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Assessment of the Future Environmental Carrying Capacity for Sustainable Development in Kochi City, Kerala State, India

Rajeev R. [1], Adinarayanane Ramamurthy [2], Ayon Kumar Tarafdar [3]
[1] Department of Planning, School of Planning and Architecture, Vijayawada, Government of India.
[2] Department of Planning, School of Planning and Architecture, Vijayawada, Government of India.
[3] Department of Planning, School of Planning and Architecture, Vijayawada, Government of India.
Corresponding author: rajeevnair@spav.ac.in

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Abstract: Globally, ecological overshoot is becoming increasingly prevalent, making biocapacity enhancement crucial for resolving these growing environmental demands. Environmental Carrying Capacity (ECC) is a critical factor for urban environmental sustainability, as it determines the maximum number of people, species, and activities that the environment can sustain over a given period of time. Urbanization is accelerating, with the global urban population projected to reach 70% by 2050, which can intensify the pressure on ecological resources. Developing urban areas within the ecological and resource limits can help achieve a sustainable urban transition over the years. The ECC tool, when integrated into spatial planning strategy, can provide a vital framework for sustainable urban development by combining resource availability, waste assimilation, and ecosystem resilience in urban planning. Therefore, considering the future ECC in urban planning is critical for the city's long-term development. In comparison to developed countries, the use of ECC in spatial planning efforts in developing countries is in the nascent stage, hampered by policy loopholes, data unavailability, and short-term development goals. For developing nations like India which are at the crossroads in terms of accelerating their economies, incorporating ECC into spatial planning is crucial for striking a balance between growth and environmental sustainability for building long-term urban resilience.For this study Kochi, a rapidly developing coastal metropolitan city located in the Vembanad-Kol backwater system of Kerala state, which is representative of the maladies of uncontrolled development with environmental constraints in southern India, have been chosen as study area. Being developed as a smart city in this region, as well as having various development initiatives under the AMRUT mission, both of which are flagship programmes of the Government of India, the economic growth in Kochi has considerably accelerated infrastructure growth and land use changes in the system. However, this urban expansion is resulting in significant environmental cost, worsening pollution levels, groundwater loss, encroachment of wetlands etc., and weakening Kochi's natural defenses. Thus, there is inevitable requirement for employing an ECC-based approach to spatial planning in this eco-sensitive study region.

This study tried to assess the Environmental Carrying Capacity (ECC) of Kochi using geo-spatial analysis through urban sustainability lens, integrating sensitivity and vulnerability concerns. Given India's complex urban fabric, a comprehensive list of ECC control parameters have been defined to justify local environmental factors, socio-economic conditions, and data availability in this analysis. The study demonstrated that Kochi's present urban expansion and resultant pressure will soon overshoot its environmental carrying capacity in near future, if unplanned. Regulatory frameworks exist in the Kochi Master Plan, but ECC is not fully integrated into urban planning as a regulatory tool, with economic priorities often sidelining ecology in the system. The study thus proposes a replicable methodology, for quantifying the future ECC, for other high-growth cities with comparable environmental contexts, offering a strategic avenue towards balancing urban growth with ecological wholeness. Based on the findings, the study facilitates the potential for a dynamic, data-driven ECC approach for spatial planning in Kochi City that can enable decision makers in the regulation of development intensity, enhance local land use practices, and minimize environmental risk, towards navigating for long-term resilient and sustainable urban development.

Keywords: Environmental Carrying Capacity, Geographically Weighted Regression, Ecological Sensitivity, Hazard Vulnerability, Development Intensity, Kochi, Sustainable Urban Development.

Introduction

Environmental Carrying Capacity (ECC) refers to the maximum upper limit of population and activities an environment can support towards achieving sustainable urban growth. With the global urban population projected to reach 68% by 2050, up from 56% in 2021 (UN-DESA, 2018), pressures on urban ecosystems have intensified. Developed nations already exhibit urbanization rates above 80%, whereas the Global South – including India – witnesses the fastest urban population increases, often in ecologically sensitive zones (Angel et al., 2010). In European and North American cities, ECC has informed zoning, green space planning, and pollution controls. In contrast, its integration in developing countries remains nascent due to data constraints and short-term growth priorities. The rapid urbanization in the context of developing and under-developed countries intensifies resource consumption and environmental degradation when left unplanned and unregulated(Mahavir et al., 2015).

India exemplifies this demographic transition, where urbanization can possibly surge from 31% in 2011 to a projected 40.8% by 2030, which can stress ecological systems and infrastructure (Town and Country Planning Organisation, 2015). Kerala stands out with one of the highest urban growth rates among Indian states, where urban population doubled from 26% in 2001 to 47.7% in 2011 (Census of India, 2011; Perianayagam & Goli, 2012). Given its dense population (~859 persons km-2) and coastal vulnerability, integrating ECC framework into spatial planning becomes essential. Kochi – a part of the Vembanad-Kol backwater estuarine system – is a rapidly evolving metropolitan area under India's Smart City and AMRUT initiatives. These developmental programs have accelerated infrastructure and urban land conversion, but have also exacerbated groundwater depletion, wetland loss, urban flooding, coastal erosion, and pollution. The lack of integration of ECC in statutory spatial planning frameworks and development zoning exacerbates these risks, especially in such coastal cities with high ecological sensitivity.

This study evaluates the future ECC of Kochi using spatial analysis, integrating environmental sensitivity, hazard vulnerability, development intensity, and ecological capacities (supportive and assimilative). This paper attempts to apply geo-spatial tools and statistical models like Geographically Weighted Regression (GWR) to estimate the future ECC more precisely at local-level across space, offering decision-makers an actionable framework. By contextualizing ECC within the dynamic urban transformation of Kochi, the paper contributes to embedding sustainability within planning practice in India and other rapidly urbanizing regions.

Environmental Carrying Capacity and Spatial Planning

Environmental Carrying Capacity (ECC) serves as a critical foundation for spatial planning, especially in urban areas grappling with rapid expansion and resource constraints. ECC refers to the maximum level of human activity that an environment can sustainably support without leading to long-term ecological degradation (Wackernagel & Rees, 1995). Integrating ECC into spatial planning helps define the thresholds within which land, water, and other ecological systems can be used without exceeding their regenerative capacities (Wu, 2014). Globally, cities that have embedded carrying capacity principles into their planning frameworks demonstrate greater resilience to environmental and socio-economic shocks (Carey, 1993; Joardar, 1998). However, despite the recognized importance of ECC, many urban planning processes—particularly in developing contexts—continue to prioritize infrastructure expansion and economic growth over ecological considerations (Gonçalves & Ferreira, 2015). This has led to unsustainable urban sprawl, strained natural systems, and increasing vulnerability to climate-related events. Effective spatial planning, when aligned with ECC, ensures that development is guided by environmental thresholds, balancing human needs with ecological preservation (Pahuluan et al., 2017).

Environmental Carrying Capacity and Sustainable Development

Sustainable development demands a delicate balance between fulfilling current human needs and preserving the environment for future generations. In this context, ECC becomes indispensable as a planning and management tool, offering a measurable means to regulate urban growth within the planet's ecological boundaries (Joardar, 1998; Shen et al., 2020). Developed nations have historically integrated carrying capacity assessments into land-use planning, environmental impact assessments, and urban policy frameworks, thus achieving better control over resource consumption and waste assimilation (Khanna et al., 1999; Mahavir et al., 2015). For example, cities in Europe and North America have increasingly adopted ecological footprint analysis and biocapacity estimations to shape sustainable urban growth trajectories. Conversely, in many developing nations, including India, the application of ECC in planning remains sporadic and underdeveloped. Rapid urbanization, coupled with weak regulatory enforcement and fragmented institutional capacities, often results in growth patterns that surpass environmental thresholds (Fuseini & Kemp, 2015). This gap emphasizes the urgent need to systematically integrate ECC assessments into mainstream urban and regional planning (Rajeev, n.d.), aligning with global goals such as the Sustainable Development Goals (SDGs), particularly SDG 11, which aims to make cities inclusive, safe, resilient, and sustainable (UN, 2015).

Literature Review

Recent studies have adopted diverse frameworks to assess Environmental Carrying Capacity (ECC), combining spatial, environmental, and socio-economic parameters. Li et al. (2019) proposed a spatially explicit GIS-based model for China, revealing ECC decline under rapid urbanization. Wu et al. (2021) applied entropy and TOPSIS methods in the Greater Bay Area, integrating environmental and socio-economic subsystems to quantify ECC. Tehrani and Makhdoum (2013) introduced the UCCLN model in Tehran to monitor urban ecosystem loads, while Qin et al. (2021) applied multiscale Geographically Weighted Regression (GWR) to capture spatial variations in ECC drivers. Supporting this, Comber et al. (2020) provided key guidance on GWR application, including bandwidth selection and residual diagnostics. In Indian context, Tailor and Tailor (2024) used a probability satisfaction approach to estimate population carrying capacity in Surat, emphasizing infrastructure and service constraints. Together, these studies show that ECC estimation is shifting toward integrated, spatially adaptive methods responsive to local urban dynamics.

Further, the authors reviewed literature specific to regional (India) and city-level ECC application contexts. Kapoor et al. (2022) assessed Agra's urban carrying capacity using the SAFE model, integrating dynamic indicators of resource use, infrastructure provision, and environmental health. However, the study revealed limitations in spatial granularity and lacked a focused evaluation of ecological thresholds. In another study, Sahasranaman and Bettencourt (2018) analyzed urban growth patterns in Indian cities, pointing out the lack of consistent spatial planning frameworks and the scarcity of reliable city-level environmental datasets. The Urban India 2022 report (NIUA, 2022) observed growing need for adoption of ECC tools in planning new towns, but emphasized a key shortfall—namely, the lack of ECC-based frameworks for existing cities, including those under the Smart Cities Mission. Moreover, studies on South Asian cities indicate that despite ecological fragility and growing urban stress, ECC integration in planning remains limited, hindered by underdeveloped environmental data systems, lack of guiding and spatially explicit methodologies at urban level.

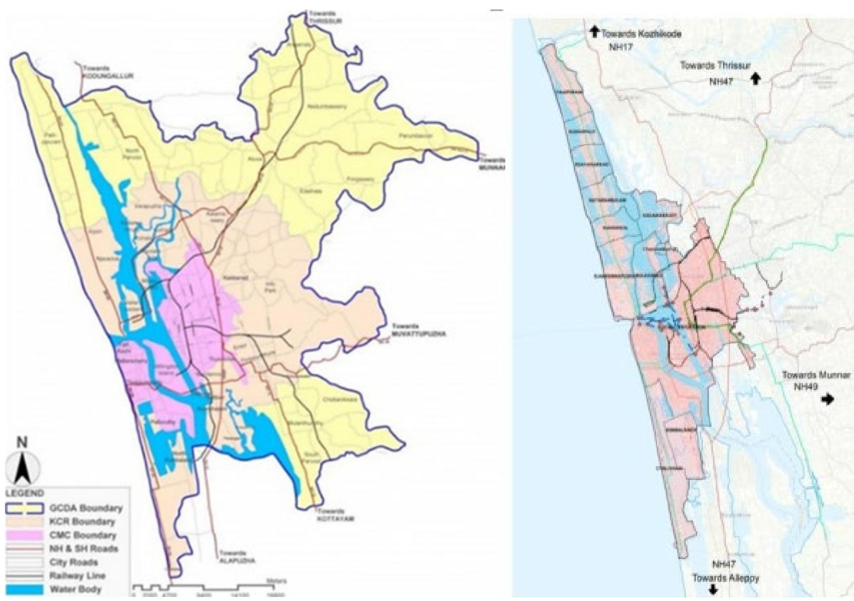
Learnings from literature indicate that mainstreaming ECC into spatial planning requires localized adjustments in methodologies, given the unique environmental, demographic, and socio-economic conditions in different regions. In the Indian context, relooking at ECC parameters becomes crucial because of diverse ecological settings, varying data availability, and the pressing nature of development needs. The selection and adaptation of relevant indicators—such as land use efficiency, water resource availability, hazard vulnerability, and ecological resilience—are essential to making ECC assessments practical and actionable in local planning contexts (Zhang et al., 2024).

Contextual Background: Kochi, Kerala State, India

Kochi, a rapidly developing coastal metropolitan city in southern Kerala, epitomizes the complex challenges faced by rapidly urbanizing regions situated within ecologically sensitive landscapes. According to the 2011 Census, Kochi Region delineated by the authors for this study had a population of approximately 1 million persons residing within an area of 230.30 square kilometers, resulting in a high population density of about 3500 persons per square kilometer. From an administrative standpoint, the selected case study region includes the Kochi Municipal Corporation comprising 74 wards, along with 11 rural areas administered by Gram Panchayats - 08 Gram Panchayats under the Goshree Islands Development Authority (GIDA) region and 03 Gram Panchayats under Greater Cochin Development Authority (GCDA). These agencies together with the Department of Town and Country Planning, Government of Kerala oversee town planning and development activities across a mix of urban, semi-urban and rural settings. The region, bounded by the Lakshadweep Sea, is intricately interwoven with canals, marshlands, and mangrove ecosystems in the Vembanad-Kol backwater system of Kerala state, making it both ecologically rich and highly vulnerable. The study area has been delineated based on ecologically coherent units – i.e. coastal urban-influenced environmental region in Kochi by the authors, ensuring that ECC estimation reflects both environmental constraints and development dynamics through a comprehensive set of parameters.

This urban region exemplifies a complex interplay of natural and anthropogenic systems collectively shaping its environmental carrying capacity. A systems approach was adopted to holistically understand the city through the lens of six interrelated sub-systems: Physical, Social, Economic, Environmental & Ecological, Infrastructure, and Institutional. The Physical sub-system is defined by its coastal morphology, estuarine networks, low-lying flood-prone terrain, and wetland-rich landscape. The Social sub-system reflects a growing, diverse, and spatially uneven population distribution with varying levels of access to services and amenities. The Economic sub-system is dominated by trade, tourism, industrial and port-based activities, but also increasingly influenced by real estate pressures and informal livelihoods. The Environmental and Ecological sub-system faces mounting degradation from land conversion, loss of wetlands, pollution, and reduced ecosystem services due to urban expansion. The Infrastructure sub-system, though well-established in core areas, shows signs of stress and disparity in peripheral zones. The Institutional sub-system reflects overlapping jurisdictions, fragmented planning frameworks, and limited integration of environmental considerations in decision-making processes.

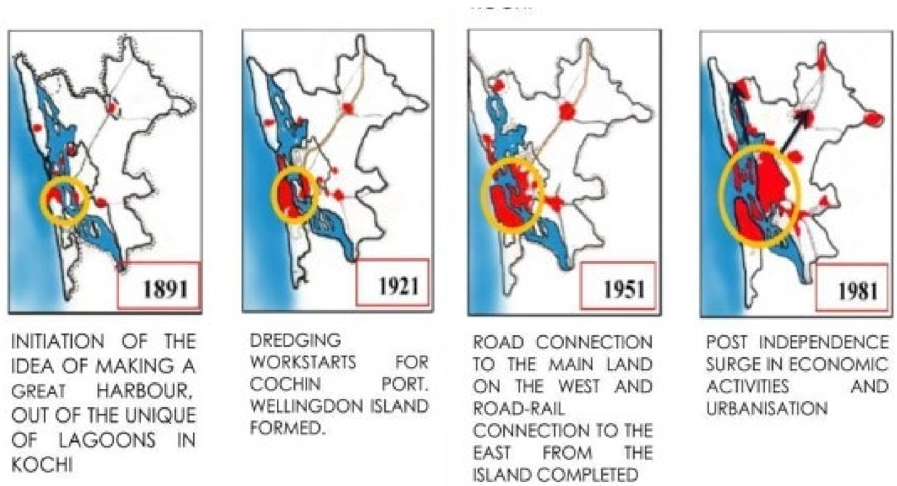
Figure 1: Administrative boundaries in Kochi Region; Base Map of Study Area – Kochi Corporation & 11 Village Panchayats



Source: Data sourced from Greater Cochin Development Authority (GCDA), Goshree Island Development Auhtority (GIDA), and DTCP, GoK (2023)

Despite its ecological significance, Kochi faces intense development pressures, including coastal land-use transformation, ecological degradation, unplanned resource exploitation, and increased climate variability impacts that threaten its sustainable urban development. With a coastline of more than 48 km, the city's ecological sensitivity is underscored by its locational setting in the coastal confluence, with much of its terrain at sea level, making it susceptible to sea-level rise and coastal erosion. Projections indicate a potential sea-level rise of 0.6 meters by 2040, exacerbating risks of flooding and habitat loss. Approximately 35% of Kochi's residents are vulnerable to heat stress, while 25% face risks of flooding, highlighting the city's hazard vulnerability. In terms of supportive capacity of the environment, the city's green spaces are diminishing; urban expansion has led to a 57.56% reduction in wetland areas and a 15% decline in croplands, replaced by commercial and residential development. Iconic ecological assets like the Mangalavanam Bird Sanctuary are under threat from unchecked urban expansion. Water supply is under strain, leading to over-extraction of groundwater and increased salinity. The assimilative capacity of Kochi's environment is compromised, with studies revealing critical levels of total suspended solids and cadmium in the estuary, and cautionary levels of copper and lead in inshore waters.

Figure 2: Historical Development of Settlements and Key Infrastructure in Kochi Region



Source: Compiled by Authors based on data from Master Plan of Kochi prepared by DTCP, GoK and GCDA website

Development pressures are mounting, with the city's population density increasing and infrastructure struggling to keep pace, resulting in traffic congestion and degradation of urban environments. In this rapidly densifying urban region, the sudden momentum generated by Kochi's Smart City status and AMRUT-backed projects in the last decade (post 2015) has intensified positive economic growth. However, this is placing considerable pressure on infrastructure systems, accelerating land use transformations in peri-urban areas outside the municipal corporation limits, and worsening ecological vulnerabilities. The physical limitations of the region—both in terms of land availability and environmental fragility—render traditional expansionist urban models unsuitable. Consequently, Kochi stands as a pertinent case to demonstrate how Environmental Carrying Capacity can be mainstreamed into planning processes to achieve a balance between development aspirations and ecological sustainability.

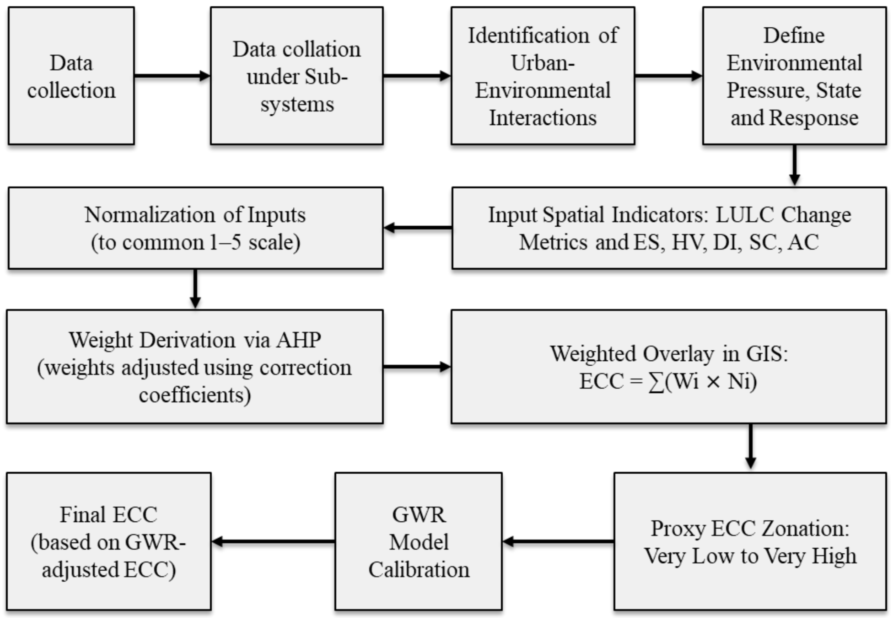
Recognizing the magnitude of data and the complexities involved in mainstreaming ECC into the spatial planning process, this study focuses specifically on assessing the future environmental carrying capacity of the coastal urban region of Kochi. Through this approach, the study aims to evolve an adaptive, evidence-based planning methodology for ECC estimation that can guide sustainable urban futures for similar coastal and environmentally sensitive regions in India and beyond.

Purpose of the Study and Methodology

The purpose of this paper is to assess the Environmental Carrying Capacity (ECC) of Kochi city in India, by integrating ecological, physical, and socio-economic dimensions into the spatial planning process. As urban pressures escalate, especially in ecologically sensitive and hazard-prone geographies like Kochi, there is a critical need to develop spatial tools that can measure and regulate development intensity within sustainable thresholds. This study aims to evaluate the current and future ECC of Kochi using geospatial techniques and localized modelling approaches, offering a scientific basis for environmentally informed decision-making. The study outputs can be used further to development replicable frameworks in the future that integrates ECC into urban planning, supporting long-term sustainability, resilience, and land use optimization in coastal Indian cities.

For this study, the authors adopted a multi-stage methodology combining urban-environmental diagnostics and spatial modeling to assess the future Environmental Carrying Capacity (ECC) of Kochi. Initially, comprehensive data documentation was carried out across major urban sub-systems—physical, environmental, ecological, social, economic, infrastructural, and institutional—to understand the prevailing urban-environmental conditions. Land Use Land Cover (LULC) mapping, along with indices such as Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), and Normalized Difference Built-up Index (NDBI), provided a spatial understanding of landscape transformation and urban growth dynamics. Based on the documented variables, five core components—Ecological Sensitivity (ES), Hazard Vulnerability (HV), Development Intensity (DI), Assimilative Capacity (AC), and Supportive Capacity (SC)—were spatially quantified using GIS-based raster and vector analysis.

Figure 3: Methodology adopted for estimating Environmental Carrying Capacity



Source: Developed by Authors

To capture ecosystem fragility and exposure to risks, Environmental Sensitivity Index (ES) and Hazard Vulnerability (HV) assessments were undertaken, integrating topographical, climatic, geological, hydrological, and demographic data. Development Intensity (DI) was mapped to reflect the pace and concentration of urban growth. Composite Pollution Index (CPI) was calculated by aggregating secondary pollution datasets, along with Carbon Sequestration Potential using InVEST, to estimate Assimilative Capacity (AC), i.e., the ability of the region to absorb pollutants. In parallel, Supportive Capacity (SC) was evaluated using indicators of resource availability, including green space distribution, barren land concentration, and groundwater potential.

Subsequently, a Proxy ECC was derived through weighted overlay analysis, integrating the spatial layers of the above components. The interrelations among ES, HV, DI, AC, and SC with Proxy ECC were statistically explored through correlation analysis and scatter plots to identify key influencing factors. To incorporate spatial heterogeneity into the model, Geographically Weighted Regression (GWR) was applied to modify the influence of each component locally, thus refining the ECC estimation with context-sensitive weights. This final ECC surface provides a spatially dynamic measure of environmental carrying capacity for Kochi, enabling more nuanced, location-specific planning interventions.

Materials and Methods

Based on the literature review, for assessing the Environmental Carrying Capacity (ECC) of the Kochi region, the study employs a multi-criteria analytical framework integrating geo-spatial and statistical methods building on ecological conditions, development pressures, and environmental resilience. The various methods, tools and methods that are employed as part of this study is discussed briefly – under LULC mapping, index calculation of NDVI, NDWI, and NDBI, Ecological Sensitivity Analysis, Hazard Vulnerability assessment, Development Intensity, Composite Pollution Index, Supportive, Capacity and Assimilative capacity – which together help in estimation of the Environmental Carrying Capacity (ECC).

LULC Derivation

LULC analysis forms the foundational step in ECC estimation by capturing spatial patterns of land transformation and identifying pressures on natural and built environments. This was performed using supervised classification (Maximum Likelihood) on Landsat data (2001–2021) sourced from USGS Earth Explorer. Pre-processing included radiometric and geometric corrections. Training samples were derived from field surveys (carried out in 2021 and 2022), existing land use maps (obtained from the Department of Town and Country Planning (DTCP Ernakulam), Government of Kerala), and Google Earth. Post-classification refinement ensured improved accuracy, with overall accuracies of 84.1% (2001), 87% (2011), and 90% (2021). The output was also validated using data from Kerala State Remote Sensing and Environment Centre (KSREC, n.d.). Change detection and transition matrix analysis revealed spatio-temporal land transformation trends, validating the dataset's reliability (Kappa > 0.6) for further ECC modeling.

NDVI, NDWI and NDBI

Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), and Normalized Difference Built-up Index (NDBI) were computed from atmospherically corrected Landsat satellite imagery (2001, 2011, 2021) using standard spectral band combinations. The indices were derived using raster calculator functions in QGIS, and the resulting outputs were classified using natural breaks to map vegetation cover, surface water extent, and built-up areas. These indices provided spatial evidence of environmental stressors and urban footprint over time (2001 to 2021).

$$NDVI = (NIR - Red) / (NIR + Red)$$

$$NDWI = (Green - NIR) / (Green + NIR)$$

$$NDBI = (SWIR - NIR) / (SWIR + NIR)$$

Ecological Sensitivity (ES)

Ecological Sensitivity (ES) was developed using multi-criteria overlay analysis. The Ecological Sensitivity was derived using multi-criteria indicators such as slope, LULC, NDVI, NDWI, groundwater depth, presence of eco-sensitive areas, proximity to coast, roads, and built-up areas. Each layer was reclassified into five sensitivity classes (parameters rescaled to a 1–5 range). The Analytic Hierarchy Process (AHP) was employed to derive weights for selected indicators based on pairwise comparisons of their relative importance. The consistency of judgments was validated using the Consistency Ratio (CR), and values less than 0.10 were considered acceptable to ensure logical coherence in weight assignments. The final index was obtained through weighted overlay in GIS, classifying zones into low to very high ecological sensitivity.

$$ES = \sum(W_i \times X_i)$$

Where:

W_i = weight assigned to parameter i

X_i = normalized value of parameter i

Hazard Vulnerability (HV)

Hazard Vulnerability (HV) highlights the spatial heterogeneity of exposure to natural and anthropogenic hazards, shaped by both physical geography and socio-economic dynamics. The Hazard Vulnerability (HV) assessment incorporated integration of geomorphology, flood susceptibility, coastal erosion, historical hazard records, drainage density, salinity, topographic wetness index (TWI), and population concentration (Census 2011 and projected values for 2021). Vulnerability indices were created by normalizing each layer (Min-Max scaling), assigning weights based on AHP, validated by checking the consistency ratio and aggregated using a GIS-based weighted overlay approach. Final outputs identified spatial zones vulnerable to multiple hazards, critical for ECC-related decision-making.

$$HV = \sum(W_i \times Y_i)$$

Where:

W_i = weight assigned to parameter i

Y_i = normalized value of parameter i

Development Intensity (DI)

Understanding the Development Intensity helps to offer key insights into land use pressures and urban expansion by highlighting regions at potential risk of exceeding their ECC. Development Intensity (DI) was calculated by combining built-up density (from LULC classification) and validated on ground using primary field observations, population density at ward and panchayat levels, infrastructure needs index (computed based on ward and sub-city level infrastructure availability), road density, land use concentration, night light intensity (as indicator of commercial and industrial area concentration). Built-up data was rasterized and overlaid with demographic boundaries using zonal statistics. Population densities and other parameters were normalized (Min-Max scaling), AHP-based weights assignment validated by checking the consistency ratio and aggregated using a GIS-based weighted overlay approach to generate the composite Development Intensity (DI) in Kochi. The final DI output highlighted urban stress zones where development pressures were highest.

$DI = \sum(W_i \times Z_i)$

Where:

W_i = weight assigned to parameter i

Z_i = normalized value of parameter i

Composite Pollution Index (PI)

Composite Pollution Index (PI) was derived by aggregating secondary pollution data from multiple sources and time periods, including air, water, soil, and noise pollution data from CPCB (2020–2021), Kerala State Pollution Control Board (KSPCB, 2020-2022), Kochi Municipal Corporation (2021), Kochi Waterways Authority (2021), published research for noise and soil data (CUSAT, 2020), and primary data on noise pollution collected in 2023. Each parametric value was normalized, spatially interpolated using Inverse Distance Weighting (IDW) in GIS, and spatially aggregated through overlay analysis to form a composite index indicating the spatial concentration and distribution of pollution considering the values for 2021.

Pollution Index of Air/ Water/Land (PI_i) = C_i / P_i

Where:

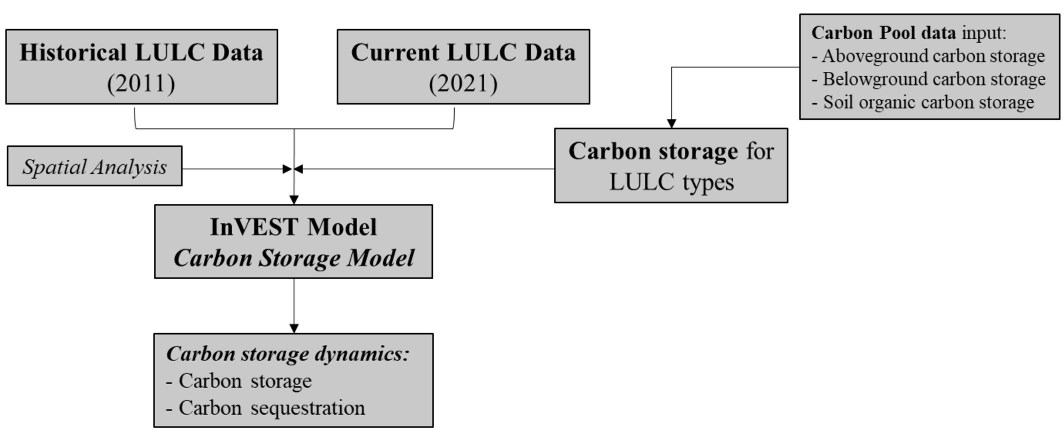
C_i = Observed concentration of pollutant i under Air/ Water/ Land

P_i = Standard permissible concentration of pollutant i

Carbon Sequestration Potential (CS)

Carbon storage and sequestration (CS) was assessed using the InVEST Carbon model, based on LULC maps and carbon pool values for above-ground, below-ground, and soil. InVEST Carbon Storage and Sequestration Model estimated carbon sequestration potential across the Kochi region utilizing spatial land use land cover (LULC) data from two time points – 2011 (historical) and 2021 (taken as current) – to assess carbon storage dynamics. Each LULC class was assigned carbon stock values based on carbon pools. Spatial overlay and reclassification were performed in a GIS environment to generate carbon storage maps. By computing the difference in carbon stored between the two time periods, the model estimated the net change in carbon stock, representing the carbon sequestration and its change resulting from land use transitions. The results were further integrated to procced with the assimilative capacity analysis to understand spatial variability in ecological functioning.

Figure 4: Method flow diagram adopted for assessing Carbon storage and sequestration using the InVEST Carbon model



Source: Sharma et al., 2024

Assimilative Capacity

Assimilative Capacity (AC) reflects the environment's ability to absorb, neutralize, or transform pollutants without degrading ecosystem health. In this study, it has been deduced as a function of both Composite Pollution Index (PI)—which indicates the intensity of anthropogenic pollution—and Carbon Sequestration Potential (CS)—which captures the landscape's natural capacity to absorb CO_2 and enhance air quality. By integrating these two - High pollution levels (high PI) indicating stress on the system; and High carbon sequestration (high CS) suggesting stronger natural resilience and regenerative potential, assimilative capacity has been derived. Assimilative Capacity, was taken inversely related to pollution load and directly related to carbon sequestration, implying that areas with high CS and low PI have greater assimilative potential, guiding environmentally informed spatial development planning.

$AC = f\,(PI/CS)$

Where:

PI = Composite Pollution Index

CS = Carbon Sequestration Potential

Supportive Capacity

Supportive Capacity (SC) denotes the ability of an environment to sustain human and ecological systems by providing essential natural resources. In this study, it has been derived by integrating three core components—Land, Biodiversity, and Water—each representing a critical resource domain necessary for supporting urban life and development. Land availability was assessed through the concentration of vacant or barren land derived from LULC analysis, indicating potential for low-impact development or conservation. Biodiversity support was proxied by the extent and continuity of green spaces, (including all vegetation cover and parks, and not considering wetlands), captured via LULC datasets. Water availability was evaluated using spatial data on groundwater potential zones (water availability at shallow depth and good water quality, and proximity) and surface water availability (proximity to surface water bodies with potential for drinking water extraction), derived from hydrological layers and NDWI. Surface water availability and supporting functions was assessed through a separate hydrological evaluation and was not factored into the Supportive Capacity index to avoid overlap. These components were normalized and integrated using a weighted overlay model, resulting in the Supportive Capacity (SC):

$SC = \sum(W_i \times S_i)$

Where:

W_i = weight assigned to parameter i

S_i = normalized value of parameter i

This index helps identify zones with varying degrees of resource support potential – critical for directing sustainable urban expansion and ensuring ecological balance.

Geographically Weighted Regression (GWR)

The spatial statistical technique of Geographically Weighted Regression (GWR) is used in this study to refine the estimation of Environmental Carrying Capacity (ECC) and further estimate ECC by examining the spatially varying relationships between the dependent variable (here, ECC_p) and independent variables (Ecological Sensitivity (ES), Hazard Vulnerability (HV), Development Intensity (DI), Supportive Capacity (SC), and Assimilative Capacity (AC)) across Kochi. In this study, first the grid-wise ECC Proxy Values (ECC_p) were used as the dependent variable, and independent variables included the spatial indicators (ES, HV, DI, SC, AC) which were normalized to a common scale. Further, the spatial weights matrix was constructed in ArcGIS and the GWR model was calibrated in ArcGIS's GWR tool under Spatial Analysis toolbar.

The Local R^2 values were mapped as output of GWR model to highlight areas where model performance varied; the spatial variance of coefficients were mapped to check the local influence of each factor on ECC; and the residuals were mapped and analysed to evaluate ECC model reliability.

Environmental Carrying Capacity (ECC)

The Environmental Carrying Capacity (ECC) estimation model adopted integrated the above-derived spatial indicators (Ecological Sensitivity (ES), Hazard Vulnerability (HV), Development Intensity (DI), Supportive Capacity (SC) and

Assimilative Capacity (AC)) along with LULC change metrics. All parameters were normalized to a common scale and weighted through AHP based on their influence on carrying capacity (with correction coefficient applied, where required). The composite Environmental Carrying Capacity (ECC) index was then computed using GIS raster overlay techniques, enabling classification of the study area into five ECC classes: Very Low, Low, Moderate, High, and Very High Carrying Capacity Zones. This zonation facilitated spatial prioritization for sustainable planning interventions and decision-making.

$ECC = \sum(W_i \times N_i)$

Where:

N_i = Individual normalized indicator values (ES, HV, DI, AC, SC)

W_i = Weights assigned to the dimension using AHP

This model provided a proxy ECC, which served as a preliminary estimation. To enhance the spatial accuracy and account for local contextual variations, this proxy ECC was further refined through Geographically Weighted Regression (GWR). The GWR-based model captured spatial heterogeneity in the relationship between ECC and its influencing factors, thereby enabling a more location-specific and realistic representation of carrying capacity across the study area. Localized insights from planning experts from Kochi were taken to help fine-tune the ECC map and guide spatially responsive planning strategies.

Results and Discussion

Synthesizing Kochi's urban-environmental interactions based on systems approach, the urban-environmental pressures – including land cover change, surface water contamination, groundwater depletion, habitat fragmentation, and air quality decline – are evident. The state of the environment indicates a gradual deterioration, with only ad-hoc response mechanisms in place, primarily reactive rather than proactive. This comprehensive 'systems' understanding formed the foundation for evaluating ecological sensitivity, vulnerability, and development intensity – key components for assessing the future Environmental Carrying Capacity (ECC) of the Kochi region, in addition to the environmental response mechanisms.

The Ecological Sensitivity (ES) assessment for the Kochi region reveals a significant spatial variation in ecological resilience. The output indicates that approximately 41% of the study area demonstrates high to very high ecological sensitivity, of which a substantial share (47.80%) is constituted by inland water bodies, reflecting their critical ecological role and vulnerability to anthropogenic stress. In contrast, low to moderate sensitivity zones account for 59% of the area, predominantly in the urbanizable fringes and peri-urban belts. These areas are potentially suitable for future urbanization, provided sustainable development controls are ensured. However, the very low ES zones—though only 2%—and low ES areas (11%) are located near regions experiencing increasing developmental pressure, leading to rapid degradation of natural ecosystems, particularly water bodies. This trend signifies a decline in the ecological health of natural assets, thereby adversely impacting the supporting and assimilative capacities of the environment.

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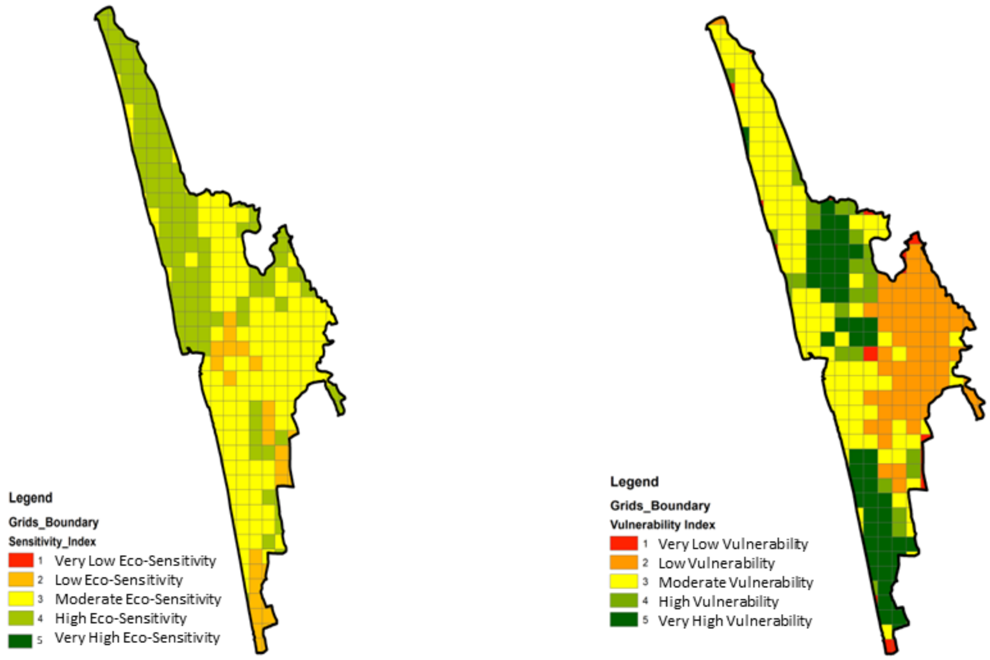
Figure 5: Output maps indicating Ecological Sensitivity (Left), and Hazard Vulnerability in Kochi (Right)



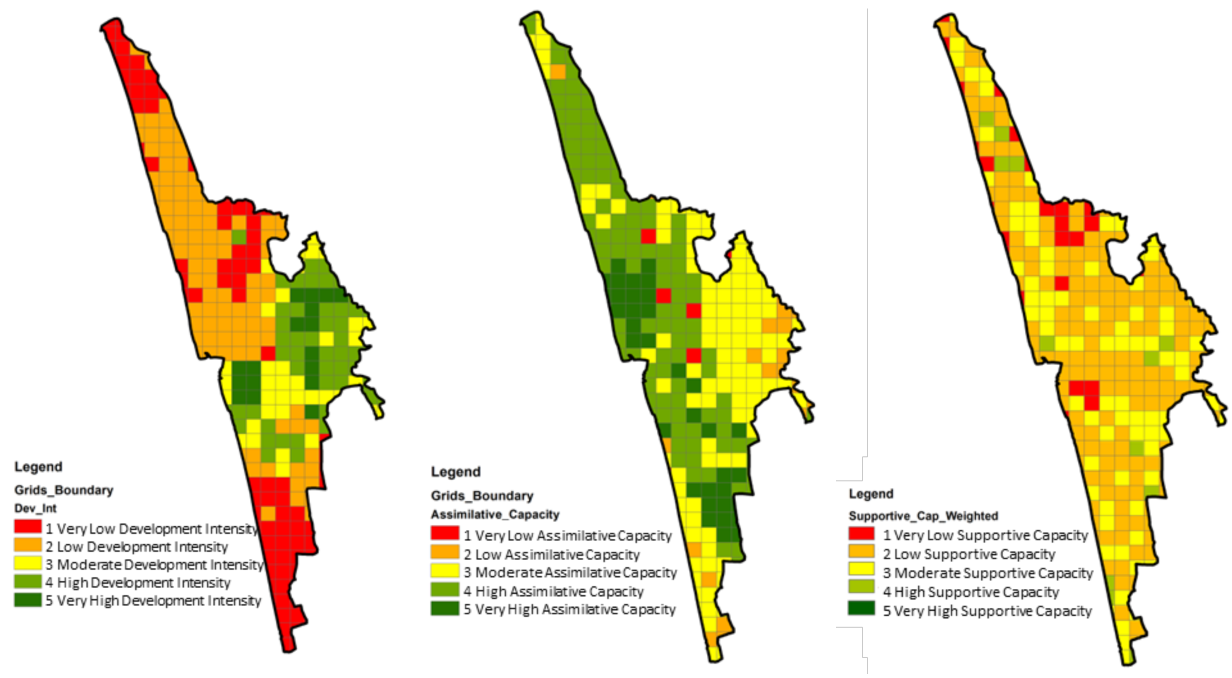
Source: Data Analysis output

Hazard Vulnerability (HV) assessment results for Kochi reveal that approximately 19% of the region falls under 'Very High Vulnerability', largely concentrated along low-lying coastal and flood-prone zones with high population density and environmental fragility. Moderately vulnerable zones (37%) and high-vulnerability zones (10%) further indicate that more than half the study area is significantly susceptible to hazards. Urban zones with dense population clusters and inadequate drainage infrastructure exhibit a compounded risk, especially under projected climate change scenarios involving sea-level rise, extreme rainfall events, and saltwater intrusion. Such spatial vulnerability adversely impacts the region's Environmental Carrying Capacity (ECC). High HV zones typically have reduced resilience, limiting the environment's ability to sustain additional development without ecological degradation or increased disaster risk. This inverse relationship between HV and ECC implies that areas with elevated hazard vulnerability are less suitable for future urbanization unless mitigative and adaptive measures are proactively implemented.

The Development Intensity (DI) was computed for the Kochi region to understand the spatial variation in the extent and concentration of urban development. The spatial pattern of DI indicates that the central and eastern sectors of the region occupied by the Kochi Municipal Corporation Area registers high development intensity (17% highly developed, and 6% faces very high DI concentrated within the urban core), marking a concentrated hub of human activity, while the surrounding Gram Panchayats (GPs) exhibit low to very low DI, reflecting limited development. Spatial analysis shows that 32% of the region falls under very low DI, and 33% under low DI, largely outside the municipal limits. In contrast, 12% of the area is moderately developed. From the perspective of ECC, DI exhibits a parabolic relationship – where very low and very high DI levels are both sub-optimal. Moderate levels of development often offer a balance between ecological preservation and urban utility, supporting sustainable land use. However, high DI zones tend to exert excessive pressure on ecological and infrastructural systems, leading to reduced resilience, environmental degradation, and decreasing the further growth suitability. Conversely, areas with extremely low development intensity in Kochi also lack essential infrastructure and economic drivers, limiting their support capacity. High DI zones exhibit negative interactions with Ecological Sensitivity (ES), Hazard Vulnerability (HV), Assimilative Capacity (AC), and Supportive Capacity (SC), reinforcing the need for controlled, well-planned development to safeguard long-term environmental sustainability.

Assimilative Capacity (AC) has been assessed using two primary indicators: Carbon Sequestration Potential, modeled through the InVEST Carbon Storage Model (Sharma et al., 2024), and the Composite Pollution Index (CPI), derived from aggregated secondary environmental pollution data. The spatial evaluation indicates that wetland areas, owing to their natural vegetative cover and hydrological functions, demonstrate the highest carbon sequestration potential, contributing significantly to the assimilative function. Further, with increased vegetation observed between 2011 and 2021, carbon sequestration has increased by 10%, underscoring the role of green infrastructure in enhancing assimilative functions. The spatial map reveals that only 6% of the region is classified as having very low AC, whereas a substantial 39% falls under high AC and 37% under moderate AC, indicating relatively strong ecological buffering potential across the region. However, zones with high CPI coincide with urban core areas, suggesting reduced AC due to elevated pollution loads. Notably, the eastern coastal stretch and the southern tip of the study area record 'very high' pollution loads, exacerbating environmental pressure in areas already facing land use intensification.

Figure 6: Output maps indicating Development Intensity (Left), Assimilative Capacity (Centre) and Supportive Capacity in Kochi (Right)

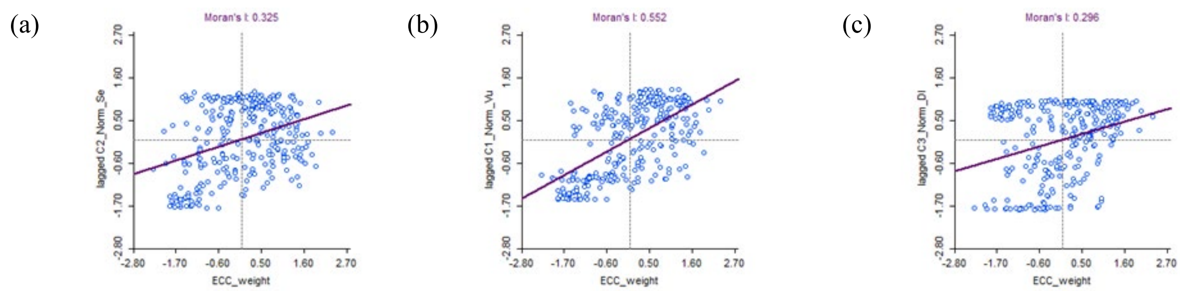


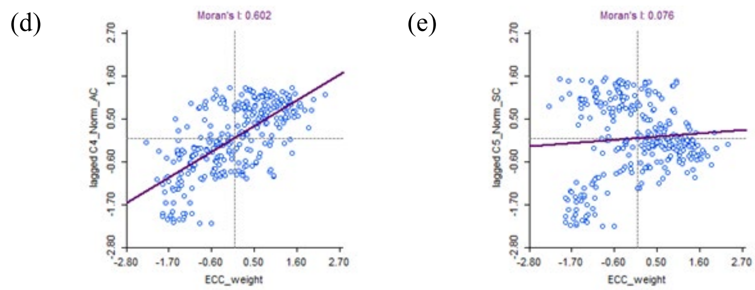
Source: Data Analysis output

The Supportive Capacity (SC) analysis reveals that a significant proportion—nearly 86%—of the study area falls within the low to moderate SC categories, indicating limited spatial potential to support increased urban loads without ecological stress. Only isolated patches in the peripheral regions exhibit relatively higher SC, mainly due to better groundwater prospects and higher green cover. Despite its relevance, Supportive Capacity (SC) demonstrates a weak correlation with the overall Environmental Carrying Capacity (ECC) in Kochi, as urban development trends appear to override resource limitations, especially in core city zones.

The Environmental Carrying Capacity (ECC) for the Kochi region was initially assessed by integrating normalized indicators such as Ecological Sensitivity, Hazard Vulnerability, Development Intensity, Assimilative Capacity, and Supportive Capacity. This proxy ECC index (here mentioned as ECC_p) served as a preliminary spatial understanding of areas under environmental stress or tolerance. Further, to understand the spatial association and the interactions between Environmental Carrying Capacity (ECC) and its constituent dimensions, a Bivariate Local Moran's I analysis was conducted. The analysis examined ECC correlation with the five key dimensions: Ecological Sensitivity (ES), Hazard Vulnerability (HV), Development Intensity (DI), Assimilative Capacity (AC), and Supportive Capacity (SC).

Figure 7: Bivariate Moran's I scatter plot showing the spatial correlation between Environmental Carrying Capacity (ECC) and (a) Ecological Sensitivity (ES), (b)Hazard Vulnerability (HV), (c) Development Intensity, (d) Assimilative Capacity, (e) Supportive Capacity in Kochi.





Moran's I value for:

ECC_p and ES – 0.325
ECC_p and HV – 0.552
ECC_p and DI – 0.296
ECC_p and AC – 0.602
ECC_p and SC – 0.076

Source: Data Analysis output

As illustrated in the Bivariate Moran's I scatterplots, the strongest positive spatial autocorrelation was observed between ECC and Assimilative Capacity (Moran's I = 0.602), followed by Hazard Vulnerability (0.552) and Ecological Sensitivity (0.325), indicating that regions with higher values of these parameters tend to coincide with higher ECC scores. Development Intensity showed a relatively weak but positive association (0.296), whereas Supportive Capacity had a very low correlation (0.076), suggesting limited spatial congruence. These findings imply that while pollution assimilation, vulnerability and sensitivity significantly influence ECC, resource availability (SC) is not a major spatial determinant within the study area.

However, to more accurately reflect spatial heterogeneity and local variation in influencing parameters, Geographically Weighted Regression (GWR) was applied to provide a dynamic and location-specific future ECC estimation, by incorporating local regression coefficients which are often overlooked by conventional models instead of a global fixed relationship.

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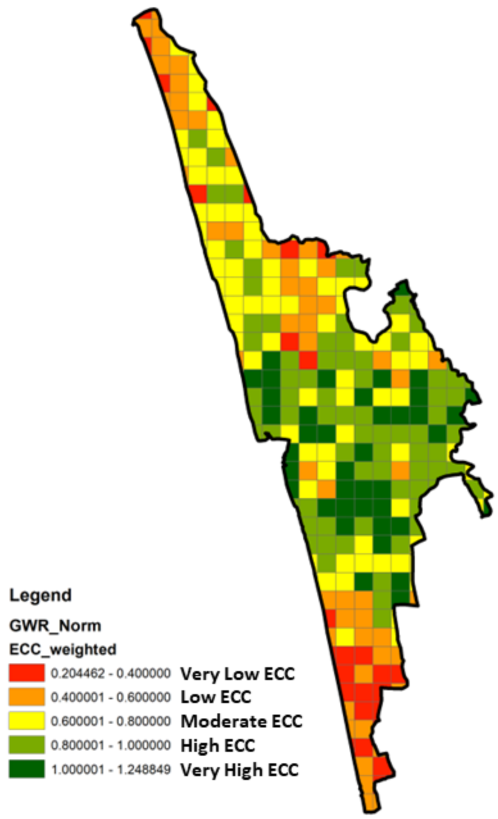
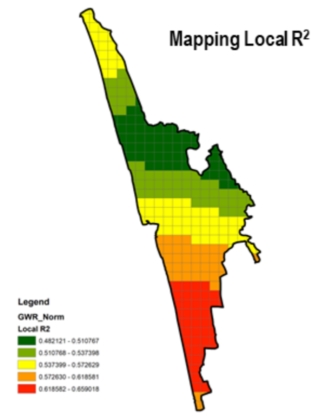
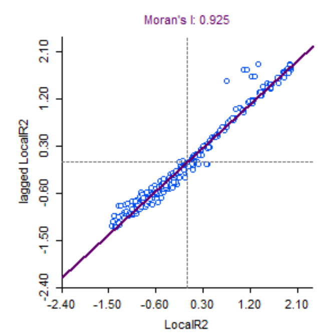
Figure 8: Output map indicating Environmental Carrying Capacity of Kochi (Left), Mapping of R^2 values (Top Right) and Moran's I scatter plot for Local R^2 values from the Geographically Weighted Regression (GWR) model. (Right)





R2 values ranges between Very strong fit (0.7 to 1) to Moderate fit (0.3 to 0.5)

Moran's I: 0.925, very close to 1: STRONG MODEL FIT



Source: Data Analysis output

The resulting final GWR enhanced ECC, which is the future Environmental Carrying capacity for Kochi region, highlights a higher ECC potential in central and southeastern zones, while peripheral, south-western and sparsely developed but sensitive northern regions exhibit low ECC. The high Moran's I value of 0.925 indicates a strong positive spatial autocorrelation, suggesting that areas with similar explanatory power of local variables cluster together. This underscores the spatial heterogeneity in the relationships influencing Environmental Carrying Capacity (ECC) across Kochi. Diagnostic metrics from the preliminary Ordinary Least Squares (OLS) regression indicate a strong model fit ($R^2 = 0.597$; Adjusted $R^2 = 0.564$) with Variance Inflation Factor (VIF) < 7.5, confirming minimal multi-collinearity among explanatory variables. Standardized residual mapping from OLS showed no evident spatial clustering and only negligible outliers (+/-2.5) near the edges, validating the robustness of the GWR-enhanced model developed for estimation of the future Environmental Carrying Capacity (ECC).

Conclusion and Way forward

This study presents a spatially nuanced assessment of the future Environmental Carrying Capacity (ECC) for the Kochi region by integrating the dimensions of ecological sensitivity, hazard vulnerability, development intensity, assimilative capacity, and supportive capacity. Notably, the application of Geographically Weighted Regression (GWR) enabled the estimation of a spatially adaptive ECC, capturing local variations and allowing for more refined and actionable planning decisions.

The results clearly indicate that high ecological sensitivity zones require stringent conservation and regulated development to sustain environmental integrity over time. Additionally, hazard-prone areas call for risk-sensitive spatial planning to redirect urban growth towards safer, less vulnerable zones. The spatial patterns of assimilative capacity underscore that ecological restoration—such as increasing green cover and reducing pollution loads—can significantly improve ECC. Conversely, the weak spatial correlation of supportive capacity reveals a critical oversight in resource-based planning, highlighting the urgent need to embed groundwater, green space, and land suitability considerations into future development strategies.

Moving forward, institutionalizing ECC-based planning frameworks and incorporating them into statutory spatial plans is essential to ensure that urban growth in Kochi remains within sustainable thresholds. Estimating city-region-specific ECC enables planners to recognize and respond to the unique environmental limits and vulnerabilities of a rapidly urbanizing context like Kochi. In India, where Master Plans and Development Plans often prioritize economic growth and infrastructure expansion, the integration of ecological parameters remains minimal or fragmented. Therefore, a comprehensive and integrated framework that embeds ECC considerations into spatial development planning—aligning land use, infrastructure provision, and environmental resilience – is essential to ensure long-term urban sustainability and enhance quality of life, meriting further study.

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Author Contributions

Conceptualization, R.R. and A.R.; data curation, R.R.; analysis, R.R.; methodology, R.R., and A.T.; supervision, A.R. and A.T.; writing—original draft, R.R.; writing—review and editing, R.R., A.R. and A.T.

Conflicts of Interest

The authors declare no conflict of interest.

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