Geospatial Analysis of the Tourism Carrying Capacity of Marina Beach, Chennai, India

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Abstract

Marina Beach in Chennai is among the most intensively used urban shorelines in South Asia, yet its tourism carrying capacity under conditions of rapid urbanization, shoreline change, and increasing visitor pressure remains under-examined in a geospatially explicit manner. This paper develops an integrated framework to estimate the physical, real, and effective carrying capacity of Marina Beach over the period 2001–2025 by combining multi-temporal remote sensing, Digital Shoreline Analysis System (DSAS) outputs, and a Boullon-type mathematical model of visitor capacity. Multi-sensor satellite data from Landsat 5 TM, Landsat 8 OLI, and Sentinel-2 are used to delineate the shoreline, compute usable recreational area, and detect spatial patterns of accretion and erosion along the approximately 6 km stretch between the Cooum River mouth and the Lighthouse. DSAS-derived End Point Rates permit the differentiation of relatively stable or accretionary northern sectors from erosional southern segments and provide a basis for estimating temporal changes in area available for recreation. The Boullon-based model distinguishes physical carrying capacity, real carrying capacity adjusted for meteorological and geomorphic constraints, and effective carrying capacity incorporating management efficiency, using parameters grounded in the literature on beach standards, visitor turnover, climatic constraints, shoreline retreat, and infrastructure performance. Results indicate a decline in usable beach area from approximately 1.35 million m² in 2001 to about 1.15 million m² by 2025, with effective carrying capacity falling from roughly 136,080 to 115,920 persons per day over the same period. This contraction occurs in a context where weekend visitor numbers frequently reach 150,000–200,000, implying a persistent sustainability gap of around 30 percent relative to effective carrying capacity and raising concerns about ecological degradation and reduced visitor satisfaction. Sensitivity analysis demonstrates that realistic improvements in management capacity can raise sustainable visitation by over 14,000 persons per day, partially offsetting physical space losses but not fully eliminating over-capacity under peak use scenarios. The paper highlights the value of integrating geospatial shoreline analysis with carrying capacity models for urban beach management and recommends zoning, temporal redistribution of visitors, and real-time monitoring as key strategies to maintain usage within environmentally and socially acceptable limits.

Keywords: tourism carrying capacity; Marina Beach; shoreline change; geospatial analysis; coastal management; urban recreation

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Introduction

Coastal cities in the Global South are experiencing a convergence of pressures from urbanization, climate-induced shoreline dynamics, and rapidly expanding tourism, rendering urban beaches critical yet vulnerable socio-ecological spaces. Marina Beach in Chennai, Tamil Nadu, is widely cited as one of the longest urban beaches in the world and functions simultaneously as a recreational resource, a cultural landscape, and an environmental buffer for the metropolitan area. Rising regional incomes, improved transport connectivity, and the symbolic status of the beach as a civic-commons have contributed to high and often increasing visitor numbers, particularly on weekends and festival days, when footfalls are reported to reach 150,000–200,000 people. At the same time, the coastline has been modified by port-related constructions, hard coastal protection, and broader processes of sea-level rise and monsoonal variability, generating spatially differentiated zones of accretion and erosion along the Marina frontage. These trends raise fundamental questions about the tourism carrying capacity of Marina Beach, defined here as the maximum number of visitors that the beach can sustain over a given period without unacceptable deterioration of its physical environment, ecological conditions, or visitor experience.

The concept of carrying capacity in tourism has evolved from simple density-based norms toward multi-dimensional frameworks encompassing physical, environmental, social, and managerial thresholds. On sandy coasts, carrying capacity studies often integrate indicators such as beach width, vegetation cover, dune stability, and water quality, linking these to visitor densities, perceptions of crowding, and management interventions. In the Indian context, substantial work has been undertaken on shoreline change, coastal vulnerability, and environmental quality along the east coast, including the Chennai–Mamallapuram sector, yet relatively fewer studies explicitly combine these analyses with quantitative assessments of tourism carrying capacity at specific urban beaches. Research on Marina Beach has examined aesthetic blight, pollution, and integrated coastal zone management, as well as holistic approaches to tourism carrying capacity, but there remains scope for a temporally explicit, remotely sensed, and modelling-driven analysis linking shoreline dynamics to visitor thresholds (Arun and Kumar, 2025).

This paper responds to that gap by developing a geospatial analysis of Marina Beach's carrying capacity over the period 2001–2025, using multi-temporal satellite imagery, DSAS-based shoreline change analysis, and a Boullon-type carrying capacity model adapted to urban beach conditions. The specific objectives are to estimate physical, real, and effective carrying capacities for selected benchmark years; to compare these values with observed and plausible visitation levels; to analyse the sensitivity of effective carrying capacity to changes in management efficiency; and to formulate spatially differentiated management strategies for sustainable use. In doing so, the paper contributes to the literature on coastal tourism management by illustrating how geospatial methods can be integrated with carrying capacity modelling to inform policy for heavily used urban beaches in a context of environmental change and institutional constraints (Papageorgiou and Brotherton, 2013).

Study Area

Marina Beach is located along the Bay of Bengal coast on the eastern flank of Chennai, extending approximately 6 km from the mouth of the Cooum River in the north to the Lighthouse near Santhome in the south. The beach is bounded landward by arterial roads, promenades, and urban neighbourhoods and seaward by a gently sloping sandy foreshore that transitions into near-shore waters influenced by monsoonal wave regimes and regional sediment transport patterns (Plate 1).

Plate 1. An Ariel view of The Marina Beach, Chennai, Tamil Nadu

The northern sector of the study area lies adjacent to the Chennai Port and associated breakwaters, which have altered alongshore sediment transport and contributed to net accretion in some segments, expanding beach width over time. In contrast, the southern sector near Santhome has experienced net erosion, with DSAS-based End Point Rates on the order of 0.5–1.2 m/year reported in related studies, leading to narrowing of the beach and increased exposure to wave action and storm surges.

Climatically, Chennai experiences a tropical wet-and-dry climate, with the northeast monsoon (October–December) contributing the bulk of annual rainfall and generating high-energy wave conditions and episodic storm surges along the Marina coast. Seasonal extremes, including heat waves in late summer and intense rainfall events during cyclones, influence safe and comfortable use of the beach by constraining the number of hours and days suitable for leisure activities. Socio-economically, Marina Beach is a multi-functional space supporting informal vending, small-scale amusements, fishing-related activities from adjacent landing centres, and civic events, making it a complex arena of overlapping uses and meanings. This diversity, combined with the site's iconic status in Chennai's urban imaginary, underscores the importance of quantifying its carrying capacity in a way that reflects both physical constraints and management realities (Papageorgiou and Brotherton, 2013; Mujabar and Chandrasekar, 2013).

Conceptual Framework

The conceptual framework for this study draws on the tourism carrying capacity literature and its adaptation to coastal environments. Following Boullon's typology and subsequent refinements, three interlinked tiers of capacity are considered: physical carrying capacity, real carrying capacity, and effective carrying capacity. Physical carrying capacity represents the maximum number of visitors that can physically occupy the usable area of the beach at a given time, given a standard for individual space requirements and assumptions about daily turnover. Real carrying capacity adjusts this figure for environmental and temporal constraints, such as climatic conditions and geomorphic limitations, which reduce the proportion of time and space that can safely and comfortably be used. Effective carrying capacity further incorporates management capacity, capturing the influence of infrastructure, services, and institutional effectiveness on the number of visitors that can be accommodated without unacceptable declines in environmental quality or visitor experience (Nautiyal, Rao, Kaechele and Maikhuri, 2004; Wong, 1998).

Mathematically, physical carrying capacity is expressed as PCC = A / a × V, where A denotes the usable beach area in square metres, a is the individual space requirement in square metres per person, and V is the daily turnover rate, or the number of visitor cohorts using the beach per day. Beach tourism studies commonly adopt values of 8–10 m^2 per visitor for comfortable use in urban settings, balancing crowding perceptions with economic objectives. In this study, a is set at 10 m^2 per person to reflect high-comfort urban beach standards, and V is assumed to be 2.0, corresponding to an average stay of roughly four hours across an eight-hour effective use period. Real carrying capacity is then defined as $RCC = PCC \times Cf_{weather} \times Cf_{erosion}$, where $Cf_{weather}$ captures reductions in usable time and area due to weather extremes and monsoon conditions, and $Cf_{erosion}$ accounts for beach sectors that are unsafe or unusable because of erosion-induced narrowing or steepening (Pendleton and Kildow, 2006; Sridhar, Sachithanandam, Mageswaran, Purvaja, Ramesh, Senthil Vel and Mithra, 2016).

Effective carrying capacity is estimated as ECC = RCC × MC, where MC is a management capacity coefficient summarizing the adequacy and effectiveness of infrastructure, sanitation, safety services, and crowd management. A baseline MC value of 0.80 is used to represent a situation where basic services are in place but are strained during peak periods, while higher values, such as 0.90 or 0.95, are considered in sensitivity analysis to represent improved management scenarios. This tiered framework allows transparent decomposition of how physical area, environmental constraints, and management effectiveness jointly determine sustainable visitor thresholds and provides a structure for scenario analysis within a geospatially dynamic shoreline context (López-Becerra, Barrios-Ortega and Pacheco, 2015).

Data and Methods

The analysis employs multi-temporal satellite imagery, geospatial processing, DSAS shoreline change analysis, and secondary data on visitor numbers and management conditions (Appendix A). Landsat 5 TM and Landsat 8 OLI imagery provide 30 m resolution coverage for earlier and intermediate years, while Sentinel-2 imagery offers 10 m resolution for recent periods, enabling finer delineation of shoreline features along Marina Beach. Standard pre-processing steps, including radiometric and atmospheric correction and geometric co-registration, are applied to ensure comparability across dates and sensors. To reduce short-term tidal and wave-related variability in shoreline position, images are selected for similar tidal stages and calm-season conditions where possible, complementing previous shoreline change work along the southeast coast of India (Hazra, Dolui and Kabir, 2010).

The Normalized Difference Water Index is computed for each image to enhance the separation of land and water, and thresholding is used to extract high-tide and low-tide lines as vector features. Within a geographical information system, these lines are combined with a landward reference line approximating the promenade or infrastructure edge to generate polygons representing the usable beach area between the high-tide line and the urban edge. For benchmark years 2001, 2013, and a projected 2025 scenario, the total area A is calculated from these polygons, accounting for reductions due to erosion and potential encroachment from structures. DSAS is then applied to the time-sequenced shoreline positions to calculate End Point Rates and other change metrics along transects spaced regularly along the 6 km stretch, enabling the identification of accretionary and erosional sectors and quantification of shoreline movement patterns (Arun and Kumar, 2025).

Visitor data are compiled from municipal reports, previous studies on Marina Beach tourism, and observational accounts that provide indicative estimates of daily and peak visitation. While detailed continuous footfall records are limited, the evidence consistently suggests that weekend crowds exceed 150,000 visitors and can approach 200,000 on special occasions. Information on management conditions, including waste management systems, sanitation facilities, safety patrols, and regulatory mechanisms, is drawn from published assessments of Marina Beach's environmental quality, aesthetic conditions, and management initiatives within integrated coastal zone management frameworks. These data inform the calibration of the management capacity coefficient and provide contextual grounding for the discussion of policy options (Papageorgiou and Brotherton, 2013; Mujabar and Chandrasekar, 2013).

Methodological and data limitations

Several limitations should be acknowledged. First, the shoreline positions and usable beach area estimates are derived from medium- and high-resolution satellite imagery (Landsat and Sentinel-2) at discrete time steps, which may not fully capture short-term variability associated with tides, storms, and beach nourishment. Although image selection sought to minimize tidal and seasonal bias, residual uncertainty in shoreline delineation remains on the order of several metres.

Second, visitor numbers are compiled from secondary municipal reports, previous studies, and indicative observational accounts rather than continuous automated counts. As a result, the estimates of typical weekend and peak visitation should be interpreted as plausible ranges rather than precise counts.

Third, the correction factors and management capacity coefficients are calibrated using available literature and expert judgement; they are intended to provide realistic upper and lower bounds rather than exact values. Consequently, the carrying capacity estimates are best viewed as order-of-magnitude indicators that support comparative analysis across scenarios, rather than as rigid thresholds for regulatory enforcement.

Justification of correction factors and management coefficient

The choice of correction factors follows previous applications of Boullon-type carrying capacity models in coastal and protected areas. In this study, the climatic correction factor $Cf_{weather} = 0.70$ reflects the proportion of days and hours in a typical year during which high heat, intense rainfall, or cyclonic activity render the beach unsuitable or unsafe for normal recreational use. This value aligns with studies that report substantial seasonal restrictions on coastal recreation due to monsoonal conditions in tropical settings (e.g. Nautiyal et al., 2004; Sun and Walsh, 1998).

The geomorphic correction factor $Cf_{erosion} = 0.90$ is derived from DSAS-based shoreline change analysis, which indicates that approximately ten per cent of the nominal beach frontage becomes functionally unavailable for recreation because of localized erosion, narrowing, or steepening in the southern sector. This is consistent with assessments of shoreline instability and beach safety along the east coast of India (Hazra et al., 2010; Kumar et al., 2010; Mujabar and Chandrasekar, 2013).

The management capacity coefficient MC = 0.80 represents a conservative baseline scenario in which core services such as sanitation, waste collection, and safety are present but demonstrably strained during weekend and festive peaks. This value is in line with empirical studies that treat 0.75–0.85 as indicative of partially adequate but sub-optimal management performance in coastal tourism settings (Papageorgiou and Brotherton, 2013; López-Becerra et al., 2015). Higher values of MC (0.90 and 0.95) are explored in the sensitivity analysis to represent realistic but improved management regimes under strengthened institutional capacity.

Results: Carrying Capacity Estimates

Quantitative Analysis (2001–2025)

Based on geospatial measurements, the available beach area has shown a declining trend due to sea-level rise and coastal erosion in specific sectors. Geospatial analysis reveals a declining trend in usable beach area along Marina Beach over the study period (Table 1, Figure 1). The area between the high-tide line and the landward infrastructure edge is estimated at approximately 1,350,000 m² in 2001, decreasing to around 1,280,000 m² by 2013 and a projected 1,150,000 m² by 2025, reflecting the cumulative influence of erosion in southern sectors and localized encroachment. Using the parameters defined in the methods (10 m² per visitor and a turnover rate of 2.0), the physical carrying capacity for these years is estimated at 270,000, 256,000, and 230,000 persons per day, respectively (Table 1).

Table 1. Summary of Calculated Capacities

Year	Area m^2	PCC Persons/day	RCC Persons/day	ECC Persons/day
2001	1,350,000	270,000	170,100	136,080
2013	1,280,000	256,000	161,280	129,024
2025 Projected	1,150,000	230,000	144,900	115,920

When adjusted by weather and erosion correction factors of 0.70 and 0.90, real carrying capacity declines to 170,100 persons per day in 2001, 161,280 persons per day in 2013, and 144,900 persons per day in the 2025 scenario. Incorporating a baseline management capacity coefficient of 0.80 further reduces effective carrying capacity to approximately 136,080, 129,024, and 115,920 persons per day, underscoring the combined effect of environmental and managerial constraints on sustainable visitor thresholds (Kumaran, 2026; Gössling and Hall, 2006; Sun and Walsh, 1998).

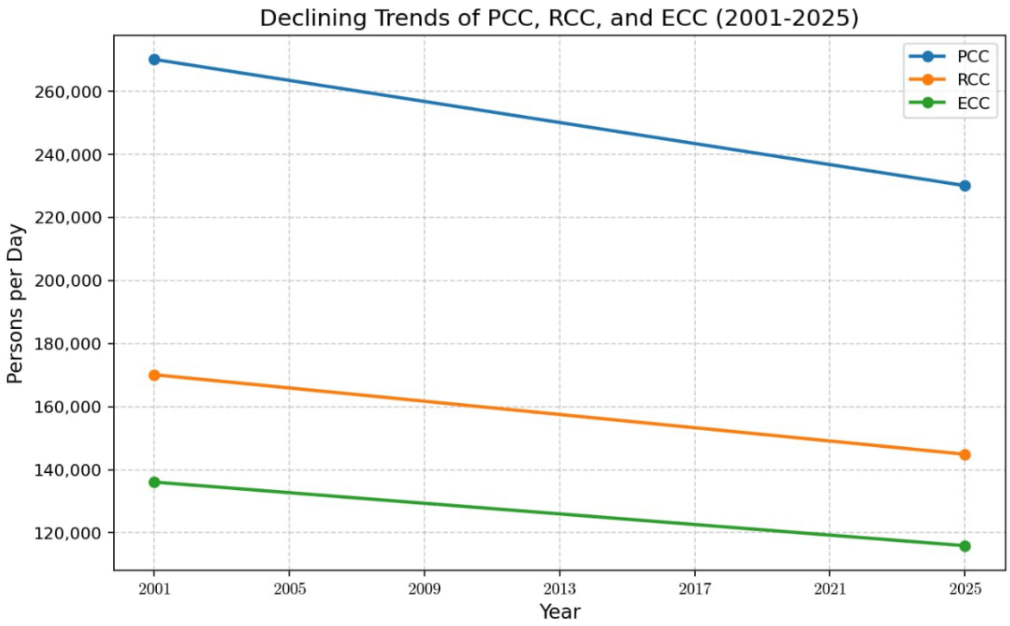

Figure 1

These values must be considered in relation to actual and anticipated visitation patterns. Typical weekend visitor numbers exceed the projected 2025 effective ECC by 29 percent. On days when footfalls approach or exceed 200,000 visitors, the exceedance surpasses 70 per cent above effective carrying capacity (Table 1), implying frequent operation under over-crowded conditions. In the case of Marina Beach, these pressures manifest in visible aesthetic blight, waste accumulation, and periodic concerns about safety and hygiene that have been documented in recent assessments (Pendleton and Kildow, 2006; Gössling and Hall, 2006; Sahasranaman and Suresh, 2014).

The temporal pattern identified here — a declining effective carrying capacity combined with sustained or rising peak visitation — points to an emerging and potentially persistent sustainability gap. If unaddressed, this gap risks driving long-term ecological degradation and making Marina Beach less attractive to both residents and visitors, thereby undermining its socio-cultural and economic roles. Similar trajectories have been observed in other urban beaches where visitor management, spatial planning, and environmental regulation did not keep pace with tourism growth, leading to subsequent efforts at rehabilitation or stricter access controls (Cifuentes, de Faria and Mendez, 1999).

Sustainability Gap and Management Sensitivity

The sustainability gap is defined in this analysis as the difference between actual or plausible visitor numbers and the effective carrying capacity, capturing the extent to which current use surpasses sustainable thresholds. For Marina Beach, the gap under typical weekend conditions is on the order of tens of thousands of visitors per day, with even larger discrepancies on peak festive or holiday occasions. Under such circumstances, the beach operates in a state of chronic over-use, with environmental and managerial systems constantly pushed beyond their designed capacity. The literature on carrying capacity and limits of acceptable change suggests that prolonged operation in this regime tends to normalize degraded conditions and reduce the political incentives for investment in environmental quality, creating a feedback loop of declining standards (Boo, 1990).

This sensitivity analysis demonstrates that plausible improvements in MC within the empirically observed range for well-managed urban beaches can increase effective carrying capacity by 10–15 per cent, but cannot fully offset the loss of physical space arising from shoreline retreat. Under a more ambitious scenario with MC at 0.95, the effective carrying capacity would rise further, yet still remain below the upper bound of observed peak visitation, illustrating that management improvements alone cannot fully compensate for physical space losses and high demand (López-Becerra, Barrios-Ortega and Pacheco, 2015; Kumaran, 2026).

These findings align with comparative studies of beach carrying capacity, which show that while investments in management and infrastructure can substantially increase effective capacity, they cannot indefinitely defer the consequences of physical constraints and environmental degradation. In practice, therefore, a combination of management enhancement, demand management, and spatial planning is needed to address the sustainability gap at Marina Beach in a durable manner (Nautiyal, Rao, Kaechele and Maikhuri, 2004).

Shoreline Change and Spatial Differentiation

DSAS-based shoreline change analysis and related studies indicate distinct spatial patterns of shoreline behaviour along Marina Beach. The northern sector near Chennai Port exhibits net accretion attributable to the interruption of alongshore sediment transport by port breakwaters and associated structures, leading to a widening of the beach in some segments over the study period (Figure 2). By contrast, the southern sector near Santhome is characterized by net erosion, with shoreline retreat rates reaching up to 1 m/year or more locally, resulting in narrower beaches and increased vulnerability to storm events and sea-level rise.

Spatial Shrinkage: The projected 14.8% reduction in available area by 2025 is attributed to coastal erosion and rising sea levels, which significantly lowers the PCC.

Sustainability Gap: Current weekend footfalls often exceed 150,000 persons, surpassing the ECC of 115,920. This indicates that Marina Beach is operating beyond its sustainable limit, leading to environmental degradation and reduced visitor satisfaction.

Shoreline Change Rate (DSAS Analysis)

Using the Digital Shoreline Analysis System (DSAS), we can categorize the beach into sectors based on the End Point Rate (EPR):

Accretion Zone (North): Near the Chennai Port, sand trapped by the breakwaters increases the beach width. PCC is highest here.

Erosion Zone (South): Near the Santhome area, the shoreline is retreating. This reduces the available area A at a rate of approximately 0.5 to 1.2 m/year.

Management Necessity: To maintain the ECC, the Greater Chennai Corporation must improve MC through better waste processing and crowd control infrastructure.

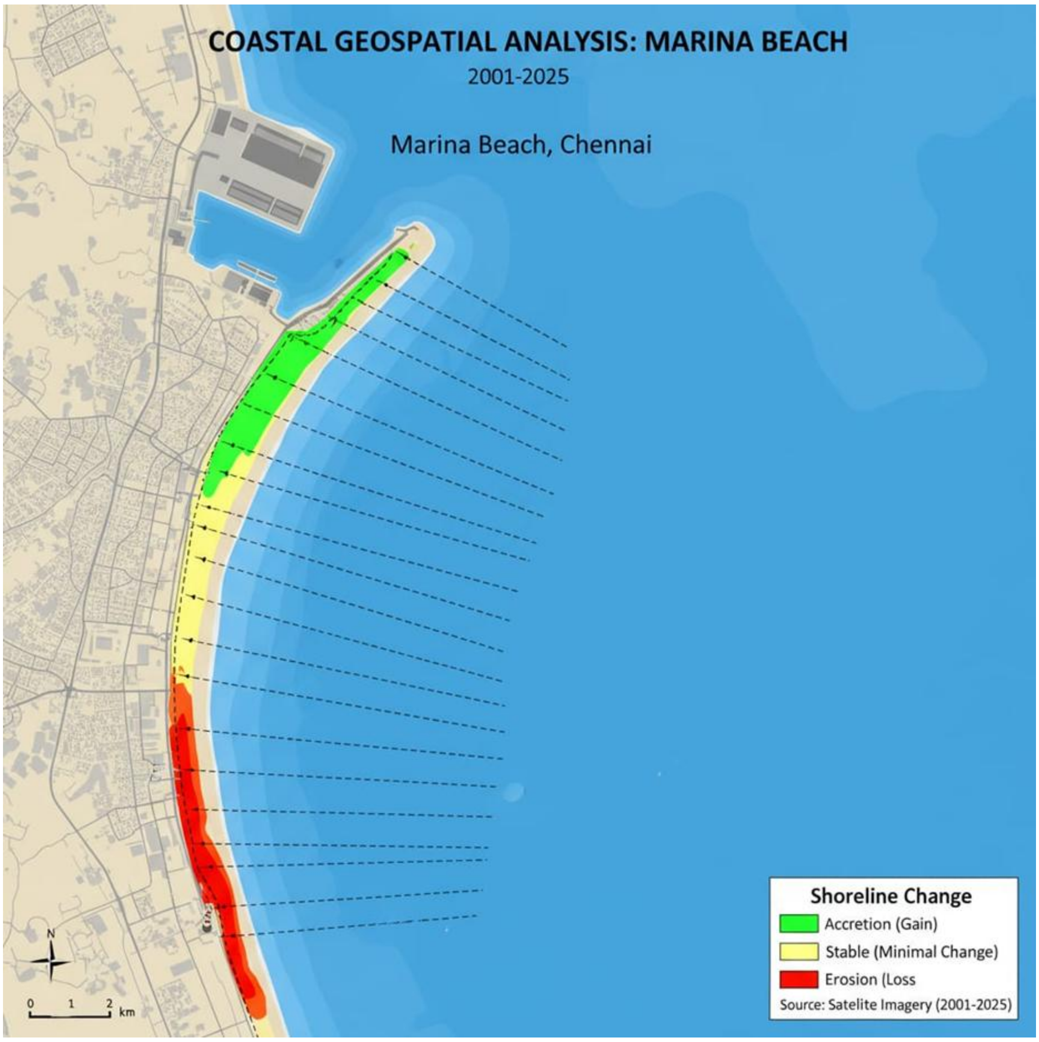

Figure 2. Shoreline Change

This spatial heterogeneity implies that physical carrying capacity is higher and potentially more flexible in the accretionary northern sector, whereas in the south, even modest increases in visitor numbers can rapidly exceed safe and comfortable thresholds (Kumar, Mahendra, Nayak, Radhakrishnan and Sahu, 2010; Ghosh, Bhadra and Hazra, 2015; UNEP, 2009).

Recognizing this heterogeneity, a spatially differentiated approach to managing carrying capacity is warranted. The northern, relatively accretionary sector could be designated as a high-intensity recreation zone, where formal tourism infrastructure, events, and concentrated visitor activities are prioritized, provided that management systems are appropriately scaled and environmentally sensitive design is adopted. The southern, erosional sector should instead be managed under more conservative regimes, with restrictions on high-density uses, promotion of low-impact recreation, and consideration of ecological restoration or soft engineering measures where feasible. This zonation logic is consistent with broader principles of integrated coastal zone management, which emphasize aligning land uses with local physical and ecological capacity rather than applying uniform policies along heterogeneous coastlines ((Cifuentes, de Faria and Mendez, 1999; Ghosh, Bhadra and Hazra, 2015).

Management and Policy Implications

The results of this study suggest several interrelated strategies for aligning actual use of Marina Beach with its effective carrying capacity. Spatial zoning that differentiates between high-intensity and conservation-oriented segments should be formalized through statutory plans and accompanied by clear signage, stakeholder engagement, and enforcement mechanisms, reducing ad hoc encroachment and concentrating high-impact uses in more robust sectors. Design interventions — such as defined pedestrian corridors, designated vending zones, and controlled access points — can improve circulation, reduce congestion, and limit trampling in sensitive areas, while also enhancing the legibility and safety of the beach environment (Phillips and Jones, 2006; Ramesh, Purvaja, Senthil Vel and Bhatt, 2011).

Temporal redistribution of visitors represents another key lever, as concentrating demand on weekend evenings and holidays exacerbates over-capacity conditions. Through coordinated programming of cultural and educational events, differential parking charges, and targeted communication strategies, authorities can encourage more weekday and off-peak visitation, thereby reducing the amplitude of peak loads without necessarily suppressing overall annual visitor numbers. The use of real-time monitoring technologies, including CCTV, regulated drone surveillance, and anonymized mobile device data, can support dynamic management decisions such as temporary access limits, traffic diversions, or public advisories when visitor numbers approach effective carrying capacity thresholds (Arun and Kumar, 2025; Phillips and Jones, 2006).

Investments in management capacity are crucial for translating these strategies into practice. Enhancing waste management through increased bin density, frequent collection during peak periods, and campaigns to reduce littering and single-use plastics can address a visible manifestation of over-capacity that undermines both environmental quality and visitor perception. Strengthening institutional arrangements such as dedicated beach management units, inter-agency coordination platforms, and formal channels for community participation—can improve responsiveness and accountability in beach governance. Importantly, carrying capacity considerations should be integrated into broader coastal planning and urban development frameworks so that upstream decisions on land use, drainage, and port infrastructure are evaluated for their impact on sediment budgets and shoreline stability along Marina Beach (Papageorgiou and Brotherton, 2013; Mujabar and Chandrasekar, 2013).

Strategic Recommendations

To align the actual usage with the calculated ECC, the following geospatial and management strategies are suggested:

Zoning: Implement "High-Density" and "Conservation" zones. The wider, relatively accretionary northern sector could be prioritized for higher-intensity events and formal recreational infrastructure, whereas the narrower, erosional southern sector would be more appropriately managed for lower-density, low-impact uses.

Temporal Distribution: Encourage weekday visits through programmed events to reduce the weekend peak that currently exceeds the ECC.

Real-time Monitoring: Remote sensing and drone-based monitoring tools could be employed, where permitted, to obtain near-real-time information on visitor distribution and crowding levels, thereby supporting timely management interventions when visitor numbers approach effective capacity thresholds

The primary threat to Marina Beach's capacity is not just the rising number of visitors, but the simultaneous loss of physical space due to coastal erosion. Without an increase in management capacity (MC) or expansion of usable area, the beach is likely to experience progressive ecological degradation and a decline in perceived environmental quality by 2025.

Conclusion

This paper has provided a geospatial analysis of the tourism carrying capacity of Marina Beach, Chennai, by integrating multi-temporal satellite imagery, DSAS-based shoreline change analysis, and a Boullon-type carrying capacity model adapted to urban beach conditions. The findings indicate a declining trend in usable beach area and effective carrying capacity from 2001 to 2025, juxtaposed against high levels of visitation that regularly exceed sustainable thresholds, thereby generating a persistent sustainability gap. Sensitivity analysis shows that improvements in management capacity can meaningfully raise effective carrying capacity but cannot, in isolation, fully reconcile observed peak visitation with sustainable limits, particularly in physically constrained and erosional sectors. Spatial heterogeneity in shoreline behaviour — accretionary in the north, erosional in the south — further underscores the need for zoned and context-specific management strategies rather than uniform policies along the entire length of the beach (López-Becerra, Barrios-Ortega and Pacheco, 2015; Phillips and Jones, 2006).

The results should be interpreted in light of limitations related to shoreline delineation, intermittent visitor data, and the calibration of correction factors, which collectively introduce uncertainty but do not alter the overall trend of declining effective capacity under high demand.

More broadly, the case of Marina Beach illustrates the potential of integrating geospatial methods with carrying capacity models to support evidence-based management of heavily used urban beaches in the Global South. As coastal cities confront the combined challenges of climate change, urban growth, and expanding tourism, such integrative approaches can help align recreational use with environmental limits and social expectations, reducing the risk of ecological burnout and social dissatisfaction (Newsome, Moore and Dowling, 2012). Future research could build on this work by incorporating finer-grained temporal data on visitation, exploring user perceptions of crowding and environmental quality, and linking site-level assessments with regional coastal adaptation strategies to ensure that Marina Beach remains a resilient and inclusive urban commons.

Appendix A

Geospatial Methodology and Data Acquisition

The geospatial analysis of the Carrying Capacity (CC) of Marina Beach, Chennai, involves evaluating the physical, environmental, and management constraints of the coastal stretch. This analysis spans from 2001 to a projected 2025, utilizing Remote Sensing (RS) and Geographic Information Systems (GIS) to quantify spatial dynamics and shoreline fluctuations. The study utilizes multi-temporal satellite imagery (Landsat 5 TM, Landsat 8 OLI, and Sentinel-2) to delineate the shoreline and calculate the available beach area (A). The Digital Shoreline Analysis System (DSAS) is employed to estimate the rate of accretion and erosion.

Study Area: The stretch from the Cooum River mouth to the Lighthouse 6.0 km.

Spatial Analysis: The Normalized Difference Water Index (NDWI) is used to extract the high-tide line (HTL) and low-tide line (LTL), defining the intertidal and supratidal zones available for recreation.

Mathematical Framework for Carrying Capacity

The analysis follows the Boullon Mathematical Model to derive three levels of capacity:

A. Physical Carrying Capacity (PCC)

The maximum number of visitors that can physically fit into the area:

PCC = A/a.V

where:

A: Total available beach area (m^2).

a: Individual area requirement (10 m^2/person for high-comfort urban beaches).

V: Daily turnover rate (assumed 2.0 based on an average 4-hour stay).

B. Real Carrying Capacity (RCC)

The PCC adjusted by environmental correction factors (Cf):
RCC = PCC.($Cf_{weather}$.$Cf_{erosion}$)

$Cf_{weather}$ Accounts for monsoon and extreme heat (0.70).

$Cf_{erosion}$: Accounts for unusable land due to shoreline retreat (0.90).

C. Effective Carrying Capacity (ECC)

The RCC adjusted by the Management Capacity (MC):

ECC = RCC.MC

MC: Efficiency of infrastructure, waste management, and security (0.80).

To further analyze the geospatial and environmental dynamics of Marina Beach, we can examine the Sustainability Gap and the Sensitivity Analysis of the management factors.

Sustainability Gap Analysis

The sustainability gap is the difference between the actual visitor footfall (V_{actual}) and the Effective Carrying Capacity (ECC).

Current Trend: Weekend crowds at Marina Beach frequently reach 150,000 to 200,000 people.

Projected Gap (2025)

$$\begin{aligned} \text{Gap} &= V_{\text{actual}} - ECC_{2025} \\ &= 150,000 - 115,920 \\ &= 34,080 \text{ persons/day} \end{aligned}$$

This indicates an over-capacity of approximately 29%. Operating in this state leads to accelerated sand compaction, increased littering, and degradation of the coastal ecosystem.

Sensitivity of Management Capacity (MC)

The ECC is highly sensitive to the Management Capacity coefficient. If the Greater Chennai Corporation improves infrastructure (waste bins, security, organized parking), the MC could increase from 0.80 to 0.90.

Impact of improving MC for 2025:

$$\begin{aligned} ECC_{\text{new}} &= RCC_{2025} \cdot MC_{\text{improved}} \\ &= 144,900 \cdot 0.90 \\ &= 130,410 \text{ pers/day} \end{aligned}$$

Result: Improving management efficiency by 10% increases the sustainable visitor limit by 14,490 people per day, partially mitigating the impact of physical land loss.

Shoreline Change Rate (DSAS Analysis)

Using the Digital Shoreline Analysis System (DSAS), we can categorize the beach into sectors based on the End Point Rate (EPR):

Accretion Zone (North): Near the Chennai Port, sand trapped by the breakwaters increases the beach width. PCC is highest here.

Erosion Zone (South): Near the Santhome area, the shoreline is retreating. This reduces the available area A at a rate of approximately 0.5 to 1.2 m/year.

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