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# Urban Expansion and Mangrove Loss in Mumbai Since 2000: Evaluating the Environmental Costs of Coastal Development

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**ABSTRACT**

This paper analyses the connection between urbanisation and mangrove degradation in Mumbai over the period of 2001-2023 with a particular interest in assessing the environmental cost of coastal development. Mangrove ecosystems are of great importance in protecting the coast, maintaining biodiversity and controlling climate although they continue to be endangered by urbanisation of the coastal cities. The paper takes a secondary quantitative methodology in which it uses the mangrove cover data from the Forest Survey of India and population data as an indicator of urbanisation. Python was used to analyse trends and correlation between mangrove cover and population growth using time-series analysis, comparative evaluation, growth rate analysis, and regression. The results indicate that there is a non-linear trend in the dynamics of mangroves. The mangrove cover started to rise around the beginning of the 2000s, and it peaked in 2017-2019, after which it began to decline. Population growth was at a constant level over the study period as a result of unremitting urban growth. The findings indicate that conservation activities and regulatory systems paid off in the short term but as cities continue to grow. The article establishes some of the relevant environmental expenses relating to the degradation of mangroves as an escalated risk of flooding, loss of biodiversity, decrease in the ability to sequester carbon, and socio-economic effects on coastal populations. These results reveal the multifaceted and dynamic interplay in which recovery on a short-term basis may lead to vulnerability on a long-term basis. This study can be used to better understand the issue of sustainability in coastal areas of rapidly urbanising cities by connecting the analysis of the environment with the implications of the analysis. The study concludes that urban expansion is increasingly undermining long-term ecological sustainability despite short-term conservation gains.

*Keywords: Mangrove Ecosystems, Urban Expansion, Mumbai, Urbanisation, and Carbon Sequestration.*

# 1. INTRODUCTION

## 1.1 Background

Mumbai is a major example of the global context of mangrove depletion and preservation, especially in fast-growing urban mangrove coastal areas. The world has seen a diminution in the mangrove ecosystems in the past decades with the general coverage dwindling by about 3.4 per cent from 1996 to 2020. The loss has been largely in land-use change, approximately 62% of the total loss associated with the increasing pressure of urbanisation. The population of people in low-elevation coastal areas has increased from 360 million in 1990 to 900 million in 2020[1]. This has been the case in Mumbai its population has increased by an average of 65 per cent in the same time span from 12.2 million to 20.4 million[2].

This high rate of growth has been a great boost to land and infrastructure leading to some cases where mangrove areas have been encroached. India is maintaining the current mangrove cover of about 4991.68 km² with Maharashtra at 315.09 km. Though Maharashtra has registered a marginal net growth of approximately 12.39 km² of mangrove forests in the period between 2021 and 2023, the growth masks localised losses especially in the Mumbai-Thane metropolitan area where urban stress is still high[3].

## 1.2 Problem Statement

Mumbai is currently facing high levels of mangrove degradation in the light of massive urban growth. The city is one of the fastest growing of the coastal megacities under a lot of pressure to support the growth in population needs, development of the infrastructure and growth of the economy. This has seen the ecologically sensitive coastal lands being turned into developed land at the mangroves' expense[4]. The Coastal Regulation Zone (CRZ) policies are aimed at ensuring limited development within the vulnerable areas. These policies have not been applied uniformly, and in most cases they have proved to be ineffective[5]. Moreover, state-scale changes in mangrove cover can hide local losses in densely urbanised areas like Mumbai. This is a pressing crisis like the way to harmonize the growth of the city and environmental friendliness in a highly sensitive city to climate-related disasters like flooding and sea level rise. Mangrove loss is known to be a factor in the natural coastal defences as well as the increase in the

[1] Shaham, Adam. "Evaluating a Decade of Mangrove Restorations in Mumbai." Consilience 27 (2024): 1-24. https://journals.library.columbia.edu/index.php/consilience/article/download/12431/6503
[2] World Population Review. “Mumbai, India Population 2024.” Worldpopulationreview.com, 2024. https://worldpopulationreview.com/cities/india/mumbai.
[3] Pib.gov.in. “Parliament Question: - Mangrove Conservation,” 2025. https://www.pib.gov.in/PressReleasePage.aspx?PRID=2146358®=3&lanmangroves'g=2.
[4] Jhade, Praveen Sharma. "Computational analysis of mangrove domestication: impact on coastal flora and fauna in Mumbai." (2023). DOI: doi.org/10.18011/2023.12(2).1903.1915
[5] Kasthala, Sindhuja, D. Parthasarathy, K. Narayanan, and Arun B. Inamdar. “A Methodological Framework for Assessing Anthropogenic Vulnerability Caused by the Coastal Regulation Zone Rules in India.” *Discover Oceans* 2, no. 1 (October 9, 2025). https://doi.org/10.1007/s44289-025-00079-0.

social and financial vulnerability particularly to communities that depend on coastal resources[6]. The biggest question is how urbanization, limitation of governance, and policy formulation collide to result in a mangrove loss, and how it adds to loss across the entire environment to the Mumbai coastal ecosystem.

### 1.3 Aim and Objectives

The major aim of this research paper is to establish a relationship between urban expansion and mangrove loss in Mumbai since 2000.

- To analyse the extent and pattern of urban expansion in Mumbai from 2000
- To assess the changes in mangrove cover within the Mumbai metropolitan region
- To identify the key drivers contributing to mangrove loss, including infrastructure development and land-use change
- To assess the environmental impacts of mangrove degradation in relation to coastal development

### 1.4 Research Questions

The following research questions are identified through this research paper.

- How has urban expansion engaged in changes in mangrove cover in Mumbai since 2000?
- What are the major drivers that contribute to mangrove loss in Mumbai?
- How existing coastal governance frameworks and policies are effective in protecting mangrove ecosystems?
- What environmental impacts have resulted from mangrove degradation in the coastal development?

### 1.5 Significance of the Study

This research is important since it help to enhance the understanding of the intricate correlation between the growth and sustainability of the environment in cities that are undergoing booming growth. Mumbai is among the highly populated cities in the developing world and it gives a critical background on which the development pressure on mangroves can be considered. The study captures a phase of accelerated urbanisation and infrastructure growth for a period since 2000 that offers insights into contemporary environmental challenges. The research is important as it highlights the environmental costs associated with coastal development such as increased flood risk, biodiversity loss, and low climate resilience.

Despite the extensive research carried out on the mangrove ecosystems and urbanisation, there has been gap in the integrated, urban level study that comprises of the temporal changes and the environmental and governance issues in the rapidly urbanising, coast cities like Mumbai. The literature tends to concentrate on either regional trends or ecological factors and neglects the interacting effects of urban growth, effectiveness of policies and environmental cost. The local disappearance of mangroves in very urbanised areas might be concealed at the state level. This paper fills this gap by offering a longitudinal analysis (2001-2023) of the mangrove cover with respect to urbanisation, as depended on population as a proxy

[6] Akram, Hina, Shoaib Hussain, Purabi Mazumdar, Kah Ooi Chua, Talib E Butt, and Jennifer Ann Harikrishna. "Mangrove Health: A Review of Functions, Threats, and Challenges Associated with Mangrove Management Practices." *Forests* 14, no. 9 (August 23, 2023): 1698–98. https://doi.org/10.3390/f14091698.

measure. It is also valuable in that it incorporates an environmental cost lens that has been utilized to demonstrate the impacts of the flood risk, loss of biodiversity and climate impacts among others, therefore, giving a comprehensive image of the dilemma of coastal sustainability in Mumbai.

## 2. LITERATURE REVIEW

### 2.1 Urban Expansion and Coastal Cities

The growth of cities has become one of the greatest sources of environmental change in coastal cities throughout the world. The land-use change has increased with urbanisation in developing regions and is identified by the conversion of natural environments into built environments[7]. This is mostly attributable to population increase, industrialisation and increasing infrastructure pressures that subject precarious conditions of the coastlines.

Researchers focused on the coastal metropolitan ties that are particularly vulnerable because of the peculiarities of their geographic location, near water bodies, and reliant on ecosystem services[8]. With the ever-growing urban population, these urban areas encounter more problems like land congestion, environmental damage and increased levels of vulnerability to climatic hazards[9]. The spread of impervious surfaces, such as roads, buildings and industrial areas was also defined as one of the causes of the ecological imbalance, as the cover of vegetation declines, and the hydrological cycle is interrupted by the spread.

Recent research also shows that urban development largely changes the ecological environmental quality such as increased land surface temperature, decreased green cover and decreased moisture availability[10]. These transformations tend to be associated with urban heat islands and ecosystem services decline. A study of the metropolitan area of Mumbai shows that over time, the ecological conditions have been degraded by a measurable amount due to the expansion of built-up areas and the reduction of vegetation[11]. Furthermore, the literature highlights how the expansion of urban areas in the coastal regions is not only a physical process, but also a socio-political process. It is determined by the system of governance, planning policies, and economy-related priorities[12]. The environmentally destructive modes of

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[12] Rabbani, M. M. Golam, Matthew Cotton, and Richard Friend. "Climate Change and Non-Migration — Exploring the Role of Place Relations in Rural and Coastal Bangladesh." *Population and Environment*, May 21, 2022. https://doi.org/10.1007/s11111-022-00402-3.

development are usually tolerated due to weak regulatory implementation and disjointed institutional structures.

**2.2 Mangrove Ecosystems and Environmental Value**

Mangrove ecosystems represent highly specialised coastal environments that are composed of trees, shrubs, and related vegetation[13]. These materials are adapted to the intertidal zones where sea and land interact. A few studies explain that mangrove ecosystems are among the most biologically diverse wetland systems that support a wide range of flora and fauna due to their unique ecological conditions and nutrient-rich environments[14]. Their structural complexity creates ideal habitats for numerous marine and terrestrial species that make them critical for biodiversity conservation. A study of Padmakumar and Murugan stated that the most significant environmental values of mangroves lie in their role in carbon sequestration[15]. Mangrove wetlands are recognised for their high capacity to store carbon in both sediment and biomass that contribute majorly to climate change mitigation. This "blue carbon" role of mangroves makes it an important ecosystem that helps lower carbon dioxide concentration in the atmosphere and enhance the resilience of global climate[16]. Mangroves also contribute significantly to ensuring coastal protection and the dense root systems stabilise the shoreline by minimising the erosion. This protective function is particularly important in coastal urban regions where the climate-related hazards are increasing[17]. Other authors clarified that mangrove ecosystem is also important in ensuring quality of water through the filtration of impurities and the suspension of particles in water. This filtration system helps in improving the water quality of the coastal waters and support the marine ecosystems around the waters such as seagrass beds[18]. Mangrove covers a vast area of wetlands along the coast and is very important in ensuring the balance of the eco-system. Mumbai shares a significant area of mangrove with 66 sq. km along its coastline areas such as Malim, Vikhroli, and Gorai. Mangrove ecosystems have experienced considerable degradation despite their ecological importance[19]. A substantial proportion of

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[19] Shaham, Adam. "Evaluating a Decade of Mangrove Restorations in Mumbai." Consilience 27 (2024): 1-24. https://journals.library.columbia.edu/index.php/consilience/article/download/12431/6503

global mangrove cover has been lost or altered due to anthropogenic pressures such as land reclamation, urban expansion, and pollution.

**2.3 Coastal Development Impacts**

Coastal development has been widely recognised as a primary driver of environmental degradation in coastal regions. The direct physical conversion of intertidal lands is the key mechanism through which it occurs[20]. These areas are frequently transformed for agricultural, aquaculture, industrial estates, ports, tourism developments, and other coastal developments. Once these tidal lands are filled then mangroves are completely removed or prevented from regenerating. Coastal development alters the natural land-usage patterns and disrupts ecological processes other than land conversion[21]. It has been shown that reclamation and construction processes disrupt tidal processes and hydrological connectivity. All these are vital towards the survival and regeneration of mangroves[22]. For the case of Mumbai, large-scale infrastructure projects and real-estate expansion have intensified these disruptions. These can be the cause of fragmentation and degradation of mangrove habitats. Environmental effects of such development are huge and even the destruction of mangroves can be detrimental to the environment[23]. Some of these damages can include diminishing the natural coastal defenses, increasing the susceptibility to flooding, and storm surges. Change of natural landscapes, which are permeable, to impervious surfaces further increases the flood risk because they lessen the absorption and capacity to drain water. The study recommends that the growth of the coastline may also enhance pollution like construction projects, industrial effluence, and littering. Coastal development affects both the environment and the socio-economic effects. The loss of the mangrove ecosystem implies that communities which depend on the coastal area as their income source, particularly fishermen communities and informal communities residing along the coastal cities may be impacted negatively[24]. The literature also shows that the costal growth is core in economic growth and urban expansion by the physical transformation of mangrove lands. This creates a clear illustration of the pressing need to have more sustainable planning strategies, which put more emphasis on ecosystem conservation and development goals[25].

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### 2.4 Mumbai Mangroves

Mumbai has a long history of study of its mangrove ecosystem because of the high rate of urban growth and the city of Mumbai being situated in a prone coastal area. The current studies predicted Mumbai to be a key example on the change between the coastal ecosystem and urbanisation[26]. The literature highlights the ecological importance of mangroves and emphasises their role in different areas. A few of such areas are water quality regulation, flood mitigation, biodiversity conservation, and fisheries support. Ecological change in empirical research is a mixed view[27]. Other studies report a significant loss and degradation of mangrove cover due to land reclamation, development of infrastructure, pollution and encroachment. These activities have changed the intertidal areas and changed the hydrological cycle required in mangrove regeneration. Recent evidence suggests that in Mumbai, the cover of mangrove has grown indicating that the restoration projects and conservation activities have brought tangible results in some places[28]. Research also highlights the rich biodiversity supported by Mumbai's mangroves. A few places such as Airoli and Vikhroli are identified as ecologically significant zones. The diverse species such as birds, aquatic organisms, and migratory species such as flamingoes live in this place[29]. Studies also indicate both progressive and limitations from a governance perspective. Maharashtra has developed a dedicated institutional framework for mangrove protection and conservation efforts. Regulatory frameworks such as Coastal Regulation Zone (CRZ) provisions continue to face implementation challenges such as ongoing encroachment and weak enforcement. Lastly, the literature suggests that conservation measures have supported the localised improvements, high urbanisation, and the limitation of governance pose significant challenges[30]. This underscores the fact that more integrated and flexible ways are needed to achieve the sustainability of the mangrove ecosystems of Mumbai in the long term.

### 2.5 Research Gap Identification

Although a growing body of literature exists on mangrove ecosystems and urban expansion in Mumbai but several important research gaps remain. Most studies focus highly on either ecological assessment or policy frameworks. There is a limited integration of these dimensions such as assessment of how urban expansion, ecological outcomes, and governance mechanisms interact over time. Most studies rely on descriptive or spatial analysis with limited statistical modelling. Many studies depend heavily on technical or spatial analysis approaches rather than providing attention to the broader environmental cost of coastal development. There is a low number of critical analyses that explain the coexistence of degradation and

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[28] Puthucherril, Tony George. "Adapting to Sea Level Rise: Is India On- or Off-Track?" *Frontiers in Marine Science* 12 (May 30, 2025). https://doi.org/10.3389/fmars.2025.1516241.

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restoration within the same urban landscape. Governance-related studies often emphasise regulatory frameworks such as CRZ policies but provide limited evaluation of their practical effectiveness in Mumbai.

## 3. METHODOLOGY

### 3.1 Research Design

The current study uses a quantitative, secondary data-driven research design, to examine the temporal changes in the mangrove cover in Mumbai and Maharashtra and to examine their relationship with the urbanisation trends. An analytical approach used is time series analysis to analyse and compare patterns and changes in the extent of mangroves between 2001 and 2023. The paper also involves a comparative approach with Mumbai with the rest of Maharashtra, to put the local trends into the state-scale dynamics.

### 3.2 Data Sources

The research is done on secondary data sourced to the Forest Survey of India by providing consecutive editions of the India State of Forest Report (ISFR). These are periodic and credible reports on mangrove cover across India through remote sensing with satellites. The data on the mangrove area (in km²) in Maharashtra and Mumbai were summed up on the selected years during 2001-2023. Moreover, population statistics were added to serve as a proxy measure of urbanisation. Population is used as a proxy for urbanisation due to the strong association between demographic growth and spatial expansion in urban studies[31]. However, it does not directly capture built-up area or land-use transformation. The population figures were estimated using the official census figures and interpolated estimates to maintain continuity between the non-census years.

### 3.3 Sampling Technique

The non-probability purposive method of sampling is used in this study which relies on the choice of certain geographic units and periods of time which are pertinent to the aims of the research. The study uses secondary data that has aggregate-level data as opposed to sampling individuals or households: sampling is used in terms of case and time selection. The geographic focus is intentionally narrowed down to Mumbai and state of Maharashtra since Mumbai is a fast-urbanising coastal megacity and, Maharashtra offers a wider regional perspective in comparison. This is permitting the case-oriented method of analysis, in which Mumbai is the main unit of analysis and Maharashtra a comparative yardstick. Regarding time sampling, the study has a time-series sampling approach, where discrete years of observation between 2001 and 2023 are picked according to the availability of consistent and reliable data in the form of official reports. These time points are matched to reporting periods within secondary data sources, and make them comparable across years. Purposive sampling is applicable considering that the research targets to examine certain dynamics of the environment and urbanisation instead of making generalisations to all regions. It is a way of making sure that the chosen data are pertinent, credible and consistent with the objectives of the research. Nevertheless, it is admitted that purposive sampling can

[31] Zhang, Yaowei. “Research on the Relationship Between Population and Urban Development in Jinan Based on Statistical Modeling.” Journal of Education, Humanities and Social Sciences 59 (October 2025): 28–33. https://doi.org/10.54097/c4zvnf90.

result in a reduced extrapolation of the results to non-selected cases. Nevertheless, the method is reasonable because the research is about the context-specific environmental change in a large city port.

### 3.4 Data Collection Methods

The only data collection method used is secondary data, whereby officially published datasets used to provide the required reliability, consistency, and comparability over time. The main source of mangrove information is the India State of Forest Report (ISFR) released by the Forest Survey of India that reports on periodic evaluations of forest and mangrove cover in remote sensing techniques of satellite use. The mangrove area data were extracted out of different editions of the ISFR that spanned the years of a portion of the study (2001-2023). The procedures adopted in these reports to classify and estimate are standard and therefore the measurements are similar over time. Besides ecological data, population data were also gathered to indicate the urbanisation trends. These figures were obtained as official ones like the Census of India, and were supplemented with estimates on intercensal to achieve continuity on non-census years.

### 3.5 Data Analysis Techniques

A quantitative approach to the analysis of data is used in this research to analyse the mangrove cover changes and their relationship to urbanisation from 2001 to 2023. The data were analysed using Python and visualised using data libraries. Trend analysis using time series was done to assess an upward level and downward trend of change in mangrove cover throughout a period of time. The differences between Mumbai and Maharashtra were compared to analyse them within a broader regional specificity. The growth rate was calculated by finding out the percentage change in the mangrove cover and population that showed the rate at which the ecosystem varied. To examine the relationship between urbanisation and the mangroves dynamics, the population and the mangrove area were correlated. Additionally, simple linear regression model was applied to analyze the trend of this relationship. Time-series analysis captures temporal trends, while correlation and regression quantify statistical associations between urbanisation proxy and mangrove dynamics. Lastly, per capita availability of mangroves was determined, in order to understand ecological pressure in the backdrop of population growth. All these methods offer a strong and systemic methodology of examination of environmental change in an urbanising coastal setting.

### 3.6 Ethical Considerations

The present work depends solely on secondary data, which can be found in publicly available and authoritative sources, such as the Forest Survey of India and the Census of India. As no primary data involving human participants were collected, issues such as informed consent and confidentiality do not directly apply. The ethical issues has carefully maintained because all the data that were used in the study was presented in an appropriate manner, interpreted appropriately and cited. The prevention of data manipulation, misrepresentation or the selection of which results to report is paid proper attention. Data processing and analysis processes are also transparent in the study, which allows finding reproducibility and verifiability.

### 3.7 Limitations

There are a few limitations of this study. The analysis is based on secondary data acquired through official sources, but these data might not be able to reflect fine-scale spatial variations and the localised changes that can occur in the mangrove ecosystems. The temporal data is not yearly data but is available only for the selected years, and the accuracy of trend analysis may be compromised. Second, the proxy is a population that does not measure built-up area or land-use change directly, but it only measures urbanisation. Although population growth suggests urban pressure, it does not necessarily capture the intricacy of urban expansion processes like developing infrastructure, reclaiming land, and industrialisation. The satellite-based mangrove data used in this study may not capture fine-scale spatial variations or localised degradation, particularly in highly urbanised zones. This creates a scale mismatch between regional mangrove estimates and micro-level urban encroachment. As a result, localised losses in Mumbai may be underestimated despite stable or increasing state-level trends.

## 4. RESULTS

### 4.1 Temporal Trends in Mangrove Cover

The mangrove cover in Maharashtra and Mumbai has experienced non-linear growth with fluctuations during the temporal analysis of the mangrove cover in the area between the years 2001 and 2023. Mangrove cover in Mumbai in mangrove cover since there were about 27 km² in 2001 and a high of about 66 km² between 2017 and 2019. This growing number of stage points towards a more successful conservation activity and increased ecological awareness over time. Still, the decrease is minimal because comparing to 2019 the mangrove cover was reduced to approximately 60 km² in 2023, which demonstrates the potential new stressors on the coastal ecosystems. Maharashtra, on the other hand, shows a greater and sustained growth in the mangrove cover. The time-series graph in Figure A1 presents year on the horizontal axis and mangrove cover on the vertical axis, illustrating the recent decline (see Figure A1, Appendix).

### 4.2 Comparative Analysis: Mumbai vs Maharashtra

The area expands from about 118 km² in 2001 to over 300 km² by 2017, reaching a peak of approximately 320 km² in 2019. Though there is a slight negative trend observed in 2021, the general trend is strongly positive, with the mangrove cover stabilising at more than 300 km² in 2023. The mangrove cover in both Mumbai and Maharashtra has been compared and it was found that there were immense differences in the size and growth pattern. The mangrove extent in Maharashtra is significantly greater between the two years and since 2001, reaching more than 300 km² after 2017. Mumbai is experiencing a more modest yet significant growth of 27 km² to an ultimate high of 66 km² and thereafter a slight drop to 60 km² in 2023. Although the two regions show general growth, Maharashtra is steadier on the trend, but Mumbai is more erratic. This indicates that local urban stresses in the city of Mumbai can affect mangrove stability instead of the patterns over the larger area. The comparative graph in Figure A2 contrasts mangrove cover between Mumbai and Maharashtra, highlighting differences in scale and growth patterns (see Figure A2, Appendix).

### 4.3 Population Growth and Urbanisation Trends

The population trends of the city of Mumbai show that the population growth has been constant and unabated within the period of study which is an indication of the ongoing urbanisation. The demographic level is steadily increasing since it stood at about 15.7 million in 1999 and above 21 million in 2023. This positive trend reflects the growing city pressures and booming demand for land, infrastructure, and resources in the city. On the other hand, the trend of mangrove cover is more variable. Although the area covered with mangroves is observed to increase slowly over the period between the early 2000s and reach its peak around 2019 (see Figure A2, Appendix).

### 4.4 Relationship Between Population and Mangrove Cover

The relationship between population increases and mangrove cover in Mumbai has larger implications on urbanisation and the environment at large. The population has been growing steadily with an approximate of 15.7 million in 1999 to 21.3 million in 2023. This shows a continuous pressure on urban expansion and rising pressure on coastal resources. Mangrove cover also increased from 27 km² in 2001 to a peak of 66 km² in 2019. While the population goes beyond 20 million the mangrove cover declined slightly to 60 km² in 2023. This shows that urbanisation may create new pressure on the ecosystem of the mangrove. The findings suggest a complex interaction between urbanisation and mangrove dynamics. Figure A3 shows the association between population (x-axis) and mangrove area (y-axis) through the scatter plot and a regression line shows the direction and strength of the association (see Figure A3, Appendix).

### 4.5 Growth Rate and Change Analysis

The growth rate and change analysis of mangrove cover in Mumbai shows a pattern of fluctuating ecological dynamics as compared to the relatively stable growth of the population. Mangrove growth rates vary significantly across the study periods, and mangrove cover declined sharply by 20.59 per cent in 2001. During 2003 and 2005 a sharp increase of 18.52 per cent and 25 per cent respectively. This upward trend does not remain constant and mangrove growth stabilises at 0 per cent during 2011, 2013, and 2019. A decline of 1.52 per cent has been observed in 2021, and a sharp decrease of 7.69 per cent in 2023 (see Table A1, Appendix). But the population growth remains stable and positive throughout the period that varies from 2 per cent to 4 per cent annually. The mangrove share of Mumbai among Maharashtra declines from 31.48 per cent in 1999 to 19.05 per cent in 2023 (see Table A2, Appendix). Lastly, these findings highlighted that inconsistent mangrove growth occurs along with continuous urban expansion.

### 4.6 Statistical Analysis of Population and Mangrove Cover

In order to explore more the relationship between the urbanisation and mangrove dynamics in Mumbai further, statistical analysis was done through correlation and regression analysis. Pearson correlation coefficient between population and mangrove area was observed to be $r = 0.916$, which shows a strong positive correlation between population and mangrove area. This implies that population increases, on average corresponded to an increase in mangrove cover during the study period (see Table A3,

Appendix). A simple linear regression analysis was performed to explore this relationship in greater detail. The estimated regression equation is:

Mangrove Area = $-85.28 + 7.17 \times 10^{-6}$ (Population)

This model gave the $R^2$ value of 0.840, which means that about 84 percent of thevariation in mangrove cover is statistically associated with population variation in the dataset. This indicates a rather good model fit. The additional statistical test indicates that the correlation is statistically significant ($p < 0.001$), which proves that population is a significant predictor of mangrove variation in the dataset (see Table A5, Appendix). Nevertheless, this solid statistical correlation is to be construed with care, despite its existence. The positive relationship does not show that urbanisation directly enhances the mangrove cover instead, it shows a complex interrelation that is affected by conservation, regulation and temporal interactions. The statistical evidence does support the fact that population growth and mangrove cover have a strong relationship, however, it also indicates that there is a need to consider the bigger ecological and governance picture in explaining such a relationship. Although a strong correlation is observed, this does not imply a causal relationship. The association may be influenced by external factors such as conservation policies, regulatory enforcement, and ecological restoration efforts.

### 4.7 Key Findings and Emerging Patterns

Through the analysis, there are an identified set of interrelated patterns to the dynamics of mangroves and urbanisation in Mumbai. The mangrove cover has been on an upward trend in the long term, which has indicated a period of ecological improvement. This is not a linear trend and is distinguished by stagnation periods in recent downfall. Contrary to the growing population, which is on a steady increasing trend that indicates a growing urban sprawl and development strain. One of the major trends that the analysis results in is the discrepancy between ecological and demographic trends of recent years. Although the population continues to increase and yet there are no corresponding increases in the mangrove cover. Relative coverage of mangrove in Mumbai vis-a-vis the total mangrove cover in Maharashtra has recorded a decrease over the years and these trends suggest a change towards recovery to stress potential.

## 5. DISCUSSION

### 5.1 Interpretation of Findings

The findings of this study reveal an evolving relationship between mangrove dynamics and urbanisation in Mumbai. The overall increase in mangrove cover from the early 2000s to the late 2010s suggests that conservative initiatives, high environmental awareness, and regulatory frameworks[32]. This period of growth indicates that mangrove ecosystems can coexist with urban expansion under certain conditions.

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The recent decline in mangrove cover after 2019 shows a potential shift in this balance[33]. The growth of the mangroves fails to maintain its initial pattern irrespective of ceaseless population growth and the growing urbanisation. This deviation indicates that there is a threshold of ecological strength of the mangrove beyond which the pressure of the anthropogenic factor starts to reach conservation benefits[34]. This variation in growth rates once again reinforces the notion that the mangrove ecosystems in Mumbai are very vulnerable to outer shocks. The eroding proportion of mangrove cover over Mumbai in comparison to Maharashtra points to the imbalance of ecological benefits[35]. Maharashtra is witnessing significant growth, and the metropolitan centre is more unstable.

**5.2 Comparison with Literature**

The findings of this study largely align with existing literature on the mangrove ecosystem and urbanisation but in some cases also show some differences. The results indicate that increasing population and urbanisation put pressure on coastal ecosystems[36]. Previous research has identified infrastructure development, urban expansion, and land-use change as key drivers of mangrove degradation[37]. This is justified by the gradual increase in population that has been noticed in Mumbai. There are also a few studies that report that mangrove expansion was constant in 2000 to 2010 [38]. Although some of the studies demonstrate the adverse trends and this deviation indicates that the mangrove ecosystems might exhibit short-term resilience with the implementation of effective conservation practices[39]. The policy interventions, restoration initiatives, and legal protections contributed to this temporary improvement in mangrove cover.

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### 5.3 Drivers of Mangrove Loss

The analysis reflects that mangrove loss in Mumbai is driven by a combination of urbanisation-related pressures and environmental stressors. One of the most significant sources is the rapid urbanism with respect to the continuous population growth[40].. Beach lands tend to be encroached, reclaimed and converted to inter tidal lands, and in so doing, mangrove lands are obliterated. Infrastructure development also adds to mangrove degradation, and even the development of infrastructures like roads, bridges and coastal developments requires clearance of mangrove covers[41]. All these activities may also alter tidal flows and sediment patterns that play a vital role in the regeneration and survival of mangroves. Urban and industrial sources of pollution and waste release have adverse impacts on the mangrove ecosystems as they reduce the water quality and soil quality[42]. This environmental pressure compromises the resilience of mangrove and diminishes their ability to recuperate after disruptions. The results of the study, and especially the recent negative trend in mangrove cover despite the constant increase in population indicate that these drivers are gaining momentum. Although conservation efforts have helped achieve the past improvements, the rise in the pressures of the urban areas seems to be working against long-term sustainability, and more integrated and effective management practices are required.

### 5.4 Governance Issues

This study has demonstrated that there are serious governance issues that exist in the management and protection of mangrove ecosystems in Mumbai and especially during the high rate of urbanisation. Despite the fact that the value of the initial increase in the mangrove cover is a positive outcome of the regulation frameworks, the recent changes towards declines are alarming in regards to the gaps of enforcement and implementation. A Coastal Regulation Zone (CRZ) Notification (2019) establishes the mangrove areas as ecologically sensitive areas with harsh development restrictions, is one of the governing tools[43].

Nevertheless, encroachment and infrastructure projects in coastal areas are clear evidence of lax enforcement and surveillance with high-pressure urban areas such as Mumbai being the worst. The level of success in preventing habitat loss can be hampered by procedural delays, exemptions, and development priorities. Cases involving environmental groups have also helped to create awareness of the gaps in

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governance and imposing compliance using judicial interventions. The second issue is founded on the fragmented institutional framework, which encompasses agencies like Maharashtra Coastal Zone Management Authority (MCZMA), municipal agencies, and forest agencies[44].

### 5.5 Environmental Implications

The findings of this study point to significant environmental implications that arise from the dynamics of mangrove cover in Mumbai. One of the important implications is the reduction in coastal protection, and mangroves are the natural protectors against environmental hazards[45]. Mangrove cover can reduce by a middle range resulting in a great exposure to extreme weather in Mumbai. Mangrove ecosystems support a wide range of biodiversity such as birds, fish, and other marine species[46]. Declinations and fluctuations in mangrove cover can disrupt these habitats that can be the cause of potential losses in species diversity. This also has some impact on livelihoods dependent on marine and coastal resources. The other interesting implication is linked to management of climate and mangroves are a valuable source of carbon sink. Any reduction in their size, may undermine this capability, aiding in the increasing amount of greenhouse gases and climatic vulnerability. At last, the study ends up and concludes that the destruction of mangroves can lead to environmental risks in the long run in Mumbai coast.

### 5.6 Mechanisms of Mangrove Change

The general trends in the mangrove cover observed in Mumbai can be explained by a phase-based process through the impact of policy, urbanisation, and ecological constraints. During the initial period (early 2000s to mid-2010s), the cover of mangroves grew continuously. This expansion may be explained by more effective conservation policies, the legal protection that is provided by CRZ regulations and the rise in environmental awareness. The recovery and growth of mangrove habitats were perhaps during this period due to the activity of regulatory enforcement and restoration. The second phase (c. 20172019) represents a time of relative stability, with mangrove cover at its highest, and growth decelerating. This implied a saturation limit, to which there was a limitation of available space and ecological capacity to extend its expansion. Mangroves cover decreases in the third phase (after 2019) although the population is growing. Urban pressure that is increasing, such as development of infrastructure, land-use alteration and encroachment on coastal lands, drives this phase. Such pressures seem to surpass the ability of current conservation interventions resulting in ecological stress and shrinkage of mangroves. On balance, this

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process indicates that there is no linear mangrove dynamics but rather the interplay of policy efficacy, urban growth and environmental limits.

## 6. ENVIRONMENTAL COST ANALYSIS

### 6.1 Flood Risk Increase

The loss of mangrove cover over the past few years is one of the high environment costs in regard to augmented flood hazard in Mumbai. Mangroves can be used as a natural barrier against the coastlines known to reduce storm surges, absorb the energy of the waves as well as controlling tidal flows. With their deterioration, this protective role is undermined, and they are more susceptible to coastal flooding during extreme weather conditions. The results of the study show that the area covered by mangrove has grown up until the late 2010s and has been experiencing some devolution in recent years because of the population growth and urbanization. This creates a condition where exposure to flood risk is increasing alongside a reduction in natural protective capacity. The environmental cost is indicated in the loss of the ecological services which can alleviate the flooding in a natural manner. The vulnerability of Mumbai to flooding has already been demonstrated by the 2017 Mumbai floods and it exposed the limitations of coastal resilience[47]. The continued degradation of mangroves can further intensify risks by weakening the natural food regulation mechanism.

### 6.2 Biodiversity Loss

The loss and seasonal variation of the mangrove cover in Mumbai is a high cost of the environment in terms of biodiversity loss. The mangrove ecosystem is one of the most bio-productive coastal parts that harbor diverse species of animals including fish, crustaceans, birds and other land-based living organisms. Their elaborate root systems offer them important feeding, breeding and shelter areas to ensure balance in ecology[48]. The instability and recent decline in mangrove cover suggest potential disruptions to these habitats. Many species are either deprived of appropriate habitats because their mangrove habitats are shrinking or getting fragmented. This affects the ecological integrity and also local livelihoods that depend on the coastal resources. The ecological importance of mangroves in supporting biodiversity has been recognised in judicial decisions such as “Bombay Environmental Action Group vs State of Maharashtra”[49]. This case shows a strong emphasis on the mangrove ecosystem. However, biodiversity degradation is a high ecological cost as it weakens the resilience of the ecosystem and diminishes the ability of coastal systems to support natural processes and human welfare in the long-run.

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### 6.3 Carbon Emissions Impact

The changing dynamics of mangrove cover in Mumbai represent a major environmental cost in terms of carbon emission and climate regulation loss. Mangrove ecosystems are the most efficient carbon sinks that can store higher carbon than terrestrial forests. Mangroves from the coastal regions of Maharashtra have shown three times more carbon consumption than non-mangrove areas[50]. This function is important because the Thane Creek region alone sequesters approximately 2688 tonnes of carbon annually[51]. Vikhroli are estimated to store around 6 lakh tonnes of carbon annually that demonstrate the large-scale carbon storage capacity of urban mangrove ecosystems[52]. The environmental costs are twofold that the future absorption of carbon can be reduced, and also lead to the release of previously stored carbon into the atmosphere. The degradation of mangroves in a city like Mumbai represents a hidden climate cost that weakens the natural carbon regulation mechanisms and increases long-term vulnerability to climate change.

### 6.4 Socio-economic Costs

Destruction and variability of mangrove cover in Mumbai have resulted in huge socio-economic expenses for high rate of urbanisation and population congestion. Mangroves offer vital ecosystem services, directly and indirectly beneficial to human well-being. Their degradation translates to both economic and social losses. Among the major socio-economic effects is on the livelihood of the coastal communities, particularly fishing communities. Mangroves are also the breeding and primary areas of numerous fish and crustacean species. Hence, their deterioration may decrease the fish stock and lead to a negative impact on local incomes. This poses a long-term economic exposure to the communities that depend on the coastal ecosystems[53]. The depletion of mangrove cover predisposes people to environmental risks, especially floods. The cost of infrastructure damages, housing damages, and utility damages are likely to rise as the natural coastal buffers are becoming weaker. This becomes a burden both to an individual and the government agencies since it would lead to a higher investment in artificial flood control systems and other disaster management systems. Additionally, deteriorating environmental conditions as a result of the loss of mangroves may decrease the overall liveability of urban areas, impacting human health and rising expenses in terms of pollution and environmental destruction. The socio-economic impact of the loss of mangroves in Mumbai is complex as it involves a decrease in livelihood, a rise in disaster-related costs, and deterioration of the environment and thus the human consequences of ecological change.

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## 7. POLICY IMPLEMENTATION AND RECOMMENDATIONS

The results of this study demonstrate how urgent it is to have extensive and evolutional policy responses in order to preserve the mangrove ecosystem in Mumbai. The positive trend in the mangrove cover within the first and middle study period is an indication of the positive impact of regulatory frameworks. The latest downturn presents the shortcomings of existing strategies and the need to have a more comprehensive system of governance. One of the key policy implications is what should be done to reinforce the implementation of the environmental regulations as provided in CRZ (2019). Although mangroves are classified as ecologically sensitive areas with strict development restrictions but the enforcement gaps still persist. Land reclamation, enforcement gaps, and infrastructure expansion continue to pose threats to mangrove ecosystems[54]. The government should implement some of the modern surveillance systems like GIS mapping, remote sensing, and real time surveillance systems to identify the offenders. Accountability can also be enhanced by regular audits and more severe punishment of non-compliance. The second important suggestion is that there should be a shift in the approach of managing the coastal zone towards integrated coastal zone management (ICZM). The prevailing governance system is divided into various agencies with several agencies with overlapping roles like forest departments, municipalities, and coastal agencies taking the same responsibilities. This often leads to coordination difficulty and policies inefficiencies. Effective mangrove conservation requires an integrated framework of governance, which would enable inter-agencies cooperation, sharing of data, and making decisions. The creation of a special coastal management agency with explicit mandate and accountability mechanism can massively enhance the implementation of the policy.

Urban planning in Mumbai must also be reoriented towards ecologically sensitive and sustainable development. It is critical to note that the infrastructural projects are in line with environmental priorities. Stern environmental impact assessment (EIAs), the development of nature-based solutions in the creation of urban areas, and the restriction of the construction in cities can all be taken in this direction. Indicatively, mangrove degradation can be reversed by restoring and replenishing degraded regions, implementing green buffers and implementing blue-green infrastructure, which can balance urbanisation with ecological conservation. Judicial interventions have been useful in clarifying the gaps in governance, as well as, in ensuring that the environment is appropriately safeguarded. The role of Judicial intervention has been important in pointing out gaps in governance, and imposing environmental protection. The need to move towards proactive policy enactment is urgent, and the environmental protection is integrated into the planning procedures, not imposed with legal actions. The other important element of effective policy implementation is community engagement, and local communities are an important element in mangrove conservation. The policies should promote management approaches that are community-led, sensitization activities and stakeholder participation in the decision-making process. Adherence to conservation processes in the mangroves is achievable through increasing the people awareness of ecological and socio-economic value of mangroves. There is a need to incorporate climate resilience and long-term

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sustainability into policy frameworks. Mangroves play a vital role in adapting to climate, reducing floods, and sequestration of carbon. The need to conserve such ecosystems and reclaim them must be incorporated into wider climate policies. The gains made in previous years will not be undone unless there is investment in mangrove restoration projects and the ecological view is continuously monitored. Finally, it is essential to mention that the management of environmental issues raised by the urban development in Mumbai demand the comprehensive approach that consider different facets, such as the strong enforcement, the collaboration of the institutions, sustainable urban planning, legal support, and engagement of the community. This can go a long way in protecting the mangroves in the wake of urbanisation.

## 8. CONCLUSION

This research paper explored the connection between urban growth and mangroves in Mumbai during the years 2001-2023. The results indicate that mangrove ecosystems in Mumbai have followed a non-linear pattern, where the growth was unprecedented followed by current indications of deterioration. Although the mangrove cover has been growing markedly between the beginning of the 2000s and the end of the 2010s, reaching the highest point in 2017-2019. Another decline suggests the development of ecological stress in the setting of long-term urbanisation. The discussion indicates that urbanisation and mangrove ecosystems can co-exist in some regulatory and conservation frameworks as depicted in the mangrove growth era. This implies that, policy intercessions, legal protection and environmental awareness has assisted in improving ecological healing. Nevertheless, the latest reduction of mangrove cover and the ongoing increase of population point out the increased pressure of urban growth. This tendency is an indicator of the fact that even the strength of the mangrove ecosystems can be pushed to their limits as an increasing number of more dangerous anthropogenic pressures are brought to bear on them. One of the main contributions of this research is that it shows that there are a number of environmental costs related to degrading mangroves. They consist of the rise in the risk of floods through loss of natural coastal buffers, low biodiversity because of habitat fragmentation, loss of capacity to regulate climate caused by reduction in carbon storage and the general socio-economic costs of the affected populations reliant on coastal resources. All these expenses add up to underline the necessity of the significance of mangroves to promote ecological stability, and urban resilience. The research also highlights the governance issues and India has a good legal framework which incorporates the environmental protection laws. Some of these are laws on coastal protection, gaps in their enforcement and surveillance of such laws affect this role. These inefficiencies have in most instances resulted to judicial interventions which have indicated reactive, rather than a proactive, type of environmental regulation. The findings support the notion that the relationship between the process of urbanisation and environmental sustainability is complex and dynamic. Though in the short term the ecological gains can be realised, the long-term sustainability can be preserved only with constant and responsive policy actions. The article has emphasized the need to have a balance between development and environmental conservation by a combination of progressive and proactive strategies as an urgent necessity. Enhancing enforcement systems, institutional coordination, integrating environmental issues in urban development and encouraging community involvement in mangrove conservation. Lastly, the results answer the research questions as they provide

evidence of the complicated interdependence between urban growth, governance issues, and the ecological impacts of mangrove destruction in Mumbai.

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## Appendix

### Appendix 1: Python Analysis

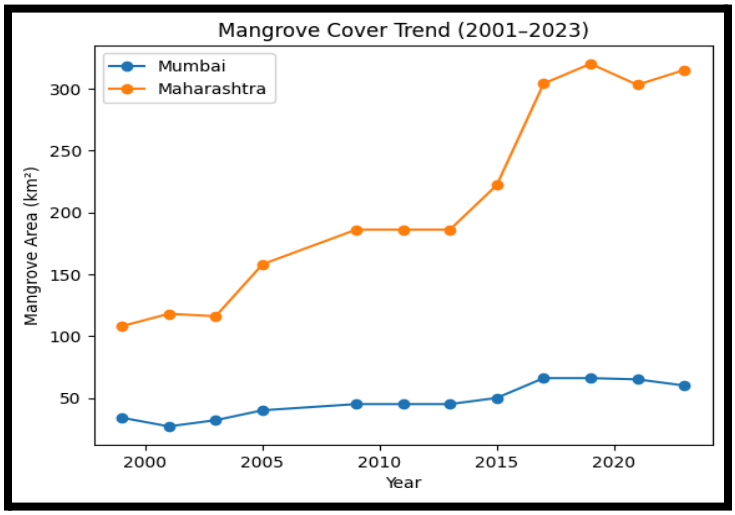


**Figure A1: Time-Series Trend of Mangrove Cover**

The comparative graph contrasts mangrove cover in Mumbai and Maharashtra, highlighting differences in scale and variation between the urban and regional levels.

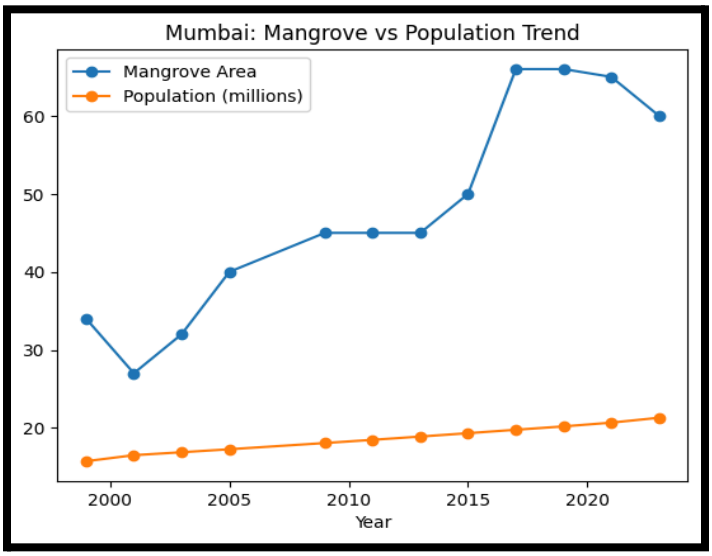


**Figure A2: Trend of Mangrove Cover and Population Growth in Mumbai (2001-2023)**

The time-series graph presents mangrove cover over time, with year on the horizontal axis and mangrove area on the vertical axis, illustrating the overall trend of growth followed by recent decline.

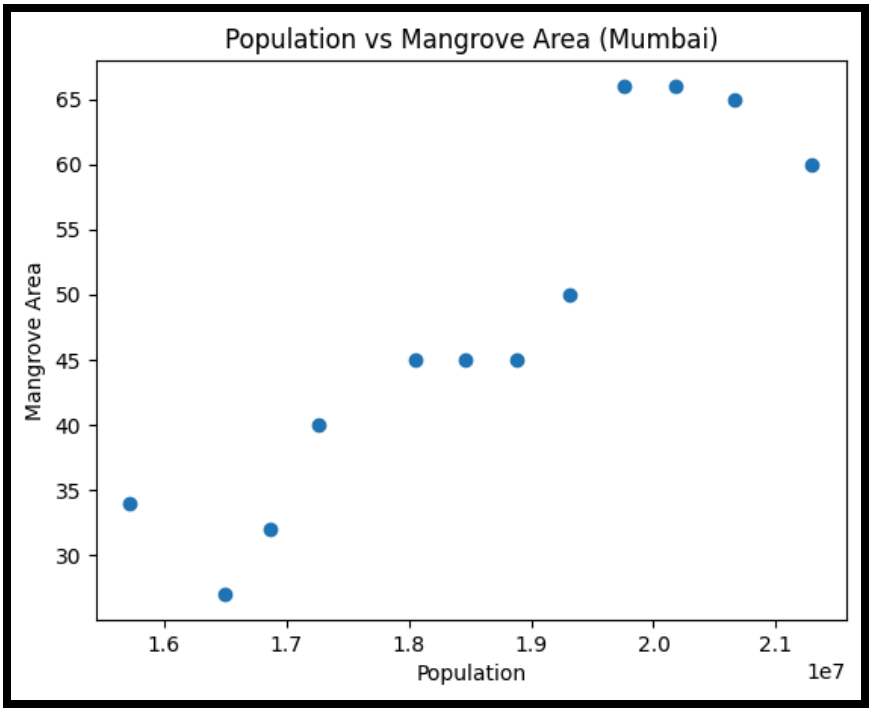


**Figure A3: Population vs Mangrove Scatter Plot (Mumbai)**

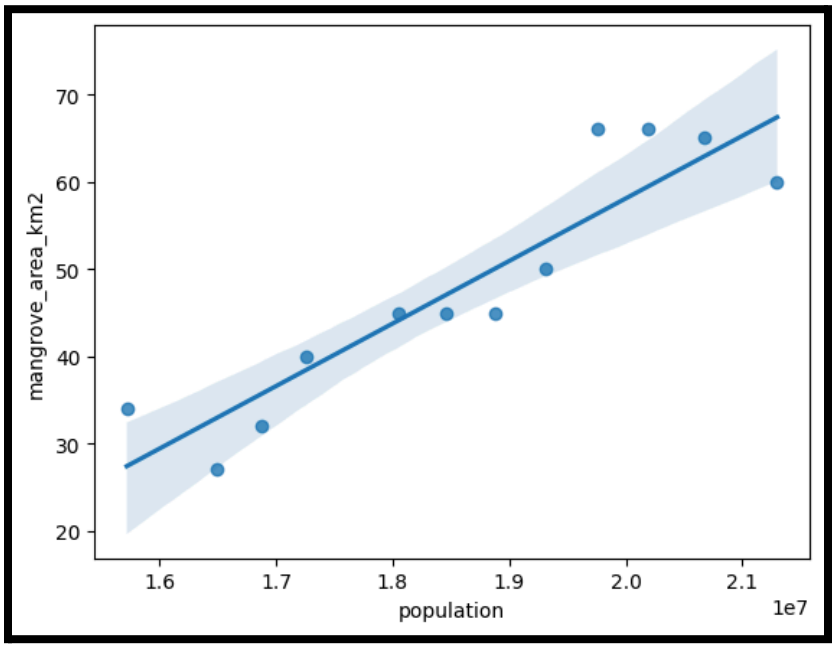


**Figure A4: Relationship Between Population and Mangrove Cover in Mumbai (2001-2023)**

The scatter plot with regression line shows the relationship between population (x-axis) and mangrove area (y-axis), indicating a positive association between urbanisation and mangrove dynamics.

| index | year | region | mangrove_area_km2 | population | change | mangrove_per_person | mangrove_growth | population_growth | trend |
|---|---|---|---|---|---|---|---|---|---|

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **1** | 1999 | Mumbai | 34 | 15722000 | NaN | 2.16E-06 | NaN | NaN | decrease |
| **3** | 2001 | Mumbai | 27 | 16496000 | -7 | 1.64E-06 | -20.58823529 | 4.923037781 | decrease |
| **5** | 2003 | Mumbai | 32 | 16872000 | 5 | 1.90E-06 | 18.51851852 | 2.279340446 | increase |
| **7** | 2005 | Mumbai | 40 | 17257000 | 8 | 2.32E-06 | 25 | 2.28188715 | increase |
| **9** | 2009 | Mumbai | 45 | 18053000 | 5 | 2.49E-06 | 12.5 | 4.612620965 | increase |
| **11** | 2011 | Mumbai | 45 | 18464000 | 0 | 2.44E-06 | 0 | 2.276629923 | decrease |
| **13** | 2013 | Mumbai | 45 | 18885000 | 0 | 2.38E-06 | 0 | 2.280112652 | decrease |
| **15** | 2015 | Mumbai | 50 | 19316000 | 5 | 2.59E-06 | 11.11111111 | 2.282234578 | increase |
| **17** | 2017 | Mumbai | 66 | 19756000 | 16 | 3.34E-06 | 32 | 2.277904328 | increase |
| **19** | 2019 | Mumbai | 66 | 20185000 | 0 | 3.27E-06 | 0 | 2.171492205 | decrease |
| **21** | 2021 | Mumbai | 65 | 20668000 | -1 | 3.14E-06 | -1.515151515 | 2.39286599 | decrease |
| **23** | 2023 | Mumbai | 60 | 21297000 | -5 | 2.82E-06 | -7.692307692 | 3.043352042 | decrease |

**Table A1: Growth Rate and Change Analysis of Mangrove Cover and Population in Mumbai (1999-2023)**

| **year** | **share_%** |
|---|---|
| 1999 | 31.481481 |
| 2001 | 22.881356 |
| 2003 | 27.586207 |
| 2005 | 25.316456 |
| 2009 | 24.193548 |
| 2011 | 24.193548 |
| 2013 | 24.193548 |

| | |
|---|---|
| 2015 | 22.522523 |
| 2017 | 21.710526 |
| 2019 | 20.625 |
| 2021 | 21.452145 |
| 2023 | 19.047619 |

**Table A2: Share of Mumbai's Mangrove Cover as a Percentage of Maharashtra's Total (1999–2023)**

| Variable | Population | Mangrove Area (km²) |
|---|---|---|
| Population | 1.000 | 0.916 |
| Mangrove Area (km²) | 0.916 | 1.000 |

**Table A3: Pearson Correlation Matrix**

| Parameter | Value |
|---|---|
| Intercept | -85.279 |
| Coefficient (Population) | $7.168 \times 10^{-6}$ |
| $R^2$ (Goodness of Fit) | 0.840 |

**Table A4: Linear Regression Results for Population and Mangrove Area in Mumbai**

| Parameter | Intercept | Population |
|---|---|---|
| Coefficient | -85.280 | $7.168 \times 10^{-6}$ |
| Std. Error | 18.482 | $9.91 \times 10^{-7}$ |
| t-value | -4.614 | 7.236 |
| p-value | 0.001 | 0.000 |
| $R^2$ | 0.840 | 0.840 |
| Adjusted $R^2$ | 0.824 | 0.824 |
| 95% Confidence Interval | [-126.461, -44.098] | [$4.96 \times 10^{-6}$, $9.38 \times 10^{-6}$] |

**Table A5: Combined Regression and Statistical Results**