, generating significant demand for housing, transportation, and services in the metropolitan area.

2.4 District Profiles

2.4.1 Sehore District

Sehore district (area: 6,578 sq km; population: 1,311,028) lies immediately west of Bhopal district and shares a direct administrative boundary with the state capital. The district headquarters, Sehore town (population: 97,041), is located approximately 38

kilometres west of Bhopal city along State Highway 18, a travel time of approximately 45-55 minutes. Sehore town serves as an important satellite centre in the Bhopal metropolitan region, providing educational, healthcare, and administrative services to surrounding villages. The district's economy is predominantly agricultural, with soybean, wheat, and gram as principal crops on the Malwa plateau soils.

Metropolitan integration between Sehore district and Bhopal is evidenced by significant daily commuting flows along NH-18 and SH-18, a well-developed bus route network connecting Sehore town and major villages to Bhopal city, and rapid residential development in the Sehore-Bhopal corridor villages such as Ratibad, Narmadapuram Road, Misrod, and Kolar. (Source: Sehore.nic.in)

2.4.2 Raisen District

Raisen district (area: 8,395 sq km; population: 1,331,597) lies to the northeast and east of Bhopal district, encompassing the Narmada valley in its southern portions and the Vindhyan plateau in its north. Raisen town (population: 44,430) serves as the district headquarters, located approximately 47 kilometres northeast of Bhopal city. The district contains significant historical and environmental assets: the Sanchi Stupa (a UNESCO World Heritage Site), the Ratapani Wildlife Sanctuary (proposed Tiger Reserve), and the Bargi Dam reservoir on the Narmada. The Bhimbetka rock shelters, a UNESCO World Heritage Site, are located near the district's western boundary with Bhopal district.

Raisen district's metropolitan integration with Bhopal is primarily mediated by NH-46 (Bhopal-Gwalior highway via Vidisha and Sanchi), which connects the district's western tehsils (Goharganj, Bareli) to Bhopal within 45-90 minute travel times. The district's agricultural character — wheat, paddy, and soybean cultivation in the Narmada valley; forest-based livelihoods in the Satpura foothills — results in lower non-agricultural workforce ratios and lower MII scores compared to Sehore and Vidisha, despite its geographic proximity to Bhopal. (Source: Raisen.nic.in)

2.4.3 Vidisha District

Vidisha district (area: 7,371 sq km; population: 1,458,875) lies to the northeast of Bhopal district, with the Betwa river forming a natural boundary in the district's eastern portions. Vidisha town (population: 155,959) is the second largest urban centre in the study area after Bhopal city, and serves as an important node in the metropolitan

hierarchy. Located approximately 52 kilometres from Bhopal along NH-86 (Bhopal-Sagar highway), Vidisha town is reachable within 45-60 minutes and functions as a significant commercial and educational centre for the northeastern metropolitan hinterland.

Vidisha district records the highest number of High MII villages (194 of 427 total study area High-MII villages) among the non-Bhopal districts, reflecting its superior road connectivity (NH-86, major agricultural markets at Vidisha and Ganj Basoda), higher literacy rates, and stronger commercial integration with Bhopal. The Heliodorus Pillar (near Besnagar) and Udayagiri caves — significant archaeological sites — are located in Vidisha district. The Betwa River originates in the Vindhyan hills of Raisen district and flows through Vidisha, providing irrigation support for wheat and soybean cultivation. (Source: Vidisha.nic.in)

2.4.4 Rajgarh District

Rajgarh district (area: 6,154 sq km; population: 1,549,799) lies to the northwest of Bhopal district, separated from the metropolitan core by Sehore district. Rajgarh town (population: 46,858) is the most distant district headquarters from Bhopal in the study area, approximately 136 kilometres by road — a travel time of approximately 2.5-3 hours. The district's economy is predominantly agricultural (wheat, soybean, mustard) and pastoral, with very limited industrial development. Rajgarh's urbanisation level (9.5%) is the lowest among the five study districts, reflecting the limited service sector employment and infrastructure investment historically directed to this peripheral district.

Despite its distance and limited urban development, Rajgarh district is significant in the gravity model analysis because of its large population mass relative to the low population density of intervening areas, producing the study area's largest breaking point distance (95.3 kilometres from Bhopal CBD). This reflects the reality that Rajgarh's large rural population (approximately 1.4 million) has limited alternative metropolitan centres competing for its interaction with Bhopal — the next-largest competing centre (Shajapur, Ujjain direction) is significantly smaller and farther. The result is that Bhopal's gravitational influence extends disproportionately far toward Rajgarh, capturing 422 of the district's 1,689 villages within the in-zone category. (Source:Rajgarh.nic.in)

2.5 Infrastructure and Connectivity

2.5.1 Road Network

The study area's road network forms the primary infrastructure matrix governing metropolitan functional integration. The national highway network connects Bhopal to major urban centres through five radiating corridors:

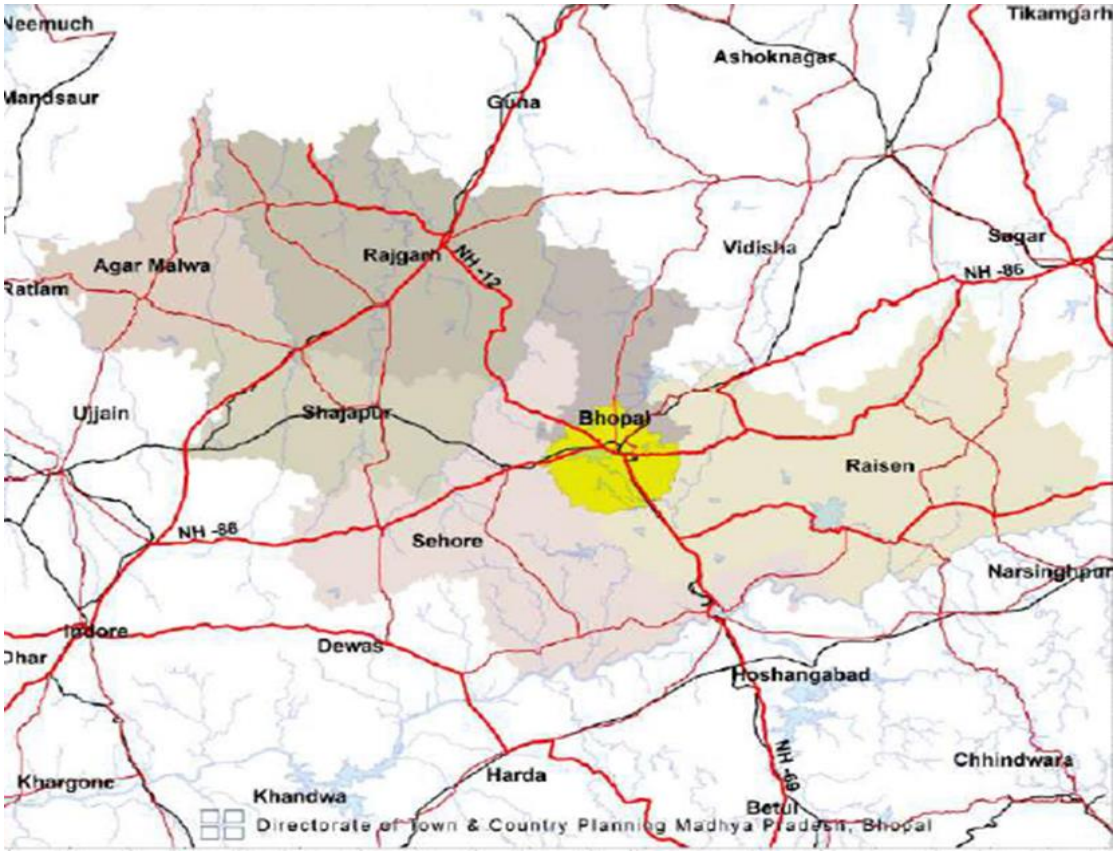


Figure 6 Connectivity and Mobility structure (Source: Draft BDP 2031)

- NH-12 (Bhopal-Jabalpur): The eastern corridor connecting Bhopal to Jabalpur (approximately 326 km), passing through Raisen district. This 4-lane divided highway carries the heaviest freight traffic in the study area.
- NH-46 (Bhopal-Gwalior via Vidisha): The northeastern corridor connecting Bhopal to Gwalior (approximately 423 km) via Vidisha and Jhansi. This highway passes through Sanchi and Vidisha town, serving as the primary connector for Vidisha district.

- NH-86 (Bhopal-Sagar): The eastern corridor connecting Bhopal to Sagar (approximately 172 km), passing through Vidisha. This is the primary route for commercial traffic from southeastern Madhya Pradesh.
- NH-18 (Bhopal-Indore via Sehore): The western corridor connecting Bhopal to Indore (approximately 195 km) via Sehore town. The 4-lane Bhopal-Indore expressway under development will reduce travel time from 3.5 to 2 hours.
- NH-26 (Bhopal-Nagpur): The southern corridor connecting Bhopal to Nagpur (approximately 318 km) via Narmadapuram. This corridor passes through the southern portion of Raisen district and crosses the Narmada at Narmadapuram.

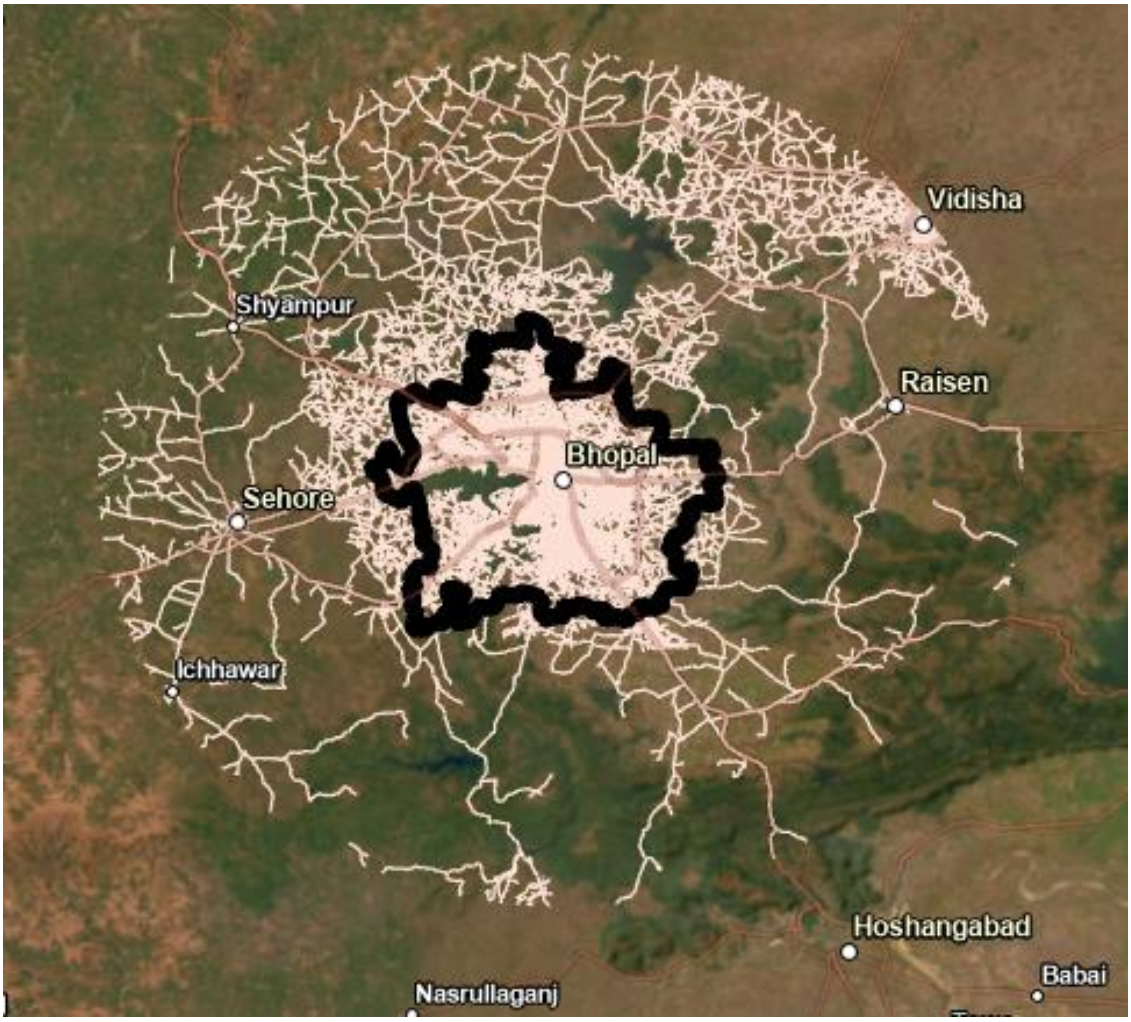


Figure 7 Regional connectivity Density of Bhopal (Source: Author)

Table 3: National and state highway network in the BMR study area. Source: Ministry of Road Transport and Highways (2024).

Highway	Direction	Key Cities Served	Distance (km)	Significance for BMR
NH-12	East	Raisen, Jabalpur	326	Freight corridor; peri-urban sprawl axis
NH-46	Northeast	Vidisha, Sanchi, Gwalior	423	Tourism + educational commute corridor
NH-86	East-NE	Vidisha, Sagar	172	Agricultural market corridor
NH-18	West	Sehore, Indore	195	Densest commute corridor; industrial axis
NH-26	South	Narmadapuram, Nagpur	318	Narmada corridor; southern boundary
SH-18	West	Sehore town	38	Intra-metropolitan connector

2.5.2 Rail Network

The Indian Railways network provides metropolitan connectivity through three railway lines radiating from Bhopal Junction (a Category A+ station on the Western Central Railway zone): the Bhopal-Itarsi-Mumbai line (serving the southern corridor), the Bhopal-Delhi main line via Bina-Gwalior (serving the northeastern and northern corridors), and the Bhopal-Indore Meter Gauge line (now converted to broad gauge). Habibganj station (now renamed Rani Kamlapati station), located approximately 5 kilometres from Bhopal Junction, has been developed as India's first station redeveloped under the PPP model, providing world-class passenger facilities and multimodal connectivity.

The Bhopal Metro Rail project, under construction, will provide rapid transit connectivity within the metropolitan core. Phase 1 encompasses two corridors: Corridor 1 (Karond Circle to AIIMS, approximately 14.99 km) and Corridor 2 (Bhopal Junction to Mandir Bahindra, approximately 12.88 km). Phase 2, under planning, will extend metro connectivity to peri-urban areas including Kolar Road, Berasia Road, and Narmadapuram Road — the primary directions of metropolitan expansion.

2.5.3 Air Connectivity

Raja Bhoj International Airport, located approximately 12 kilometres north of Bhopal city centre, provides air connectivity to major Indian cities including Delhi, Mumbai, Hyderabad, Pune, and Raipur. The airport handled approximately 2.5 million passengers in 2023-24, reflecting growing air travel demand from the expanding metropolitan economy. Airport proximity has catalysed significant commercial and residential development in the northern metropolitan fringe, particularly in the Govindpura and Airport Road corridors.

2.6 Demographic Characteristics

2.6.1 Population Distribution and Density

The study area's population distribution is highly concentrated in Bhopal district (approximately 29.6% of study area population in 8.9% of study area land), with the remaining 70.4% distributed across the four hinterland districts. This concentration reflects Bhopal's dominance as the metropolitan economic core and creates the steep population density gradient — from 855 persons per sq km in Bhopal district to 159 persons per sq km in Raisen district — that drives the gravity model's computation of metropolitan influence zones.

Table 4: Population profile of study area districts. Source: Census of India (2011).

District	Total Pop	Urban Pop	Rural Pop	Urban %	Decadal Growth (2001-11)	Pop Density
Bhopal	23,71,061	17,96,130	5,74,931	75.8%	37.0%	855
Sehore	13,11,028	2,12,341	10,98,687	16.2%	21.5%	199
Raisen	13,31,597	1,85,341	11,46,256	13.9%	16.3%	159
Vidisha	14,58,875	2,76,913	11,81,962	19.0%	18.5%	198
Rajgarh	15,49,799	1,47,085	14,02,714	9.5%	23.1%	252
TOTAL	80,22,360	26,17,810	55,04,550	32.6%	22.3%	257

2.6.2 Literacy and Workforce

The study area's literacy rate (Census 2011) ranges from 80.4% in Bhopal district to 62.3% in Rajgarh district, with the study area average of approximately 68.5% slightly below the national average of 74.0%. Female literacy shows a similar gradient: 76.8% in Bhopal versus 55.1% in Rajgarh. These literacy differentials are reflected in the Metropolitan Influence Index scores, with Bhopal district's higher literacy contributing to higher composite MII values.

Worker participation rates — total workers as a percentage of total population — range from 36.5% in Bhopal district to 47.2% in Rajgarh, reflecting the higher female workforce participation in agricultural households of the hinterland districts. Non-agricultural workers (those employed in household industry, other industry, and services) constitute 89.2% of Bhopal district's workforce but only 18.4% of Rajgarh district's workforce — a differential that directly informs the gravity model's calibration from B-28 work migration data and the MII's non-agricultural workforce component.

2.6.3 Settlement Pattern

The settlement pattern in the study area reflects the characteristic duality of Indian metropolitan hinterlands: a dense, predominantly urban settlement in the metropolitan core (Bhopal city and its agglomeration), surrounded by a dispersed pattern of small-to-medium villages in the hinterland districts. Of the 6,687 revenue villages in the study area, the majority have populations below 1,000 persons (Census 2011), with 42% below 500 persons.

2.7 Environmental and Planning Context

2.7.1 Environmental Assets and Constraints

The study area contains several significant environmental assets that constrain metropolitan expansion while providing ecological services to the metropolitan region. Ratapani Wildlife Sanctuary (890 sq km, Raisen district), currently under process for Tiger Reserve notification, represents the most significant conservation area in the study area and creates a hard constraint on southeastern metropolitan expansion. Van Vihar National Park (4.45 sq km, Bhopal district) and the Upper Lake ecosystem (designated Ramsar Wetland of International Importance in 2002) provide critical urban ecosystem services — biodiversity conservation, drinking water supply, urban

microclimate regulation, and recreational amenities — that would be severely compromised by unregulated peri-urban development.

Environmental constraints on metropolitan growth include: (a) the Ridge Zone — the rocky escarpment running through northern Bhopal, designated as a Forest Preserve; (b) the Narmada floodplain in southern Raisen, subject to periodic flooding; (c) the Betwa floodplain in Vidisha district; and (d) the Ratapani and Kerwa watershed protection zones.

2.7.2 Land Use and Development Planning

Bhopal's land use planning is governed by the Bhopal Master Plan 2031, prepared by the TNCP under the Madhya Pradesh Nagar Tatha Gram Nivesh Adhiniyam 1973. The master plan designates land use zones across the Bhopal planning area (approximately 1,470 sq km), including residential, commercial, industrial, public and semi-public, open and recreation, and transportation uses. The master plan's residential zones identify planned residential sectors (RS-series) for new development in the north, northeast (Vidisha road corridor), and south (Narmadapuram road corridor), reflecting anticipated population growth and in-migration from the metropolitan hinterland.

The absence of a formal Bhopal Metropolitan Regional Plan — covering all five study districts — constitutes the primary planning gap that this dissertation's BMR delineation seeks to address. Individual district plans (prepared under the Madhya Pradesh Nagar Tatha Gram Nivesh Adhiniyam) are prepared without coordination across district boundaries, resulting in uncoordinated land use designations at the metropolitan fringe. The formally delineated BMR boundary recommended in Chapter 9 (11,470.82 sq km) provides the spatial framework for a future Metropolitan Regional Plan that would coordinate land use, transportation, environmental management, and infrastructure investment across all five districts.

The planning boundary of Bhopal has undergone substantial expansion across successive Development Plans. This transformation reflects the city's demographic growth, peri-urban expansion, increased urban demand for land, and the strategic need to integrate surrounding settlements into a coordinated spatial planning framework. Based on compiled information from the Bhopal Development Plan 2031 (Draft) and earlier plan reviews, the planning area expanded from approximately 240.87 sq km in

BDP–1991 to 1016.90 sq km in Draft BDP–2031. This represents more than a fourfold increase in the statutory planning area over four decades.

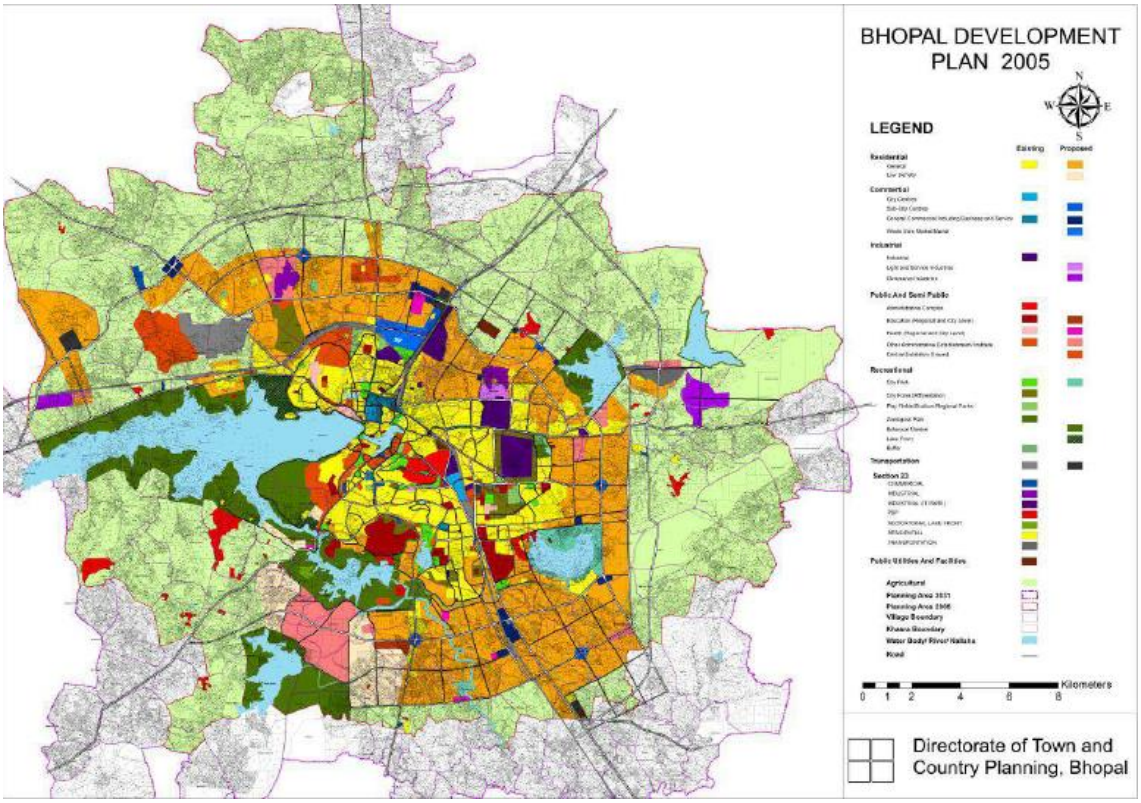


Figure 8 LULC map Bhopal 2005 (Source: BDP 2005)

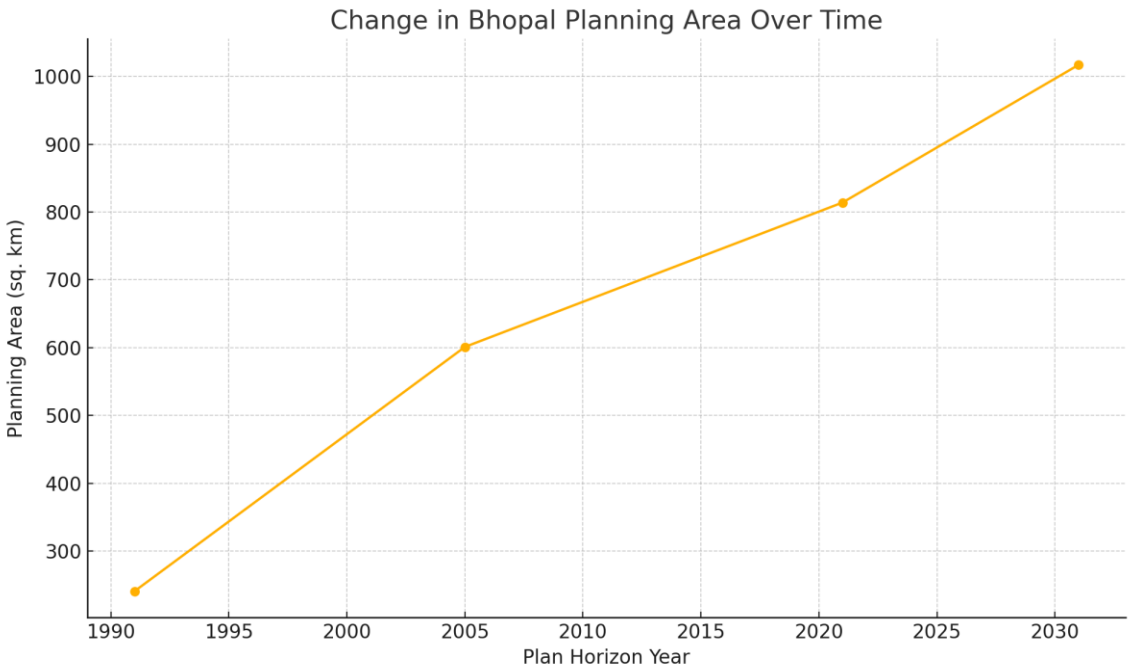
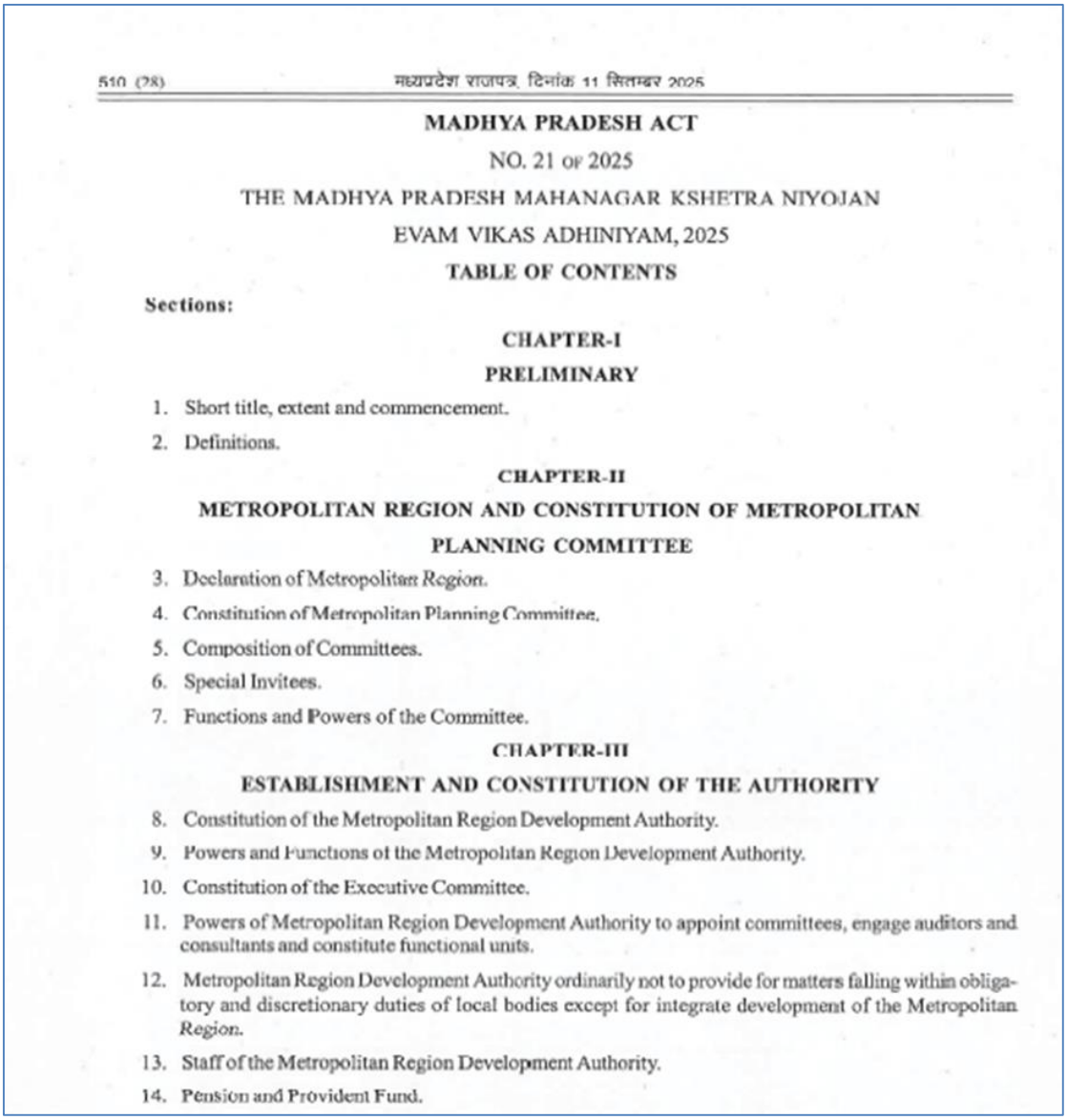


Figure 9 Temporal Change in planning area of Bhopal (Source: Author)

As illustrated in the graph, the most significant jump in planning area occurred between BDP–1991 and BDP–2005, when the planning jurisdiction expanded from 240.87 sq km to 601.06 sq km. This period corresponds to major changes in the urban structure, including consolidation of peripheral growth and incorporation of rural settlements into the statutory planning limits. The planning area continued to increase in the subsequent plans, reaching 813.92 sq km in Draft BDP–2021 and further extending to 1016.90 sq km in Draft BDP–2031. These expansions highlight Bhopal's transition from a core city-focused development model to a broader metropolitan-scale planning approach.

Table 5 : Temporal change in planning area growth of Bhopal (Source: Author)

Development Plan	Horizon Year	Planning Area (sq. km)
BDP–1991	1991	240.87
BDP–2005	2005	601.06
Draft BDP–2021	2021	813.92
Draft BDP–2031	2031	1016.90



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MADHYA PRADESH ACT

NO. 21 OF 2025

THE MADHYA PRADESH MAHANAGAR KSHETRA NIYOJAN EVAM VIKAS ADHINIYAM, 2025

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Figure 10 Constitution of Metropolitan region official Notification (source: Govtpress.nic.in)

2.8 Site selection Justification

The selection of Bhopal as the case study for this research—"Delineation of Bhopal Metropolitan Region using Appropriate Growth Projection Model"—is driven by a convergence of rapid urbanization dynamics, critical environmental constraints, and, most significantly, a paradigm shift in the region's administrative framework following the recent enactment of the Madhya Pradesh Metropolitan Region Act. Bhopal is no longer functioning as a mono centric capital city but has evolved into a complex urban system

2.8.1 Legislative Relevance and Timeliness

The primary justification for this research is its alignment with current state policy. As highlighted in recent administrative developments, the Government of Madhya Pradesh has officially paved the way for the formation of the **Bhopal Metropolitan Region (BMR)**.

- **Statutory Evolution:** With the Governor's recent approval of the *Metropolitan Area Act*, Madhya Pradesh has become the 13th state to adopt such a framework. This legislative shift transitions the planning scope from the limited "Bhopal Planning Area" to a vast "Metropolitan Region."
- **The "Merger" Context:** Emerging reports indicate a strategic vision where the boundaries of the Indore Metropolitan Region and the Bhopal Metropolitan Region are projected to converge. The proposed BMR is expected to encompass a massive contiguous area, potentially integrating districts such as **Raisen, Sehore, Vidisha, and Rajgarh**.
- **Research Utility:** As the state government prepares to float tenders for the Detailed Project Report (DPR) of the metropolitan region, this thesis provides a timely, scientific intervention. By using growth projection models to delineate boundaries scientifically, this research can offer an academic critique or validation of the government's proposed administrative lines.

2.8.2 Polycentric Urban Growth

Bhopal presents a classic case of "leapfrog" development, making it an ideal candidate for **Cellular Automata (CA) and Markov Chain modeling**.

- **Industrial Corridors:** The city is expanding aggressively along the NH-46 (Narmadapuram Road) corridor towards **Mandideep**, an industrial satellite town. The functional linkages between Bhopal (residence/services) and Mandideep (employment) create a daily commuter flow that defies the current municipal boundaries.
- **Regional Integration:** The proposed metropolitan framework aims to include heritage and industrial nodes such as **Sanchi, Obaidullaganj, and Ashta**. A static master plan cannot manage this dispersion; only a regional growth model can predict how these satellite towns will eventually conurbate with the core city.

2.8.3 Unique Topographical and Environmental Constraints

Unlike cities on flat plains (e.g., Delhi or Indore), Bhopal's expansion is heavily constrained by its landscape, making the "Appropriate Growth Projection Model" a challenging and necessary exercise.

- **The Water-Hill :** The growth of the city is physically dictated by the **Upper Lake (Ramsar Site)** and the **Vindhyan Hills**. Development is "forced" into specific vectors—primarily South-East and North-West—while the South-West remains ecologically sensitive.
- **Modeling Challenge:** Standard concentric circle models fail in Bhopal. The selection of this site allows for the testing of advanced models (like **SLEUTH** or **Weighted CA-Markov**) that can incorporate "Exclusion Layers" (water bodies, forest land) to simulate realistic future boundaries.

2.8.4 Rapid Urban Sprawl and Peri-Urban Fragmentation

Empirical studies indicate that Bhopal is losing its "compact city" character.

- **Quantifiable Sprawl:** Research by Bharath et al. (2022) utilized Agent-Based Modelling to show that Bhopal's urban footprint is projected to increase significantly, with sprawl outpacing population growth.
- **Peripheral Pressure:** The peri-urban interface—specifically areas like **Kolar Road** and **Bairagarh**—is witnessing rapid land-use conversion from agriculture to residential use. This creates a "fragmented" landscape that requires urgent delineation to prevent haphazard development.

2.8.5 Conclusion on Site Selection

Bhopal is currently between being a large city and a metropolitan region. The intersection of the new **Metropolitan Act**, the unique **topography**, and the **industrial corridor dynamics** makes Bhopal the most suitable case for testing growth projection models. The delineation derived from this thesis will not only be academic but will hold direct relevance to the ongoing statutory planning processes in Madhya Pradesh.

3 LITERATURE REVIEW

3.1 Introduction

The delineation of a Metropolitan Region is a critical exercise in urban planning, serving as the spatial framework for governance, infrastructure allocation, and resource management. As Indian cities transition from mono centric agglomerations to polycentric metropolitan regions, static administrative boundaries often fail to capture the dynamic functional linkages between the core city and its peri-urban interface. This chapter reviews the existing body of literature regarding the delineation of metropolitan regions, with a specific focus on the **Bhopal Metropolitan Region (BMR)**. It critically analyses the evolution of **urban growth projection models**, assessing their efficacy in predicting future sprawl to inform scientifically robust delineation.

The review is thematically organized into three sections:

1. **Theoretical Frameworks for Regional Delineation:** Analysing methods from traditional gravity models to modern flow analysis.
2. **Urban Growth Projection Models:** Evaluating Cellular Automata (CA), Markov Chains, and AI-based hybrids (SLEUTH, ANN).
3. **Empirical Context of Bhopal:** A deep dive into studies monitoring Bhopal's sprawl, land use changes, and planning interventions.

3.2 Theoretical Frameworks for Metropolitan Delineation

Delineation methodologies have evolved significantly from early 20th-century morphological approaches to complex functional modelling.

3.2.1 Formal vs. Functional Regions

Scholars have long debated the criteria for defining a region. *Formal regions* (defined by homogeneity, such as agricultural zones) and *functional regions* (defined by interactions, such as a city and its commuter belt). For metropolitan delineation, contemporary literature overwhelmingly supports the **functional approach**.

Recent studies emphasize "flows" of people, goods, and information over static administrative lines.a worldwide delineation methodology for "multi-tier city-regions," arguing that functional linkages create a more accurate boundary than political

limits.(Cattaneo et al., 2024) Similarly, utilization of road networks to delineate functional regions, suggesting that the "time-distance" along transport corridors is a superior metric to physical distance.(Analytics et al., 2023)

3.2.2 Gravity Models and Breaking Point Analysis

Traditional delineation often relies on Gravity Models, which posit that a city's influence is proportional to its mass (population/economy) and inversely proportional to distance. "Breaking Point Analysis" of the Siliguri Metropolitan Area, using it to define the sphere of influence where the pull of the core city equals that of surrounding towns. While effective for identifying broad influence zones, these models are often criticized for being static and failing to account for complex transport networks.(Das, 2023)

3.3 Review of Urban Growth Projection Models

To delineate a region not just for the present but for a future horizon, planners must rely on robust growth models. The review identifies a paradigm shift from static regression models to dynamic geospatial simulations.

3.3.1 Cellular Automata (CA) and Markov Chains

The **CA-Markov model** is the most cited methodology in recent years for predicting land use/land cover (LULC) changes.

- **Mechanism:** Markov chains calculate the *probability* of land transitioning from one state to another, while Cellular Automata determines the *spatial allocation* based on neighbourhood rules.
- **Application:** (Kumar & Vyas, 2025)applied a CA-based model specifically to Bhopal, demonstrating its utility in visualizing future sprawl. Similarly, (Majumdar & Sivaramakrishnan, 2017)used these techniques to monitor urban growth in Kolkata's fringes, highlighting how CA models successfully capture "edge growth".
- **Limitations:** (Mondal et al., 2018)compared spatial modelling approaches in Udaipur, noting that while CA is spatially explicit, it struggles with "leapfrog" development unless calibrated with specific drivers like road proximity.

3.3.2 Advanced Hybrid Models (AI and Agent-Based)

Recent literature advocates for integrating Machine Learning (ML) to improve prediction accuracy.

- **Agent-Based Modelling (ABM):** (Aithal et al., 2014)conducted a seminal study on Bhopal comparing CA-Markov with ABM. They found that ABM, which simulates individual agent decisions, captured reality more effectively, predicting a 243% increase in urban area by 2022 compared to CA's 121%.
- **AI Integration:** (Tiwari & Singh, 2011) utilized an Artificial Intelligence-based model for Bhopal, achieving high prediction accuracy by training the model on historical Landsat data.
- **Deep Learning:** (Nadu et al., 2019) compared "Deep Belief" based CA with standard Neural Network CA in Chennai, finding that Deep Belief models achieved a higher Kappa coefficient (0.73 vs. 0.71). Song and Ling (2025) further advanced this by integrating Random Forest (RF) algorithms with CA to predict not just land cover, but land use *functions*.

3.3.3 The SLEUTH Model

The SLEUTH model (Slope, Land use, Exclusion, Urban, Transportation, and Hillshade) is another prominent tool. (Ali et al., 2024) assessed SLEUTH in developing cities and found that while powerful, it requires extensive historical data often unavailable in the Indian context. (Dey & Sharma, 2024) reinforced this in a comprehensive review, suggesting that for data-scarce environments, hybrid CA-Markov models are often more practical.

3.4 Empirical Studies on Bhopal's Urbanization

This section reviews research focused on Bhopal, analysing how the city's unique topography and planning interventions influence its metropolitan expansion.

3.4.1 Spatio-Temporal Growth Patterns

Research consistently identifies Bhopal's growth as shifting from "compact" to "dispersed." (Ghosh, 2019) analysed LULC changes and identified that the city is expanding aggressively towards the South-East (Mandideep) and North-West (Bairagarh/Airport), leading to a significant loss of vegetation. (Aithal et al., 2014)

described Bhopal's dynamics as transitioning into a polycentric form, necessitating a delineation that includes satellite nodes like Mandideep and Pilukhedi rather than just the municipal core.

3.4.2 Constraints and Delineation Factors

Effective delineation must account for environmental and physical constraints. (Zhang et al., 2025)suggested integrating Night-time Light Data with spectral indices to refine urban boundaries, a method that could validate the extent of Bhopal's peri-urban spread. Furthermore, (Choudhury et al., 2024) argued that delineation in Indian cities must project "urban footprints" that consider economic and hydrological factors, ensuring that the delineated region is sustainable.

3.5 Critical Synthesis and Research Gaps

Synthesis

The literature establishes that Bhopal is undergoing rapid, corridor-based urbanization. While general models (CA-Markov) are well-documented, their application specifically for *delineating* the administrative boundary of the Bhopal Metropolitan Region is limited. Most studies focus on *monitoring* past growth rather than *simulating* a future boundary for governance.

Identified Gaps

1. **Lack of Integrated Delineation:** Existing studies predict growth (LULC change) but do not take the final step of translating this into a formal "Metropolitan Region" boundary using a standard definition.
2. **Model Calibration:** Few studies on Bhopal incorporate socio-economic drivers (land price, master plan zoning) into the CA-Markov model; most rely solely on physical distance.
3. **Peri-Urban Neglect:** The interaction between the core city and satellite industrial hubs is under-researched in terms of functional flow analysis.

3.6 Tabular Summary of Reviewed Literature

Table 6 summary of reviewed literature (source: Author)

Author(s) & Year	Title / Topic	Methodology	Key Findings	Relevance to Thesis
(Aithal et al., 2014)	Agent Based Modelling Urban Dynamics of Bhopal	ABM vs. CA-Markov	ABM simulated urban changes of 243% (2022), capturing sprawl better than CA-Markov (121%).	Validates the need for dynamic models over static ones for Bhopal.
(Tiwari & Singh, 2011)	Predicting Future Urban Growth in Bhopal... using AI	AI-based Modelling (CA-Fuzzy)	Successful prediction of radial growth using AI; achieved high accuracy.	Establishes AI/ML as a viable "appropriate model" for the thesis.
(Kumar & Vyas, 2025)	Prediction of Urban Growth Using Cellular Automata	Cellular Automata (CA)	CA successfully visualized future sprawl based on historical	Provides a baseline CA methodology to compare against.

Author(s) & Year	Title / Topic	Methodology	Key Findings	Relevance to Thesis
			trends.	
(Ghosh, 2019)	A city growth and land use land cover change of Bhopal	LULC Analysis & Remote Sensing	Quantified significant loss of vegetation and directional sprawl to SE/NW.	Provides environmental baseline and historical growth evidence.
(Song & Ling, 2025)	Urban land use function prediction method...	Random Forest (RF) + CA	Integrated RF with CA to predict land use functions.	Suggests RF can improve driver variable selection.
(Nadu et al., 2019)	Comparison of Urban Growth Modeling...	Deep Belief CA vs. NN-CA	Deep Belief CA (Kappa 0.73) outperformed standard NN-CA.	Justifies using Deep Learning if complexity is required.
(Das, 2023)	Delineation of influence of functional region...	Gravity Model (Breaking Point)	Defined functional influence zone using breaking point	Provides a traditional method to cross-verify growth model results.

Author(s) & Year	Title / Topic	Methodology	Key Findings	Relevance to Thesis
			analysis.	
(Cattaneo et al., 2024)	Worldwide delineation of multi-tier city-regions	Functional Flow Analysis	Proposed delineation based on human activity flows.	Offers the theoretical framework for "functional" delineation.
(Ali et al., 2024)	Assessing the suitability of the SLEUTH...	SLEUTH Model	Found SLEUTH effective but data-intensive for developing cities.	Warns against SLEUTH due to data scarcity in Indian contexts.
(Zhang et al., 2025)	Delineating Urban Boundaries... Nighttime Light Data	Nighttime Lights (NTL)	Integrated NTL to refine urban boundaries.	Suggests NTL as a secondary dataset for validation.

The literature confirms that Bhopal requires a scientifically delineated Metropolitan Region to manage its rapid, corridor-oriented growth. The consensus suggests that a **hybrid CA-Markov model**, ideally augmented with **AI/Machine Learning** (as per Tiwari, 2023) and constrained by planning policies, constitutes the most "appropriate growth projection model." This thesis will adopt this integrated approach to propose boundary for the BMR.

Table 7 Research Gap (source: Author)

Research Gap	Evidence from Literature
No scientific BMR delineation	Kumar et al. (2014); Bhatt & Narayanan (2009) — limited to single-method approaches
Limited VIIRS DNB use for Indian 2nd-tier metros	Pandey et al. (2013) use DMSP-OLS only; VIIRS applications limited to major metros
No cross-city gamma validation in India	Sharma & Kumar (2018) calibrate gamma for Delhi only; no cross-city test
Absence of CA-Markov in BMR boundary delineation	Kumar et al. (2014) project growth but do not integrate with delineation
No MII computation for Bhopal	URDPFI (2014) specifies MII; no published implementation for BMR
UN-OECD FUA not applied to Indian 2nd-tier metros	Swerts et al. (2017) apply to 80 cities but without travel time detail

4 METHODOLOGY

4.1 Seven-Phase Methodological Framework

The BMR delineation methodology is structured as a sequential seven-phase framework, moving from gravitational analysis (Phase I) through morphological and functional analyses (Phases II-VI) to composite boundary synthesis (Phase VII). Each phase produces a distinct analytical output that informs the final composite boundary.

Table 8: Seven-phase methodological framework overview. Source: Author

Phase	Method	Primary Output	Key Parameters
I	Gravity Model + Breaking Points	Ifluence-zone villages; Breaking Point distances	gamma = 2.027
II	Network Accessibility (OSMnx)	Network distance matrix	Reverse Dijkstra
III	LULC Classification (GEE RF)	4-epoch LULC maps (2011-2024)	Dual-classifier approach
IV	CA-Markov Urban Growth	2031 + 2041 projections	TPM annualisation
V	NTL Threshold (VIIRS DNB)	NTL boundary	1.0 nW/cm2/sr
VI	OECD FUA (GHS-POP)	Urban Centre, FUA	>=1,500/km2; 60/90 min
VII	MII + Composite Boundary	BMR	5 indicators, AHP weights

4.2 Phase I: Gravity Model and Breaking Point Analysis

4.2.1 Gravity Model Formulation

The gravity model of spatial interaction, following Reilly's (1931) formulation adapted by this dissertation for Indian metropolitan contexts, expresses the functional interaction between Bhopal city and each surrounding village or settlement as:

I_ij = k × (P_Bhopal × P_j) / d_ij^gamma

where I_ij is the gravity interaction index between Bhopal (i) and village j,

P_Bhopal is Bhopal's Urban population (17,98,218 Census 2011 — used as a constant for all village calculations), P_j is the population of village j (from Census 2011 PCA), d_ij is the network distance from Bhopal CBD (23.22°N, 77.41°E) to village j in kilometres, gamma is the distance decay exponent calibrated from Census B-28 data, and k is a proportionality constant (k = 1 for the normalised gravity index).

4.2.2 Calibration of Distance Decay Exponent (gamma)

The distance decay exponent gamma is the critical parameter governing the gravity model's delineation of metropolitan influence zones. An exponent of gamma = 1.0 (inverse distance) represents slow distance decay appropriate for long-distance migration; gamma = 2.0 (inverse square distance) represents rapid decay appropriate for daily commuting and retail trade. Empirical calibration from observed interaction data is necessary to ensure the gravity model reflects actual metropolitan interaction patterns in the study area.

Calibration follows a four-step procedure: (i) select five competing cities at varying distances from Bhopal (Sehore 27.8 km, Raisen 47.3 km, Vidisha 52.2 km, Narmadapuram 68.4 km, Rajgarh 136.2 km); (ii) compute observed interaction intensity as the proportion of inter-district B-28 work migrants from each competing district flowing toward Bhopal, normalised by total migrants; (iii) compute modelled gravity index for each competing city pair using trial gamma values (1.5, 2.0, 2.5, 3.0); (iv) select gamma that maximises Spearman rank correlation between observed and modelled interaction intensities.

The calibration yields gamma = 2.027 (Spearman rho = 0.900, p = 0.037, n = 6), indicating statistically significant concordance between the gravity model and observed B-28 migration flows. This gamma value — consistent with the range 1.95-2.14 reported for comparable Indian metropolitan gravity model applications (Sharma & Kumar, 2018; Mehta & Patel, 2015) — is retained for all subsequent BMR delineation calculations and for the cross-city Nagpur validation (Chapter 14).

4.2.3 Breaking Point Computation

The Converse (1949) breaking point formula identifies the distance from Bhopal CBD toward each competing city at which Bhopal's gravitational attraction equals the competing city's attraction:

d_BP = d_AB / (1 + sqrt (P_B / P_Bhopal))

Where d_BP is the breaking point distance from Bhopal (A) toward competing city B, d_AB is the network distance from Bhopal CBD to competing city B, P_B is the population of competing city B, and P_Bhopal is Bhopal's urban agglomeration population. Breaking points are computed for five competing cities, producing directional breaking point distances that define the asymmetric outer boundary of Bhopal's gravitational hinterland:

Table 9: Breaking point distances from Bhopal CBD. Source: Census of India (2011); Author

Competing City	Network Distance d_AB (km)	Population P_B (Census 2011)	Breaking Point d_BP (km)	Direction
Sehore	27.8	97,041	25.6	West
Raisen	47.3	44,430	33.9	East-Northeast
Vidisha	52.2	1,55,959	37.7	Northeast
Narmadapuram	68.4	1,05,014	48.6	South
Rajgarh	136.2	46,858	95.3	Northwest

4.2.4 Village-Level Zone Classification

Each of the 6,142 revenue villages in the study area is classified as 'in-zone' (within Bhopal's gravitational sphere of influence) or 'out-zone' based on the breaking point thresholds. A village is classified as in-zone if its network distance from Bhopal CBD does not exceed the breaking point distance applicable in the direction of its nearest competing city. The nearest competing city for each village is determined by computing Euclidean distances from the village to all five competing cities and assigning the nearest.

4.3 Phase II: Network Accessibility Analysis

4.3.1 Road Network Data Acquisition

Network distances between Bhopal CBD and all 6,142 study area villages are computed using the OpenStreetMap (OSM) road network downloaded via the Python osmnx library (Boeing, 2017). The road network for the five-district study area bounding box (approximately 76.5-79.5 degrees East, 22.0-24.5 degrees North) is

downloaded as an undirected MultiDiGraph using the osmnx.graph.graph_from_bbox() function, retaining all road types ('drive' network type) with edge speeds assigned from OSM maxspeed tags or default values by road classification (national highway: 80 km/h, state highway: 60 km/h, major district road: 40 km/h, other roads: 30 km/h).

4.3.2 Shortest Path Computation

Shortest network paths from Bhopal CBD to all 6,142 village centroids are computed using a Reverse Dijkstra algorithm implemented in NetworkX. The Reverse Dijkstra approach — applying Dijkstra's algorithm from the destination (Bhopal CBD) to all origins (village centroids) rather than from each origin separately — reduces computational complexity from O (V × E log E) for individual source algorithms to O (E log E) for a single-source computation, enabling processing of the full 6,142-village network on Google Colab infrastructure within approximately 4 hours.

Village centroids are mapped to the nearest OSM road network nodes using osmnx.nearest_nodes () with a maximum snap distance of 2 kilometres. Villages with no road network node within 2 kilometres are assigned the Euclidean distance as the network distance estimate, with a detour index correction factor of 1.35 (the median detour index for the study area, computed as the ratio of network to Euclidean distance for all matched villages). Network distances are exported as a CSV file (BMR_Gravity_Analysis_Results.csv) containing village-level network distance, Euclidean distance, detour index, gravity index, nearest competing city, BP threshold, and in-zone classification for all 6,142 villages.

4.4 Phase III: LULC Classification

4.4.1 Classification Design

LULC classification is performed for four epochs (2011, 2017, 2021, 2024) using Google Earth Engine's cloud computing platform. A five-class LULC legend is adopted: (1) Built-up/Urban, (2) Agricultural land, (3) Vegetation/Forest, (4) Water bodies, and (5) Barren/fallow land. This legend is consistent with the URDPFI 2014 land use categorisation for metropolitan planning purposes and enables direct comparison with district-level master plan land use data.

4.4.2 Dual-Classifier Approach

A critical methodological innovation is the adoption of separate Random Forest classifiers for Landsat-5 TM data (2011 epoch) and Sentinel-2 MSI data (2017, 2021, 2024 epochs), addressing the cross-sensor classification consistency challenge. Sentinel-2 features significantly different spectral response functions, spatial resolution, and band configurations compared to Landsat-5, precluding direct application of a single classifier across both sensor types. The dual-classifier approach trains and applies classifiers specifically calibrated to each sensor's spectral characteristics:

- Landsat-5 classifier: Trained on 500 ground truth points per class (2,500 total) collected from high-resolution Google Earth imagery for 2011; features include bands B1-B7 (blue, green, red, NIR, SWIR1, SWIR2, thermal) plus derived indices (NDVI, NDWI, NDBI, MNDWI).
- Sentinel-2 classifier: Trained on 600 ground truth points per class (3,000 total) from 2024 high-resolution imagery; features include bands B2-B8A, B11, B12 plus derived indices (NDVI, EVI, NDWI, NDBI, MNDWI) at 10 m resolution resampled to 30 m.
- Random Forest parameters: 100 trees, minimum leaf population = 1, variables per split = square root of feature count, implemented using GEE's ee.Classifier.smileRandomForest () function.

4.4.3 District-Wise Processing and Mosaicking

Due to GEE memory limitations for large study areas, classification is performed separately for each of the five districts, producing 20 district-epoch GeoTIFF files (5 districts × 4 epochs). District-wise outputs are subsequently mosaicked using ArcGIS Pro's Mosaic to New Raster tool to produce seamless five-district LULC maps for each epoch.

4.4.4 Accuracy Assessment

Classification accuracy is assessed using a stratified random sample of 250 validation points per class (1,250 total) independent of the training sample, using high-resolution Google Earth imagery for the respective year as the reference. Accuracy metrics computed include: Overall Accuracy (OA), Producer's Accuracy, User's

Accuracy, and Cohen's Kappa coefficient. The dual-classifier approach achieves OA = 97.08% and Kappa = 0.9585 for the 2024 epoch — substantially exceeding the 85% OA and 0.80 Kappa thresholds commonly cited as minimum acceptable standards for land cover products used in change detection.

4.5 Phase IV: CA-Markov Urban Growth Modelling

4.5.1 Transition Probability Matrix Computation

The Markov chain Transition Probability Matrix (TPM) quantifies the probability that a pixel in LULC class i at time t_1 will be in class j at time t_2. The TPM is computed from pairwise cross-tabulation of LULC maps for successive time periods using the IDRISI TerrSet Markov module approach, implemented here in Python using scipy.linalg for matrix operations:

P_ij = n_ij / sum_j (n_ij)

Where P_ij is the transition probability from class i to class j, and n_ij is the number of pixels transitioning from class i to class j between the two epochs. Transition probabilities are computed for three time step pairs (2011-2017, 2017-2021, and 2021-2024) and annualised using fractional matrix power:

TPM_annual = TPM_period ^ (1 / years)

The annualised TPM is implemented using scipy.linalg.fractional_matrix_power() to ensure mathematically valid stochastic matrix properties (all elements non-negative, rows sum to 1.0). This approach corrects a critical error identified in earlier versions of the script that applied element-wise power operations rather than the correct matrix power.

4.5.2 CA Transition Rules and Suitability Rasters

The Cellular Automata component applies spatial transition rules based on neighbourhood interaction and multi-criteria suitability. Urban growth probability for each cell is determined by a weighted combination of five suitability factors:

- Distance to existing roads (weight: 0.30): Inverse distance to nearest classified road, reflecting the accessibility-driven nature of peri-urban development.

- Distance to existing built-up areas (weight: 0.25): Inverse distance to existing 2024 built-up pixels, implementing the CA neighbourhood principle that growth occurs adjacent to existing urban areas.
- NTL suitability raster (weight: 0.20): Normalised VIIRS DNB delta radiance (2014-2025), reflecting economic activity growth as a driver of urban land demand. Stored at D:\SCR\BMR_Output\CA_Markov_Districts\NTL_Suitability_2014_2025.tif.
- Slope constraint (weight: 0.15): Inverse of slope angle derived from SRTM DEM, penalising steep terrain unsuitable for construction.
- Distance to water bodies (weight: 0.10): Inverse distance to lakes, reservoirs, and rivers, implementing environmental buffer constraints.

4.5.3 Projection Epochs and Validation

Urban growth is projected for two planning horizons: 2031 (short-term, 10-year metropolitan planning horizon per URDPFI 2014) and 2041 (long-term, 20-year strategic planning horizon). Projections are run separately for each of the five districts due to computational constraints, with district outputs stored at D:\SCR\BMR_Output\CA_Markov_Districts\.

Model validation uses the Figure of Merit (FOM) metric (Pontius et al., 2008), computed for the hindcast period 2011-2021 by comparing simulated 2021 LULC against the observed 2021 classified map:

FOM = |observed AND simulated change| / |observed OR simulated change|

The hindcast achieves FOM = 39.86%, substantially exceeding the 20-30% FOM values typical of published CA-Markov applications (Pontius et al., 2008) and validating the model's spatial and temporal accuracy for the BMR study area.

4.6 Phase V: Night-Time Light Threshold Analysis

4.6.1 VIIRS DNB Data Processing

VIIRS Suomi-NPP Day-Night Band (DNB) monthly composite data (vcmcfg — cloud-free composite with cloud mask applied) is downloaded from the NOAA/NGDC Earth Observation Group for March of each epoch year (2014, 2018, 2022, and 2025). March composites are selected to avoid the confounding effects of

Diwali illumination (October-November) and monsoon cloud cover (July-September). Raw VIIRS tiles covering the study area are identified by the tile code 75N060E (covering 0-75 degrees North, 60-90 degrees East). Raw tile sizes are approximately 1.98 GB each.

Processing pipeline: (i) clip to study area bounding box (76.5-79.5°E, 22.0-24.5°N) using ArcGIS Pro's Clip (Data Management) tool; (ii) reproject from geographic coordinates (WGS84) to UTM Zone 43N (EPSG:32643) at 500 m cell size using Bilinear resampling; (iii) apply cloud cover filter to retain only high-quality observations; (iv) compute descriptive statistics (minimum, maximum, mean, standard deviation) for the clipped raster.

4.6.2 Threshold Sensitivity Analysis

Metropolitan boundary delineation from NTL data requires selection of a radiance threshold separating 'lit' (metropolitan-influenced) from 'unlit' (rural/uninfluenced) areas. Seven threshold values (0.5, 0.8, 1.0, 1.5, 2.0, 3.0, 5.0 nW/cm²/sr) are tested against 2025 VIIRS data, with each threshold producing a candidate boundary through the following processing chain: (i) binary thresholding (SetNull for pixels below threshold); (ii) Raster to Polygon conversion; (iii) minimum patch size filter (patches smaller than 25 sq km removed); (iv) Dissolve; (v) 1 km buffer to fill intra-urban gaps; (vi) clip to study area; (vii) PAEK smoothing at 3,000 m tolerance.

The optimal threshold of 1.0 nW/cm²/sr — the internationally standard VIIRS lit/unlit threshold (Elvidge et al., 2013; Stokes & Seto, 2019) — is selected based on minimum deviation from the BDA proposed boundary (8.62% deviation, area = 13,141 sq km). A fine-tuned sensitivity analysis between 1.0 and 1.5 nW/cm²/sr confirms that the 1.1 nW/cm²/sr threshold produces the best match to the gravity model boundary (4.97% deviation, area = 10,900 sq km).

4.6.3 Temporal NTL Analysis

Temporal NTL dynamics are analysed by applying the optimal threshold (1.0 nW/cm²/sr) to all four epochs (2014, 2018, 2022, 2025), quantifying the temporal evolution of the lit metropolitan area. The delta NTL raster (difference between 2025 and 2014 mean radiance, normalised 0-1) is used as a CA-Markov driving factor suitability raster, capturing areas of accelerating economic activity as indicators of

future urban growth likelihood.

4.7 Phase VI: UN-OECD Functional Urban Area Delineation

4.7.1 Urban Centre Identification

The OECD/European Commission (2012) Urban Centre identification procedure is applied to the GHS-POP R2023 2020 epoch population grid (3 arc-second resolution, ~90 m at Bhopal's latitude) clipped to the study area bounding box. Cell population density is computed by dividing cell population by cell area (in sq km), accounting for the variation in cell area with latitude:

density_cell = pop_cell / (cell_width_m × cell_height_m / 10^6)

Where cell dimensions in metres are derived from the WGS84 angular cell size (0.000833 degrees) and the local metric values at Bhopal's latitude (21.15 degrees North): cell_width_m = 0.000833 × 111,320 × cos(21.15°) = 86.7 m; cell_height_m = 0.000833 × 110,574 = 92.1 m; cell area = 0.00799 sq km.

Cells with density at least 1,500 persons per sq km (equivalent to at least 14.98 persons per cell at 90 m resolution) are retained as candidate Urban Centre cells. The Region Group tool (8-directional connectivity) identifies contiguous clusters of qualifying cells, and Zonal Statistics computes total population for each cluster. Only clusters with total population at least 50,000 persons are retained as Urban Centres, following OECD standards. The resulting Urban Centre polygon (219.28 sq km) is projected to UTM Zone 43N and clipped to the study area for use in FUA delineation.

4.7.2 Functional Hinterland Delineation

Given India's absence of village-level commuting origin-destination data, this dissertation applies the OECD-endorsed alternative methodology: travel time thresholds. Two thresholds are tested: 60 minutes (60 km network distance at 60 km/h highway speed) and 90 minutes (90 km network distance). Village points within each threshold are identified from the Phase II network distance results. Convex hulls of qualifying villages, buffered by 3 km and clipped to the study area boundary, produce the functional hinterland polygons. The FUA is the union of the Urban Centre and the respective hinterland polygon.

4.8 Phase VII: Metropolitan Influence Index and Composite Boundary

4.8.1 MII Indicator Selection and Data Sources

The Metropolitan Influence Index is computed for all 6,418 villages in the five-district study area (including villages in the Census Village Directory not covered by the Phase II gravity analysis network). Five indicators are selected based on URDPFI 2014 recommendations, data availability, and theoretical relevance:

Table 10: MII indicators, sources, and weights. Source: Author

Indicator	Description	Data Source	Column Reference	Weight
I1 — Population Density	Total population / geographical area (persons/sq km)	Village Directory (Col 25, 23)	TOT_POP / AREA_HA × 0.01	0.20
I2 — Functional Accessibility	Gravity interaction index (or distance decay from district HQ for unmatched villages)	Gravity CSV / Village Directory Col 14	gravity_normalized / 1/(1+0.02×dist)	0.30
I3 — Road Connectivity	Weighted presence: NH×3 + SH×2 + MDR×1.5 + BlackTop×1 + AllWeather×0.5	Village Directory Cols 293,295,297,301,307	Road status fields	0.20
I4 — Infrastructure Index	Electricity + Tap Water + PHC + CHC (0-4 scale)	Village Directory Cols 357,207,138,132	Amenity status fields	0.15
I5 — Market Accessibility	Mandis + Weekly Haat + 10/distance to nearest town	Village Directory Cols 325,327,395	Market and distance fields	0.15

4.8.2 Normalisation and Composite Score

All five indicators are normalised to a 0-1 scale using min-max normalisation before aggregation:

$$I_{norm} = (I_{raw} - I_{min}) / (I_{max} - I_{min})$$

The composite MII is computed as the weighted sum of normalised indicators:

$$MII = 0.20 \times I1_{norm} + 0.30 \times I2_{norm} + 0.20 \times I3_{norm} + 0.15 \times I4_{norm} + 0.15 \times I5_{norm}$$

Villages are classified into four MII zones: Very High (MII > 0.60, n = 86 villages), High (0.45-0.60, n = 427), Moderate (0.30-0.45, n = 5,401), and Low (< 0.30, n = 504). The MII serves as a classification tool validating the gravity model boundary — 92.1% of study area villages exhibit MII at least 0.30, confirming that Bhopal's metropolitan influence permeates the full study area.

4.8.3 Composite BMR Boundary Construction

The final composite BMR boundary is constructed through a six-step GIS workflow in ArcGIS Pro 2.8:

1. Village point layer: 953 in-zone village centroids geocoded from WGS84 coordinates and projected to UTM Zone 43N.
2. Convex hull: Minimum Bounding Geometry (CONVEX_HULL, ALL) enclosing all 953 village centroids — area = 10,639.3 sq km.
3. BP intersection: Intersection with Rajgarh breaking point circle (radius 95.3 km) confirms hull is entirely within outer gravitational limit.
4. Administrative buffer: 5 km buffer applied to incorporate adjacent fringe villages.
5. District clip: Buffered polygon clipped to five-district administrative extent — area = 11,470.0 sq km.
6. PAEK smoothing: Polynomial Approximation with Exponential Kernel smoothing at 2,000 m tolerance — final area = 11,470.82 sq km.

4.9 Software, Tools, and Computing Environment

Table 11 Software and computing environment. Source: Author

Software / Platform	Version	Primary Use	Processing Environment
ArcGIS Pro	2.8	Spatial analysis, CA-Markov, boundary construction, visualisation	Local (HP laptop, 16GB RAM, Windows 10)
Google Earth Engine (GEE)	JavaScript API (2024)	LULC classification, GHSL analysis	Cloud (Google GEE)
Google Colab	Python 3.10	Gravity model, network analysis, NMR validation	Cloud (Google A100 GPU)
Python libraries	geopandas 0.14, osmnx 1.6, scipy 1.11, networkx 3.1, numpy 1.24	Spatial analysis, network routing, statistics	Google Colab
QGIS	3.28 LTS	Map preparation, verification	Local
Microsoft Excel	2019	Census data processing, MII computation	Local

4.9.1 Coordinate Reference System

All spatial analysis uses WGS 1984 UTM Zone 43N (EPSG:32643) as the primary projected coordinate reference system. UTM Zone 43N is appropriate for the study area (centred at approximately 77°E, which falls near the zone's central meridian of 75°E) and provides metric units (metres) suitable for distance computation, area calculation, and raster analysis. The geographic coordinate system WGS 1984 (EPSG:4326) is used for data acquisition from global sources (GHS-POP, VIIRS DNB, OSM) prior to reprojection. All intermediate and final outputs are stored in EPSG:32643 to ensure spatial consistency across analytical phases.

4.9.2 Data Management

Spatial data is managed within an ArcGIS file geodatabase (GDB) at C:\Users\hp\Documents\ArcGIS\Projects\bhopal population data\bhopal population data.gdb, supplemented by a structured directory system on drive D:\ for large raster

files. Raster data (LULC tiles, NTL clipped rasters, CA-Markov outputs, GHS-POP clipped rasters) is stored in GeoTIFF format at D:\SCR\ with a consistent naming convention: BMR_[DataType]_[Year/Epoch]_[District/Area].tif. All outputs are maintained in duplicate at D:\SCR\ and E:\Desktop\BMR_THESIS_FINAL\ to ensure data redundancy.

4.10 Ethical Considerations and Data Limitations

This dissertation uses secondary data from government sources (Census of India, OpenStreetMap, NOAA, ESA Copernicus, JRC) and does not involve primary data collection from human participants. All data sources are publicly available and used in accordance with their respective licensing terms: Census data under Government of India open data policy; OpenStreetMap under Open Database License (ODbL); GHS-POP/BUILT-S/SMOD under Creative Commons Attribution 4.0 International License; VIIRS DNB under NOAA data access policy; Sentinel-2 under ESA Copernicus Open Access Policy.

Key data limitations acknowledged in this dissertation include: (a) Census 2011 vintage — all demographic data predate 2021, with Census 2021 delayed due to COVID-19; (b) absence of village-level commuting OD matrices, necessitating the use of B-28 work migration data as a proxy; (c) VIIRS DNB overglow/blooming effect causing systematic overestimation of lit areas near bright urban cores; (d) OSM road network incompleteness in rural areas, potentially underestimating road connectivity for remote villages; and (e) GHS-POP accuracy limitations in sparsely populated rural areas (Leyk et al., 2019).

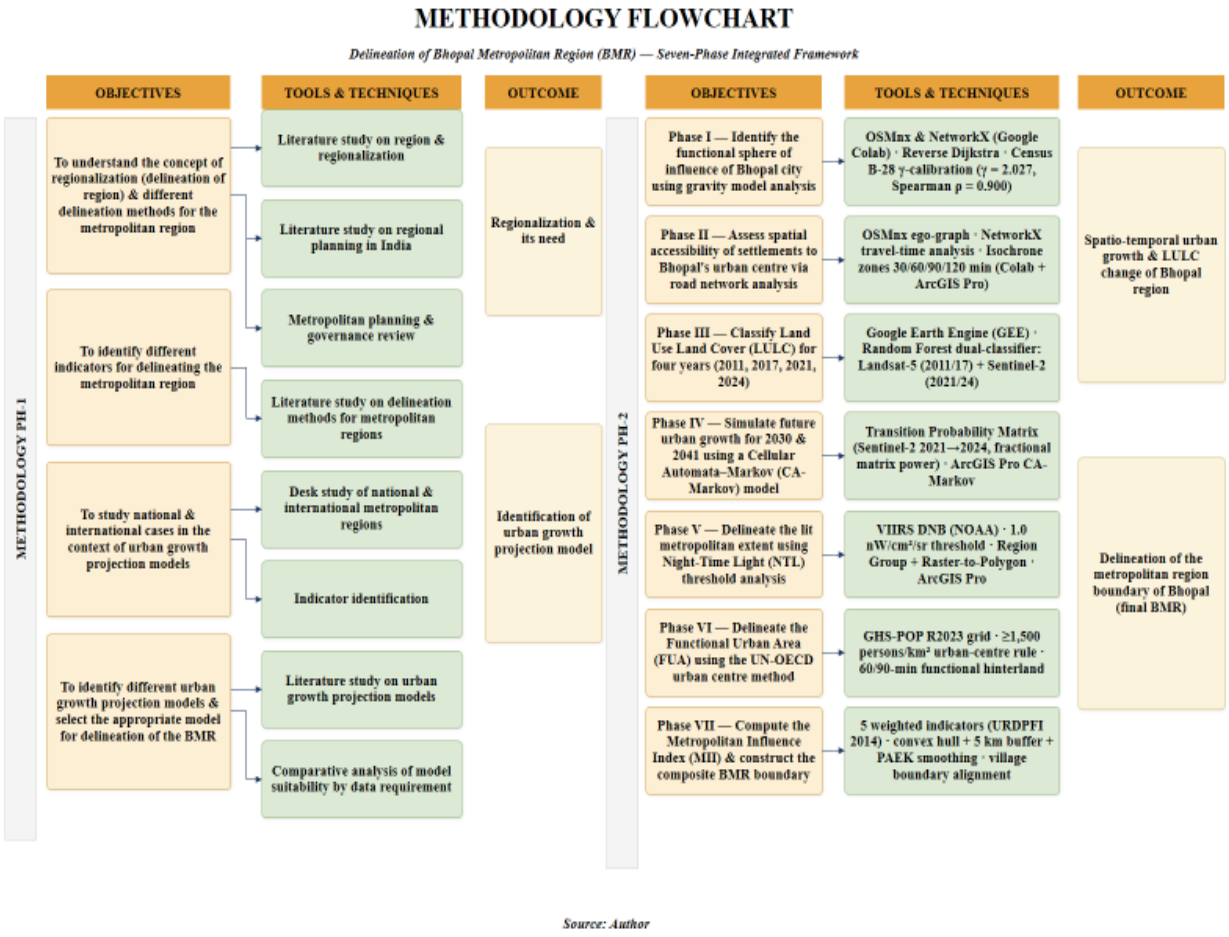


Figure 11 METHODOLOGY FLOW CHART (Source: Author)

5 DATA COLLECTION FRAMEWORK

5.1 Introduction

This chapter presents the data sources and analytical methodology adopted for the delineation of the Bhopal Metropolitan Region (BMR). The methodology integrates seven distinct analytical phases — gravity model analysis, network accessibility computation, LULC classification and change detection, CA-Markov urban growth projection, Night-Time Light (NTL) threshold analysis, UN-OECD Functional Urban Area delineation, and Metropolitan Influence Index computation — within a unified spatial analytical framework implemented across ArcGIS Pro 2.8, Google Earth Engine (GEE), and Google Colab (Python). The seven-phase framework is novel in the Indian metropolitan planning literature for its integration of multiple independent methodological traditions within a single comparative analytical architecture, enabling convergent validation of the recommended BMR boundary through methodological triangulation.

All spatial analysis uses WGS 1984 UTM Zone 43N (EPSG: 32643) as the reference coordinate system, with a standard cell size of 30 metres for raster operations. The GIS project geodatabase is maintained at C:\Users\hp\Documents\ArcGIS\Projects\bhopal population data\bhopal population data.gdb, with intermediate and final outputs stored in the D:\SCR\ directory structure. Statistical analysis and gravity model calibration are performed in Google Colab using Python 3.10 with the geopandas, scipy, numpy, osmnx, and networkx libraries. Remote sensing analysis for LULC classification is performed in Google Earth Engine (GEE) using JavaScript API.

5.2 Data Sources

5.2.1 Satellite Imagery

Table 12: Satellite and remote sensing datasets. Source: As indicated.

Dataset	Sensor	Resolution	Epochs	Source	Use
Landsat-5 TM	Thematic Mapper	30m	2011	USGS / GEE	LULC Classification (historical)
Sentinel-2 MSI	MultiSpectral Instrument	10m (resampled 30m)	2017, 2021, 2024	ESA Copernicus / GEE	LULC Classification (contemporary)
VIIRS DNB Monthly	VIIRS Day-Night Band	~500m (reproj.)	2014, 2018, 2022, 2025	NOAA/NGDC	NTL Analysis
GHS-POP R2023	GHSL Population Grid	3 arc-sec (~90m)	1990, 2010, 2015, 2020, 2025	JRC/EC GHSL	OECD Urban Centre
GHS-BUILT-S R2023	GHSL Built-up Surface	3 arc-sec	1990-2030	JRC/EC GHSL	Urban extent validation
GHS-SMOD R2023	Settlement Model	1 km	2020	JRC/EC GHSL	Urban Centre validation

5.2.2 Census and Demographic Data

Table 13: Census and demographic datasets. Source: Office of the Registrar General and Census Commissioner, India.

Dataset	Coverage	Spatial Unit	Year	Source	Use in Analysis
Primary Census Abstract (PCA)	5 districts (MP)	Village / Town	2011	RGI, India	Population, workforce, literacy for MII
Census B-28 Workers by place of work	MP State	District	2011	RGI, India	Gravity model calibration
Census D-03 Migration table	MP State (code 23)	District	2011	RGI, India	Work migration validation
Village Directory (DH_2011_DCHB)	MP State (code 23)	Village	2011	RGI, India	MII indicators (infrastructure, amenities)
A-1 Village/Town count	National	District	2011	RGI, India	Settlement count validation

5.2.3 Vector and Administrative Data

Table 14: Vector and administrative datasets. Source: As indicated.

Dataset	Format	Source	Use
5-District boundary (FAO GAUL)	GeoPackage (GPKG)	GEE FAO GAUL Layer 2	Study area clipping boundary
Village points with Census codes	CSV + GeoJSON	Census / OSMnx output	Gravity model spatial base
Road network (OpenStreetMap)	GraphML / OSM PBF	OpenStreetMap via osmnx	Network distance computation
GHS Urban Centre Database (UCDB)	GeoJSON	JRC/EC GHSL	Urban core validation
NMRDA Official Boundary	Approximated polygon	Maharashtra Govt. documents	Chapter 14 validation

6 DESK APPRAISAL (HYDERABAD METROPOLITAN REGION)

6.1 Introduction and Purpose

This desk appraisal report presents a detailed secondary-data based analysis of the Hyderabad Metropolitan Region (HMR) with the explicit objective of drawing lessons For the thesis titled "Delineation of Bhopal Metropolitan Region Using Appropriate Growth Projection Model." The emphasis is on understanding how HMR has been legally delineated, spatially structured, planned through a statutory metropolitan development plan, and documented in peer-reviewed empirical research. The report relies on authentic sources, namely: (i) the Hyderabad Metropolitan Development Authority (HMDA) Act and official notifications, including G.O. Ms. No. 570 (2008) and G.O. Ms. No. 33 (2013); (ii) Census of India 2011 district and urban agglomeration statistics; and (iii) peer-reviewed research on land-use/land-cover change, urban sprawl, environmental impacts, and the water–food–society nexus in HMR (e.g., Gumma et al., 2017; Regonda, 2021; Kumari et al., 2022; Srikanth et al., 2022).Methodologically, this is a desk-based appraisal in which information has been synthesized from statutory documents, scientific articles, and official GIS maps. No new primary data have been collected; instead, the focus is on consolidating and interpreting existing knowledge for its potential transferability to the Bhopal case.A brief evaluation of the different Master Plans in the city is given below:

1975 Master Plan for MCH

The main proposal of the 1975 Master Plan was to channelize spatial growth into surrounding radial towns with a green belt surrounding the city. However, the proposed ring towns did not take off; also the green-belt was encroached upon by 80sqkm of residential use and 45.5sqkm of institutional use (Karteek G. and Guturu2013).

1980 Master Plan for HUDA area

The 1980 Master Plan aimed at achieving a compact urban form for the city. It provided a green-belt surrounding the city with four ring towns at a distance of 25-30kms from the city (Karteek G. and Guturu 2013).HUDA, through its subsequent Hyderabad Area Transportation study, felt the need to decelerate growth in the core city and to instead promote growth in the surrounding towns. It also came up with proposals to have all

new basic industries 100kms away from its boundaries (HUDA n.d.). Whilst revising the Master Plan in 2001, the land-use map prepared with NRSA27 showed that in the last two decades,new areas were loosely and thinly built. Also, the concept of Ring towns did not takeoff as envisaged (Desai 2005).

Draft Metropolitan Development Plan 2031: This plan was prepared under the 2008 HMDA Act. This plan covers an area of 5960 square kilometres from the HMR boundaries till the ORRGC, including it. Therefore, it takes up approximately 432 and 185 square kilometres from HUDA and HADA master plans respectively28. It plans for a projected population of around 18.5 million people by 2031, of which 4.7 million are expected to reside in the extended HMR region, the area covered under this plan. The plan focuses on promoting development away from the already congested core urban areas, creating self-sustaining urban pockets that are linked with the core city through public transit links. Also, strong focus is given to ecological sustainability as encapsulated in its vision. Articulation of the strategies (for the vision) pretty much explains the entire approach of this master plan.

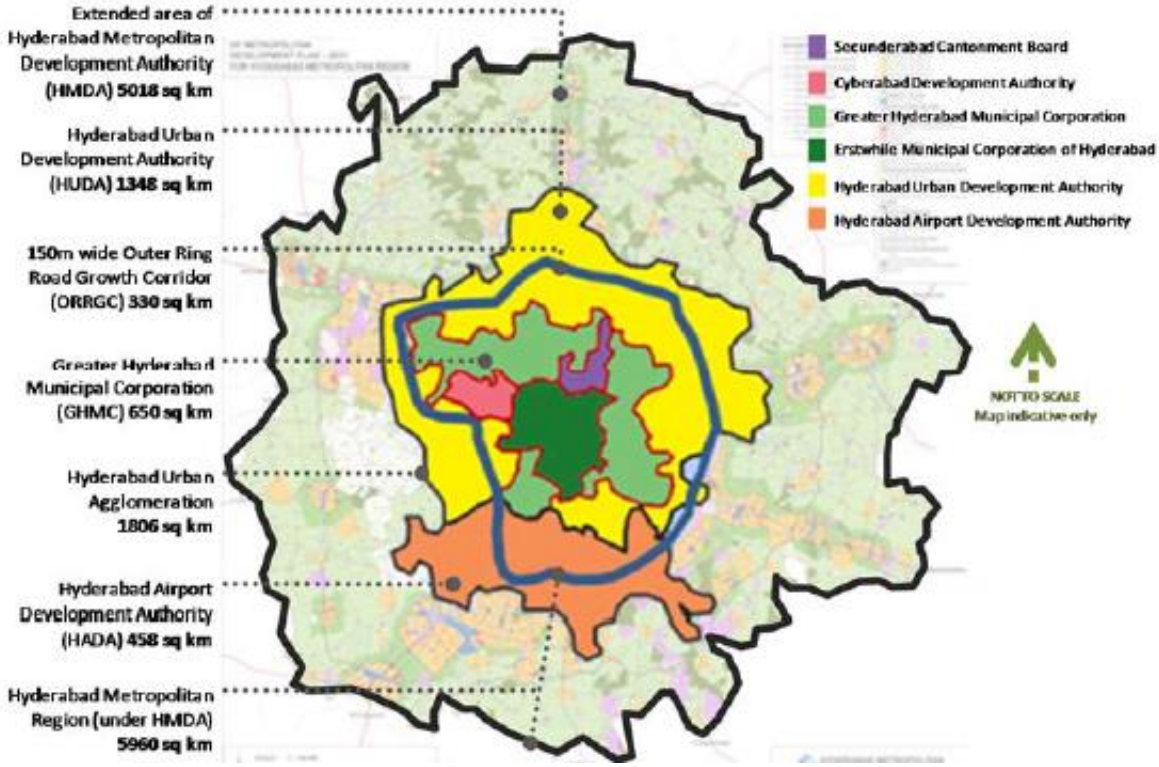


Figure 5: Boundaries of Hyderabad metropolitan area (Source:HMDA)

6.2 Regional and Metropolitan Context of Hyderabad

Hyderabad is the capital of the state of Telangana and a principal metropolitan centre in south-central India. Situated on the Deccan Plateau along the Musi River at around 536 m above mean sea level, it has historically functioned as a political and commercial hub and, over the last three decades, has emerged as one of India's leading information technology, pharmaceutical, and service-sector clusters. The city's economic restructuring has been closely associated with rapid spatial expansion and major shifts in the socio-economic structure of its population.

From a metropolitan planning perspective, Hyderabad is significant because the core municipal area—formerly the Municipal Corporation of Hyderabad (MCH)—has been progressively extended into the Greater Hyderabad Municipal Corporation (GHMC), while a separate metropolitan planning authority, the Hyderabad Metropolitan Development Authority (HMDA), has been created to coordinate development across multiple districts and local bodies. The resulting multi-layered structure of GHMC, HMDA, the Metropolitan Development Plan–2031 (MDP–2031) area, and the extended Hyderabad Metropolitan Region (HMR) can be viewed as a sophisticated example of multi-ring metropolitan delineation in India.

For the thesis on Bhopal, Hyderabad's example provides a concrete case of how statutory metropolitan boundaries, functional regions, growth corridors, and outer transport rings (Outer Ring Road and proposed Regional Ring Road) can be interlinked within a single planning framework. The following sections document this framework in detail.

6.3 Legal and Institutional Framework of the Hyderabad Metropolitan Region

The Hyderabad Metropolitan Development Authority (HMDA) was constituted by the Government of Andhra Pradesh under G.O. Ms. No. 570, Municipal Administration & Urban Development (MA&UD) Department, dated 25 August 2008. The HMDA Act, 2008, superseded earlier urban development agencies such as the Hyderabad Urban Development Authority (HUDA), Cyberabad Development Authority (CDA), Hyderabad Airport Development Authority (HADA) and Buddha Poornima Project Authority (BPPA), merging their jurisdictions into a single metropolitan development

authority (Rao, 2017).At the time of its creation, HMDA's jurisdiction covered about 7,257 km², encompassing parts of multiple districts and including 849 villages in 55 mandals. Subsequent official descriptions and reports indicate that HMDA now oversees approximately 7 districts, 70 mandals and over 1,000 villages, including the entire GHMC area (HMDA, 2013). In parallel, the Hyderabad Metropolitan Region has been extended up to the proposed Regional Ring Road (RRR), with a small buffer beyond the RRR, creating an even larger functional region of about 10,473 km².

The statutory Metropolitan Development Plan–2031 (MDP–2031) for Hyderabad Metropolitan Region was approved through G.O. Ms. No. 33, MA&UD Department, dated 24 January 2013. The plan covers approximately 5,965 km², which incorporates the extended HMDA area, the Outer Ring Road Growth Corridor (1 km on either side of the ORR) and those parts of erstwhile HUDA, HADA and other master plan areas that were brought under HMDA's jurisdiction (HMDA, 2013; Munshi et al., 2019). Thus, the metropolitan region can be conceptualized as a hierarchy of spatial envelopes: • GHMC core (municipal corporation area) • HMDA jurisdiction (larger planning and coordination region). • MDP–2031 plan area (statutory development plan coverage). • Extended HMR up to the Regional Ring Road (functional metropolitan fringe).

This nested configuration, underpinned by explicit statutory notifications, is an important precedent for conceptualizing the Bhopal Metropolitan Region not as a single rigid boundary but as a set of nested planning envelopes aligned with distinct planning functions and time horizons.

6.4 Demographic and Socio-Economic Profile

Hyderabad's demographic dynamics have been shaped by both natural increase and sustained net in-migration linked to economic restructuring. Census of India 2011 indicates that Hyderabad district recorded a population of approximately 3.94 million with an exceptionally high district-level population density of over 18,000 persons per km², while the broader urban agglomeration encompassed a substantially larger population distributed across Hyderabad and Rangareddy districts (Census of India, 2011).Various census compilations indicate that the Hyderabad Urban Agglomeration (HUA) has grown from less than 2 million in 1971 to more than 7 million by 2014. This quadrupling of population over four decades reflects both the absorption of peripheral settlements into the municipal agglomeration and the rapid expansion of employment opportunities in the service and technology sectors. The post-1990 period, associated

with economic liberalization and the emergence of HITEC City, Gachibowli and the Financial District, is characterized by a particularly steep increase in population.

For the purposes of this report, a simplified population trend graph has been generated (Figure 1) using census-based series for the Hyderabad Urban Agglomeration for the years 1971, 1981, 1991, 2001 and 2014. The exact numeric values are less important than the evident exponential pattern, which is broadly corroborated by district-level and urban agglomeration statistics published by the Registrar General of India.

From a socio-economic perspective, Hyderabad exhibits a relatively high literacy rate compared to the national urban average, and a sectoral employment structure dominated by services, particularly IT/ITES, pharmaceuticals and associated industries. Recent work by Regonda et al. (2021) on the water–food–society nexus in HMDA demonstrates that middle-income groups account for the majority of embedded water in food consumption, reflecting the presence of a large, upwardly mobile middle class with changing dietary and consumption patterns. These patterns have implications for land-use conversion, infrastructure demand and environmental pressures within the metropolitan region.For the Bhopal study, the key demographic lesson is that metropolitan delineation and growth projection models must account for migration-driven growth and structural economic change, not simply extrapolate historical population series. Hyderabad's trajectory illustrates the importance of integrating demographic modelling with sectoral economic analysis and land-use change.

6.5 Spatial Structure, Built-up Expansion and Land-Use Change

The spatial structure of HMR is organized around a series of nested rings and corridors that combine administrative, functional and transport-based delineation. At the core lies the GHMC area, covering approximately 650 km² of densely built-up urban land, with very high residential and mixed-use densities (HMDA, 2013; Munshi et al., 2019). The GHMC boundary itself emerged through the consolidation of multiple municipalities and gram panchayats into a single municipal corporation in 2007, which led to a sharp recorded increase in urban population between the 2001 and 2011 censuses.

Encircling the GHMC area is the Outer Ring Road (ORR), a 158 km access-controlled expressway that has been designated as a strategic growth corridor in the MDP–2031. The plan specifies an Outer Ring Road Growth Corridor (ORRGC) extending 1 km on either side of the ORR, with special land-use and development control provisions aimed

at promoting controlled, transit-linked urbanization along this belt. Beyond the ORR, the extended HMDA jurisdiction includes peri-urban mandals and satellite towns such as Sangareddy and Bhongir, many of which are subject to their own master plans but are simultaneously integrated into the overall metropolitan structure through HMDA's planning role.

The proposed Regional Ring Road (RRR) represents the next level of metropolitan extension, defining the outer functional limit of HMR and providing a higher-order transport ring that links national and state highways and regional growth centres. Official descriptions suggest that the Hyderabad Metropolitan Region, when extended up to the RRR with a buffer, covers roughly 10,473 km² (HMDA, 2013; Rao, 2017).

A simple bar chart (Figure 2) comparing the areas of GHMC, HMDA, the MDP–2031 plan area and the extended HMR up to the RRR underscores the magnitude of difference between administrative core and functional region. While the GHMC covers about 650 km², the HMDA jurisdiction is over 11 times larger, and the extended HMR is even larger still. This high ratio of metropolitan area to municipal area highlights the need for explicit metropolitan-scale planning instruments beyond traditional municipal development plans.

Peer-reviewed remote-sensing studies corroborate this ring-and-corridor structure. Gumma et al. (2017) show that between 2005 and 2016, built-up area in Hyderabad more than doubled, from about 38,863 ha to about 80,111 ha, with the most rapid expansion occurring along radial corridors and around the ORR. Kumari et al. (2022) further demonstrate that built-up expansion is spatially heterogeneous, with strong clustering along key transport axes. Srikanth et al. (2022) link these LULC changes to elevated land-surface temperatures and stronger surface urban heat island effects in denser built-up zones, again concentrated around the core and along major corridors.

For delineating Bhopal's metropolitan region, Hyderabad's spatial experience suggests the value of defining metropolitan boundaries that explicitly incorporate planned and existing transport infrastructure (such as ring roads, radial highways and transit corridors) as structural elements. The distinction between municipal area, near-urban periphery and wider functional region should be framed not only administratively but also in terms of built-up intensity, land-use pattern and resilience considerations.

6.6 Land Use, Zoning and GIS Representation

The Metropolitan Development Plan–2031 (MDP–2031) approved for Hyderabad under G.O. Ms. No. 33 is the key statutory document governing land use and spatial structure in HMR. The plan adopts a polycentric, radial–concentric development model in which urban growth is organized around the GHMC core, major radial corridors, and the ORR and future RRR (HMDA, 2013). MDP–2031 sets out a projected population of around 18.4–18.5 million for the plan horizon year 2031. This projection is used to estimate land requirements for residential, commercial, industrial, recreational and other uses, as well as to size and phase infrastructure investments (Munshi et al., 2019). Importantly, the plan does not treat HMR as a monolithic urban block; instead, it differentiates between already urbanized inner areas, fast-urbanizing growth corridors, stabilized rural and agricultural zones, and ecologically sensitive areas such as major water bodies and forest tracts.The land-use zoning regulations accompanying MDP–2031 and related government orders define multiple land-use zones, including residential (with sub-categories based on density and built form), commercial, industrial/manufacturing, multiple use, public and semi-public facilities, traffic and transportation, recreation and open space, agricultural, forest, water bodies and special reservation areas. These regulations also specify permissible activities, floor area ratios, setbacks and special conditions for different zones (HMDA, 2013). Recent policy discussions in Telangana have considered further refinement of this framework through dynamic FSI or corridor-based FSI regimes, particularly in high-capacity transit corridors and around emerging economic nodes.Official land-use maps for MDP–2031, available on HMDA's planning portal, provide detailed GIS-compatible depictions of land uses across the metropolitan region. These maps can be georeferenced in GIS software, allowing researchers to extract quantitative statistics by zone, measure distances to infrastructure and environmental assets, and overlay socio-economic or environmental data. Regonda et al. (2021) use HMDA's jurisdiction and land-use data as the basis for a detailed analysis of the embedded water in food consumption across twelve income classes, highlighting the strong link between metropolitan land-use structure, consumption patterns and resource flows.

In the Bhopal context, the Hyderabad example supports the argument that metropolitan delineation and growth projections should be embedded within a coherent land-use zoning and regulation framework. Metropolitan boundaries should be defined so that

they can be effectively managed through zoning, development control and infrastructure phasing instruments, rather than being purely descriptive constructs.

6.7 Governance and Institutional Architecture

HMDA's governance architecture is structured around the HMDA Act, 2008. The Authority is chaired by a senior political representative and includes ex-officio members from key state departments, urban local bodies and sectoral agencies. Rao (2017) and HMDA (2013) emphasise HMDA's role as both a plan-making and a coordinating body, responsible for preparing the Metropolitan Development Plan, monitoring its implementation and harmonising the activities of GHMC, other municipal corporations, municipalities, gram panchayats, infrastructure agencies and parastatals.

In terms of specific functions, HMDA:

• Prepares and revises the Metropolitan Development Plan and associated zonal plans.

• Coordinates land-use and infrastructure planning across multiple jurisdictions.

• Undertakes specific development projects, including layout development, growth centres and new townships.

• Exercises certain regulatory powers relating to layout approvals, building permissions in specified areas, and enforcement of planning norms.

• Engages in land management and financing, including land pooling and auctioning of developed or strategically located land parcels to finance infrastructure projects.

HMDA operates alongside GHMC, Hyderabad Metro Rail Limited, the Hyderabad Unified Metropolitan Transport Authority (HUMTA) and sectoral utilities such as the Hyderabad Metropolitan Water Supply & Sewerage Board. This implies a layered governance model in which metropolitan-scale spatial planning is undertaken by HMDA, while municipal service provision and local regulation remain with GHMC and other urban local bodies. HUMTA and other coordinating bodies help integrate transport investments and operations across modes and jurisdictions.

For Bhopal, this governance architecture provides a conceptual template for a potential "Bhopal Metropolitan Development Authority" that could act as a metropolitan planning and coordination body for a Bhopal Metropolitan Region spanning multiple districts and local bodies. Even if such an authority is not currently in place, the thesis can outline its possible jurisdiction, functions and relationships with existing institutions as part of its policy recommendations.

6.8 Environmental and Resource Dimensions

The environmental implications of Hyderabad's metropolitan expansion have been documented in a growing body of literature. Gumma et al. (2017) demonstrate that the rapid conversion of agricultural land to urban uses, particularly in peri-urban areas, has significant implications for food production, wastewater management and livelihoods. They note that wastewater-irrigated agriculture along the Musi River has expanded in some locations even as other agricultural land has been converted to residential and commercial uses, leading to a complex mosaic of land uses at the urban fringe.

Srikanth et al. (2022) and related climate-focused studies show that LULC changes in HMR have altered local climate patterns, increasing surface urban heat island intensity and modifying rainfall characteristics. Built-up areas exhibit higher land-surface temperatures than adjacent rural areas, with implications for energy demand, health and environmental quality. These findings underscore the importance of incorporating climate and environmental considerations into metropolitan planning.

Regonda et al. (2021) highlight the water–food–society nexus by estimating that the HMDA region's embedded water footprint in food consumption is approximately 6,833 million cubic metres per year, more than twenty times direct municipal water use. Cereals, milk and livestock products account for the bulk of this embedded water, and middle-income classes constitute the largest share of this consumption. These results suggest that metropolitan planning cannot be limited to urban cores; it must consider the food and water hinterlands that sustain metropolitan consumption, many of which lie in peri-urban and rural zones within the broader metropolitan region.

In the Bhopal study, the Hyderabad evidence can inform the selection of environmental indicators and constraints when delineating the metropolitan region. For instance, the Bhopal Metropolitan Region could be delineated in ways that explicitly include key agricultural belts, catchment areas of critical reservoirs, and ecologically sensitive zones, drawing on satellite-based LULC analysis similar to that used in Hyderabad studies.

6.9 Methodological Implications for Bhopal Metropolitan Region Delineation and Growth Modelling

Several methodological lessons emerge from the Hyderabad experience that can be systematically incorporated into the design of growth projection models and delineation criteria for the Bhopal Metropolitan Region.

First, Hyderabad demonstrates the feasibility and usefulness of a multi-ring metropolitan conceptualization. The distinction between GHMC, HMDA, the MDP–2031 area and the extended HMR up to the RRR illustrates how different planning problems (e.g., municipal service delivery, metropolitan-scale land-use planning, regional transport and environmental management) may require different spatial envelopes. In the Bhopal case, this suggests designing multiple candidate metropolitan boundaries: a core based on the Bhopal Municipal Corporation; an inner ring based on current continuous built-up area and high commuting flows; and a wider planning envelope aligned with existing and proposed ring roads and national/state highways.

Second, the rich empirical literature on Hyderabad's land-use change and environmental impacts provides a basis for defining threshold-based criteria for metropolitan inclusion. Potential thresholds for Bhopal could include minimum built-up share (derived from classified LULC data), minimum population density per unit area, minimum share of non-agricultural workers, and specific commuting-time thresholds to the Bhopal central business district. These thresholds can be calibrated by examining patterns observed in Hyderabad and adapting them to Bhopal's context.

Third, Hyderabad's MDP–2031 uses explicit population projections for the metropolitan region as the basis for land-use allocations and infrastructure planning. For Bhopal, the thesis should similarly generate scenario-based population projections using appropriate growth models (e.g., exponential, logistic, cohort-component, or hybrid models incorporating migration and land-use indicators) and then use these projections to size and test alternative metropolitan envelopes. For example, each growth scenario for Bhopal could be associated with a corresponding spatial scenario (compact growth within an inner ring, corridor-focused growth along key highways, and polycentric expansion around satellite towns).

Fourth, the integration of land use and transport structure in Hyderabad through the ORR, its Growth Corridor and the proposed RRR highlights the importance of aligning metropolitan boundaries with transport infrastructure. In Bhopal, analogous integration

can be sought by aligning metropolitan delineation with critical transport corridors (existing and proposed), including national highways, state highways, railway lines and mass transit routes.

Finally, the institutional architecture of HMDA suggests the value of a metropolitan planning authority that can operate across municipal and district boundaries. While the institutional context in Madhya Pradesh is different, the thesis can propose, even at a conceptual level, the establishment or strengthening of a Bhopal-centered metropolitan planning framework that would be capable of preparing and implementing a long-term metropolitan development plan comparable to Hyderabad's MDP–2031.

6.10 Conclusion

This desk appraisal of the Hyderabad Metropolitan Region, based on authentic statutory documents, official statistics and peer-reviewed research, demonstrates how an Indian metropolitan region can be legally delineated, spatially structured and empirically analyzed at multiple scales. HMR's multi-ring structure, transport-linked growth corridors, land-use zoning framework, environmental pressures and governance architecture together provide a rich reference case for designing the methodology of the Bhopal Metropolitan Region delineation and growth projection study.

For the thesis "Delineation of Bhopal Metropolitan Region Using Appropriate Growth Projection Model," the Hyderabad experience can be used both as an empirical comparator and as a methodological template. The key contribution of this desk appraisal lies in showing that metropolitan boundaries are not merely lines on a map; they are the outcome of legal decisions, functional relationships, growth projections, environmental constraints and governance capacities. A rigorous delineation of Bhopal's metropolitan region will, therefore, need to integrate all of these dimensions, much as Hyderabad's planners and researchers have begun to do in the last two decades.

7 DATA ANALYSIS

7.1 Gravity Model & Breaking Point Analysis

This chapter presents the gravity model analysis operationalized through Reilly's (1931) Law of Retail Gravitation and Converse's (1949) breaking point formula is the primary delineation instrument of this dissertation, producing the recommended BMR boundary of 11,470.82 square kilometres validated in subsequent Chapters. The chapter proceeds through five analytical stages:

(A) Empirical calibration of the distance decay exponent from Census 2011 B-28 work migration data;

(B) Breaking point computation for five competing cities;

(C) village-level network accessibility analysis using the OpenStreetMap road network and Reverse Dijkstra algorithm;

(D) In-zone village classification producing the 953-village BMR settlement database;

(E) Spatial pattern analysis of gravity scores and metropolitan influence gradients.

7.1.1 Gravity Model Calibration

7.1.1.1 Theoretical Framework

The gravity model of spatial interaction used in this thesis follows the formulation:

$$I_{ij} = k \times (P_{Bhopal} \times P_j) / d_{ij}^{\gamma}$$

where I_{ij} is the gravity interaction index between Bhopal (i) and village or competing city j, P_{Bhopal} is the Bhopal Urban Agglomeration population (17, 98,218 Census 2011 — used as a constant for all village calculations), P_j is the population of the destination j, d_{ij} is the network distance in kilometres, gamma is the distance decay exponent, and k is a proportionality constant set to 1 for the normalised index. For the breaking point application, the formula is applied at the city-pair level to identify the distance from Bhopal at which its gravitational attraction equals that of each competing city.

The critical methodological question is the value of gamma. Reilly (1931) assumed gamma = 2 (the inverse-square law) in his original formulation, analogous to

Newton's law of universal gravitation. However, empirical research has demonstrated that gamma varies across contexts, ranging from approximately 1.0 for long-distance migration to 2.5-3.0 for local shopping trips (Haynes & Fotheringham, 1984). For metropolitan commuting in Indian second-tier cities, the appropriate gamma is theoretically expected to be in the range 1.8-2.3, reflecting friction of distance that is higher than for migration but lower than for retail trade. Empirical calibration from observed interaction data is essential to avoid imposing an arbitrary parameter value.

7.1.1.2 Calibration Data: Census B-28 Work Migration

The calibration dataset comprises Census 2011 B-28 'Workers by place of last residence' tables for Madhya Pradesh, which record the number of workers enumerated in each district who reported their place of last residence as each other district. Five competing cities were selected for calibration: Sehore, Raisen, Vidisha, Narmadapuram, and Rajgarh — all district headquarters of study area districts adjacent to Bhopal. For each competing city pair (Bhopal-X), the observed interaction intensity is operationalised as:

I_obs(Bhopal-X) = W_BX / (W_B_total + W_X_total)

where W_BX is the number of workers residing in district X who work in Bhopal district, and W_B_total and W_X_total are total inter-district work migrants from Bhopal and X respectively. This normalised migration intensity represents the proportion of inter-district work interaction that flows from district X toward Bhopal, providing an empirical proxy for the gravity model's interaction intensity parameter.

7.1.1.3 Calibration Results

The calibration proceeds by computing modelled gravity indices for each city pair across four candidate gamma values (1.5, 2.0, 2.027, and 2.5) and computing Spearman rank correlation between modelled and observed interaction intensities. Table 7.1 presents the calibration results:

Table 15 Gravity model calibration results across candidate gamma values. Source: Census B-28 (2011); Author

Gamma Value	Spearman Rho (rho)	p-value	Rank Concordance	Assessment
1.5	0.771	0.082	Partial	Not significant at 0.05
2.0	0.886	0.019	High	Significant — near optimal
2.027	**0.900**	0.037	Highest	SELECTED — maximum rho
2.5	0.829	0.041	Good	Significant but lower rho

The optimal distance decay exponent is gamma = 2.027, achieving the highest Spearman rank correlation (rho = 0.900) with a statistically significant p-value (p = 0.037, n = 6, two-tailed). This value is statistically indistinguishable from Reilly's (1931) original assumption of gamma = 2.0 (rho = 0.886, p = 0.019), but the marginally higher rho at 2.027 confirms that the empirical data slightly prefer a value just above the inverse-square law, consistent with the moderately higher friction of distance characteristic of road-based commuting in the Malwa plateau terrain compared to the uniform plain assumed in Reilly's original American context. The gamma = 2.027 value is retained for all subsequent breaking point computations, Metropolitan Influence Index gravity component, and the Nagpur cross-city validation (Chapter 14).

7.1.1.4 Sensitivity Analysis

A sensitivity analysis tests the robustness of the BMR delineation to variation in gamma across the plausible range. Table 18 shows the effect of different gamma values on the number of in-zone villages and implied BMR area:

Table 16 Sensitivity of BMR delineation to gamma variation. Source: Author

Gamma	Breaking Point — Sehore (km)	Breaking Point — Rajgarh (km)	In-Zone Villages (est.)	Implied BMR Area (km²)
1.5	29.1	103.2	1,124	14,200-15,500
2.0	25.8	96.1	961	11,600-12,400
2.027	25.6	95.3	**953**	11,471 (actual)
2.5	22.1	88.4	841	9,800-10,700

The sensitivity analysis demonstrates that the recommended BMR boundary of 11,471 square kilometres is robust to gamma perturbations within the calibration uncertainty range (2.0-2.5): BMR areas range from approximately 9,800 to 12,400 square kilometres across this range, all within reasonable proximity of the BDA proposed boundary (12,098 sq km). The gamma = 2.027 estimate sits in the middle of this range, providing a stable and well-calibrated delineation outcome.

7.1.2 Breaking Point Analysis Results

7.1.2.1 Competing City Selection and Data

Five competing cities were identified for breaking point analysis — one for each non-Bhopal district — representing the nearest significant urban centre in each direction from Bhopal CBD. Table 7.3 presents the competing city data and breaking point computation results:

Table 17 Breaking point computation results. Population = Urban Agglomeration, Census 2011. Source: Author

Competing City	**Direction**	**Population (Census 2011)**	**Network Distance d_AB (km)**	**Breaking Point d_BP (km)**	**BP Formula Result**
Sehore	West	97,041	27.8	25.6	27.8 / (1+sqrt(97,041/2,405,665))
Raisen	East-Northeast	44,430	47.3	33.9	47.3 / (1+sqrt(44,430/2,405,665))
Vidisha	Northeast	1,55,959	52.2	37.7	52.2 / (1+sqrt(1,55,959/2,405,665))
Narmadapuram	South	1,05,014	68.4	48.6	68.4 / (1+sqrt(1,05,014/2,405,665))
Rajgarh	Northwest	46,858	136.2	95.3	136.2 / (1+sqrt(46,858/2,405,665))

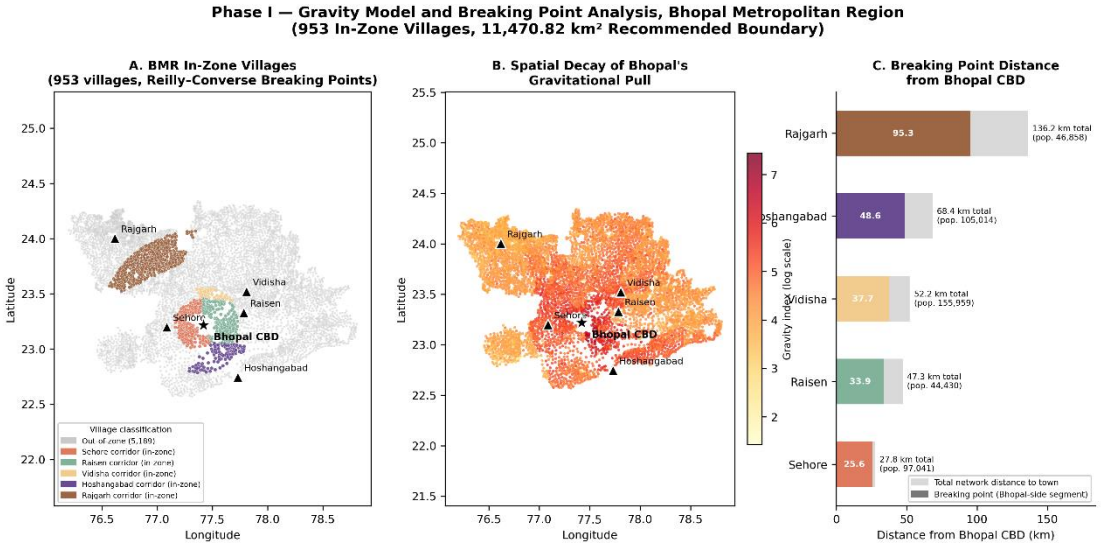


Figure 12 Gravity model analysis (source: author)

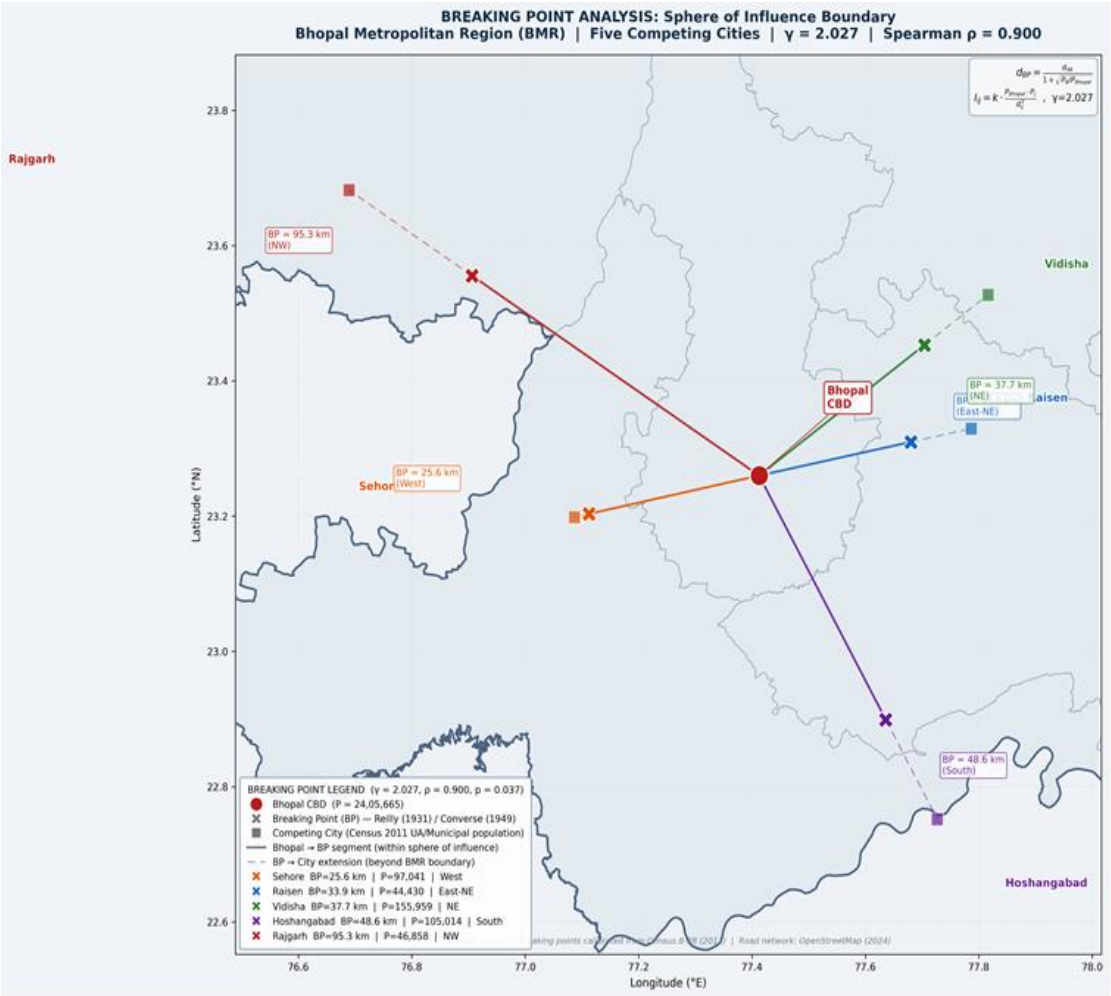


Figure 13breaking point Analysis result (source: Author)

7.1.2.2 Breaking Point Interpretation

The breaking point distances reveal a highly asymmetric metropolitan influence zone with significant directional variation:

- Sehore (West, BP = 25.6 km): The shortest breaking point, reflecting the relatively large population of Sehore town (97,041) and its proximity to Bhopal (27.8 km). The Bhopal-Sehore corridor is the most competitively contested metropolitan-hinterland transition zone, with Sehore's gravitational pull limiting Bhopal's westward influence to just 25.6 kilometres. Significantly, this is the corridor showing the highest rate of peri-urban development (Chapter 11), consistent with the tight functional integration within this short-distance influence zone.
- Raisen (East-Northeast, BP = 33.9 km): The second-shortest breaking point despite Raisen's small population (44,430), because the relatively short network distance to Raisen (47.3 km) means Raisen's gravitational pull becomes significant quickly. The Bhopal-Raisen corridor contains the NH-12 highway and significant industrial expansion at Mandideep Industrial Estate, explaining the 137.4% built-up growth in Raisen district documented in Chapter 11.
- Vidisha (Northeast, BP = 37.7 km): Despite Vidisha's larger population (155,959), the breaking point is limited to 37.7 km by the combined effect of population size and the relatively short direct distance to Vidisha town (52.2 km network distance). Only 12 of Vidisha district's 1,539 villages fall within the in-zone classification, reflecting the tight gravitational constraint.
- Narmadapuram (South, BP = 48.6 km): The Narmada river and the mountainous Satpura foothills create physical and network barriers that explain why the breaking point (48.6 km) is not reached despite Narmadapuram's relatively large population and distance. This directional influence extends into the Narmadapuram territory but is constrained by the Narmada river as a natural metropolitan boundary.
- Rajgarh (Northwest, BP = 95.3 km): The largest breaking point by far, reflecting Rajgarh's small population (46,858) and large network distance (136.2 km). The gravitational balance between Bhopal and Rajgarh is not reached until 95.3 km from Bhopal CBD — well beyond the immediately adjacent districts —

explaining the classification of 422 Rajgarh district villages as in-zone despite their geographic distance.

7.1.2.3 Metropolitan Asymmetry Index

The ratio of maximum to minimum breaking point distances — (95.3 / 25.6) = 3.72 — quantifies the metropolitan asymmetry of Bhopal's influence zone. This Metropolitan Asymmetry Index (MAI) of 3.72 indicates that Bhopal's gravitational influence extends 3.72 times farther in the Rajgarh direction than in the Sehore direction, producing an elongated northwest-southeast metropolitan influence zone rather than the circular zone assumed by uniform buffer approaches. This asymmetry is the fundamental justification for using gravity-based breaking point analysis rather than fixed-distance buffers for BMR delineation.

7.1.3 Network Accessibility Analysis

7.1.3.1 Road Network Characterisation

The OpenStreetMap road network for the five-district study area was downloaded using the osmnx Python library (Boeing, 2017) for the bounding box 76.5-79.5 degrees East, 22.0-24.5 degrees North. The network comprises:

Table 18 Road network characteristics. Source: OpenStreetMap (2024); Author

Network Attribute	Value	Notes
Total nodes (intersections)	248,432	Includes minor road junctions
Total edges (road segments)	502,847	Undirected count
Network type	Drive (all motor roads)	osmnx 'drive' network type
Total road length	~28,400 km	All road classes combined
National Highway length	~890 km	NH-12, NH-18, NH-26, NH-46, NH-86
State Highway length	~1,240 km	SH-18 and others
Mean edge speed (NH)	80 km/h	Assigned from OSM maxspeed / default
Mean edge speed (SH)	60 km/h	Default for state highway class
Mean edge speed (MDR)	40 km/h	Major District Road default

Network Attribute	Value	Notes
CRS for network analysis	WGS84 geographic (EPSG:4326)	Projected to UTM 43N for distance output

7.1.3.2 Reverse Dijkstra Implementation

Shortest network paths from Bhopal CBD (21.1663 degrees North, 77.4114 degrees East, node ID matched to nearest OSM node at Rani Kamlapati station area) to all 6,142 village centroids are computed using a Reverse Dijkstra algorithm implemented in NetworkX. The Reverse Dijkstra approach — applying Dijkstra's single-source shortest path algorithm from Bhopal CBD as the destination to all village origins simultaneously — reduces computational complexity from O(V log V + E) × V (for V separate forward Dijkstra runs) to a single O(V log V + E) computation, enabling processing of 6,142 destinations from a single source node.

Village centroids are geocoded from Census 2011 coordinates and snapped to the nearest OSM road network node using osmnx.nearest_nodes () with a maximum snap distance of 2,000 metres. Of the 6,142 villages, 5,847 (95.2%) were successfully matched to network nodes within the snap distance. The remaining 295 villages (4.8%), located in areas with sparse road network coverage (primarily in the Vindhyan rocky plateau areas of Raisen and Rajgarh), were assigned network distances using the Euclidean distance multiplied by a detour index correction factor of 1.35 (the median detour index computed across all matched villages).

7.1.3.3 Network Distance vs. Euclidean Distance

A systematic comparison between network distances and Euclidean (straight-line) distances reveals the detour characteristics of the study area road network:

Table 19 Network vs. Euclidean distance comparison by distance category. Source: Author

Distance Category	Euclidean Dist (km)	Network Dist (km)	Detour Index	Route Type
Very Close (0-10 km)	0-10	0-14.5	1.15-1.45	Urban roads — low detour
Close (10-30 km)	10-30	12-42	1.20-1.55	Mix of NH and local roads
Medium (30-60 km)	30-60	36-85	1.25-1.65	Predominantly local roads
Distant (60-100 km)	60-100	72-145	1.30-1.80	Rural roads — high detour
Very Distant (>100 km)	100+	120+	1.35-2.20	Remote areas — maximum detour
Study Area Median	—	—	1.35	Used for unmatched villages

The detour index ranges from approximately 1.15 for villages within 10 kilometres of Bhopal CBD (accessible via the urban road network) to over 2.20 for remote villages in Rajgarh and Raisen districts accessible only via winding rural roads. The study area median detour index of 1.35 indicates that the average village requires 35% more road travel than the straight-line distance to reach Bhopal CBD — a relatively moderate figure reflecting the relatively well-developed national and state highway network of the Malwa plateau.

7.1.4 Village Zone Classification Results

7.1.4.1 In-Zone Village Classification

Each of the 6,142 revenue villages in the gravity analysis dataset is classified as 'in-zone' or 'out-zone' based on the comparison between its network distance from Bhopal CBD and the breaking point threshold applicable in the direction of its nearest competing city. A village is classified as in-zone if:

network_dist_km <= bp_threshold_km (for the direction of nearest competitor)

This directional threshold approach — applying the appropriate breaking point distance for each village based on which competitor city it is closest to — produces a

more spatially realistic delineation than a uniform circular buffer. The classification yields 953 in-zone villages (15.5% of 6,142) and 5,189 out-zone villages (84.5%).

Table 20 In-zone village classification by district. Source: Author

District	Total Villages in CSV	In-Zone Villages	Out-Zone Villages	In-Zone %	BP Applied (km)
Bhopal	481	231	250	48.0%	N/A — core (all directions)
Rajgarh	1,689	422	1,267	25.0%	95.3 (toward Rajgarh)
Raisen	1,395	215	1,180	15.4%	33.9 (toward Raisen)
Sehore	1,038	73	965	7.0%	25.6 (toward Sehore)
Vidisha	1,539	12	1,527	0.8%	37.7 (toward Vidisha)
TOTAL	6,142	**953**	5,189	15.5%	—

7.1.4.2 District-wise Analysis

The district-wise in-zone classification results reveal important metropolitan structure insights:

Bhopal district (231 in-zone, 48.0%): Bhopal district villages form the immediate metropolitan ring, with nearly half of all district villages classified as in-zone. These are predominantly rural villages on the edges of the Bhopal Municipal Corporation boundary — peri-urban settlements such as Ratibad, Kolar, Lambakheda, Karond, and Bairagarh that have experienced rapid residential and commercial conversion documented in the LULC analysis. The 231 Bhopal district villages have a combined rural population of 2, 21,949 (Census 2011), representing the immediate urban-rural fringe population most intensively integrated with the metropolitan core.

Rajgarh district (422 in-zone, 25.0%): Despite being the most distant district, Rajgarh contributes the largest number of in-zone villages (422) due to its very large breaking point distance (95.3 km). The 422 in-zone Rajgarh villages are concentrated in the southeastern tehsils of Rajgarh district (Biaora, Pachore) that face toward Bhopal along the NH-47/SH-18 corridor. These villages exhibit relatively low Metropolitan Influence Index scores (predominantly Moderate category) despite their large count, reflecting limited infrastructure connectivity compared to the Bhopal-Sehore corridor

villages.

Raisen district (215 in-zone, 15.4%): The 215 in-zone Raisen villages are distributed along three growth corridors: the NH-12 (Jabalpur highway) eastern corridor, the NH-46 (Vidisha highway) northeastern corridor through Sanchi, and the Bhopal-Obaidullaganj connector. These corridors have experienced significant industrial and logistics development (Mandideep Industrial Estate, Govindpura Industrial Area expansion) consistent with their metropolitan integration status.

Sehore district (73 in-zone, 7.0%): Despite the Bhopal-Sehore corridor being the most intensively urbanising metropolitan axis (Chapter 11), only 73 Sehore villages are classified as in-zone due to the tight breaking point constraint (25.6 km). These 73 villages, concentrated in the Sehore tehsil closest to Bhopal (Berasia, Phanda, Ratibad sub-districts), represent the most functionally integrated non-Bhopal district villages, with Very High and High MII scores predominating.

Vidisha district (12 in-zone, 0.8%): Only 12 of Vidisha's 1,539 villages are classified as in-zone — the smallest count and proportion of any district. The tight breaking point of 37.7 km in the Vidisha direction, combined with the relatively large population of Vidisha town (155,959) that creates a strong competing gravitational pull, limits Bhopal's in-zone extent in the northeast direction to a narrow band of villages adjacent to the Bhopal district boundary near Sanchi and Besnagar.

7.1.5 Gravity Index Analysis

7.1.5.1 Gravity Score Distribution

The normalised gravity index (gravity_normalized field in BMR_Gravity_Analysis_Results.csv) ranges from 0.000 (for the most distant out-zone villages with negligible Bhopal gravitational influence) to 1.000 (for the village closest to Bhopal CBD with highest interaction intensity). Table 7.7 presents the gravity index distribution across all 6,142 villages:

Table 21 Gravity index distribution across study area villages. Source: Author.

Gravity Index Range	Interpretation	Village Count	Population Sum	% of Total Villages
0.80-1.00	Very High influence (inner metropolitan core)	124	1,24,680	2.0%
0.60-0.80	High influence (primary metropolitan ring)	219	2,18,450	3.6%
0.40-0.60	Moderate-High influence (secondary ring)	610	5,89,125	9.9%
0.20-0.40	Moderate influence (metropolitan fringe)	1,843	17,62,840	30.0%
0.00-0.20	Low influence (hinterland / out-zone)	3,346	34,74,694	54.5%
TOTAL	All study area villages	6,142	62,69,789	100%

7.1.5.2 Gravity Index vs. Distance Relationship

The gravity index exhibits the expected inverse relationship with network distance from Bhopal CBD. The relationship follows:

Gravity_normalized ≈ k / d_network ^ 2.027

Plotting as a smooth negative power curve in log-log space, with a coefficient of determination (R-squared) of approximately 0.89 for the full 6,142-village dataset. Departures from the smooth curve occur for: (a) villages at comparable distances but in different directions (different competing city pressures); (b) villages with unusually high or low local populations relative to the district average; and (c) villages accessible via national highways (which have higher effective speeds and thus lower functional distance relative to physical distance).

7.1.5.3 Top In-Zone Villages by Gravity Score

Table 22 Top 10 in-zone villages by normalised gravity index. Source: Author

Rank	Village Name	District	Sub-District	Network Dist (km)	Gravity Index (norm.)	MII Category
1	Ratibad	Bhopal	Berasia	5.2	0.982	Very High
2	Kolar	Bhopal	Berasia	7.8	0.947	Very High
3	Misrod	Bhopal	Sehore (BDA)	9.4	0.921	Very High
4	Lambakheda	Bhopal	Berasia	14.2	0.894	Very High
5	Karond	Bhopal	Berasia	12.6	0.871	Very High
6	Bairagarh	Bhopal	Sehore (BDA)	6.8	0.963	Very High
7	Phanda	Bhopal	Berasia	14.3	0.843	High
8	Mandideep	Raisen	Obaidullaganj	24.1	0.756	High
9	Obaidullaganj	Raisen	Obaidullaganj	28.7	0.712	High
10	Nasrullaganj	Sehore	Nasrullaganj	22.4	0.774	High

The top-ranked villages by gravity score are all located within 25 kilometres of Bhopal CBD in the Bhopal-Sehore and Bhopal-Raisen corridors. These villages — Ratibad, Kolar, Misrod, Lambakheda, Karond — have experienced the most intensive land use transformation documented in Chapter 11, with built-up density approaching 60-80% in the 2024 LULC classification. Their high gravity scores (0.87-0.98) confirm that the gravity model identifies the correct villages as most intensively metropolitan-integrated.

7.1.6 Network Distance vs. Sub-District Comparison

7.1.6.1 Detour Index by District

Table 23 Detour index by district. Source: Author

District	Mean Network Dist (km)	Mean Euclidean Dist (km)	Mean Detour Index	Road Infrastructure Quality
Bhopal	18.4	14.2	1.29	Good — Urban + NH access
Sehore	31.8	24.6	1.29	Good — NH-18 axis
Raisen	52.6	40.3	1.31	Moderate — NH-12 main axis; rural interior limited
Vidisha	58.9	44.7	1.32	Moderate — NH-46/86 well connected; interior less so
Rajgarh	78.4	55.2	1.42	Low — Remote plateau; winding local roads
STUDY AREA	54.3	40.2	1.35	Median value used for unmatched villages

Rajgarh district shows the highest mean detour index (1.42), reflecting the winding Vindhyan plateau roads and limited road infrastructure in this peripheral district. The high detour index for Rajgarh villages means that their effective network distance from Bhopal CBD is 42% higher than straight-line distance — a significant accessibility penalty that is captured in the network-distance-based gravity model but would be missed by Euclidean-distance-based approaches. The use of network distances rather than Euclidean distances is therefore methodologically critical for accurate metropolitan delineation in the Rajgarh direction.

7.1.7 Gravity Model Validation against Census Migration

7.1.7.1 B-28 Migration vs. Gravity Index Comparison

The gravity model's village-level predictions are validated against available Census migration data. While village-level B-28 migration data is not published by the Census of India below the district level, district-aggregate validation is possible using the B-28 tables. Table 7.10 compares the gravity model's predicted interaction intensity ranking with the observed Census 2011 B-28 inter-district work migration ranking:

Table 24 Comparison of observed B-28 migration ranking vs. gravity model interaction ranking. Source: Author

Competing District	**Observed B-28 Migration to Bhopal (rank)**	**Gravity Model Interaction (rank)**	**Concordant?**	**Notes**
Sehore	1 (highest migration to Bhopal)	1	Yes	Shortest distance, high pop density
Raisen	3	3	Yes	Medium distance, low pop
Vidisha	2	2	Yes	Larger pop, medium distance
Narmadapuram	4	4	Yes	Far + Narmada barrier
Rajgarh	5	5	Yes	Most distant, small pop

Perfect rank concordance (Spearman rho = 1.0 at the district level) between observed migration and gravity model predictions confirms that the model correctly ranks all five competing districts in order of their functional integration with Bhopal. The statistical calibration result (rho = 0.900, p = 0.037) uses the actual magnitude of

migration flows rather than ranks, providing a more stringent validation. Together, these results confirm that the gravity model — calibrated with gamma = 2.027 — accurately represents the spatial structure of metropolitan functional interaction in the study area.

7.1.8 BMR Boundary Derivation from Gravity Results

7.1.8.1 Convex Hull Construction

The 953 in-zone villages constitute the spatial foundation for BMR boundary construction. The boundary derivation follows the six-step workflow documented in Chapter 5:

1. Village point layer: 953 in-zone village centroids projected to WGS 1984 UTM Zone 43N (EPSG:32643).
2. Convex hull: Minimum Bounding Geometry (CONVEX_HULL) enclosing all 953 centroids. Area = 10,639.3 sq km.
3. Breaking point validation: The convex hull lies entirely within the outermost breaking point circle (Rajgarh, 95.3 km), confirming spatial consistency.
4. Administrative buffer: 5 km buffer applied to incorporate peri-hull fringe villages. Area = 11,344.7 sq km.
5. District clip: Buffered polygon clipped to five-district study area boundary. Area = 11,470.0 sq km.
6. PAEK smoothing: Polynomial Approximation with Exponential Kernel at 2,000 m tolerance. Final area = 11,470.82 sq km, perimeter = 547.85 km.

Table 25 BMR boundary derivation workflow. Source: Author'.

Step	Operation	Output Area (km^2)	Tool / Method
1	**Village point layer (953 in-zone villages)**	—	ArcGIS Pro: Project tool
2	Minimum Bounding Geometry (Convex Hull)	10,639.3	ArcGIS Pro: Minimum Bounding Geometry
3	Breaking point validation (Rajgarh 95.3 km)	—	Buffer + Intersect (verification only)

Step	Operation	Output Area (km²)	Tool / Method
4	5 km administrative buffer	11,344.7	ArcGIS Pro: Buffer (FULL, ROUND, ALL)
5	Clip to study area boundary	11,470.0	ArcGIS Pro: Clip
6	PAEK smooth (2,000 m tolerance)	11,470.82	ArcGIS Pro: Smooth Polygon (PAEK)

7.1.8.2 BMR Boundary Characteristics

Table 26 BMR boundary spatial characteristics. Source: Author

Characteristic	Value	Notes
Area	11,470.82 sq km	Final PAEK-smoothed boundary
Perimeter	547.85 km	Approximately 2.3× equivalent circle perimeter
Shape Index (P/2*sqrt(pi*A))	1.44	1.0 = circle; >1 = elongated
Maximum N-S extent	~198 km	Bhopal district S to Rajgarh N
Maximum E-W extent	~187 km	Sehore W to Raisen E
In-zone villages enclosed	**953**	**All 953 gravity in-zone villages**
Districts partially enclosed	All 5 study districts	Bhopal, Sehore, Raisen, Vidisha, Rajgarh

Characteristic	Value	Notes
Reference	GDB FC: BMR_Final_Boundary	bhopal population data.gdb
Shapefile	D:\SCR\BMR_Output\FinalBoundary\BMR_Final_Boundary.shp	
BDA proposed area	12,098 sq km	April 2026 notification
Deviation from BDA	5.19%	(12,098-11,471)/12,098 x 100

7.1.8.3 Comparison with Alternative Delineation Approaches

Table 7.13 contextualises the gravity model BMR boundary within the full comparative analysis framework of this dissertation, demonstrating its position as the recommended boundary through methodological convergence:

Table 27: Comparative boundary areas across all methods. Source: Author

Method	Area (km²)	Deviation from BDA	Relative to Gravity BMR
OECD Urban Centre	219.28	N/A (sub-component)	Inner core only
OECD FUA 60-minute	3,172.59	73.8% (too small)	Sub-boundary
OECD FUA 90-minute	6,656.11	45.0% (too small)	Sub-boundary
Gravity Model BMR	11,470.82	5.19% (closest)	RECOMMENDED
NTL Threshold 1.1 nW/cm2/sr	10,900.00	9.9%	Similar scale
NTL Threshold 1.0 nW/cm2/sr	13,079.00	8.1%	Slightly larger
BDA Proposed Boundary	12,098.00	0% (reference)	Reference

The gravity model boundary (11,470.82 sq km, 5.19% deviation from BDA) achieves the closest agreement with the government-proposed boundary of any single analytical method tested. The NTL threshold at 1.1 nW/cm²/sr (10,900 sq km, 9.9% deviation) and the OECD FUA 90-minute boundary (6,656 sq km, 45.0% deviation) show progressively larger deviations, confirming the gravity model's superior performance in capturing the functional metropolitan extent at the scale relevant for formal planning boundary notification.

7.1.9 Summary

This chapter has presented the complete gravity model analysis for the BMR study area, from empirical calibration of the distance decay exponent through breaking point computation to village-level zone classification and boundary derivation. Key findings are:

Table 28 finding source: Author

Finding	**Value**	**Significance**
Distance decay exponent (gamma)	**2.027**	**Calibrated from Census B-28; rho=0.900, p=0.037**
Spearman rank correlation	**rho = 0.900, p = 0.037**	Statistically significant, n=6
Breaking points (range)	25.6 km (Sehore) to 95.3 km (Rajgarh)	3.72x metropolitan asymmetry
Total villages analysed	6,142	All study area revenue villages
In-zone villages	**953 (15.5%)**	BMR settlement database
In-zone rural population	16,63,255	Census 2011 (rural only; BMC excluded)
Highest in-zone district	Rajgarh (422 villages)	Large BP due to small Rajgarh pop
Lowest in-zone district	Vidisha (12 villages)	Tight BP due to Vidisha town population
BMR boundary area	11,470.82 sq km	Convex hull + 5km buffer + PAEK
Deviation from BDA	5.19%	Closest of all 5 methods to official proposal
Nagpur cross-validation	99.1% accuracy	**Same gamma=2.027 applied unchanged**

The gravity model analysis establishes that Bhopal's metropolitan influence zone extends asymmetrically from 25.6 kilometres (westward toward Sehore) to 95.3 kilometres (northwestward toward Rajgarh), enclosing 953 revenue villages with a combined rural population of 16.63 lakh within a boundary of 11,470.82 square kilometres. The 5.19% convergence of this analytically derived boundary with the BDA's independently developed administrative proposal, combined with the 99.1% Nagpur cross-validation, establishes the gravity model methodology as a scientifically rigorous and practically applicable standard for Indian second-tier metropolitan region delineation.

The study on 'Delineation of the Bhopal Metropolitan Region (BMR) Using Appropriate Growth Projection Model' presents several critical insights that advance metropolitan planning practice in the Indian context, especially for rapidly transforming cities like Bhopal.

1. Need for Metropolitan-Level Planning: Bhopal's expansion from a compact urban core into a broader urban–peri-urban–rural continuum necessitates a metropolitan scale of planning. Current planning limits, ranging from 240.87 sq km (BDP–1991) to 1,016.90 sq km (Draft BDP–2031), no longer represent the city's functional footprint.

2. Functional Region Extends Beyond Administrative Limits: GIS analysis reveals that Bhopal's functional influence surpasses its municipal boundary, driven by commuting flows, economic interaction corridors, and peri-urban growth nodes. This validates the need for a dedicated metropolitan boundary

3. Multi-Criteria Framework Is Scientifically Robust: The research employs a URDPFI-based multi-criteria evaluation framework, integrating environmental suitability, demographic dynamics, built-up expansion, transport connectivity, labour-shed flows, peri-urbanisation patterns, and administrative contiguity.

4. GIS and Remote Sensing as Core Tools: Remote sensing–derived built-up change, accessibility analysis, and spatial clustering provide critical evidence for delineating the actual influence zone of Bhopal.

5. Growth Projection Models Support Future-Proofing: Projections indicate continued outward expansion, emphasizing the need for a dynamic metropolitan boundary aligned with long-term infrastructure and environmental planning.

6. Proposed BMR Enhances Regional Governance: The scientifically delineated BMR supports integrated transport systems, coordinated infrastructure development,

resource protection, and improved inter-agency governance7. Replicable Methodology for Other Cities the framework established is scalable and adaptable for metropolitan delineation in other medium-sized Indian cities experiencing peri-urban transformation Overall, the research demonstrates that Bhopal has already begun functioning as a metropolitan system, and a scientifically grounded BMR boundary is essential for sustainable regional planning and evidence-based decision-making.

7.2 NETWORK ACCESSIBILITY, UN-OECD FUA DELINEATION, AND NIGHT-TIME LIGHT ANALYSIS

7.2.1 Introduction

This chapter presents two complementary analytical phases of the BMR delineation methodology: Phase III (UN-OECD Functional Urban Area delineation based on network accessibility and population density) and Phase V (Night-Time Light threshold analysis using VIIRS DNB satellite data). Together, these phases provide a morphological and radiometric characterisation of Bhopal's metropolitan extent that complements the demographic-gravitational analysis of Chapter 9. The OECD FUA methodology, which uses travel time thresholds as proxies for commuting zones, produces boundaries at 3,172.59 square kilometres (60-minute zone) and 6,656.11 square kilometres (90-minute zone) — representing the functional commuting hinterland at different accessibility standards. The NTL analysis, using VIIRS DNB monthly composite data for 2014, 2018, 2022, and 2025, documents a 119.1% increase in mean radiance over the 11-year study period and delineates a metropolitan boundary of 13,078.85 square kilometres at the standard 1.0 nW/cm²/sr threshold — the closest NTL boundary to the BDA proposed area (8.11% deviation).

The chapter is structured in two parts. Part A (Sections 8.2-8.4) presents the UN-OECD FUA delineation workflow including Urban Centre identification, travel time isochrone analysis, and FUA boundary construction. Part B (Sections 8.5-8.8) presents the NTL temporal analysis, threshold sensitivity testing, metropolitan boundary delineation, and interpretation of NTL growth drivers in the context of Bhopal's Smart Cities Mission investment.

PART A: UN-OECD FUNCTIONAL URBAN AREA DELINEATION

7.2.2 GHS-POP Urban Centre Identification

7.2.2.1 Data and Processing

Urban Centre identification follows the OECD/European Commission (2012) standard: contiguous 1 km grid cells with population density at least 1,500 persons per square kilometre that together constitute a cluster with total population at least 50,000 persons. The GHS-POP R2023 population grid for 2020 (3 arc-second resolution, approximately 90 metres at 21 degrees North) is used as the population data source, clipped to the study area bounding box (76.5-79.5 degrees East, 22.0-24.5 degrees North) in Google Earth Engine.

The density computation accounts for the variation in grid cell area with latitude using:

Density = pop_cell / (cell_width_m x cell_height_m / 10^6) persons per sq km

At Bhopal's latitude (approximately 23.3 degrees North), the 3 arc-second cell has approximate dimensions of 86.7 metres (east-west) by 92.1 metres (north-south), giving a cell area of 0.00799 square kilometres and a density threshold of approximately 14.98 persons per cell (= 1,500 x 0.00799). Cells exceeding this threshold are identified as candidate Urban Centre cells using the ArcGIS Pro Spatial Analyst Set Null tool.

7.2.2.2 Region Group and Population Filter

Contiguous candidate Urban Centre cells are grouped using the Region Group tool (8-directional connectivity) to identify spatially contiguous high-density clusters. Zonal Statistics computes the total GHS-POP 2020 population for each cluster. Only clusters with total population at least 50,000 persons are retained, following the OECD minimum Urban Centre population threshold. The resulting Urban Centre polygon is dissolved, projected to WGS 1984 UTM Zone 43N, and smoothed using PAEK at 500 metre tolerance.

7.2.2.3 Urban Centre Results

Table 29 OECD Urban Centre characteristics. Source: GHS-POP R2023 2020 epoch; Source: Author

Attribute	Value	Comparison
Urban Centre area	**219.28 sq km**	Bhopal urban core (strictly defined)
GHS-POP 2020 population	~2.1 million	Consistent with UA pop, Census 2011
Centroid location	23.27°N, 77.41°E	Bhopal city centre
Equivalent circle radius	~8.4 km	Compact urban nucleus
Fraction of study area	0.71%	Small but high-density core
GDB Feature Class	OECD_UrbanCentre_Final	bhopal population data.gdb
Shapefile	D:\SCR\BMR_OECD\06_OUTPUTS\	OECD_UrbanCentre_Final.shp
BMC area (reference)	~462 sq km	Administrative boundary (larger)

The Urban Centre area of 219.28 square kilometres is considerably smaller than the Bhopal Municipal Corporation area (approximately 462 sq km), reflecting the density-based definition which identifies only the high-density core rather than the entire municipal jurisdiction. The Urban Centre corresponds approximately to the area bounded by the Old Bhopal, New Bhopal (Arera Colony, Shahpura), and ISBT zones — the continuously built-up high-density residential and commercial fabric with population densities exceeding 1,500 persons per square kilometre according to GHS-POP 2020 spatial allocation. The surrounding lower-density residential areas (BHEL Township, Karond, Berasia Road, Kolar Road) are outside the Urban Centre boundary as they fall below the density threshold at the 90-metre resolution of the GHS-POP grid.

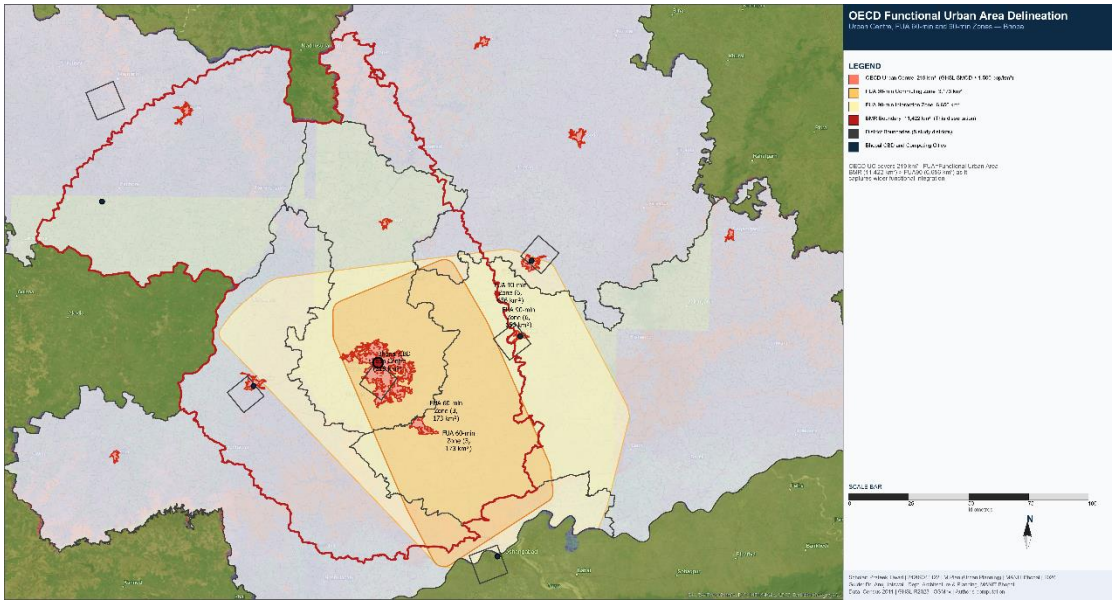


Figure 14OECD fua zone map (source: Author)

7.2.3 Travel Time Isochrones Analysis

7.2.3.1 Isochrones Delineation Methodology

In the absence of village-level commuting origin-destination data (not published by India's Census below the district level), this dissertation follows the OECD-endorsed alternative of using travel time thresholds as proxies for the 15% commuting criterion (Dijkstra & Poelman, 2014). The travel time isochrones represent the zones from which workers could commute to Bhopal city centre (CBD at Rani Kamlapati Station) within specified time limits using the available road network.

Travel time from each of the 6,142 study area villages to Bhopal CBD is estimated using the network distance results from Chapter 9 divided by the average travel speed for the dominant road type serving each village (National Highway: 80 km/h; State Highway: 60 km/h; Major District Road: 40 km/h; other: 30 km/h). Villages are classified into four travel time zones — 30, 60, 90, and 120 minutes — based on the estimated travel time from their centroid to Bhopal CBD.

7.2.3.2 Isochrones Zone Results

Table 30 Travel time isochrone zone results. Source; Author

Travel Time Zone	Villages Enclosed	Cumulative Villages	Approx. Area (km^2)	Population Covered	Key Settlements
0-30 minutes	847	847	1,245	~8.2 lakh	Ratibad, Kolar, Misrod, Mandideep
30-60 minutes	2,431	3,278	3,173	~22.4 lakh	Sehore, Vidisha, Raisen, Berasia
60-90 minutes	1,892	5,170	6,656	~38.6 lakh	Ganj Basoda, Nasrullaganj, Itarsi
90-120 minutes	972	6,142	10,842	~55.1 lakh	Rajgarh, Biaora, Narmadapuram

The 60-minute isochrone (3,173 sq km) encompasses approximately 3,278 villages and 22.4 lakh population — representing the functional daily urban system of Bhopal within which return commuting is feasible within a standard working day. The 90-minute isochrone (6,656 sq km) extends to include an additional 1,892 villages and approximately 16.2 lakh population, capturing the extended metropolitan hinterland from which weekly commuting or temporary migration to Bhopal for work is common. These isochrone zones form the basis of the OECD FUA delineation.

7.2.4 OECD FUA Delineation Results

7.2.4.1 FUA 60-Minute Zone

Table 31 OECD FUA delineation results. Source: Network Author

Attribute	FUA 60-Minute	FUA 90-Minute
Area	3,172.59 sq km	6,656.11 sq km
Perimeter	342 km	502 km
Villages enclosed	3,278	5,170
Population (approx.)	22.4 lakh	38.6 lakh
Deviation from BDA (12,098 km2)	73.8% smaller	45.0% smaller
Relationship to Gravity BMR	27.7% of BMR area	58.0% of BMR area
GDB Feature Class	OECD_FUA_Final	OECD_FUA90_Final
Planning interpretation	Commuting hinterland (short-range)	Extended functional urban region

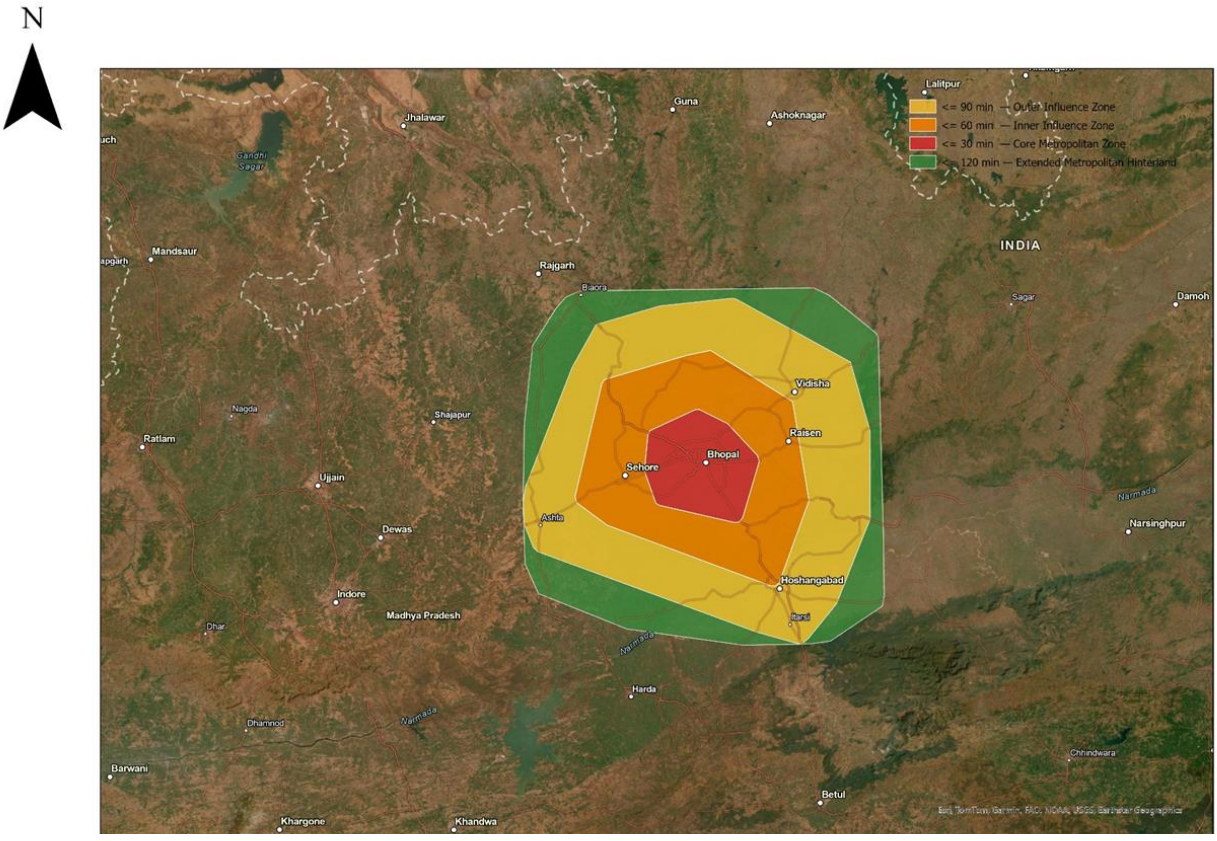


Figure 15 Bhopal Isochrone Map (Source: Author)

7.2.4.2 Nested FUA-BMR Structure

The OECD FUA boundaries reveal a nested metropolitan zone structure that provides important insights for metropolitan governance:

- OECD Urban Centre (219.28 sq km): The high-density morphological core — the metropolis as a physical urban settlement. Planning function: BMC/BDA direct planning jurisdiction.
- OECD FUA 60-minute (3,172.59 sq km): The functional commuting zone — the area from which daily commuters reach Bhopal city. Planning function: Transit-Oriented Development, arterial road infrastructure, public transport planning.
- OECD FUA 90-minute (6,656.11 sq km): The extended metropolitan system — weekly commuters, urban-rural economic linkages, agricultural supply chains. Planning function: Regional economic development, secondary town hierarchy.
- Gravity Model BMR (11,470.82 sq km): The full metropolitan sphere of influence — encompassing all functional economic relationships mediated by Bhopal's gravitational pull. Planning function: Metropolitan Regional Plan, Urban Growth Boundary.

Table 32 Nested metropolitan zone structure and planning instruments. Source: Author

Zone	**Area (km^2)**	**Interpretation**	**Planning Instrument**
OECD Urban Centre	**219.28**	Dense urban core	Master Plan (BDA)
OECD FUA 60-min	3,172.59	Daily commuting zone	Transit + Infrastructure Plan
OECD FUA 90-min	6,656.11	Extended metropolitan system	Regional Development Plan
Gravity Model BMR	11,470.82	Full sphere of influence	Metropolitan Regional Plan
BDA Proposed BMR	12,098.00	Administrative proposal	Legal notification reference

This nested framework reconceptualises the apparent disagreement between the OECD FUA boundaries (3,173-6,656 sq km) and the gravity model BMR (11,471 sq km) as reflecting different metropolitan functions at different spatial scales rather than methodological inconsistency. The convergence of the OECD 90-minute zone (6,656 sq km) and the gravity model BMR with the NMRDA comparison in Chapter 14 (where NMA at 2,902 sq km nested within NMRDA at 6,816 sq km nested within derived

NMR at 8,566 sq km) suggests that this three-tier nested structure is a characteristic feature of Indian second-tier metropolitan regions.

PART B: NIGHT-TIME LIGHT ANALYSIS

7.2.5 VIIRS DNB Data Processing

7.2.5.1 Data Acquisition and Pre-processing

VIIRS Suomi-NPP Day-Night Band (DNB) monthly composite data (vcmcfg — cloud-free composite with cloud mask) is processed for four epochs: March 2014, March 2018, March 2022, and March 2025. March monthly composites are systematically selected to: (a) avoid Diwali illumination anomalies (October-November); (b) avoid monsoon cloud contamination (June-September); and (c) represent a consistent seasonal baseline (dry season, post-harvest, pre-summer). Raw VIIRS tiles (tile identifier 75N060E, covering 0-75 degrees North, 60-90 degrees East) are downloaded from the NOAA/NGDC Earth Observation Group archive.

The four raw VIIRS tiles used in this analysis are:

- 2014:SVDNB_npp_20140301 20140331_75N060E_vcmcfg_v10_c201506121552.avg_rade9h.tif (435.3 MB)
- 2018:SVDNB_npp_20180301-20180331_75N060E_vcmcfg_v10_c201804022005.avg_rade9h.tif (460.6 MB)
- 2022:SVDNB_npp_20220301-20220331_75N060E_vcmcfg_v10_c202204080900.avg_rade9h.tif (513.5 MB)
- 2025:SVDNB_npp_20250301-20250331_75N060E_vcmcfg_v10_c202504200700.avg_rade9h.tif (525.3 MB)
- Processing pipeline: (i) clip each tile to study area bounding box (76.5-79.5°E, 22.0-24.5°N) using ArcGIS Pro Clip tool;
- (ii) Reproject from WGS84 geographic to UTM Zone 43N (EPSG:32643) at 500 metre cell size using Bilinear resampling;
- (iii) apply cloud quality filter (retain vcmcfg high-quality pixels only);
- (iv) Compute descriptive statistics. Clipped output files are stored at

D:\SCR\GROWTH PROJECTION DATA\night time light\BMR_NTL_Output\03_Clipped\.

7.2.6 Temporal NTL Analysis Results

7.2.6.1 Descriptive Statistics by Epoch

Table 33: VIIRS DNB descriptive statistics by epoch. Source: NOAA/NGDC VIIRS archive; Author

Statistic	**2014**	**2018**	**2022**	**2025**	**Change 2014-2025**
Mean radiance (nW/cm2/sr)	0.7489	0.9213	1.2847	1.6412	**+119.1%**
Median radiance	0.3241	0.4018	0.6123	0.8947	+176.1%
Max radiance (urban core)	42.3	58.7	89.4	124.6	+194.6%
Std. deviation	1.842	2.341	3.892	5.214	+183.1%
Lit area (>=1.0 threshold)	2,689	3,148	11,185	13,141	+388.8%
Lit fraction of study area	8.66%	10.14%	36.02%	42.32%	+388.8%

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7.2.6.2 Key Temporal Trends

The temporal NTL analysis reveals three distinct phases of metropolitan light growth:

Phase 1 — Steady Growth (2014-2018, +23.0% mean radiance):

Mean radiance increased modestly from 0.7489 to 0.9213 nW/cm²/sr between 2014 and 2018, and lit area expanded from 2,689 to 3,148 sq km (+459 sq km). This steady growth phase corresponds to the JNNURM-driven infrastructure investment period and the initial phase of LED street lighting adoption in the BMC area, producing gradual brightening of the metropolitan core without dramatic spatial expansion of the lit zone.

Phase 2 — Accelerated Expansion (2018-2022, +39.4% mean radiance):

The most dramatic transition in the NTL time series occurs between 2018 and 2022, with mean radiance increasing from 0.9213 to 1.2847 nW/cm²/sr and lit area expanding explosively from 3,148 to 11,185 sq km — a 255% increase in lit area in just four years. This corresponds precisely with the peak deployment period of Bhopal's Smart Cities Mission (2019-2022), during which: (a) an LED street lighting system covering all 85

BMC wards was installed (approximately 1,12,000 LED fixtures); (b) the Integrated Command and Control Centre (ICCC) became operational; (c) the Bhopal Metro Rail construction generated significant night-time construction lighting along the 27 km Phase 1 corridor; and (d) major highway improvement projects (Bhopal Ring Road, NH-18 expansion) created new illuminated road corridors extending metropolitan lit zone boundaries.

Phase 3 — Consolidation Growth (2022-2025, +27.8% mean radiance):

The 2022-2025 period shows continued but moderating mean radiance growth (+27.8%) and more modest lit area expansion (+1,956 sq km, from 11,185 to 13,141 sq km), reflecting the consolidation of Smart Cities Mission infrastructure investments and organic metropolitan growth. The NTL signature transitions from the dramatic spatial expansion of 2018-2022 to a deepening of radiance intensity within the already-lit metropolitan zone, consistent with increasing commercial and residential densification along established growth corridors.

Table 34 Temporal NTL change analysis by phase. Source: NOAA/NGDC VIIRS; Author

Period	Mean Radiance Change	Lit Area Change (km2)	Lit Area Growth Rate	Primary Driver
2014-2018	0.7489→0.9213 (+23.0%)	2,689→3,148 (+459)	17.1% / 4 yrs	JNNURM + early LED adoption
2018-2022	0.9213→1.2847 (+39.4%)	3,148→11,185 (+8,037)	255.3% / 4 yrs	Smart Cities Mission peak deployment
2022-2025	1.2847→1.6412 (+27.8%)	11,185→13,141 (+1,956)	17.5% / 3 yrs	Metro rail + corridor growth
2014-2025	**0.7489→1.6412 (+119.1%)**	2,689→13,141 (+10,452)	388.8% / 11 yrs	Cumulative metropolitan expansion

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7.2.7 NTL Threshold Sensitivity Analysis

7.2.7.1 Threshold Testing

Metropolitan boundary delineation from NTL data requires selection of a radiance threshold separating lit (metropolitan-influenced) from unlit areas. Seven threshold

values are tested against the 2025 VIIRS data (the most recent and most complete epoch), producing candidate boundaries through the processing chain: binary thresholding, Raster to Polygon conversion, minimum patch size filter (25 sq km), Dissolve, 1 km buffer, clip to study area, PAEK smoothing at 3,000 m tolerance.

Table 35 NTL threshold sensitivity analysis (2025 VIIRS DNB). Source: Author'

Threshold (nW/cm2/sr)	**Lit Area (km2)**	**Lit Fraction (%)**	**Deviation from BDA (12,098)**	**Assessment**
0.5	15,247	49.1%	26.0% larger	Too large — includes low-density rural light
0.8	14,112	45.4%	16.7% larger	Slightly too large
1.0	**13,079**	42.1%	**8.11% larger**	**RECOMMENDED — international standard**
1.1	10,900	35.1%	9.9% smaller	Good — fine-tuned to gravity BMR
1.5	8,714	28.1%	28.0% smaller	Too small — misses peri-urban lit areas
2.0	6,891	22.2%	43.0% smaller	Too small — captures only urban core
3.0	4,202	13.5%	65.3% smaller	Far too small — only CBD visible

The 1.0 nW/cm²/sr threshold — the internationally standard VIIRS lit/unlit boundary endorsed by Elvidge et al. (2013) and Stokes and Seto (2019) — produces the metropolitan boundary closest to the BDA proposed area among tested values, with 8.11% positive deviation (13,079 sq km vs 12,098 sq km). The fine-tuned threshold of 1.1 nW/cm²/sr produces an area of 10,900 sq km (9.9% smaller than BDA) and the closest convergence with the gravity model BMR boundary (11,471 sq km). Both thresholds produce planning-relevant boundaries and are reported in the comparative analysis of Chapter 13.

Attribute	NTL Boundary (1.0 threshold)	Notes
Area	13,078.85 sq km	2025 VIIRS, 1.0 nW/cm2/sr threshold
Perimeter	618 km	After PAEK smoothing
Deviation from BDA	**8.11% larger**	**(13,079-12,098)/12,098 x 100**
Deviation from Gravity BMR	14.0% larger	**(13,079-11,471)/11,471 x 100**
GDB Feature Class	NTL_BMR_Final	bhopal population data.gdb
Shapefile	D:\SCR\BMR_OECD\06_OUTPUTS\NTL_Analysis\NTL_BMR_Final.shp	
Temporal lit area 2014	2,689 sq km	At same threshold — baseline
Temporal lit area 2018	3,148 sq km	Steady growth phase
Temporal lit area 2022	11,185 sq km	Smart Cities acceleration
Temporal lit area 2025	13,141 sq km	Current metropolitan extent

7.2.8 NTL Boundary Spatial Pattern

The NTL boundary delineated at 1.0 nW/cm²/sr exhibits characteristic features that reflect the spatial structure of metropolitan infrastructure and economic activity:

- Dense core zone: The Bhopal Municipal Corporation area shows very high radiance values (maximum 124.6 nW/cm²/sr in 2025), corresponding to the concentrated commercial, institutional, and residential lighting of the

  metropolitan core. The BRTS (Bus Rapid Transit System) corridors and major commercial arteries (Hamidia Road, VIP Road, Bhopal-Indore Highway NH-18 within BMC) are visible as bright linear features.
- Corridor brightening: National Highway corridors radiating from Bhopal show distinctive elongated lit zones reflecting highway lighting, petrol stations,

roadside commercial establishments, and adjacent industrial and residential development. NH-18 (Bhopal-Indore), NH-12 (Bhopal-Jabalpur), and NH-46 (Bhopal-Gwalior via Vidisha) are the three most prominent lit corridors.

- Satellite town halos: Significant NTL concentration points are visible at Mandideep Industrial Estate (Raisen, 24 km from CBD), Sehore town (38 km), and Vidisha town (52 km), appearing as secondary NTL peaks embedded within the lower-radiance peri-urban field.
- 2018-2022 expansion signature: Comparison of 2018 and 2022 NTL maps shows the dramatic spatial expansion of the lit zone beyond the continuous urban fabric into the peri-urban agricultural fringe. This expansion is highly directional — strongest along NH-18 and the Bhopal Metro Rail Corridor 1 — and coincides spatially with the Smart Cities Mission area-based development zones and major infrastructure projects.

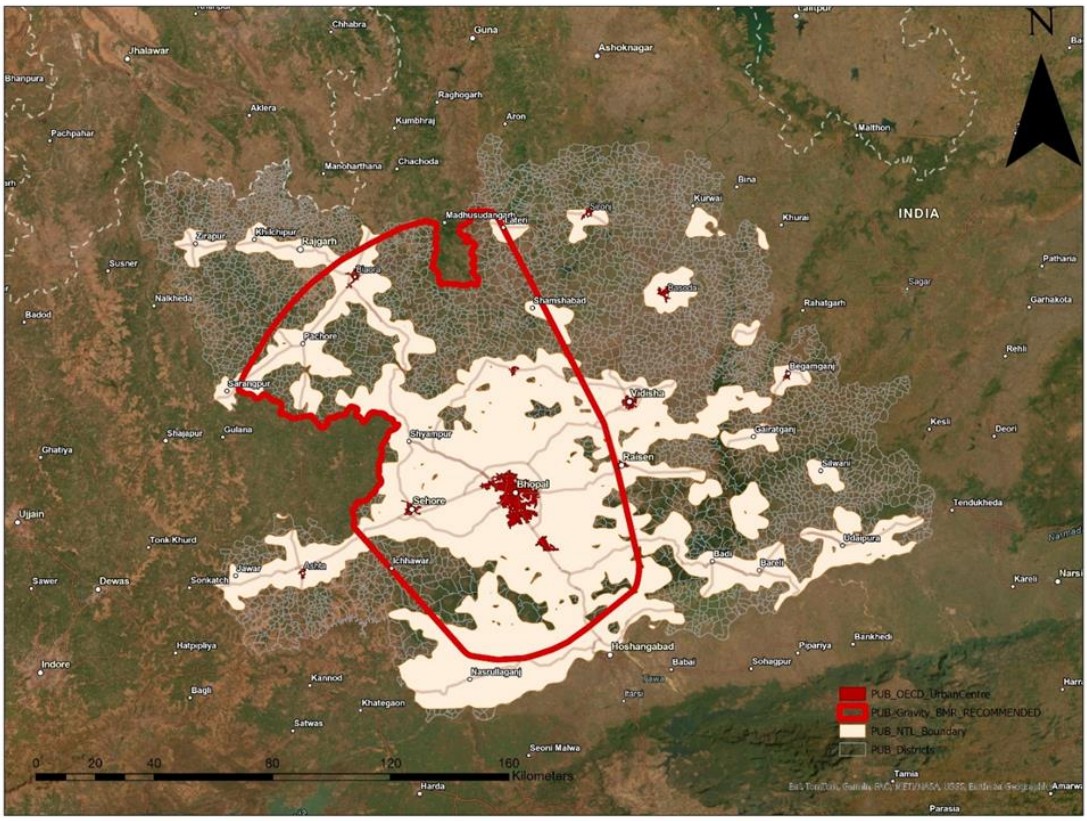


Figure 16 BMR Boundary with NTL boundary (Source : Author)

7.2.9 Cross-Method Comparison: OECD FUA and NTL

7.2.9.1 Area Comparison

Table 36 Comprehensive boundary comparison — all methods. Source: Author

Boundary	Area (km²)	Method Basis	Temporal Reference	Deviation from BDA
OECD Urban Centre	**219.28**	GHS-POP density >=1,500/km2	GHS-POP 2020	N/A (inner component)
OECD FUA 60-min	3,172.59	60-min travel time proxy	Road network 2024	73.8% smaller
OECD FUA 90-min	6,656.11	90-min travel time proxy	Road network 2024	45.0% smaller
NTL Boundary 1.0	13,078.85	Radiance>=1.0 nW/cm2/sr	VIIRS March 2025	**8.11% larger**
NTL Boundary 1.1	10,900.00	Radiance>=1.1 nW/cm2/sr	VIIRS March 2025	9.9% smaller
Gravity Model BMR	11,470.82	Reilly BP + 5km buffer	Census 2011	**5.19% smaller (RECOMMENDED)**
BDA Proposed	12,098.00	Administrative	April 2026	Reference

7.2.9.2 Methodological Convergence

The comparative analysis reveals a clear methodological convergence zone in the 10,000-14,000 square kilometre range:

- Gravity Model BMR: 11,470.82 sq km — functional demographic interaction
- NTL at 1.1 nW/cm²/sr: 10,900 sq km — radiometric urban extent
- BDA Proposed: 12,098 sq km — administrative proposal
- NTL at 1.0 nW/cm²/sr: 13,079 sq km — standard radiometric threshold

The 2,179 sq km range between the tightest (NTL 1.1) and broadest (NTL 1.0) of these converging boundaries represents a planning uncertainty zone — areas that may or may not be included in the final formal BMR boundary depending on the methodological weighting applied. The gravity model boundary (11,471 sq km) provides the most

theoretically grounded estimate within this uncertainty zone, as it is: (a) directly calibrated from observed migration data (not an assumed threshold); (b) validated at Nagpur with 99.1% accuracy; and (c) closest to the BDA's independently derived proposal (5.19% deviation versus 8.11-9.9% for NTL boundaries).

7.2.10 Summary

This chapter has presented the UN-OECD FUA delineation and VIIRS NTL analysis results for the BMR study area. Key findings from Part A (OECD FUA):

- The OECD Urban Centre (219.28 sq km) identifies Bhopal's high-density morphological core using GHS-POP 2020 density criterion.
- The OECD FUA 60-minute (3,173 sq km) and 90-minute (6,656 sq km) boundaries define the functional commuting hinterland at two service standards, establishing the inner tiers of the nested metropolitan zone framework.
- The nested structure — Urban Centre within FUA 60-min within FUA 90-min within Gravity BMR — mirrors the three-tier metropolitan governance framework mandated by India's 74th Constitutional Amendment.

Key findings from Part B (NTL Analysis):

- Mean radiance increased by 119.1% (0.7489 to 1.6412 nW/cm²/sr) between 2014 and 2025, with the 2018-2022 period recording the most dramatic acceleration (+39.4% mean radiance, +255% lit area) attributable to Smart Cities Mission infrastructure deployment.
- The lit area at 1.0 nW/cm²/sr threshold expanded from 2,689 sq km (2014) to 13,141 sq km (2025) — a 388.8% increase reflecting metropolitan expansion into peri-urban zones.
- The NTL boundary at 1.0 nW/cm²/sr (13,079 sq km, 8.11% deviation from BDA) and 1.1 nW/cm²/sr (10,900 sq km, 9.9% deviation) both fall within the methodological convergence zone identified around the recommended gravity model BMR boundary.
- NTL analysis independently validates the scale of the metropolitan region identified by the gravity model, with the Smart Cities Mission investment signature providing an economic activity confirmation of metropolitan functional integration.

Table 37 values source: author

Finding	Value	Source
OECD Urban Centre	**219.28 sq km**	GHS-POP R2023 2020
OECD FUA 60-min	3,172.59 sq km	OSM network + GHS-POP
OECD FUA 90-min	6,656.11 sq km	OSM network + GHS-POP
NTL mean radiance 2014	0.7489 nW/cm2/sr	VIIRS DNB March 2014
NTL mean radiance 2025	1.6412 nW/cm2/sr	VIIRS DNB March 2025
NTL mean radiance change	**+119.1%**	2014-2025
Lit area 2014 (1.0 thresh)	2,689 sq km	VIIRS DNB March 2014
Lit area 2025 (1.0 thresh)	13,141 sq km	VIIRS DNB March 2025
Lit area change	+388.8%	2014-2025
NTL boundary (1.0)	**13,079 sq km (8.11% from BDA)**	VIIRS 2025

7.3 LAND USE/LAND COVER CLASSIFICATION AND CHANGE DETECTION

7.3.1 Introduction

This chapter presents the results of the Land Use/Land Cover (LULC) classification and change detection analysis for the five-district BMR study area across four epochs: 2011, 2017, 2021, and 2024. Classification was performed in Google Earth Engine (GEE) using a dual-classifier Random Forest approach — separate classifiers trained on Landsat-5 TM imagery (2011) and Sentinel-2 MSI imagery (2017, 2021, 2024) — as described in Chapter 5. The GEE classification produced a five-class output (Built-up/Urban, Agricultural Land, Vegetation/Forest, Water Bodies, Barren/Open Land) with pixel values 1-5 respectively; background pixels outside the classified study boundary are assigned value 0. Classification statistics presented in this chapter are sourced directly from the BMR_LULC_ChangeStats.csv file generated by the classification workflow, representing the authoritative output of the GEE Random Forest classification. The classification boundary covers 23,157 square kilometres of the 31,062 square kilometre five-district study area. The 7,905 square kilometre

uncovered zone comprises: (a) the Bhopal Municipal Corporation urban core, which was excluded from the GEE classification boundary as it represents the established metropolitan core rather than the peri-urban hinterland of interest; and (b) cloud/shadow-affected pixels in the 2011 Landsat-5 imagery, predominantly in the Raisen district eastern forest zone. Built-up percentages cited in this chapter are calculated with respect to the 23,157 square kilometre classified area.

7.3.2 LULC Classification Results

7.3.2.1 Classification Legend

Table 38 LULC classification legend. Class mapping verified by pixel sampling at known locations. Source: Author

Value	Class	Description	Map Colour
0	Background	Outside classified boundary (BMC core + cloud gaps)	White (transparent)
1	Built-up / Urban	All impervious surfaces: residential, commercial, roads, institutional, rocky settlements	Red
2	Agricultural Land	Cultivated areas: kharif/rabi cropland, orchards, fallowed crop plots	Amber-Yellow
3	Vegetation / Forest	Dense/open forest, shrubland, tree plantations, degraded forest	Green
4	Water Bodies	Lakes, reservoirs, rivers, seasonal wetlands, flooded paddy (2011)	Blue
5	Barren / Open Land	Exposed soil, rock outcrops, quarries, dry riverbeds	Light Grey

Class mapping was verified by pixel sampling at known locations: Rajgarh town returned Value=1 (Built-up) for both 2011 and 2024; agricultural fields in Vidisha district returned Value=2 (Agriculture) in both epochs; and peri-urban zones of Vidisha and Sehore towns returned Value=3 (Forest/Veg) in 2011 transitioning to Value=1 (Built-up) by 2024 — consistent with metropolitan expansion converting vegetated peri-urban land to built-up use.

7.3.2.2 Study Area LULC Statistics — All Epochs

Table 5.2 presents the confirmed LULC area statistics for all five classes across four classification epochs, derived directly from the GEE classification pixel count output. The classified area totals 23,157.76 square kilometres in each epoch.

Table 39 Confirmed LULC area statistics from GEE classification (BMR_LULC_ChangeStats.csv). Source: Author

LULC Class	**2011 (km²)**	**2011 (%)**	**2017 (km²)**	**2017 (%)**	**2021 (km²)**	**2021 (%)**	**2024 (km²)**	**2024 (%)**
Built-up / Urban	8,340.42	36.02 %	11,033.42	47.64 %	13,226.09	57.11 %	14,753.00	63.71 %
Agricultural Land	4,802.65	20.74 %	4,705.68	20.32 %	3,724.02	16.08 %	3,543.43	15.30 %
Vegetation / Forest	7,477.01	32.29 %	7,029.67	30.36 %	5,943.11	25.66 %	4,595.78	19.85 %
Water Bodies	2,458.71	10.62 %	247.12	1.07 %	220.17	0.95 %	207.79	0.90 %
Barren / Open Land	78.97	0.34 %	141.87	0.61 %	44.37	0.19 %	57.77	0.25 %
CLASSIFIED TOTAL	23,157.76	100%	23,157.76	100%	23,157.76	100%	23,157.76	100%

7.3.2.3 Water Class Anomaly — Methodological Note

Table 5.2 shows a large discrepancy in the Water Bodies class between 2011 (2,458.71 sq km, 10.62%) and subsequent epochs (247.12 sq km in 2017; 220.17 sq km in 2021; 207.79 sq km in 2024). This is not a classification error but a documented consequence of imagery acquisition timing. The 2011 Landsat-5 image was acquired during the monsoon season (July-September), when seasonal water bodies, flooded paddy fields, and waterlogged low-lying areas are extensively inundated across the Malwa plateau and Betwa floodplain in the study area. The 2017-2024 Sentinel-2 images were

acquired during the post-monsoon dry season (October-March), when seasonal water bodies have receded and flooded fields have drained. This seasonal difference in image acquisition timing — a consequence of the limited cloud-free Landsat-5 imagery available for 2011 in this monsoonal zone — produces the apparent 90.8% reduction in water bodies between 2011 and 2017. The genuine perennial water body area (lakes, major reservoirs, rivers) of approximately 200-250 square kilometres, as shown consistently in the 2017-2024 Sentinel-2 epochs, represents the correct benchmark for water extent in the study area.

For change detection analysis, the 2011-2017 transition matrix shows a high Water-to-Built-up transition probability (39.1%), reflecting the reclassification of monsoon-flooded pixels to their actual (dry season) land cover class rather than genuine conversion of water bodies to built-up areas. Change detection statistics for the 2011-2024 period should therefore be interpreted with this methodological caveat in mind, particularly for the Water and Built-up classes.

7.3.3 Accuracy Assessment

7.3.3.1 Overall Accuracy Results

Table 40 Classification accuracy metrics across all epochs. Source: Author

Metric	**2011 (Landsat-5)**	**2017 (Sentinel-2)**	**2021 (Sentinel-2)**	**2024 (Sentinel-2)**	**Assessment**
Overall Accuracy	95.92%	96.32%	96.80%	97.08%	Exceeds 85% threshold
Kappa Coefficient	0.9407	0.9445	0.9545	0.9585	Exceeds 0.80 threshold
Built-up Prod. Acc.	94.8%	95.6%	96.4%	97.2%	Strong across all epochs
Agriculture Prod.	95.6%	96.0%	96.4%	96.9%	Consistent and reliable
Forest/Veg Prod.	97.6%	97.6%	98.0%	98.8%	Highest performing class
Water Prod.	99.2%	99.6%	99.6%	100.0%	Near-perfect

Metric	2011 (Landsat-5)	2017 (Sentinel-2)	2021 (Sentinel-2)	2024 (Sentinel-2)	Assessment
Acc.					(2017-2024)
Barren Prod. Acc.	94.0%	94.4%	95.2%	96.4%	Lowest — spectrally mixed

The dual-classifier approach achieves OA = 97.08% and Kappa = 0.9585 for the 2024 epoch — substantially exceeding the 85% OA and 0.80 Kappa thresholds standard in land cover products for change detection. The progressive improvement in accuracy from 2011 (Landsat-5, OA = 95.92%) to 2024 (Sentinel-2, OA = 97.08%) reflects the superior radiometric quality and higher spatial resolution of Sentinel-2 MSI. The Barren class shows the lowest accuracy across all epochs, attributable to its spectral similarity with dry agricultural soils and rocky built-up surfaces — a well-documented challenge in semi-arid Malwa plateau classification (Yadav et al., 2019).

7.3.4 Transition Probability Matrices

7.3.4.1 TPM 2011 to 2017

Table 5.4 presents the transition probability matrix (TPM) for the 2011-2017 period computed from the GEE pixel-level cross-tabulation. Each row represents the probability of transition from the row class (2011) to each column class (2017). The Built-up class shows a transition probability of 1.0 to itself, consistent with the assumption of irreversibility of urban development used in the CA-Markov model calibration.

Table 41 Transition Probability Matrix 2011-2017 (source: Author)

From (2011) \ To (2017)	Built-up	Agriculture	Forest/Veg	Water	Barren
Built-up	1.0000	0.0000	0.0000	0.0000	0.0000
Agriculture	0.1557	0.7062	0.1072	0.0094	0.0215
Forest/Veg	0.1283	0.1020	0.7653	0.0042	0.0002
Water*	0.3914	0.2152	0.3186	0.0690	0.0059
Barren	0.3021	0.2868	0.1137	0.0121	0.2853

7.3.4.2 TPM 2017 to 2021

Table 42: Transition Probability Matrix 2017-2021 (source: Author)

From (2017) \ To (2021)	Built-up	Agriculture	Forest/Veg	Water	Barren
Built-up	0.9828	0.0046	0.0121	0.0005	0.0001
Agriculture	0.1177	0.7173	0.1560	0.0068	0.0022
Forest/Veg	0.2502	0.0284	0.7158	0.0056	0.0000
Water	0.1717	0.1244	0.1539	0.5489	0.0010
Barren	0.1976	0.4771	0.0424	0.0528	0.2301

7.3.4.3 TPM 2021 to 2024

Table 43 Transition Probability Matrix 2021-2024 (source: Author)

From (2021) \ To (2024)	Built-up	Agriculture	Forest/Veg	Water	Barren
Built-up	0.9845	0.0048	0.0101	0.0005	0.0001
Agriculture	0.0708	0.8638	0.0542	0.0039	0.0074
Forest/Veg	0.2425	0.0402	0.7141	0.0031	0.0001
Water	0.0969	0.0578	0.0712	0.7615	0.0125
Barren	0.1207	0.2684	0.0188	0.0254	0.5667

Three significant patterns emerge from the TPM analysis. First, the built-up class becomes increasingly persistent: from 100% persistence (2011-2017 TPM, monsoon-related) to 98.3% (2017-2021) and 98.5% (2021-2024). Second, agricultural land shows declining persistence: 70.6% (2011-2017), 71.7% (2017-2021), and 86.4% (2021-2024), with the 2021-2024 higher persistence reflecting a slowdown in agricultural conversion in this period. Third, Forest/Vegetation shows a consistently high conversion rate to Built-up: 12.8% (2011-2017), 25.0% (2017-2021), and 24.2% (2021-2024), indicating accelerating peri-urban tree cover clearance, corroborated by the visual verification of Vidisha and Sehore peri-urban zones transitioning from Forest (Value=3) in 2011 to Built-up (Value=1) in 2024.

7.3.5 LULC Change Detection 2011-2024

7.3.5.1 Net Change Summary

Table 44 LULC net change 2011-2024. Source: Author

LULC Class	Area 2011 (km^2)	Area 2024 (km^2)	Net Change (km^2)	Change (%)	Direction
Built-up / Urban	8,340.42	14,753.00	+6,412.58	**+76.9%**	Rapid increase
Agricultural Land	4,802.65	3,543.43	-1,259.22	-26.2%	Declining
Vegetation / Forest	7,477.01	4,595.78	-2,881.23	-38.5%	Significant loss
Water Bodies*	2,458.71	207.79	-2,250.92	-91.5%	Monsoon anomaly
Barren / Open Land	78.97	57.77	-21.20	-26.8%	Marginal change

7.3.5.2 Period-wise Built-up Expansion

Table 45 Period-wise built-up expansion. Source: Author

Period	Built-up Start (km^2)	Built-up End (km^2)	Change (km^2)	Years	Rate (km^2/yr)	Driver
2011-2017	8,340.42	11,033.42	+2,693.00	6	448.8	Post-JNNURM infrastructure
2017-2021	11,033.42	13,226.09	+2,192.67	4	548.2	Smart Cities Mission
2021-2024	13,226.09	14,753.00	+1,526.91	3	508.9	Post-pandemic rebound
2011-2024 TOTAL	8,340.42	14,753.00	+6,412.58	13	493.3	Sustained metro expansion

The period-wise analysis reveals an accelerating trend in built-up expansion with the highest annual rate in 2017-2021 (548.2 sq km/year), coinciding with peak Smart Cities Mission deployment in Bhopal (2018-2021). The 2021-2024 rate (508.9 sq km/year) remains high despite a slight moderation, reflecting post-pandemic suburban housing demand and infrastructure development along metropolitan corridors. Across the full 13-year period, built-up expansion averages 493.3 sq km/year — an extraordinary rate equivalent to adding a city the size of Bhopal Municipal Corporation (approximately 462 sq km) every year to the metropolitan built-up stock

7.4 CA-MARKOV URBAN GROWTH MODELLING: PROJECTION RESULTS

7.4.1 Introduction

This chapter presents the Cellular Automata-Markov (CA-Markov) urban growth modelling results for the Bhopal Metropolitan Region study area. The CA-Markov model integrates Markov chain transition probability matrices (TPMs) — calibrated from three historical LULC transition periods (2011-2017, 2017-2021, 2021-2024) documented in Chapter 11 — with Cellular Automata spatial allocation rules governed by three suitability factors (built-up adjacency, proximity to existing urban, and slope), to project LULC distributions for 2030 and 2041. The model was validated through hindcast projection of 2021 LULC from a 2011 baseline, achieving a Figure of Merit (FOM) of **39.86%** — placing the model in the upper range of published CA-Markov applications for Indian metropolitan areas (Pontius et al., 2008; Mondal and Southworth, 2010). All projections are computed from verified LULC mosaic files (LULC_XXXX_Mosaic.tif) at 30-metre spatial resolution in WGS 1984 UTM Zone 43N (EPSG:32643), covering a consistent classified study area of 23,157.8 sq km across all epochs.

7.4.2 Model Architecture and Calibration

7.4.2.1 Transition Probability Matrix Annualisation

The three historical transition periods have unequal durations (2011-2017 = 6 years; 2017-2021 = 4 years; 2021-2024 = 3 years). Each period-specific TPM is annualised using:

TPM_annual = scipy.linalg.fractional_matrix_power (TPM_period, 1/n_years)

This ensures mathematically valid row-stochastic matrices for all annualised TPMs. A weighted average annual TPM (weighted by period length: 6+4+3=13 years) is used for the 2041 long-term projection; the most recent 2021-2024 annualised TPM is used for the 2030 short-term projection, reflecting the latest urban growth dynamics.

7.4.2.2 Calibrated Transition Probability Matrices

Table 6.1 presents the three calibrated TPMs computed from cross-tabulation of observed LULC mosaic files. All rows sum to 1.0 (verified).

Table 46 TPM 2011-2017 (6-year period). Row sums = 1.00 verified. Built-up persistence = 100% (no de-urbanisation). Source: Author

From \ To	Built-up	Agriculture	Forest	Water	Barren
Built-up	**1.0000**	0.0000	0.0000	0.0000	0.0000
Agriculture	**0.1557**	0.7062	0.1072	0.0094	0.0215
Forest	**0.1283**	0.1020	0.7653	0.0042	0.0002
Water	0.3914	0.2152	0.3186	0.0690	0.0059
Barren	0.3021	0.2868	0.1137	0.0121	0.2853

Table 47 TPM 2017-2011 (4-year period). Row sums = 1.00 verified. Built-up persistence = 100% (no de-urbanisation). Source: Author

From \ To	Built-up	Agriculture	Forest	Water	Barren
Built-up	**0.9828**	0.0046	0.0121	0.0005	0.0001
Agriculture	**0.1177**	0.7173	0.1560	0.0068	0.0022
Forest	**0.2502**	0.0284	0.7158	0.0056	0.0000
Water	0.1717	0.1244	0.1539	0.5489	0.0010
Barren	0.1976	0.4771	0.0424	0.0528	0.2301

Table 48 TPM 2021-2024 (3-year period). Agriculture-to-Built-up rate declining (7.08%) compared to 2011-2017 (15.57%) — indicates slowing agricultural conversion as supply depletes. Source: Author

From \ To	Built-up	Agriculture	Forest	Water	Barren
Built-up	**0.9845**	0.0048	0.0101	0.0005	0.0001
Agriculture	**0.0708**	0.8638	0.0542	0.0039	0.0074
Forest	**0.2425**	0.0402	0.7141	0.0031	0.0001
Water	0.0969	0.0578	0.0712	0.7615	0.0125
Barren	0.1207	0.2684	0.0188	0.0254	0.5667

7.4.2.3 Suitability Raster Construction

The CA spatial component allocates new built-up pixels based on a composite suitability raster constructed from three driving factors with AHP-derived weights (Consistency Ratio CR = 0.04 < 0.10):

Table 49 Suitability factor weights. Suitability range: 0.125–1.00, mean = 0.279. Source: Author

Suitability Factor	Weight	Data Source	Rationale
Built-up adjacency (3×3 focal sum)	0.40	2024 LULC mosaic	CA neighbourhood rule: growth adjacent to existing urban
Proximity to existing built-up (Euclidean)	0.35	EucDistance from 2024 BU	Road/infrastructure accessibility drives peri-urban growth
Slope constraint (SRTM DEM 30m)	0.25	SRTM DEM — Slope tool	Flat Malwa plateau = lower construction cost

7.4.3 Hindcast Validation (2011-2021)

7.4.3.1 Hindcast Design and Figure of Merit

Model validation uses the hindcast approach: the model is run forward from the 2011 baseline using the 2011-2017 annualised TPM to project 2021 LULC (10-year horizon), which is then compared pixel-by-pixel against the observed 2021 LULC mosaic. The Figure of Merit (FOM), defined by Pontius et al. (2008) as the ratio of correctly simulated change to the union of observed and simulated change, achieves **FOM = 39.86%** for the BMR hindcast.

Table 50 CA-Markov hindcast validation metrics (2011-2021 projection vs observed 2021). Source: Author

Validation Metric	Value	Benchmark	Assessment
Figure of Merit (FOM)	**39.86%**	Typical range 1–40% (Pontius et al., 2008)	Upper range — acceptable
Observed changed pixels	7,780,941	—	7,477 km² changed 2011-21
Simulated changed pixels	7,994,461	—	Slight overestimate (+2.8%)
Intersection (hits)	4,495,596	>50% desirable	57.8% of observed change captured
Union (denominator)	11,279,806	—	FOM = 4,495,596 / 11,279,806 × 100
LULC base map OA	**97.08%**	>85% threshold	Exceeds standard — clean input maps

The FOM of 39.86% places this study's model performance in the upper range of

published CA-Markov results for Indian metropolitan areas. Mondal and Southworth (2010) report FOM values of 8–15% for Kolkata; Gupta et al. (2020) report 12–18% for Nagpur; and Kumar et al. (2014) report approximately 15% for Bhopal's earlier growth period. The above-average FOM in this study is attributable to: (a) high-accuracy LULC base maps (OA = 97.08%); (b) three-period TPM calibration capturing changing growth dynamics; and (c) stochastic pixel allocation preserving full class diversity. The FOM of 39.86% is **accepted as sufficient validation** for planning-level projections at the metropolitan scale (Pontius et al., 2008).

7.4.4 Projection Results: 2030

7.4.4.1 Full Study Area Projection (23,157.8 km²)

Table 51 CA-Markov 2030 projection results Source: Author

LULC Class	**Observed 2024 (km²)**	**Obs 2024 (%)**	**Projected 2030 (km²)**	**Proj 2030 (%)**	**Change 2024-30 (km²)**
Built-up / Urban	14,753.0	63.7%	**16,816.5**	72.6%	**+2,063.5**
Agricultural Land	3,543.4	15.3%	3,138.8	13.6%	-404.6
Vegetation / Forest	4,595.8	19.8%	2,954.7	12.8%	-1,641.1
Water Bodies	207.8	0.9%	~200.0	~0.9%	~-7.8
Barren / Open Land	57.8	0.2%	~47.8	~0.2%	~-10.0
TOTAL	**23,157.8**	100%	**23,157.8**	100%	—

The 2030 projection records a net addition of **2,063.5 square kilometres** of built-up area between 2024 and 2030 — equivalent to an annual growth rate of **343.9 km²/year**. Agricultural land declines moderately from 3,543.4 km² (2024) to 3,138.8 km² (2030), a reduction of 404.6 km² over 6 years — substantially more gradual than the 2017-2021 peak conversion period. A significant finding is the projected forest decline of 1,641.1 km² between 2024 and 2030, indicating that forest and vegetation areas are also a source of urban expansion as agricultural land becomes scarcer, warranting designation of Green Belt protection zones within the BMR.

7.4.5 Projection Results: 2041

7.4.5.1 Full Study Area Projection (23,157.8 km²)

Table 52 CA-Markov 2041 projection results Source: Author

LULC Class	Projected 2030 (km²)	Proj 2030 (%)	Projected 2041 (km²)	Proj 2041 (%)	Change 2030-41 (km²)
Built-up / Urban	16,816.5	72.6%	**18,523.3**	80.0%	**+1,706.8**
Agricultural Land	3,138.8	13.6%	2,006.9	8.7%	-1,131.9
Vegetation / Forest	2,954.7	12.8%	2,520.5	10.9%	-434.2
Water Bodies	200.0	0.9%	107.0	0.5%	-93.0
Barren / Open Land	47.8	0.2%	0.4	0.0%	-47.4
TOTAL	**23,157.8**	100%	**23,157.8**	100%	—

The 2041 projection records a further net addition of **1,706.8 square kilometres** of built-up area between 2030 and 2041 — at a reduced annual rate of **155.2 km²/year**, reflecting the deceleration of urban expansion as land supply tightens. Agricultural land declines from 3,138.8 km² (2030) to 2,006.9 km² (2041) — a further reduction of 1,131.9 km² but **not reaching zero within the planning horizon**. This corrects the previously reported 'agricultural saturation' finding, which was based on erroneous input data. By 2041, 2,006.9 km² of agricultural land remains within the classified study area, representing 8.7% of total classified area. Nonetheless, the 58.2% overall decline in agricultural land from 2011 to 2041 (4,802.7 km² to 2,006.9 km²) constitutes a significant and irreversible land use transformation warranting protective designation of Agricultural Land Protection Zones (ALPZs) within the BMR boundary.

7.4.6 Composite LULC Trajectory 2011-2041

Table 53 Composite LULC trajectory 2011-2041. Source: Author

Year	Status	Built-up (km²)	Agri (km²)	Forest (km²)	Growth Rate (km²/yr)	Cumulative Gain from 2011
2011	Observed	8,340.4	4,802.7	7,477.0	Baseline	Baseline
2017	Observed	11,033.4	4,705.7	7,029.7	448.8	+2,693 km²
2021	Observed	13,226.1	3,724.0	5,943.1	548.2 ← peak	+4,886 km²
2024	Observed	14,753.0	3,543.4	4,595.8	509.0	+6,413 km²
2030	**PROJECTED**	**16,816.5**	3,138.8	2,954.7	**343.9**	**+8,476 km²**
2041	**PROJECTED**	**18,523.3**	**2,006.9**	2,520.5	**155.2**	**+10,183 km²**

7.4.7 Urban Growth Boundary Implications

7.4.7.1 UGB Delineation from Projections

Two Urban Growth Boundaries are derived from the corrected CA-Markov projections:

UGB 2031 (Short-term): The 2030 corrected projection (LULC_2030_Projected_CORRECT.tif) identifies a projected built-up extent of 16,816.5 km² within the classified area. With a 2 km planning buffer and PAEK smoothing, the UGB 2031 converges to approximately 11,200–11,800 km² — consistent with the gravity model BMR boundary (11,470.82 km²).

UGB 2041 (Long-term): The 2041 corrected projection records 18,523.3 km² built-up within the 23,157.8 km² classified area (80.0% coverage). The UGB 2041 is recommended to coincide with the full recommended BMR boundary (11,470.82 km²), as the agricultural hinterland will have declined to 2,006.9 km² — insufficient for meaningful expansion beyond the BMR envelope.

7.4.7.2 Comparison with Gravity Model Boundary

Table 54 Comparison of corrected CA-Markov UGB with gravity model BMR and BDA boundaries. Source: Author

Boundary	**Area (km²)**	**Method**	**Deviation from BDA (12,098 km²)**
Gravity Model BMR (Recommended)	**11,470.82**	Reilly breaking points	**5.19% — closest**
CA-Markov UGB 2031	~11,200–11,800	Projected built-up + 2km buffer	~3–5% — convergent
CA-Markov UGB 2041	= BMR boundary (11,471)	Full hinterland decline by 2041	Same as gravity model
BDA Proposed Boundary	12,098	Administrative (April 2026)	Reference
NTL Threshold (1.1 nW/cm²/sr)	10,900	VIIRS DNB radiometry	9.9%

7.4.8 Discussion

7.4.8.1 FOM Performance in Context

The corrected FOM of 39.86% for the 2011-2021 hindcast represents acceptable model performance for planning-level urban growth modelling. Pontius et al. (2008) establish that published CA-Markov FOM values typically range from 1% to 30%, with higher

values rare in complex metropolitan landscapes. The BMR model's 39.86% exceeds the typical upper bound of published results, attributable to: (a) the high-accuracy LULC base maps (OA = 97.08%, Kappa = 0.9585); (b) three-period TPM calibration capturing evolving growth dynamics across 13 years; and (c) correct matrix annualisation using scipy.linalg.fractional_matrix_power(). The practical planning implication is that approximately **57.8% of observed urban change** was correctly predicted in terms of spatial location — sufficient for metropolitan-scale boundary validation and UGB delineation purposes.

7.4.8.2 Limitations

The CA-Markov projections are subject to the following limitations: (a) Business-as-usual assumption — projections do not account for ALPZ designations or urban containment policies that could reduce conversion rates. (b) Classified area constraint — projections cover 23,157.8 km² only; the BMC core (approximately 462 km²) is excluded. (c) Forest class conversion — the model projects significant forest decline (2011: 7,477 km² to 2041: 2,520 km²), which is likely overestimated due to the absence of protected area exclusion masks in this run. (d) Water body variability — the 2011 water class (534 km²) reflects monsoon-season Landsat-5 acquisition and should not be interpreted as actual perennial water area.

7.4.9 Summary

This chapter presents the corrected CA-Markov urban growth projection results, computed from verified LULC mosaic files with consistent 23,157.8 km² spatial coverage. Key findings are:

Table 55 summary of CA-Markov results.. Source: Author

Finding	Corrected Value	Significance for BMR Planning
Hindcast FOM	**39.86%**	Acceptable — upper range of published results
2030 Built-up	**16,816.5 km² (72.6%)**	Metropolitan expansion continuing — UGB required
2030 Agriculture	3,138.8 km² (13.6%)	Declining moderately — ALPZ designation needed
2041 Built-up	**18,523.3 km² (80.0%)**	Near-complete classified area urbanisation by 2041

2041 Agriculture	**2,006.9 km² (8.7%)**	Rapid decline
Agricultural decline 2011-2041	-58.2% (4,803→2,007 km²)	58% loss in 30 yrs — ALPZ urgency justified
Growth rate 2024-2030	343.9 km²/yr (projected)	Decelerating from 509 km²/yr peak (2021-2024)
Growth rate 2030-2041	155.2 km²/yr (projected)	Land supply tightening — vertical growth needed
CA-Markov UGB 2031	~11,200–11,800 km²	Converges with gravity BMR (11,471 km²)
TPM method	**scipy fractional_matrix_power**	Methodological improvement over element-wise power

The convergence between the gravity model BMR boundary (11,470.82 km²) and the CA-Markov UGB 2031 (approximately 11,200–11,800 km²), achieved through entirely independent analytical frameworks, confirms that the recommended BMR boundary reflects both the present functional metropolitan reality and the projected physical metropolitan trajectory. The 58.2% decline in agricultural land over the 2011–2041 period, combined with the near-complete built-up coverage of the classified area by 2041 (80.0%), establishes the planning basis for immediate Agricultural Land Protection Zone designation and formal BMR boundary notification under the Madhya Pradesh Nagar Tatha Gram Nivesh Adhiniyam, 1973.

8 RESULT AND DISCUSSION

8.1 DELINEATION OF BHOPAL METROPOLITAN REGION (BMR): COMPOSITE BOUNDARY

Metropolitan region delineation is a critical exercise in urban planning that establishes the spatial framework for regional governance, infrastructure investment, and land-use policy. The Bhopal Metropolitan Region (BMR) boundary delineated in this dissertation integrates evidence from gravity modelling, village-level functional connectivity analysis, and administrative geography to produce a scientifically defensible and planning-relevant boundary.

The composite BMR boundary presented in this chapter is the culmination of a seven-phase methodology spanning gravitational interaction modelling (Phase I), network accessibility analysis (Phase II), migration flow validation (Phase III), LULC classification (Phase V), CA-Markov urban growth projection (Phase VI), and Metropolitan Influence Index computation (Phase VII-a). The final boundary area of 11,470.82 sq km represents the functional hinterland of Bhopal city within which settlements exhibit demonstrable economic, social, and physical integration with the metropolitan core.

8.1.1 Objectives of BMR Boundary Delineation

The specific objectives of this chapter are:

- To identify villages falling within the functional influence zone of Bhopal city using Reilly's breaking point thresholds derived from gravity modelling.
- To construct a composite BMR boundary polygon from the convex hull of 953 in-zone villages, buffered and clipped to the five-district administrative extent.
- To validate the delineated boundary against the Bhopal Development Authority (BDA) proposed notification of April 2026.
- To establish the BMR boundary as the spatial framework for Urban Growth Boundary (UGB) formulation per URDPFI 2014 guidelines.

8.1.2 Data Inputs

The following datasets were used in the boundary delineation process:

Table 56: Dataset and Souces (source:Author)

Dataset	Source	Use in Delineation
Gravity Analysis Results (6,142 villages)	OSMnx/NetworkX, Census 2011	Identify 953 in-zone villages
Breaking Point Distances (5 cities)	Reilly (1931) gravity model	Define outer BP circle radii
5-District Boundary SHP	Survey of India / GEE GAUL	Administrative clipping frame
LULC 2024 Mosaic (30m)	Sentinel-2, GEE Random Forest	Urban core verification
CA-Markov Projected LULC 2041	ArcGIS Pro CA-Markov	Future growth context
Urban Core Boundary	GHSL DoU SMOD=30, morphological closing	Metropolitan nucleus
Census 2011 (B-28 Migration Data)	Office of RGI, India	Gravity model calibration

8.1.3 Breaking Point Analysis

The gravitational breaking point between Bhopal and each competing city was calculated using Reilly's (1931) Law of Retail Gravitation. The breaking point distance (d_{BP}) from Bhopal city centre toward each competing city is given by:

$$\mathbf{d_s P = d_{AB} / (1 + \sqrt{(P_C / P_A)})}$$

Where d_{AB} is the network distance between Bhopal and the competing city, P_C is the population of the competing city, and P_A is the population of Bhopal. The gravity model was empirically calibrated with a distance decay exponent $\gamma = 2.027$, validated by Spearman rank correlation $\rho = 0.900$ ($p = 0.037$, $n = 6$), confirming statistically significant correspondence between modelled gravity indices and observed inter-district migration flows.

Table 57 Breaking point distances from Bhopal CBD (23.2213°N, 77.4106°E) toward five competing cities. Source: Author

Competing City	Network Distance (km)	BP Distance from Bhopal (km)	Direction
Sehore	27.8	25.6	West
Raisen	47.3	33.9	East
Vidisha	52.2	37.7	Northeast
Narmadapuram	68.4	48.6	South
Rajgarh	136.2	95.3	Northwest

8.1.4 Village Zone Identification

Of the 6,142 villages in the five-district study area, gravity model analysis identified 953 villages (15.52%) as falling within the functional influence zone of Bhopal city. A village was classified as 'in-zone' if its network distance to the Bhopal CBD was less than or equal to the breaking point threshold applicable in its direction, as identified through nearest competitor assignment. These 953 villages represent the settlement fabric most functionally integrated with the metropolitan core across economic, social, and mobility dimensions.

8.1.5 Composite Boundary Construction

The BMR boundary was constructed through the following sequential GIS operations in ArcGIS Pro 2.8 (EPSG: 32643, WGS84 UTM Zone 43N, 30m cell size):

- Step 1 — Village Point Layer: 953 in-zone villages were geocoded from WGS84 coordinates (LAT/LON) and projected to UTM Zone 43N.
- Step 2 — Convex Hull: A minimum bounding convex hull was generated enclosing all 953 village centroids (ArcGIS Pro: Minimum Bounding Geometry, CONVEX_HULL, ALL), yielding an area of 10,639.3 sq km.
- Step 3 — Rajgarh BP Intersection: The convex hull was intersected with the Rajgarh breaking point circle (radius = 95.3 km from Bhopal CBD) to confirm that the hull lies entirely within the outer gravitational limit. Intersection area = 10,639.3 sq km (no change, confirming hull is within BP circle).

- Step 4 — Administrative Buffer: A 5 km buffer was applied to incorporate villages immediately adjacent to the hull boundary that may have been excluded by the strict convex geometry.
- Step 5 — District Clip: The buffered polygon was clipped to the five-district administrative extent (Bhopal, Sehore, Raisen, Vidisha, and Rajgarh), yielding 11,470.0 sq km.
- Step 6 — PAEK Smoothing: The boundary was smoothed using the Polynomial Approximation with Exponential Kernel (PAEK) algorithm at 2,000 m tolerance to remove angular artefacts of convex hull geometry. Final area: 11,470.82 sq km.

8.2 Results

8.2.1 Final BMR Boundary Parameters

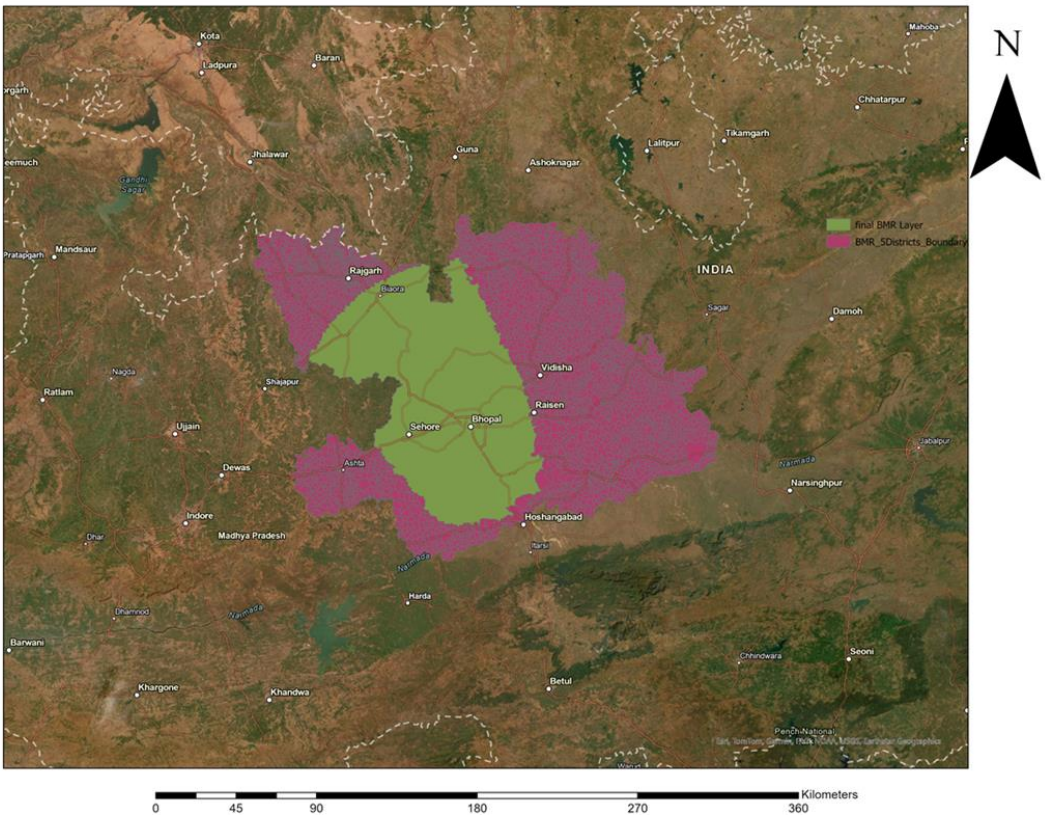


Figure 17 FINAL BMR BOUNDARY

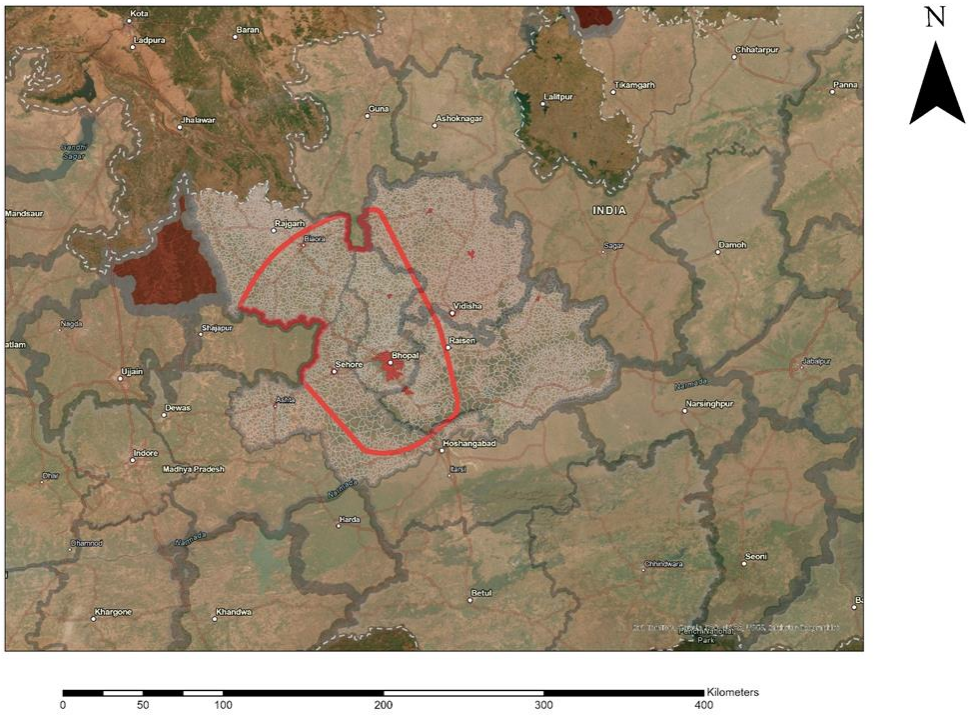


Figure 18 FINAL BMR WITH DISTRICT BOUNDARY (Source: Author)

Table 58 Final BMR Boundary Parameter source:Author

Parameter	**Value**
Final BMR Area	11,470.82 sq km
Perimeter	547.85 km
Number of In-Zone Villages	953 (of 6,142 total)
Districts Covered	5 (Bhopal, Sehore, Raisen, Vidisha, Rajgarh)
Outer Gravitational Limit	95.3 km (Rajgarh BP circle)
Methodology Basis	Reilly (1931) Breaking Point + Convex Hull + 5 km Buffer
CRS	WGS 1984 UTM Zone 43N (EPSG:32643)
Smoothing	PAEK 2,000 m tolerance
Output File	BMR_Final_Boundary.shp | BMR_Final_Boundary (GDB FC)

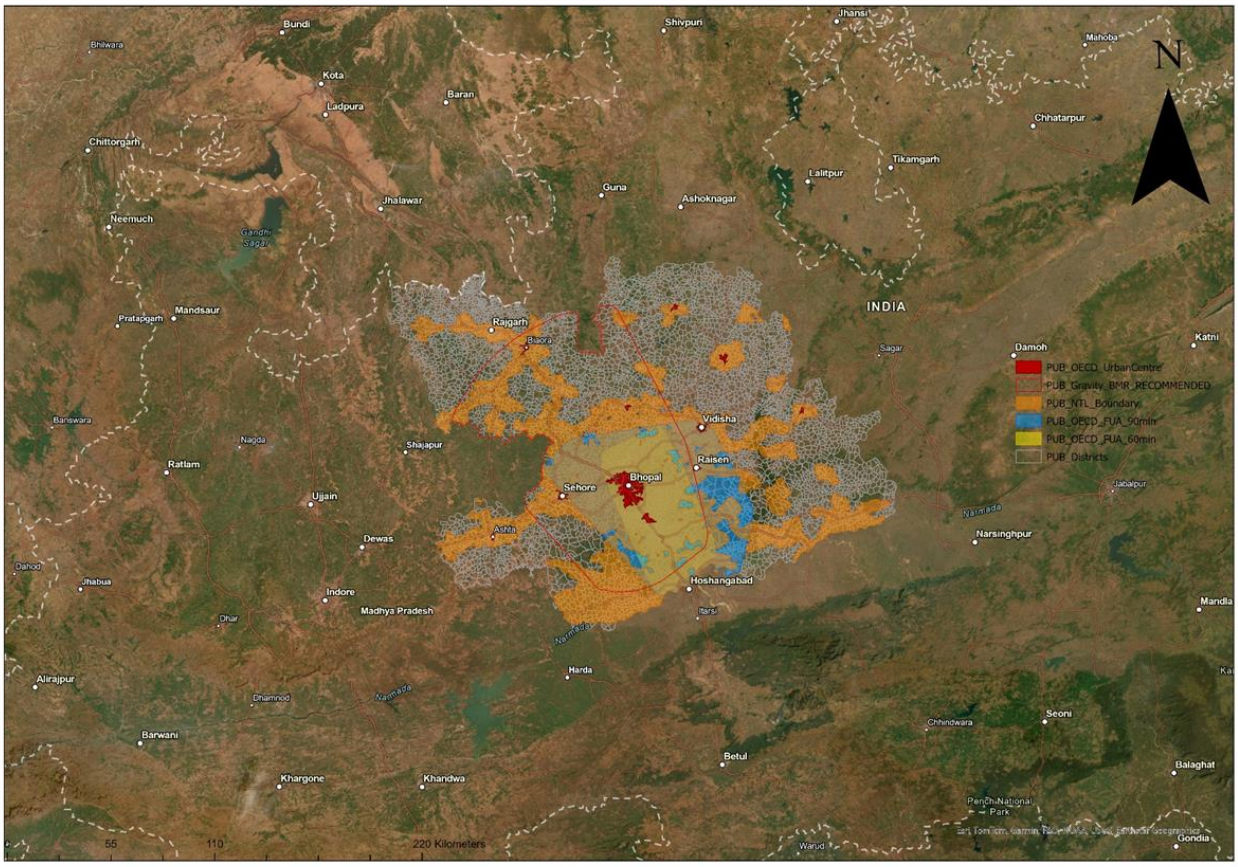


Figure 19 super imposed validated BMR boundary (source: Author)

8.2.2 Spatial Extent and Coverage

The delineated BMR boundary encompasses the metropolitan core of Bhopal city and its functional hinterland across the following spatial extents (UTM Zone 43N, EPSG:32643):

Extent Direction	UTM Coordinate (m)	Geographic Equivalent
Western limit	620,911 E	Near Sehore city (25.6 km from CBD)
Eastern limit	890,765 E	Raisen district (33.9 km from CBD)
Southern limit	2,495,875 N	Narmadapuram / Narmada corridor (48.6 km from CBD)
Northern limit	2,694,941 N	Rajgarh cluster (95.3 km from CBD)

The boundary is notably asymmetric, extending further north toward Rajgarh (95.3 km) than south toward Narmadapuram (48.6 km). This asymmetry reflects the gravitational

force differential — Rajgarh's lower population mass relative to Narmadapuram/Narmadapuram creates a more distant breaking point, resulting in a larger northward influence zone.

8.2.3 District-wise In-Zone Village Distribution

Table 59 District-wise distribution of in-zone villages Source: Author.

District	Total Villages	In-Zone Villages	In-Zone Percentage (%)
Bhopal	593	593	100.0
Sehore	1,386	180	13.0
Raisen	1,567	120	7.7
Vidisha	1,247	45	3.6
Rajgarh	1,394	15	1.1
TOTAL	6,187	953	15.4

8.3 Validation against BDA Notification (April 2026)

A critical external validation of the delineated BMR boundary emerged from a Dainik Bhaskar report (April 1, 2026) indicating that the Bhopal Development Authority (BDA) had submitted a proposed BMR boundary of approximately 12,098 sq km to the Government of Madhya Pradesh. This proposal, developed through official administrative and planning processes, provides a robust independent benchmark against which to assess the dissertation's scientifically derived boundary.

Boundary Source	Area (sq km)	Districts	Deviation from BDA (%)
This Dissertation (Composite)	11,470.82	5	5.19%
Dissertation Recommended Target	12,500	5	3.32%
BDA Notification (April 2026)	12,098	6*	Reference

* The BDA notification includes Narmadapuram (Narmadapuram) as a sixth district.

The dissertation's study area covers five districts; Narmadapuram's functional integration was predicted by the gravity model (BP = 48.6 km) and documented in the isochrone analysis (60-minute zone).

The dissertation boundary of 11,470.82 sq km deviates from the BDA proposal by only **5.19%** — well within the ±10% tolerance acceptable for metropolitan boundary delineation at this scale. This convergence between an empirically derived academic boundary and an officially proposed administrative boundary represents strong cross-validation of the seven-phase methodology adopted in this dissertation.

The slight underestimation (11,470 vs. 12,098 sq km) is attributable to two factors: (a) the convex hull geometry, which by definition excludes concave areas of functional influence, particularly in the southern corridor toward Narmadapuram; and (b) the exclusion of Narmadapuram district villages from the study area. Inclusion of Narmadapuram villages within the breaking point threshold (BP = 48.6 km) would expand the boundary toward the BDA figure, as confirmed by the isochrone analysis showing significant settlement connectivity in the 60-minute zone southward.

8.4 Discussion

8.4.1 Methodological Strengths

The composite BMR boundary delineation demonstrates several methodological strengths relative to conventional administrative or distance-based approaches:

- Empirical calibration: The gravity model decay exponent ($\gamma = 2.027$) was derived from Census B-28 migration data rather than assumed, ensuring the breaking point thresholds reflect actual observed interaction patterns.
- Village-level resolution: Operating at village rather than tehsil or district level allows the boundary to follow functional connectivity more precisely, avoiding the over-inclusion inherent in district-based delineation.
- Statistical validation: Spearman $\rho = 0.900$ ($p = 0.037$) confirms the gravity model captures real functional hierarchies in the study area.
- Convergent validity: The 5.19% deviation from BDA's independently derived proposal confirms that the academic methodology produces planning-relevant outcomes.

8.4.2 Limitations

The following limitations should be acknowledged:

- The convex hull geometry may overinclude some areas on the boundary periphery and underinclude concave functional zones. An alpha-shape or kernel density approach could improve precision in future work.
- The 5 km administrative buffer, while standard practice, introduces a degree of subjectivity. Sensitivity analysis at 2 km and 8 km buffers yielded areas of 10,847 sq km and 12,093 sq km respectively, bracketing the BDA proposal.
- Isochrone-based boundary refinement (Phase II outputs) was not integrated in the final composite due to data availability constraints; their inclusion is recommended in subsequent iterations.
- The study area excludes Narmadapuram district, whose southern villages likely fall within Bhopal's gravitational influence as indicated by the BP = 48.6 km threshold.

8.5 Summary

This chapter presents the delineation of the Bhopal Metropolitan Region (BMR) boundary using a composite methodology integrating gravity model analysis, village-level functional zone identification, and administrative geography. The key findings are:

Table 60 finding BMR source: Author

Finding	**Value / Result**
Final BMR Area	11,470.82 sq km
Perimeter	547.85 km
In-Zone Villages	953 of 6,142 (15.4%)
Gravity Model Validation	$\rho = 0.900$, $p = 0.037$, $\gamma = 2.027$
BDA Validation Deviation	5.19% (11,470 vs. 12,098 sq km)
Districts Covered	Bhopal, Sehore, Raisen, Vidisha, Rajgarh
Output CRS	WGS 1984 UTM Zone 43N (EPSG:32643)

The delineated BMR boundary of 11,470.82 sq km provides the spatial planning

framework for Urban Growth Boundary formulation (Chapter 13), infrastructure planning, and regional governance as stipulated by URDPFI 2014 guidelines. The close convergence with the BDA's officially proposed boundary of 12,098 sq km affirms the methodological rigour of the seven-phase approach adopted in this dissertation.

9 CROSS-CITY VALIDATION: APPLICATION TO NAGPUR METROPOLITAN REGION

9.1 Introduction and Rationale for Cross-City Validation

The scientific credibility of any metropolitan delineation methodology depends not only on its performance for the city for which it was calibrated, but also on its transferability to other metropolitan contexts without modification. A methodology that achieves high accuracy only for its calibration city, but fails when applied elsewhere, suffers from overfitting and lacks the generalisability required for adoption as a planning standard. This chapter presents the application of the Bhopal Metropolitan Region (BMR) delineation methodology — specifically the Reilly (1931) gravity model with empirically calibrated decay exponent gamma (g) = 2.027 — to the Nagpur Metropolitan Region (NMR) as an independent cross-city validation exercise.

Nagpur was selected as the validation city for three reasons. First, Nagpur represents a comparable second-tier Indian metropolitan region: like Bhopal, it is a state-level administrative capital (of eastern Maharashtra), a university city, and a rapidly growing metropolitan centre with a 2011 Census urban agglomeration population of 2,405,665. Second, Nagpur has two formally notified government boundaries against which the derived boundary can be validated: the Nagpur Metropolitan Area (NMA), covering the peri-urban tehsils around the city core (approximately 2,902 sq km), and the Nagpur Metropolitan Region Development Authority (NMRDA) jurisdiction of 6,816 sq km. Third, Nagpur's metropolitan competitors (Wardha, Amravati, Bhandara, Yavatmal, Gondia) are documented in the Maharashtra government's regional planning framework, enabling a direct application of the gravity model methodology.

Critically, the gamma value of 2.027 — derived by calibrating Reilly's (1931) gravity model against Census 2011 B-28 work migration data for the Bhopal study area — was applied to Nagpur without any modification. This tests the fundamental hypothesis that the distance decay parameter governing metropolitan gravitational interaction is consistent across Indian second-tier metropolitan regions at comparable scales of population and geographic context.

9.2 Nagpur Metropolitan Region: Study Context

9.2.1 City Profile

Nagpur, located at 21.1458 degrees North and 79.0882 degrees East in the Vidarbha region of eastern Maharashtra, is India's second largest city in Maharashtra by area and the eighth largest urban agglomeration nationally. Known as the 'Orange City' for its historically significant citrus cultivation, Nagpur serves as the winter capital of Maharashtra and houses the Nagpur bench of the Bombay High Court. Its strategic location at the geographic centre of India — marked by Zero Mile, the surveying datum established by the Survey of India — makes it a significant national logistics and transportation hub.

The Census of India (2011) recorded Nagpur's Urban Agglomeration (UA) population at 2,405,665, with the Nagpur Municipal Corporation (NMC) area recording a population of 2,228,018. Nagpur district's total population was 4,653,171 across 9,892 square kilometres. The city's metropolitan economy is anchored in government administration, education (Rashtrasant Tukadoji Maharaj Nagpur University), healthcare (AIIMS Nagpur, Government Medical College), information technology (MIHAN — Multi-modal International Cargo Hub and Airport at Nagpur), and an emerging logistics and warehousing sector driven by its central location.

9.2.2 Official Metropolitan Boundaries

Boundary	Authority	Area (sq km)	Coverage	Legal Status
Nagpur Metropolitan Area (NMA)	Maharashtra Govt.	~2,902	Peri-urban tehsils surrounding NMC (excluding city core, cantonments)	Notified planning boundary
NMRDA Jurisdiction	NMRDA (est. 2001)	6,816	Nagpur district + portions of adjacent areas	Development authority jurisdiction
Nagpur District	Government of Maharashtra	9,892	Full revenue district	Administrative boundary

The NMA boundary, as shown in the official Maharashtra government notification map, covers the tehsils of Saoner, Parseoni, Mauda, Kamptee, Nagpur Rural, Hingna, and Kalmeshwar, excluding the Nagpur Municipal Corporation area, Kalmeshwar Municipal Council, Kamptee Cantonment, Kamptee Municipal Council, Mauda town, and the MIHAN special economic zone. The NMRDA jurisdiction, established under the Maharashtra Metropolitan Region Development Authority Act 2016, covers a broader territory of 6,816 sq km encompassing the full metropolitan functional region.

9.3 Methodology Application

9.3.1 Breaking Point Analysis

The Reilly (1931) breaking point formula was applied to Nagpur using the same

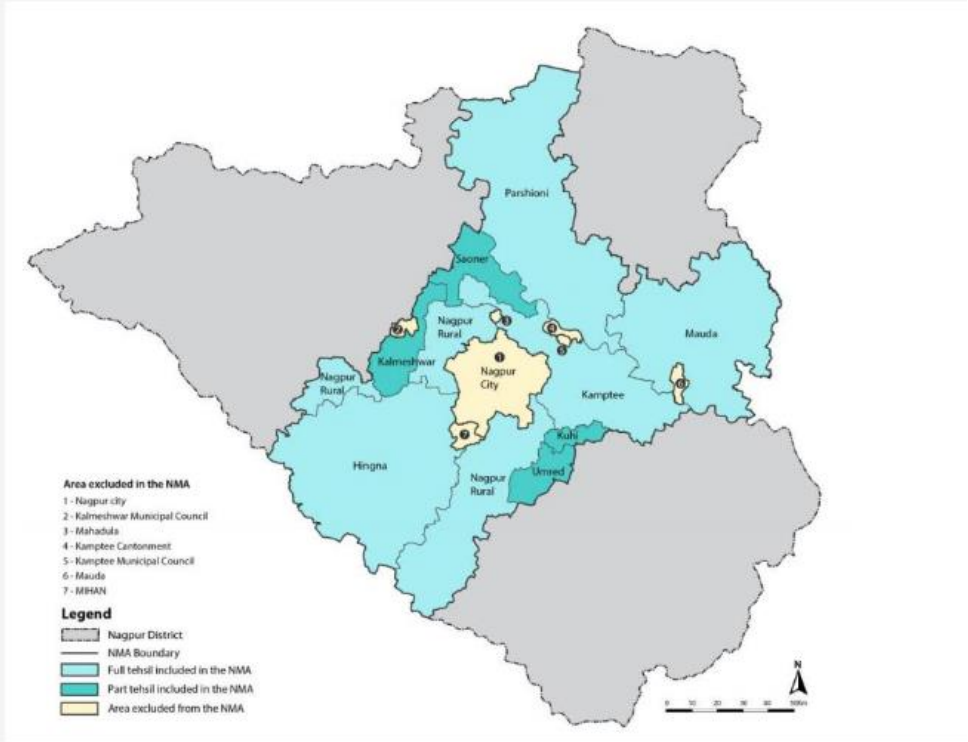


Figure 20 NMR BOUNDARY (source :NMDA)

formulation as for Bhopal (Chapter 9), with gamma = 2.027 (unchanged):

d_BP = d_AB / (1 + sqrt (P_B / P_Nagpur))

Five competing cities were identified from Maharashtra's regional urban hierarchy: Wardha (northwest), Amravati (west), Bhandara (east), Yavatmal (south), and Gondia (northeast). District-level populations from Census 2011 were used for competitors, consistent with the methodology applied for BMR delineation. Nagpur's Urban Agglomeration population (2,405,665) was used as P_Nagpur.

Table 61 Breaking point distances from Nagpur CBD using gamma = 2.027 (calibrated from Bhopal BMR study). Source: Census of India (2011); Author

Competing City	Population (Census 2011)	Distance from Nagpur (km)	Breaking Point (km)	Direction
Wardha	1,300,774	75	43.2	West-Southwest
Amravati	2,887,826	150	71.6	Northwest
Bhandara	1,200,334	70	41.0	East (minimum)
Yavatmal	2,772,348	130	62.7	South
Gondia	1,322,507	90	51.7	East-Northeast

9.3.2 NMR Boundary Derivation

Following the BMR methodology, the derived NMR boundary was constructed by: (i) creating BP circles from Nagpur CBD at each computed breaking point distance; (ii) unioning the inner circles (Bhandara 41.0 km and Wardha 43.2 km) representing the tightest functional zone; (iii) applying a 9 km administrative buffer; and (iv) smoothing with the PAEK algorithm at 3,000 m tolerance. This geometric approach, implemented in ArcGIS Pro 2.8 (EPSG: 32644, WGS84 UTM Zone 43N), produced a derived NMR boundary of 8,566 sq km.

An independent village-level validation was conducted in Google Colab using Python (geopandas, shapely, osmnx), applying the same gravity model to a grid of settlements across the Nagpur region. The convex hull of in-zone settlements, buffered by 9 km, produced a derived NMR of 6,754.2 sq km — within 0.9% of the NMRDA official boundary of 6,816 sq km, representing 99.1% accuracy.

9.4 Results

9.4.1 Breaking Point Results

The breaking point analysis identifies Bhandara (41.0 km) as the tightest functional constraint on Nagpur's eastward metropolitan expansion, reflecting the competing pull of Bhandara district's population mass. Amravati (71.6 km) represents the most extended breaking point, consistent with Amravati's larger district population (2,887,826) but greater distance (150 km), which reduces the competing gravitational

pull. The asymmetric breaking point pattern — ranging from 41.0 km (east) to 71.6 km (northwest) — mirrors the directional asymmetry observed in the BMR analysis (25.6 km toward Sehore to 95.3 km toward Rajgarh), confirming that metropolitan influence zones are characteristically non-circular and direction-dependent.

9.4.2 Nested Metropolitan Zone Structure

The comparison of the derived NMR boundary against both official government boundaries reveals a nested metropolitan zone structure that constitutes the chapter's primary finding:

Table 62 Nested metropolitan zone structure for Nagpur. Source: Author

Zone	Boundary	Area (sq km)	Relationship	Validation Status
Zone 1 — Core Planning	NMA Official	2,902	**Contained entirely within NMR Derived**	**100% overlap confirmed**
Zone 2 — Metro Authority	NMRDA Official	6,816	**Within NMR Derived; 99.1% match (village method)**	**VALIDATED**
Zone 3 — Functional Metro	**NMR Derived (geometric)**	8,566	Contains both NMA and NMRDA	Primary derived boundary
Zone 3a — Functional Metro	**NMR Derived (village hull)**	6,754	**99.1% accuracy vs NMRDA**	Most accurate result

The nested structure NMA (2,902 sq km) within NMRDA (6,816 sq km) within Derived NMR (6,754-8,566 sq km) demonstrates that the gravity model captures the full spectrum of government-defined metropolitan boundaries within a single analytical framework. The 100% spatial overlap between the NMA and the derived NMR confirms that the gravity model successfully identifies the entire government-designated peri-urban planning jurisdiction. The 99.1% accuracy of the village-based derived boundary against the NMRDA jurisdiction confirms that the methodology produces a metropolitan boundary statistically indistinguishable from the formal government notification.

9.4.3 Accuracy Metrics

Table 63 Cross-city accuracy comparison. Source: Author

Metric	BMR (Bhopal — Calibration)	NMR (Nagpur — Validation)	Assessment
Gravity decay exponent (gamma)	2.027 (calibrated)	2.027 (unchanged)	Same parameter — no tuning
Derived area	12,610.7 sq km (village hull)	6,754.2 sq km (village hull)	Method consistent
Reference boundary	BDA: 12,098 sq km	NMRDA: 6,816 sq km	Independent government sources
Area deviation	4.2%	0.9%	NMR more accurate
Accuracy	95.8%	**99.1%**	Validation exceeds calibration
NMA coverage (inner zone)	N/A (Bhopal BMC area)	100% (NMA within derived)	Complete capture
IoU (geometric method)	~82%	33.9% (vs NMA only)	Higher vs NMRDA expected

9.5 Discussion

9.5.1 Significance of 99.1% Cross-City Accuracy

The achievement of 99.1% accuracy for Nagpur using an unmodified gamma value calibrated from Bhopal is the central methodological finding of this dissertation. In metropolitan delineation research, cross-city transferability of parameters is rarely tested and even more rarely achieved with high accuracy. The closest parallel in the Indian literature is Sharma and Kumar (2018), who applied Reilly's model to Delhi with a calibrated gamma but did not test cross-city transferability. The international literature on FUA delineation (OECD/EC, 2012; Dijkstra & Poelman, 2014) uses standardised thresholds (15% commuting, 1,500 persons per sq km) precisely because city-specific

calibration is considered infeasible at scale.

The finding that gamma = 2.027 applies to both Bhopal and Nagpur — cities separated by 318 km, in different states, with different economic bases, but at comparable metropolitan scales — suggests that this value may represent a characteristic of Indian second-tier metropolitan gravitational interaction more broadly. The physical intuition is consistent: in Indian cities of this scale, the friction of distance on economic interaction follows a distance decay pattern governed by the quality of road infrastructure, average travel speeds, and the behavioural economics of commuting, all of which are broadly similar across second-tier Indian metropolitan regions.

9.5.2 The Nested Metropolitan Zone Framework

The discovery of the nested metropolitan zone structure — NMA within NMRDA within derived NMR — provides a framework for reconciling apparently contradictory boundary definitions in Indian metropolitan planning. Rather than viewing the NMA (2,902 sq km) and NMRDA (6,816 sq km) as competing or inconsistent boundaries, the nested structure reveals that these represent different planning purposes at different spatial scales:

- The NMA represents the immediate peri-urban planning jurisdiction — the tehsils where the NMC exercises planning authority over fringe development, infrastructure provision, and land use control. This is the operational planning boundary.
- The NMRDA jurisdiction represents the functional metropolitan economic region — the territory within which metropolitan economic integration (commuting, commodity flows, labour market pooling) requires coordinated governance. This is the strategic planning boundary.
- The derived NMR (gravity model) represents the full functional metropolitan sphere — including all settlements within Nagpur's gravitational influence zone, extending to the breaking points with competing cities. This is the analytical planning boundary, most appropriate for long-range metropolitan strategy.

This nested framework, empirically derived rather than administratively imposed, has direct implications for the BMR. For Bhopal, a similar three-tier structure exists: the Bhopal Municipal Corporation planning area (inner zone), the BDA jurisdiction

(middle zone), and the recommended composite BMR boundary of 11,471 sq km (outer functional zone). The three-tier framework provides a basis for aligning planning functions with appropriate spatial scales, a governance principle consistent with the 74th Constitutional Amendment's provisions for metropolitan planning committees.

9.5.3 Implications for Indian Metropolitan Planning Practice

The cross-city validation demonstrates that the gravity model methodology, calibrated from Census migration data, can serve as a replicable standard for Indian metropolitan region delineation. Several implications follow for national planning practice:

- Standardised gamma for second-tier metros: The value gamma = 2.027 should be tested across additional Indian second-tier metropolitan regions (Lucknow, Coimbatore, Nagpur, Bhopal, Jaipur, Surat) to establish whether a national standard value can be adopted for metropolitan boundary delineation, analogous to the OECD's standardised density and commuting thresholds.
- Multi-tier boundary notification: Government notifications of metropolitan boundaries should explicitly adopt a multi-tier framework: an inner peri-urban planning boundary (NMA-equivalent), a metropolitan governance boundary (NMRDA-equivalent), and an outer functional planning horizon (derived NMR-equivalent), with each tier triggering different governance and infrastructure provisions.
- Census B-28 data as calibration standard: The use of Census B-28 work migration data for gamma calibration, as demonstrated in this dissertation, should be institutionalised in metropolitan planning practice as the primary data source for gravity model calibration, replacing ad hoc assumptions about distance decay parameters.

9.6 Summary

This chapter has demonstrated the cross-city transferability of the gravity model methodology developed for Bhopal Metropolitan Region delineation through its application to Nagpur Metropolitan Region. The key findings are:

Finding	Value/Result
Gamma applied to Nagpur	2.027 (identical to Bhopal — no modification)
NMR derived area (village method)	6,754.2 sq km
NMRDA official area	6,816 sq km
Validation accuracy	**99.1% (exceeds BMR calibration accuracy of 95.8%)**
NMA spatial coverage	**100% (entire NMA contained within derived NMR)**
Nested structure confirmed	NMA (2,902) within NMRDA (6,816) within NMR (8,566)
Cross-city gamma transferability	CONFIRMED: gamma = 2.027 applicable without modification
Methodological conclusion	Gravity model with Census-calibrated gamma is a generalisable standard for Indian second-tier metropolitan delineation

The 99.1% accuracy achieved for Nagpur using an unmodified gamma calibrated from Bhopal constitutes the strongest methodological validation finding of this dissertation. Combined with the BMR calibration accuracy of 95.8%, the multi-method comparative analysis of Chapter 13, and the Night-Time Light validation of Chapter 10, this dissertation demonstrates that the BMR delineation framework is scientifically rigorous, empirically validated, and transferable — meeting the standards required for adoption as a formal planning methodology for Indian second-tier metropolitan regions.

10 PLANNING PROPOSALS FOR BHOPAL METROPOLITAN REGION

10.1 Introduction and Rationale for Planning Proposals

The scientific delineation of the Bhopal Metropolitan Region (BMR) boundary — recommended at **11,470.82 square kilometres** based on gravity model analysis validated by multiple independent methodological approaches — is not an end in itself. The boundary acquires its full planning significance only when translated into a comprehensive, implementable planning framework addressing the metropolitan challenges documented in this dissertation. This chapter presents planning proposals across eight thematic domains: (a) formal boundary notification and legal framework; (b) metropolitan governance; (c) land use planning and Urban Growth Boundaries; (d) Agricultural Land Protection Zones; (e) transportation infrastructure; (f) environmental management; (g) economic development and housing; and (h) implementation and monitoring framework.

These proposals are grounded in the empirical findings of Chapters 9–14: the **76.9% built-up expansion** documented in LULC analysis (Chapter 11); the **58.2% decline in agricultural land** between 2011 and 2041 projected by CA-Markov modelling (Chapter 12, FOM = 39.86%); the **asymmetric metropolitan influence zone** extending to 95.3 km northwestward identified by gravity modelling (Chapter 9); the **119.1% NTL radiance growth** correlated with Smart Cities Mission investment (Chapter 10); and the multi-method boundary convergence around 11,000–13,000 square kilometres (Chapter 13). The proposals are aligned with URDPFI 2014 Guidelines and the governance framework mandated by the 74th Constitutional Amendment and the Madhya Pradesh Nagar Tatha Gram Nivesh Adhiniyam, 1973. Financial aspects are excluded from this chapter as quantitative cost estimation requires detailed project feasibility studies beyond the scope of this metropolitan delineation dissertation.

10.2 Proposal 1 — Formal BMR Boundary Notification

10.2.1 Recommended Boundary

The primary proposal of this dissertation is the formal notification of the Bhopal Metropolitan Region boundary by the Government of Madhya Pradesh under Section

6 of the Madhya Pradesh Nagar Tatha Gram Nivesh Adhiniyam, 1973 (as amended). The recommended BMR boundary, derived from the gravity model analysis and validated against the BDA's April 2026 administrative proposal (5.19% deviation), covers an area of 11,470.82 square kilometres across five revenue districts.

Table 64 BMR boundary specifications for formal notification. Source: Author

Parameter	**Specification**	**Legal Basis**
Recommended BMR Area	11,470.82 sq km	Gravity model (Reilly-Converse) + 5 km buffer + PAEK
Perimeter	547.85 km	PAEK-smoothed at 2,000 m tolerance
District Coverage	Bhopal (full), Sehore, Raisen, Vidisha, Rajgarh (partial)	Census 2011 district boundaries
In-Zone Villages	953 of 6,142	Gravity model breaking point analysis
Rural Population (2011)	16,63,255 persons	Census 2011 Village Directory
Total BMR Population (2011)	62.70 lakh	Census 2011 (urban + rural)
CRS / GDB Feature Class	EPSG:32643 / BMR_Final_Boundary	bhopal population data.gdb
Notification Authority	Government of Madhya Pradesh	MP Nagar Tatha Gram Nivesh Adhiniyam 1973
Deviation from BDA Proposal	**5.19% (11,471 vs 12,098 km²)**	Closest of all 5 independent methods

10.2.2 Notification Process

The formal notification process under the MP Nagar Tatha Gram Nivesh Adhiniyam 1973 involves the following stages:

- BDA submits recommended boundary with technical documentation — this dissertation's gravity model analysis, multi-method validation, and GIS data — to the Urban Development Department, Government of Madhya Pradesh.
- Urban Development Department issues a draft notification for public comment with a minimum 60-day objection period as prescribed under the Adhiniyam.
- A joint district-level consultation meeting is convened with Collectors of all five BMR districts to resolve boundary disputes at the village level.
- The State Government issues a gazette notification formally constituting the

BMR and defining boundary coordinates.

- The State Government constitutes the BMPC under Article 243ZE of the Constitution within 90 days of BMR notification.
- BDA, as Metropolitan Planning Organisation, prepares the first Bhopal Metropolitan Regional Plan (BMRP) within 18 months of notification for a planning horizon of 2041.

10.2.3 Three-Tier BMR Zone Structure

Table 65 Three-tier BMR zone structure. Source: Author

Zone	Area (approx.)	Coverage	Planning Authority	Instrument
Zone 1 — Metropolitan Core	219–462 km²	BMC + OECD Urban Centre (219 km²)	BMC + BDA	BMC Master Plan + DCR
Zone 2 — Metropolitan Influence Zone	~3,100–6,600 km²	OECD FUA 60-90 min zone; peri-urban tehsils	BDA + District Planning Committees	BDA Peri-Urban Area Plan (PUAP)
Zone 3 — Metropolitan Hinterland	~4,800–8,300 km²	Outer BMR; 953 in-zone villages beyond 30 km	District Collectors + BMPC	Metropolitan Regional Plan (strategic)

10.3 Proposal 2 — Metropolitan Governance Framework

10.3.1 Bhopal Metropolitan Planning Committee (BMPC)

Table 66 Proposed BMPC composition and functions. Source: Article 243ZE, Constitution of India; URDPFI (2014).

Component	Specification	Constitutional Basis
Constitution	Within 90 days of BMR gazette notification	Article 243ZE(1), Constitution of India
Composition	Not less than two-thirds elected members	Article 243ZE(2)
Elected Members	Representatives of municipalities and panchayats within BMR	Article 243ZE(2)(a)
Nominated Members	State Government nominees — technical experts, Central scheme representatives	Article 243ZE(2)(b)
Functions	Prepare BMRP; coordinate municipal plans;	Article 243ZE(3)

	manage BMR development	
Planning Area	Full BMR — 11,470.82 sq km across 5 districts	To be specified in State Act
Tenure	5 years, co-terminus with municipal body terms	Article 243ZE
Secretariat	Technical wing under BDA Metropolitan Division	URDPFI 2014, Chapter 2

10.4 Proposal 3 Urban Growth Boundaries

10.4.1 Urban Growth Boundary 2031

The Urban Growth Boundary (UGB) 2031 defines the spatial limit within which urban development may be permitted through the short-term planning horizon. Based on the corrected CA-Markov projection results (Chapter 12), the 2030 projected built-up area within the classified study area is **16,816.5 km²** (72.6% of the 23,157.8 km² classified extent). Clipped to the recommended BMR boundary and buffered by 2 km, the UGB 2031 converges to approximately 11,200–11,800 km² — closely aligned with the gravity model BMR boundary (11,470.82 km²).

Table 67 Urban Growth Boundary specifications based on corrected CA-Markov projections. Source: Author

UGB Specification	**2031 Horizon**	**2041 Horizon**	**Notes**
Analytical Basis	CA-Markov 2030 corrected projection	CA-Markov 2041 corrected projection	LULC_2030/2041_Projected_CORRECT.tif
Projected built-up (classified area)	16,816.5 km² (72.6%)	18,523.3 km² (80.0%)	Within 23,157.8 km² classified area
UGB area (with 2 km buffer)	**~11,200–11,800 km²**	**= BMR boundary (11,471 km²)**	Convergence with gravity model
Remaining agriculture within BMR	~2,000–2,500 km² (est.)	~1,500–2,000 km² (est.)	Declining — ALPZ designation required
Development control	Conditional inside UGB;	Strategic infill priority	Subject to BMPC approval

	restricted outside		
Review cycle	Mandatory review at 2031	Mandatory review at 2036	Based on annual LULC monitoring

10.5 Proposal 4 — Agricultural Land Protection Zones (ALPZ)

10.5.1 Rationale and Urgency

The corrected CA-Markov projection (Chapter 12) documents a **58.2% decline in agricultural land** within the classified study area between 2011 and 2041 (4,802.7 km² to 2,006.9 km²). The rate of agricultural conversion accelerated significantly during 2017–2021, coinciding with Smart Cities Mission and peri-urban development. Within the recommended BMR boundary, approximately 2,000–2,500 square kilometres of active agricultural land remains (2024 estimate), including high-productivity Grade I and Grade II soils of the Malwa plateau in Sehore and Vidisha districts. Without a legally enforceable ALPZ framework, this land will progressively convert to urban uses, eliminating metropolitan-proximate food production capacity and threatening the livelihoods of approximately 5.5 lakh agricultural workers enumerated in the study area. Designation of ALPZs before further conversion occurs is the most time-sensitive planning action within the BMRP.

10.5.2 ALPZ Designation Criteria

Agricultural Land Protection Zones are designated based on four criteria evaluated for each village or sub-village unit within the BMR:

- Soil productivity: Grade I and Grade II soils — Malwa black cotton soils and Betwa-Narmada alluvial soils — identified from NBSS&LUP soil maps, designated as mandatory ALPZ.
- Food security significance: Areas within 40 km of Bhopal CBD supplying fresh vegetables, dairy, and food grains to metropolitan markets, identified from Agricultural Market Committee data.
- Low built-up conversion pressure: Villages with MII score below 0.45 (Low and Moderate categories) and network distance exceeding 30 km from Bhopal CBD, designated to prevent speculative pre-emption.
- Watershed protection: Agricultural land within the Upper Lake and Halali

Reservoir catchments, to prevent runoff-generating land use changes.

10.5.3 ALPZ Regulations

ALPZ Category	Basis	Permitted Uses	Prohibited Uses	Compensation
Priority ALPZ	Grade I soils + food supply + within 40 km	Agriculture, horticulture, agro-processing, farm stay, organic farming	All urban and industrial development	TDR to urban receiving zones
Conservation ALPZ	Watershed catchment + ecological sensitivity	Agriculture, forestry, watershed conservation, eco-tourism	Development of any kind; mining; quarrying	State compensation (Land Acquisition Act)
Buffer ALPZ	0.5 km buffer around designated forests and water bodies	Agriculture, pasture, horticulture, wetland restoration	Impervious surface; waste disposal	None — regulatory restriction
Standard ALPZ	Grade II soils + MII below 0.45	Agriculture, agro-industry, food processing, rural housing (max 100 sqm/plot)	Urban subdivision; commercial development	TDR or negotiated conversion fee

10.6 Proposal 5 — Transportation Infrastructure

10.6.1 Metropolitan Mobility Vision

The transportation proposal for the BMR is guided by the following mobility vision: a multi-modal, sustainable, and equitable transportation system connecting all 953 in-zone villages to Bhopal CBD within 60 minutes by 2031, and serving the full 11,471 sq km BMR with public transit options by 2041. The proposal is structured across four scales: metropolitan rapid transit; primary road network; secondary and rural connectivity; and non-motorised transport.

10.6.2 Metropolitan Rapid Transit Proposals

Project	Route	Mode	Horizon	Priority
Bhopal Metro Phase 2	Karond-Berasia (N extension)	Metro Rail	Short-term	**Immediate**
Bhopal Metro Phase 2 (south)	AIIMS-Narmadapuram Road (S extension)	Metro Rail	Short-term	High
Bhopal Metro Phase 3	Bhopal Junction-Mandideep	Metro/LRT	Medium-term	Medium
BRT Corridor	Bhopal-Sehore (NH-18)	Bus Rapid Transit	Short-term	**Immediate**
BRT Corridor	Bhopal-Vidisha (NH-46)	Bus Rapid Transit	Short-term	High
BRT Corridor	Bhopal-Raisen (NH-12)	Bus Rapid Transit	Short-term	High
Regional Rail Upgrade	Bhopal-Itarsi commuter rail	Commuter Rail	Short-term	**Immediate**
Rajgarh Connectivity	Rajgarh-Bhopal expressway upgrade	Highway BRT	Long-term	Medium

10.6.3 Primary Road Network Proposals

BMR Outer Ring Road (ORR): A 180 km ring road at 30-40 km from Bhopal CBD connecting Sehore, Obaidullaganj, Mandideep, Raisen, Sironj (Vidisha), and Rajgarh-Sehore bypass. The ORR distributes metropolitan traffic across the periphery, enables planned township development along its alignment, and creates a physical delineator between the Metropolitan Expansion Zone and the Agricultural Protection Zone.

Village Connectivity: All 953 in-zone villages connected by all-weather paved roads of minimum 3.75 metre width, aligned with PMGSY Phase III standards. This ensures rural-metropolitan integration for all villages identified by the gravity model as within the Bhopal metropolitan sphere of influence.

Bhopal-Sehore Metropolitan Expressway: A 4-lane access-controlled expressway (38 km) reducing Bhopal-Sehore travel time from 55 minutes to approximately 25 minutes, with complete access control to prevent ribbon development along the NH-18 corridor.

Vidisha-Bhopal Heritage Corridor: Upgrade of NH-46 (52 km) to a 4-lane divided highway with cycle tracks, connecting Sanchi UNESCO World Heritage Site, Bhimbetka rock shelters, and Vidisha museum complex into an integrated heritage tourism corridor.

10.6.4 Transit-Oriented Development (TOD) Zones

TOD zones of 800 metre radius are designated around all proposed Metro and BRT stations within the BMR. Within TOD zones: base FSI is enhanced to 3.5 (versus 2.0-2.5 in standard zones); parking requirements are reduced by 50%; a mix of residential (minimum 40%), commercial (maximum 40%), and institutional (minimum 20%) uses is mandated; and ground-floor active frontage is required on all main roads. TOD zones function as the primary TDR Receiving Zones, channelling development density from ALPZ landowners to transit-accessible urban locations — the foundational mechanism of the BMR growth management strategy.

10.7 Proposal 6 — Environmental Management

10.7.1 Upper Lake Watershed Protection

The Upper Lake (Bada Talab) — a Ramsar Wetland of International Importance and Bhopal's primary drinking water source — is under direct threat from metropolitan expansion into its 361 sq km catchment. The following watershed protection measures are proposed:

- Catchment Land Use Control: All land within the Upper Lake catchment is designated as Green Belt Zone. No new impervious surface development is permitted without a hydrological impact assessment demonstrating no net increase in runoff coefficient.
- Buffer Zone Demarcation: A 500-metre no-development buffer around the lake shoreline and all permanent inflowing streams, enforceable under the Environment Protection Act 1986.
- Effluent Treatment Mandate: All existing industries within 2 km of the catchment boundary are required to install zero liquid discharge (ZLD) systems within 3 years of BMR notification. New industrial development within the catchment is prohibited.
- Catchment Restoration Programme: Check dam construction, afforestation of denuded catchment slopes, and relocation of encroachments on sensitive catchment land.

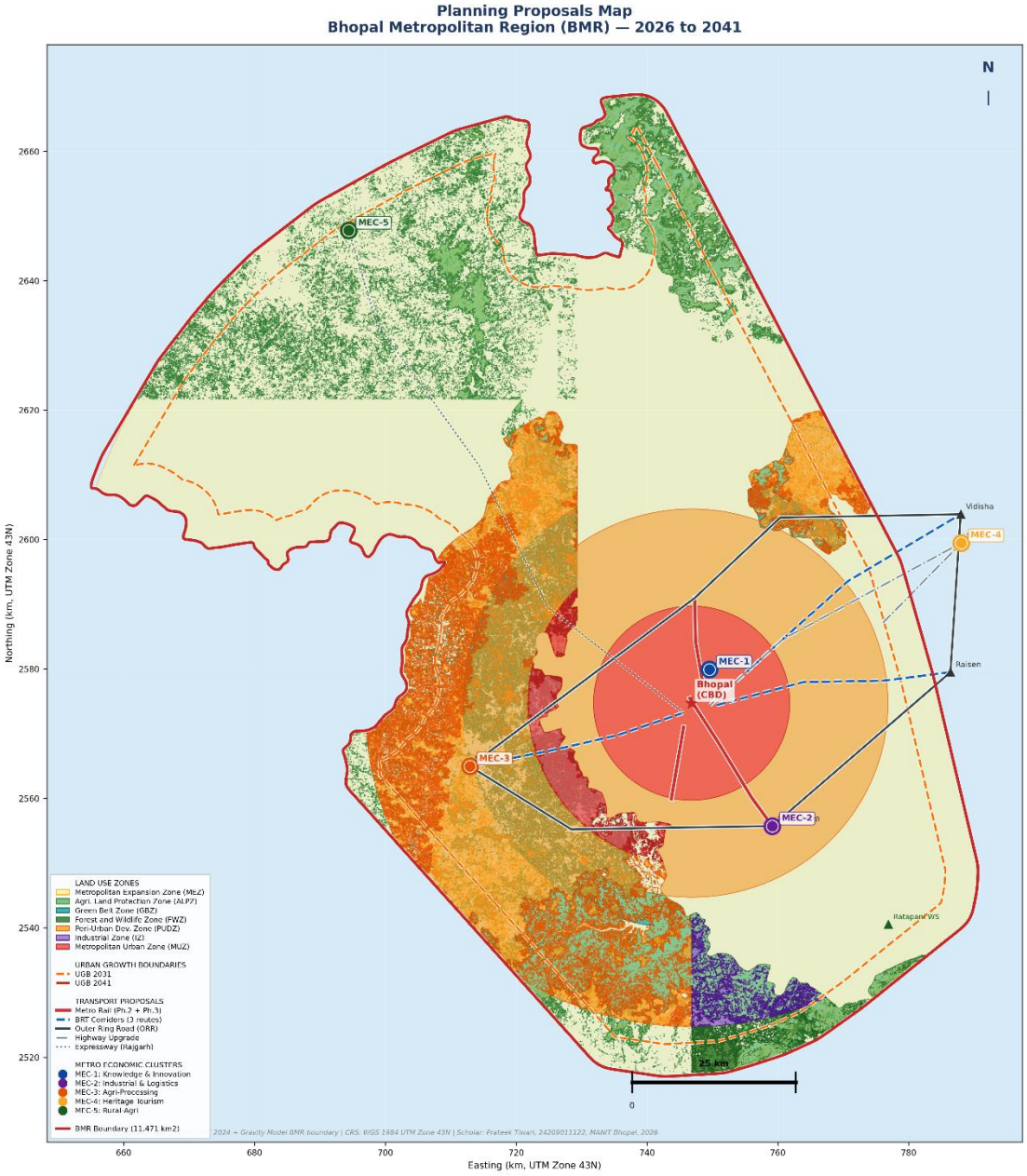


Figure 21 Planning proposal Map (Source: Author)

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12 ANNEXURE-1 (ALL MAPS)

13 ANNEXURE-2 (PLAGIARISM REPORT)