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Research Article

A GIS-Based Comparative Environmental Sustainability Assessment of an Underground Metro Corridor in Coastal Mumbai

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Abstract *- Coastal cities are also experiencing growth in their urban areas, and hence the need to develop alternative and better transportation facilities. The underground metro rail is a viable alternative for the population and is also beneficial for environmental sustainability. However, there are major challenges to be addressed while constructing such facilities. For instance, excavation in such regions demands thorough analysis, and tracks cannot be laid without a thorough understanding of the regions beneath the earth's surface. This research is focused on Mumbai Metro Line 11 and attempts to assess various environmental factors such as air quality, noise pollution, and changes to the ecosystem and CRZ regulations. Using Geographic Information System technology, the research attempts to integrate genuine environmental data and compare them with other metro rail projects. Based on the secondary indicators examined, the findings suggest that environmental sensitivity tends to be greater in cities that are both coastal and densely populated, although this observation is indicative rather than conclusive and warrants further primary validation. Hence, thorough planning is required to include innovative designs to address geographical constraints and environmental damage.*

Keywords *- GIS analysis, Sustainability of metro rail systems, Coastal Regulation Zone, Environmental effects, Urban transportation planning.*

1. Introduction

Metro rail systems are being increasingly used as cities grow and become more crowded. In terms of traffic congestion, which is a common phenomenon in almost all cities, a notable trend is a move towards more intelligent transportation systems. Metro rail systems, which are built underground, are particularly prominent in densely populated cities. This is because they require little land to be acquired during construction, which is a significant advantage [1]. However, metro rail projects have several localized environmental effects, including negative impacts on air quality, noise levels, flora, fauna, and regulatory challenges. The metro rail projects also have significant environmental concerns because they traverse areas classified as Coastal Regulation Zone I or II, which is a significant issue in coastal cities like Mumbai. Therefore, to ensure that metro rail projects are built without having a negative impact on the environment, a thorough examination of the project using geospatial techniques is necessary. Environmental Impact Assessments are a set of techniques used to assess the environmental impact of a particular project. However, a notable drawback of traditional Environmental Impact Assessments is that they are site-specific. Therefore, while they can effectively assess a particular project site, they are not very helpful for a macro-level study. Moreover, traditional Environmental Impact Assessments are also limited to assessing a particular site without a comparative study of several sites. For example, while building a metro rail, it is necessary to know which route is more environmentally friendly. This is a drawback because a traditional Environmental Impact Assessment is not possible without a benchmark. This study is a notable exception to traditional Environmental Impact Assessments because it has gone beyond traditional techniques to propose an innovative framework for a comparative study of the Mumbai Metro Line [2]. Environmental Impact Assessments are also limited to a descriptive study, which is a drawback because a traditional Environmental Impact Assessment is more concerned with checking a set of regulatory requirements. This is a drawback because a traditional Environmental Impact Assessment is more concerned with checking a set of regulatory requirements. This review has used a set of innovative techniques to ensure a more nuanced understanding of a particular project.

As metro rail transport is becoming more popular as a sustainable means of transportation in the urban landscape, there is a need to consider the specificities of its operation in coastal areas, which have been overlooked by academia. Cities such as Mumbai are exposed to increased environmental challenges as a result of dense population, weak ecosystems, and Coastal Regulation Zone (CRZ) guidelines.

There remain considerable gaps in the literature concerning metro rail sustainability, even as more research is being conducted in this field: Studies mainly concentrate on isolated environmental factors (such as air quality OR noise pollution) and not holistic multi-criteria evaluation. GIS analysis, for example, does not often go hand in hand with environmental benchmarking of underground metro rail projects. There is limited academic study on the problems involved in the development of metro rail projects in CRZ coastal regions. Benchmarking criteria for evaluating metro rail projects on environmental measures have not been fully developed in Indian coastal cities.

The use of GIS technology also increases our ability to more finely pinpoint areas of environmental sensitivity along the metro corridor, including different segments of that corridor. GIS allows us to identify areas that are more likely to experience disruptions to the environment. This includes areas like wetlands, densely populated areas, or areas with a high level of biodiversity. The inclusion of various measures of sustainability, including issues like air quality, water quality, social issues, and economic issues, helps to ensure that a more holistic approach is used to evaluate the potential impact on the environment. This is also significant because these measures are based on various standards that are considered to be the most effective internationally. This means that the study is both relevant on a global scale and applicable on a local scale. This is significant because it helps to ensure that a more positive impact is made on the environment. The study is significant because it is an innovative approach that offers a clear framework for conducting site-specific evaluations and can be used to inform future metro rail planning on a larger scale[3].

While many previous studies have looked into environmental factors concerning metro rail systems, such as the effects of air quality, noise pollution, emissions reductions, and the environmental impact throughout the lifecycle of metro rail lines, the majority of the research is conducted based on single indicators of sustainability. There have been a few cases where different indicators of environmental performance have been combined under a GIS-based spatial approach, especially in the case of underground metro railways in environmentally vulnerable coastal metropolises. Further, studies on the relationship between metro railway and Coastal Regulation Zone (CRZ) classifications are rare in India.

The current study focuses on answering the following research questions:

1. How do air pollution, noise pollution, and groundwater quality near Metro Line 11 compare with national regulations and metro projects in other places?
2. Are there any interactions that exist between the proposed metro structure and CRZ zones?
3. In what way can spatial analysis using GIS improve the environmental sustainability of underground metro corridors in coastal cities?

What makes this research novel is the use of environmental indicator benchmarking along with a spatial analysis based on GIS technology for understanding the interaction between the CRZ and the proposed underground metro route. Where other researchers have focused on one particular dimension of sustainability at a time, the current research considers all four dimensions of air pollution, noise pollution, groundwater pollution, and sensitivity associated with CRZ together.

The Objectives of this article are as below.

- Carefully examine the case of Metro Line 11, evaluating the environmental impact through various secondary data sources to measure sustainability.
- Examine the relationship between the development of the metro line and the sensitive Coastal Regulation Zone areas, weighing the pros and cons of the potential impact on the environment.
- Carefully compare the air quality and noise levels associated with the operation of Metro Line 11, evaluating the impact against regulatory requirements and recent studies on the environmental impact of metro lines.
- Develop a framework to provide a practical tool on the best practices, the challenges, and the innovative ideas to mitigate the impact on the environment, which can be used to make decisions to protect the environment in the future.

2. Literature Review

The quick development of towns and cities in metro areas has really raised how much we require good, lasting city transport. As cities get bigger and more people live in them, problems like traffic, polluted air, and the energy used by people driving their own cars have become major problems for the environment [4]. Because of this, metro rail systems in cities are now a key part of plans for city transport, which are meant to be lasting, particularly in very busy metro areas [5]. If metro systems work well with how land is used and with several different kinds of transport linked together, they could bring down emissions for each person travelling, and lessen the use of private cars [5, 6]. However, you can't judge how environmentally good metro systems are just from how well they run or how many people they can carry. When metro buildings are being put up is also very important in finding out what the general effect on the environment will be. Metro building work usually causes problems for the environment; things like polluted air, noise, disturbing underground water, and changes in what land is used for. These effects can be especially clear in cities which are developing fast, where very big building projects are being done at the same time [7]. Studies of building work in main metro cities have shown that digging, making tunnels, and moving materials can raise the amount of small particles in the air in close areas, sometimes going over what the air quality should be at its worst during building [8].

Noise pollution is another big problem with metro building, and when it is running. Studies done in neighbourhoods where people live, near metro routes, have recorded noise going from 65 to 75 dB - which is more than what rules say is acceptable and makes people worry about the health of the community and how good the city is to live in. Apart from air and noise pollution, the development of metro facilities may affect groundwater levels as well. There have been various studies on the impact of metro construction on groundwater levels, which have established that the levels are within the acceptable limits [9, 16]. However, there have been discrepancies in regions where there has been extensive construction activity. It is therefore important to have effective environmental management to reduce the impact on hydrogeology while constructing the metro.

The environmental challenges are more complicated in metropolitan cities where there is a need to balance the impact of metro development with the ecologically sensitive zones. For instance, cities such as Mumbai, which are on the coast, have to adhere to the regulations set by the Coastal Regulation Zone (CRZ), which seeks to protect ecologically sensitive zones such as the coasts. Previous studies have established that there has been a lack of effective enforcement of the regulations set by the CRZ, which has resulted in environmental conflicts, especially where there has been the development of infrastructure through the ecologically sensitive zones such as the coasts and the mangroves [6, 10]. There is, therefore, a need to have effective spatial planning tools to understand the impact of infrastructure development on ecologically sensitive zones. "Geographic Information System" has evolved as an important analytical tool for the assessment of environmental factors and the spatial planning of urban infrastructure projects. GIS methodologies provide tools to integrate diverse environmental data sets such as land use patterns, population distribution, areas of environmental sensitivity, and infrastructure configurations into a unified system. This provides the planners with the tools to visualize the environmental implications of the various designs of the infrastructure. In the specific case of metro rail systems, GIS has been widely applied to examine the patterns of environmental exposure, identify the areas of environmental sensitivity along transportation corridors, and provide decision support tools within the framework of sustainable urban transportation planning [6, 10]. Additionally, apart from spatial analysis tools, life cycle assessment tools are also increasingly being applied to evaluate the environmental performance of metro rail systems at various stages of development. LCA studies examine the environmental impacts of the construction, operation, and maintenance of transportation infrastructure. Investigations into the LCA of underground metro rail systems in metropolitan cities of India have identified construction activities such as tunnelling and the development of metro rail systems as significant contributors to the overall carbon footprint of the metro rail system [11]. Metro rail systems exhibit an overall pattern of enhanced sustainability performance over time, owing to the reduction of emissions resulting from the shift to public transportation from private transportation modes [7].

2.1. Background of the Study

The rapid urbanization of metropolitan areas has intensified the demand for sustainable urban transportation solutions. As cities expand and population densities increase, challenges including traffic congestion, air pollution, and energy consumption from private vehicle use have emerged as critical environmental concerns. Metro rail systems have consequently become central components of sustainable urban transport strategies, particularly in high-density metropolitan regions. When effectively integrated with land use planning and multimodal transport networks, metro systems can significantly reduce per-capita emissions and decrease private vehicle dependency [12]. Metro systems perform a significant function for millions of riders worldwide, as urban passengers rely on secure, reliable, and accessible underground transportation for their regular conveyance [13]. As a mass transit mode, metros attract passengers from vast catchment areas through various feeding modes, including walking, cycling, and bus connections [14].

Recent studies have extended the exploration of the considerable environmental advantages of metro systems in large urban agglomerates. Studies have established the fact that the expansion of metro systems in urban agglomerates can lead to a considerable reduction in transport emissions through modal shift effects. For instance, [4, 15] undertook a research study to evaluate the environmental performance of metro systems in the Mumbai Metropolitan Region. The research established the fact that the deployment of metro services in the region can lead to a considerable reduction in the level of carbon emissions through the modal shift effect, where commuters opt to use metro services instead of private vehicles. Similar research findings have been established in the case of newly established metro corridors in urban agglomerates, where the enhanced level of transit accessibility has resulted in a considerable reduction in transport emissions. Spatially explicit environmental assessments provide a better understanding of the environmental impacts associated with metro systems. For instance, [16] undertook a research study to evaluate the environmental impacts of metro systems through the application of spatial econometric modelling. The research established the fact that the enhancement of air quality through the expansion of metro systems has considerable spatial variability depending on the land use pattern of the urban districts. Noise pollution is another critical environmental issue associated with metro development. While it is accepted that metro systems are more environmentally sustainable than road-based transportation systems, it is also acknowledged that operational noise pollution is a critical element of metro systems.

Further studies using spectral characterization have shown that it is possible to differentiate between noise pollution associated with metro systems and road traffic noise using frequency analysis [14]. In addition, vibroacoustic studies have shown that exposure to in-train noise varies according to various operational characteristics, such as acceleration and braking patterns [17]. Although there is a growing body of literature that focuses on sustainability and its associated impacts on metro systems and their associated environment, there are a number of gaps that need to be filled. A significant body of literature is focused on specific and isolated aspects of metro sustainability, such as air quality, noise pollution, and reduction of emissions [18]. However, these studies fail to integrate these elements using a comprehensive spatial evaluation approach. There is a critical need to develop analytical methodologies that integrate these elements and provide a comprehensive understanding of metro sustainability. The integration of GIS spatial analysis and benchmarking methodologies is critical to providing a comprehensive understanding of sustainability and its associated impact [3]. In addition, it is critical to note that a number of regulatory compliance assessments are necessary to ensure that sustainability is achieved.

This study contributes novelty by adopting a multi-indicator approach that jointly incorporates air quality, noise levels, groundwater quality, and CRZ interaction within a single GIS-based benchmarking framework. This contrasts with earlier research, which has generally examined environmental indicators separately for example, prior work has assessed the life-cycle environmental performance of Mumbai's underground metro with a focus on air-quality-related impacts [15], while other studies have examined metro-related noise and vibroacoustic conditions in isolation [17]. By integrating these indicators together with spatial CRZ analysis, the present study offers a more holistic, comparative basis for evaluating metro sustainability in environmentally sensitive coastal settings.

2.1.1. Spatial Benchmarking using GIS

Although GIS is used in transport planning [13, 18], there are limited cases where GIS spatial analysis and regulatory benchmarking are used for assessing the performance of underground metro corridor in CRZ coastal zones. Analysis of Metro Rails Interaction with CRZ in Coastal Areas a systematic study to assess the interaction of metro rail components with CRZ-II and CRZ-III in Mumbai coastal area helps fill the void in Indian metro rail studies, which do not quantify the extent of interaction of metro rail components with CRZ zones.

2.1.2. Comparative Benchmarking Framework for Indian Metro Rail Projects

The research develops a benchmarking framework that will help compare the performance of different metro rail projects using the same indicators and benchmarks, which will be useful in future EIA research.

3. Methodology

3.1. Research Design

The present research has utilized an in-depth and integrated research methodology. The research has primarily focused on secondary research. The present research has utilized the following integrated research framework in order to assess the environmental sustainability of the Mumbai Metro Line 11 corridor. The research framework has primarily focused on the comparative evaluation of the environmental sustainability of the proposed metro corridor. The environmental sustainability of the proposed metro corridor has been examined in the context of the existing regulatory norms and the results obtained from the existing metro projects.

The research design uses a mixed methodological approach consisting of the following three interrelated steps:

1. Data Gathering and Standardization

Gathering of secondary environmental data from EIA reports, DPRs, and regulatory reports. Data verification by cross-checking across multiple sources. Standardization of units and timeframes [9, 10, 12].

2. Environmental Indicators Analysis

Analysis of air quality parameters (PM_{10}, $PM_{2.5}$, NO_2, SO_2). Evaluation of noise levels based on Leq (equivalent continuous sound level) criteria. Evaluation of groundwater quality based on BIS (Bureau of Indian Standards) norms. Comparison with Central Pollution Control Board (CPCB) standards [17].

3. GIS-based Spatial Analysis

Geo-referencing and digitizing of metro alignment, overlay analysis with CRZ zone boundaries, determination of conflict areas Calculation of spatial statistics [10, 18, 19].

The proposed research has utilized the following integrated methodological framework in order to evaluate the environmental sustainability of the proposed Mumbai Metro

Line 11 corridor. The proposed methodological framework has utilized the quantitative, spatial, and qualitative research dimensions in order to evaluate the environmental sustainability of the proposed metro corridor [19]. The quantitative research dimension has utilized the following parameters in order to evaluate the environmental sustainability of the proposed metro corridor [19]. The environmental parameters considered in the present research include air quality indices, noise levels, and groundwater quality parameters. The required data has been collected from the Environmental Impact Assessment Reports and the existing literature. Moreover, the spatial analysis has been performed by utilizing the Geographic Information System techniques. The Geographic Information System techniques facilitate the exploration of the relationship between the proposed metro infrastructure and the environmentally sensitive zones, such as the Coastal Regulation Zone areas. The proposed metro infrastructure may pose environmental conflicts in the Coastal Regulation Zone areas. The proposed research has utilized the spatial overlay technique in order to evaluate the spatial relationship between the proposed metro infrastructure and the environmentally sensitive zones. Furthermore, the proposed research has utilized the qualitative research dimension in order to evaluate the environmental sustainability of the proposed metro corridor [19]. The proposed research has utilized the existing regulatory norms in order to evaluate the environmental sustainability of the proposed metro corridor [19]. The existing regulatory norms in India have been established by the Bureau of Indian Standards and the Central Pollution Control Board.

3.2. Data Sources & Selection Sriteria

The research conducted for this study is based on an intensive examination of secondary data collected from credible and authentic sources, thereby ensuring academic integrity as well as the dependability of the data itself. Environmental factors relevant to this particular study, such as air quality, ambient noise levels, nature of groundwater, and soil composition, were collected from credible sources such as Environmental Impact Assessment reports, scholarly articles, and official government reports concerning metro rail development in Mumbai. These sources offer an exhaustive platform for evaluating the environmental impacts of massive urban infrastructure projects. To maintain uniformity in the evaluation process, this particular study has followed regulatory guidelines and permitted limits set by various government agencies, such as the Central Pollution Control Board and the Ministry of Environment, Forest, and Climate Change. These regulatory guidelines act as benchmarks for evaluating various environmental quality parameters and ascertaining levels of compliance within the study region. Additionally, spatial data concerning urban planning and environmental sensitivity, such as CRZ notification, were collected from official government notifications as well as relevant scholarly articles. One of the most critical aspects of the data selection process was to ensure uniformity in methodology with respect to the various data sets selected for this particular study. The selection criterion for this particular study was based on choosing data sets from various scholarly articles and reports that employed uniform data collection methodology, monitoring patterns, and analytical tools within a specific time frame. This selection criterion was critical for ensuring uniformity in methodology, thereby allowing for more accurate results. By ensuring uniformity in methodology with respect to the data sets, this particular study has ensured that the final results obtained are accurate, relevant, and in line with academic standards.

3.3. Environmental Indicator Framework

Compiled from the standards established by the Central Pollution Control Board, the CRZ Notification (2019) from the Ministry of Environment, Forest and Climate Change, along with the Environmental Impact Assessment (EIA) and Detailed Project Reports (DPR) related to metro projects including the Mumbai Metropolitan Region Development Authority (MMRDA) and the Delhi Metro Rail Corporation (DMRC) [7, 15].

The environmental variables chosen for the study have been specifically designed in the context of the Mumbai Metropolitan Region and have been based on the parameters most frequently reported in the literature on the sustainability and environmental impact assessment of metro rail projects. These parameters have been chosen to include the most important environmental variables such as ambient air quality parameters (PM_{10}, $PM_{2.5}$, NO_2, and SO_2), noise levels, and groundwater quality parameters, as shown in Table 2. These parameters provide a comprehensive basis for the evaluation of the environmental performance of urban infrastructure projects.

The values chosen for the study on Metro Line 11 have been based on a range to account for the spatial variations in the project area. These values have been derived from the baseline values reported in the Environmental Impact Assessment (EIA) and the Detailed Project Report (DPR) documents. These values account for the regional variations in the different segments of the metro rail project. This ensures that the spatial variations in the environmental parameters, which might be caused by factors such as land use, traffic density, and the distance from environmentally sensitive zones, are accounted for in the study. For the purpose of the comparative evaluation, the national regulatory standards prescribed by the Central Pollution Control Board and the Bureau of Indian Standards (BIS) have been chosen as the benchmark criteria. These standards provide a framework for the evaluation and identification of deviations in the different environmental parameters. Additionally, the inclusion of the Coastal Regulation Zone (CRZ) interaction as a spatial indicator has been chosen, as a spatial indicator and represents a critical factor in the study, in the context of urban infrastructure projects.

Table 1. Presents a comparative analysis of environmental indicators in relation to state guidelines and the reports of metro projects

Environmental Indicator	Unit	National Standard (CPCB/MoEFCC)	Metro Line 11 (Mumbai) - DPR/EIA Reported Range	Comparable Metro Projects (Reported Range)
PM_{10}	µg/m³	100 (24-hr)	85-90	70 - 140 (Delhi, Mumbai Line 3, Chennai)
$PM_{2.5}$	µg/m³	60 (24-hr)	45-60	40 -90 (Delhi, Bengaluru, Mumbai Line 3)
NO_2	µg/m³	80 (24-hr)	30 - 65	25 - 70 (Delhi, Hyderabad)
SO_2	µg/m³	80 (24-hr)	10 - 25	10 - 30 (Chennai, Kochi)
Ambient Noise (Leq - Day & Night)	dB(A)	55-45 (Residential)	53-45 (near stations & depots)	55 - 70 (elevated corridors)
Ambient Noise (Leq - Night)	dB(A)	65-55 (Commercial)	60–55	56-68
Groundwater pH	-	6.5 - 8.5	7.1 - 7.8	6.8 - 8.2
Total Dissolved Solids (TDS)	mg/L	500 (desirable)	420-585	400 - 750
Chlorides	mg/L	250	180-220 (coastal influence)	150 - 350
Sulphates	mg/L	200	120-195	110 - 230
CRZ Interaction	Qualitative	CRZ Notification 2011/2019	Alignment intersects CRZ-II and CRZ-III stretches	Similar interactions in Mumbai Line 3 & coastal corridors

The application of GIS-based spatial overlay techniques has been chosen to assess the interactions between the metro rail infrastructure and the Coastal Regulation Zone (CRZ)-designated areas. These areas have been designated by the Government of India and are subject to stringent regulatory controls due to the high ecological and geomorphological sensitivity.

Environmental indicators used in this study have been selected because of their regular use in assessing the sustainability of metro systems documented in earlier literature. The indicators of air quality (PM_{10}, $PM_{2.5}$, NO_2, SO_2) were selected owing to their relationship with emissions from construction and transport operations [1, 15]. Ambient sound level indicators were selected owing to the relationship of such indicators in assessing impacts arising from operation and construction activities [20].

Indicators for groundwater quality (pH, TDS, chlorides, sulphates) were selected because of their use in hydrogeological assessment in infrastructure development projects. CRZ Interaction has been selected as a spatial indicator because of the environmental significance of Mumbai's coast and regulations set under the CRZ Notification (MOEFCC, 2019).

3.3.1. Justification for the Environmental Indicator Section

Indicators related to the environment are selected according to known methodologies of sustainability assessment of infrastructure, taking into consideration the coastal nature of the city of Mumbai:

Air quality indicators (PM_{10}, $PM_{2.5}$, NO_2, SO_2)

Reasoning: Such indicators stand out as major pollutants in urban areas and are always considered major sources of health hazards by the WHO (2018) and guidelines by CPCB.

Connection to metro projects: The construction process influences the levels of particulate matter. The presence of gaseous pollutants (NO_2, SO_2) is a sign of emissions due to combustion processes.

Noise Level Indicator (Leq Day/Night)

Noise pollution is an important environmental problem associated with the construction and operation of metro system with proven health effects [17]. Importance: Residential and industrial areas lying along the alignment will experience increased noise pollution due to tunnel boring machine, piling activities, and running of trains.

Legal Rationale: CPCB (2000) has prescribed specific noise standards for various land uses [9].

Indicators of Groundwater Quality (pH, TDS, Chlorides, Sulphates)

The underground metro project may have an impact on the groundwater system because of dewatering, infiltration of chemicals, and hydrogeology changes.

Coastal Importance: Mumbai, being a coastal city, groundwater salinization is a major issue, thus making chlorides and TDS important parameters.

Literature Support: Reference levels are available from drinking water quality standards of BIS and previous EIA literature [20].

Interaction between CRZ

Spatial indicator CRZ interaction reflects the regulatory and ecological sensitivity of the coastal area.

Importance: Metro Line 11 passes through the regions that fall into the CRZ-II and CRZ-III categories.

Literature Review Support: Studies show the lack of proper regulation concerning CRZ compliance [6, 10].

3.4. Comparative Statistical and Tabular Analysis

A comparative analysis of particulate matter concentrations was conducted by comparing the average $PM_{2.5}$ concentrations observed along the Metro Line 11 corridor with those observed along the Mumbai Metro Line 3 and other prominent metro corridors currently in operation in India. This analysis provided a context for understanding the ambient air quality conditions within the broader context of metro corridors. To achieve this objective, the 24-hour ambient air quality standard specified in the Central Pollution Control Board guidelines was used as a reference standard and incorporated into the analysis as a dashed line on the chart for visual representation purposes. The results suggest that while there is a slight increase in average $PM_{2.5}$ concentrations observed along the Metro Line 11 corridor compared to those observed along Metro Line 3 in Mumbai, these concentrations are still within a range consistent with those reported for metro corridors in other cities in India. As shown in Figure 1.

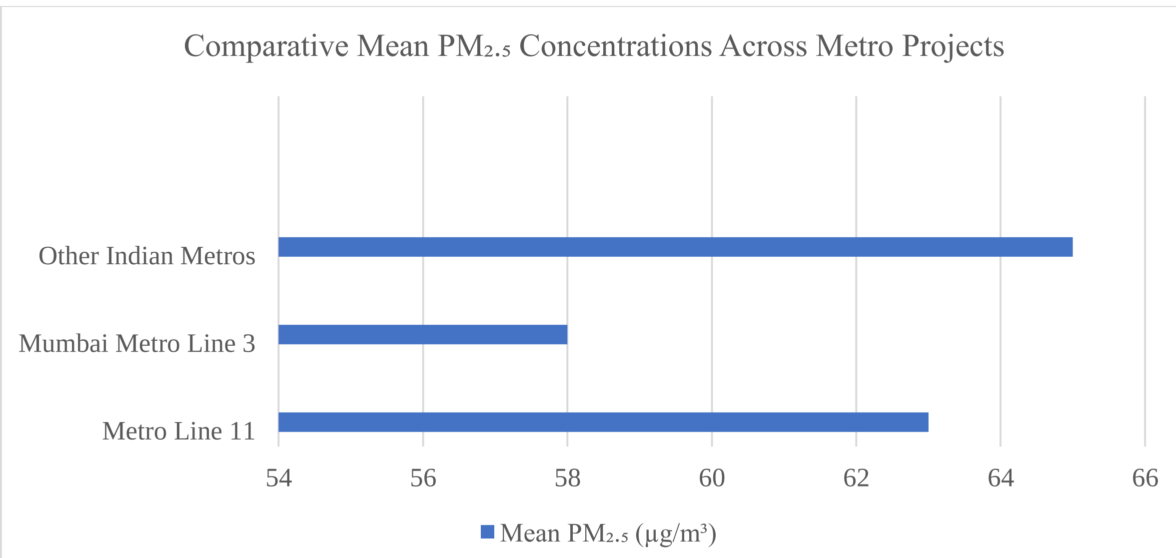

Fig. 1 The average reported concentrations of $PM_{2.5}$ during both the construction and operational phases

The comparative evaluation also reveals that the $PM_{2.5}$ concentration levels for Metro Line 11 are similar to those found in existing metropolitan transit systems, where high levels of particulate matter concentration are generally attributable to general metropolitan pollution conditions rather than project-specific conditions.

Thus, the presence of mixed land use, high vehicle volumes, and poor dispersion conditions in metropolitan cities contributes to the maintenance of high levels of pollutant concentration. Therefore, it is important to note that the slightly elevated concentration levels in the study area must be viewed in the context of general metropolitan environmental conditions.

The above analysis reveals that there is a difference in the concentration levels of $PM_{2.5}$ between Metro Line 11 and some of the existing metro corridors. However, it is also evident from the analysis that the concentration levels are within acceptable limits. This reveals that the general air quality conditions in the proposed corridor are in line with the existing metropolitan conditions.

The current study attempts to incorporate regulatory guidelines along with technical information obtained from reliable sources such as the Central Pollution Control Board publications and project reports prepared by the Mumbai Metropolitan Region Development Authority (2022), along with relevant reports obtained from the Delhi Metro Rail

Corporation (2019). The national ambient air quality standards established by the Central Pollution Control Board can be considered an essential reference point in determining key air quality parameters such as particulate matter (PM_{10} and $PM_{2.5}$), along with gases such as NO_2 and SO_2 [20].

In addition, Environmental Impact Assessment reports, along with Detailed Project Reports relating to metro rail development initiatives, can be considered significant sources of information in relation to the availability of extensive data regarding the environment. These reports can be considered significant references in understanding the environmental performance of such mega infrastructure development initiatives. The amalgamation of such standardized information can be considered significant in providing a coherent scientific approach in relation to the evaluation of the environment. projects [6, 7].

3.5. GIS-based Spatial Analysis

The relationship of Metro Line 11 infrastructure and the different classes of CRZ has been analysed through a GIS-based spatial overlay study [21]. Geographic Information System (GIS)-based spatial overlay analysis was carried out in order to study the interaction between the proposed Metro Line 11 infrastructure and the environmentally sensitive Coastal Regulation Zone (CRZ) areas. Geo-referenced maps showing the metro alignment were overlaid with the officially recognized maps showing the different classifications of the CRZ areas. The maps showing the metro infrastructure were obtained from publicly available planning documents, while the maps showing the boundaries of the CRZ areas were obtained from government notifications. As the availability of high-resolution spatial data was not possible in the present case, the study was carried out using only secondary geo-referenced maps.

Table 2. Presents the distribution of metro infrastructure components across CRZ categories based on project reports (MMRDA, 2022; MOEFCC, 2019)

Infrastructure Component	Total Count	Within CRZ-II	Within CRZ-III	Outside CRZ
Metro Stations	10	2	1	7
Ventilation / Access Shafts	6	1	1	4
Traction Substations / Utilities	3	1	0	2
Alignment Length (km)	16.8	2.4	1.1	13.3

3.5.1. Data Preparation

The datasets used in GIS analysis include the following:

Metro Alignment Data: Digital representation of the 16.8 km corridor with 10 stations from MMRDA (2022) detailed project reports. CRZ Boundary Data: Acquired from MOEFCC (2019) CRZ notification maps. Base Maps: Land use, road networks, and administrative boundaries from government data sources. All the above-mentioned datasets were converted to the same coordinate system (UTM zone 43N, WGS 84). Spatial resolution was maintained at a 1:25,000 scale.

3.5.2. Spatial Overlay Procedure

The overlay analysis was performed in the following order:

- Digitization: Digitization of all elements of the metro infrastructure (alignment, stations, shafts, substations) was done manually using ArcGIS 10.8
- Buffer Analysis: 50 m buffer was prepared around the metro alignment to determine the possible zones of impact
- Intersect: Intersection between the metro layers and CRZ polygons were performed using the Intersect function.
- Classification: Overlapping zones were categorized based on CRZ (CRZ I, II, III)
- Quantification: Calculation of the length of alignment and the number of infrastructure elements in each CRZ category

3.5.3. Quality Control Measures

For ensuring accuracy, all digitizing was done using a secondary data verification technique. Spatial accuracy was checked by visual inspection of the overlay process. Consistency in coordinate systems was ensured in all stages of analysis.

In the present case, the spatial overlay was carried out using the geo-referenced maps obtained from secondary sources. The geo-referenced maps were standardized in terms of the spatial coordinates system in order to carry out the spatial overlay analysis. The spatial overlay was carried out in such a way that the interaction between the different components of the metro infrastructure and the CRZ areas was identified.

The interaction between the metro infrastructure was found with the different zones of the CRZ areas, such as the CRZ-II and the CRZ-III zones. The zones under the CRZ-II category showed a higher degree of interaction with the metro alignment. The zones under the CRZ-III category showed lower encroachment in terms of the metro infrastructure. The zones under the CRZ-III category are generally found in undisturbed areas.

The spatial interaction between the different components of the metro infrastructure was quantified using the derived summary statistics. The quantified data were used in the present case in order to evaluate the degree of environmental sensitivity. The results obtained using the spatial overlay were represented in the form of thematic maps [21].

3.6. Benchmarking against Regulatory Standards

This analysis juxtaposes the observed environmental indicators against the regulatory thresholds established in project reports and national standards [7, 11]. As shown in Figure 2, represents Key environmental variables related to Metro Line 11 (as benchmarked against national regulatory criteria) A comparative evaluation of environmental parameters was conducted based on a comparison between mean baseline values as indicated in Detailed Project Reports (DPRs) and Environmental Impact Assessment (EIA) reports and those prescribed standards for groundwater, ambient air, and noise quality. The parameters for assessing groundwater quality were based on guidelines provided by the Bureau of Indian Standards (BIS). On the other hand, ambient air and noise levels were compared based on criteria provided by the Central Pollution Control Board. This method provided a framework for evaluating and comparing compliance levels and areas of non-compliance for various environmental parameters. The results have indicated areas where there are exceedances beyond recommended parameters, especially in residential areas along the Metro corridor.

The ambient noise levels have exceeded recommended parameters. This can be attributed to high traffic volume and density on the road, as well as background noise typical of metropolitan areas. On the other hand, concentrations of particulate matter such as PM_{10} and $PM_{2.5}$ remain within CPCB limits across the corridor, consistent with the results reported in Table 3. In terms of groundwater parameters, concentrations of Total Dissolved Solids (TDS) have exceeded the BIS desirable limit of 500 mg/L in some areas, although concentrations remain within the BIS permissible limit of 2000 mg/L for some areas along Metro Line 11.

This can be attributed to the fact that Metro Line 11 passes through a coastal region characterized by high concentrations of dissolved solids as a result of saline intrusion and other geochemical processes. However, overall environmental parameters are comparable to those found in other metropolitan areas, and remain within the normal range for a metropolitan area, notwithstanding localized areas of non-compliance for specific parameters.

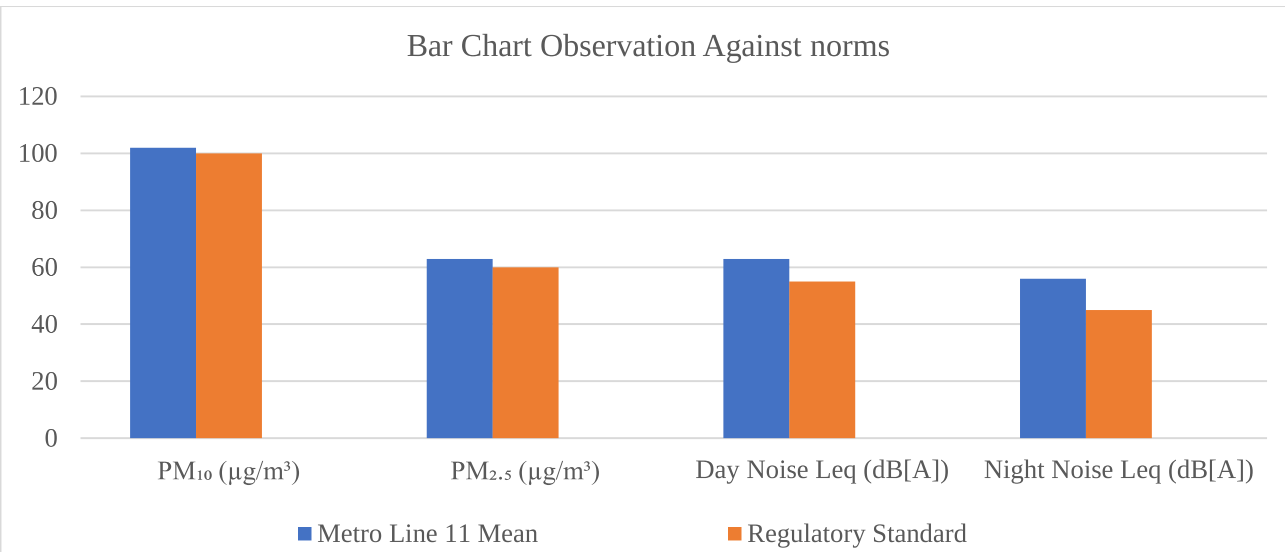

Fig. 2 Bar chart of observation against regulatory standards

3.7. Metro GIS Mapping

Geographic Information System (GIS) was used during the preliminary stage of this research to analyze the spatial relationship existing between the proposed Metro Line 11 and the identified areas falling under the Coastal Regulation Zones (CRZ). The main aim of this analysis was to determine the feasibility of developing infrastructure in an extremely constrained environment where the demands of density, sensitivity, and compliance have to be addressed.

This was achieved through the use of GIS techniques, which enabled the integration of various geo-referenced datasets. These datasets include the proposed metro line, existing road infrastructure, developed areas, mangroves, and notified areas falling under CRZ.

The datasets were then integrated and standardized to a universal coordinate system to ensure consistency. This analysis provided an extensive understanding of the interaction that exists between the metro line and various features, both man-made and naturally occurring.

In this case, the integration of the metro line with the CRZ was done to identify areas where development might be possible while addressing issues related to environmental sensitivity.

Another important aspect of the GIS analysis was the evaluation of the feasibility of the construction process in the context of the pile foundation in the highly populated areas characterized by high intensity of traffic and lack of availability of right-of-way. The spatial analysis included parameters such as the width of the road, proximity of the adjacent structures, utility availability, and the intensity of the traffic. The application of the spatial parameters in the construction process was facilitated by the GIS system in such a manner that the feasible construction zone was identified in the context of the least disturbance in the urban environment. The application of the spatial parameters in the construction process is highly significant in the context of metropolitan cities such as Mumbai, where the development of the infrastructure is required in the already congested environment.

In addition to the spatial parameters, such as the availability of the right-of-way in the already congested environment, the presence of sensitive zones, such as the mangrove ecosystem in the coastal regions, characterized by the classification under the CRZ-I zone, required stringent spatial evaluation. The application of the spatial parameters in the construction process is highly significant in the context of the development in the mangrove ecosystem, characterized by the importance in the context of ecosystem services such as shoreline protection, biodiversity conservation, and carbon sequestration.

The development in the mangrove ecosystem is highly restricted in the context of the regulatory guidelines issued by the Ministry of Environment, Forest and Climate Change. The application of the spatial parameters in the construction process was facilitated in such a manner that the development of the metro alignment did not encroach upon the areas characterized by the presence of the mangrove ecosystem.

Furthermore, the application of the spatial parameters in the construction process was facilitated by the GIS system in such a manner that the spatial relationships were visually represented in the context of the potential conflict zones between the infrastructure development and the environmental constraints. The application of the spatial parameters in the construction process is highly significant in the context of the visualization of the spatial relationships in the context of the alternative scenarios in the construction process. The application of the spatial parameters in the construction process is highly significant in the context of the integration of the spatial parameters with the environmental parameters in the unified analytical system.

In general terms, as shown in Figure 3, the application of GIS techniques in the initial stage of the study adopted a holistic approach in the evaluation of the interrelation between metro infrastructure and coastal regulatory zones. The methodology adopted in the study ensures that the planning of metro infrastructure is not only environmentally friendly but also feasible in terms of engineering considerations.

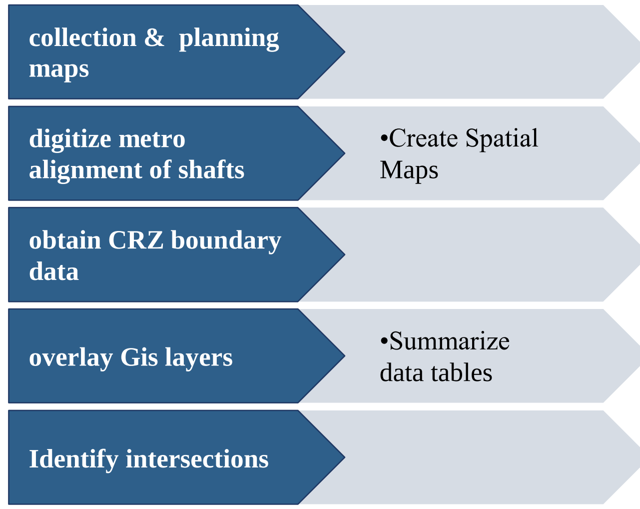

Fig. 3 Flow chart of GIS-based analysis

The methodology employed to perform the spatial analysis was based on a specific workflow comprising a series of sequential steps, structured to ensure the accuracy and reproducibility of the results obtained. Firstly, the relevant planning maps and datasets - including the metro alignment plans, shaft location plans, and base maps - were collected and compiled from publicly notified sources. Subsequently, the metro alignment and infrastructure elements were digitized into a geo-referenced vector format suitable for spatial analysis. The relevant datasets related to the Coastal Regulation Zone boundaries were then obtained and integrated with the Geographic Information System.

Following this, an overlay operation was performed across the metro infrastructure, CRZ boundaries, and existing land use layers, enabling identification of the intersection zones where metro infrastructure elements intersect with the CRZ zones. Finally, statistics were generated to obtain a quantitative representation of these interaction zones. This study demonstrates the spatial relationship between Metro Line 11 and CRZ zones through GIS-based analysis (MMRDA, 2022; MOEFCC, 2019).

To achieve uniformity in the analysis, environmental performance indicators were assessed against national regulatory standards and metro projects that have been cited in previous studies on EIA. Using this standard approach makes it possible to evaluate relative environmental performance across various metro projects.

4. Results

Other comparable metro projects used for the assessment were chosen depending on their size, urban setting, construction details, and data on environmental monitoring. This makes the process of benchmarking more consistent, which contributes to better comparability of the results achieved by Metro Line 11.

4.1. Air Quality Benchmark Comparison

A comparative evaluation of the existing levels of various parameters of air quality for the proposed Metro Line 11 route has been conducted as per the guidelines set by the CPCB, along with the results obtained from earlier Environmental Impact Assessment studies conducted for various proposed Metro projects in Mumbai. The parameters evaluated were critical ambient air quality parameters such as PM_{10}, $PM_{2.5}$, and gases such as nitrogen dioxide (NO_2) and sulphur dioxide (SO_2), which are recognized as critical parameters for air quality in urban environments. The results show that the levels of particulate matter such as PM_{10} and $PM_{2.5}$ are within the acceptable limits as per CPCB guidelines, consistent with the DPR/EIA reported range summarized in Table 1, as shown in Table 3. These levels are also comparable to those measured for operational metro routes in other densely populated urban environments. Although there were minor variations in levels of particulate matter at various locations along the route, these variations are insignificant and can be explained by factors such as traffic density, etc. The results obtained for gaseous pollutants such as NO_2 and SO_2 show that these levels are well within acceptable limits as per national guidelines. The relatively low levels of these pollutants can be explained by the lack of major industrial activities in the area, with vehicular traffic being the main contributor to ambient air pollution. This is in line with general observations for Mumbai city, where vehicular traffic is recognized as the main contributor to air pollutants in non-industrial areas [8].

The dataset used in the present study is obtained from secondary sources; therefore, the methodology is sound, and the study is in line with the ethics of research [21]. The dataset is comprised of information obtained from credible sources such as Environmental Impact Assessment reports and Detailed Project Reports prepared by the Mumbai Metropolitan Region Development Authority.

Furthermore, the dataset is supplemented with information obtained from scholarly articles that examine the metro rail system in the context of the environment in different settings. The amalgamation of the dataset with such information is significant in the context of the research study. Additionally, the guidelines provided by the Central Pollution Control Board have been incorporated in the study in order to establish parameters in the context of the environment, such as air quality, noise levels, and water quality parameters.

Table 3. Comparative air quality benchmarking (metro11 DPR)

Parameter	Metro Line 11 (µg/m³)	Other Mumbai Metro Studies (µg/m³)	CPCB Standard (µg/m³)
PM_{10}	85-90	90-100	100
$PM_{2.5}$	45-60	50-60	60
NO_2	30-65	37-68	80
SO_2	10-25	25-40	80

The amalgamation of the different types of reliable information helps in the creation of an in-depth analytical study; therefore, the need for primary data collection is eliminated. The methodology used in the study is not only beneficial in the context of the credibility of the study, but is also in line with the current scientific practices in the context of research in the Environmental Board [9].

4.2. Noise Level Assessment Compliance

A comparative analysis of ambient noise levels has been carried out based on the observed equivalent continuous sound levels (Leq) and permissible limits as per the Central Pollution Control Board for different categories of land use. From the analysis, it can be observed that the ambient noise levels in residential as well as commercial areas along Metro Line 11 are above the recommended threshold as per the Central Pollution Control Board norms for both day-time and nighttime conditions [22]. This is a clear indication of high ambient background noise levels, which are commonly observed in highly populated areas [9].

In residential areas, high ambient noise levels are prescribed for protecting public health and overall well-being. The observed ambient noise levels are a clear indication of continuous vehicular movement, mixed land use activities, and a high density of population. In commercial areas, ambient noise levels are high compared to residential areas due to high economic activities, traffic congestion, and the presence of public transport facilities [23]. The overall impact of these activities results in high ambient noise levels, which are above the prescribed norms for residential as well as commercial areas. The ambient noise levels are high during peak hours [23].

This pattern is consistent with high ambient background noise levels typically observed in densely urbanized areas. The CPCB-prescribed limits As shown in Table 4, used for this comparison are derived from the applicable land-use noise standards [7, 9, 24].

Table 4. Noise level comparison with CPCB standards

Area Type	Observed Leq (dB(A))	CPCB Day Limit	CPCB Night Limit
Residential	53-45	55	45
Commercial	60-55	65	55

4.3. Evaluation of Groundwater Quality

An assessment of groundwater quality in the influence zone of the proposed Metro Line 11 corridor in Mumbai was conducted by utilizing secondary data collection methods based on Environmental Impact Assessment reports of other metro rail projects in the region. This assessment was based on important physicochemical parameters like pH, Total Dissolved Solids (TDS), chlorides, and sulphates, which have been commonly cited as important parameters in groundwater quality assessment. This assessment was performed based on the parameters' conformity with the Bureau of Indian Standards (BIS) regulations on permissible limits for drinking water quality.

The results of the assessment have shown that the majority of the parameters related to groundwater quality are within acceptable limits, thereby suggesting that the hydro geo chemistry of the region is stable. The groundwater quality parameters recorded above show that the pH level is within the range of 7.1 to 7.8, which falls well within the allowable limit set by BIS of 6.5 to 8.5, thus proving that there is neutral to slightly alkaline groundwater present. The TDS levels recorded above (420 to 585 mg/L) are generally in line with the hydrogeology of the Mumbai coastal area. Although some places record a slightly higher value than the desirable limit of 500 mg/L, the groundwater quality is still the same as the baseline data recorded in other metro corridors.

Concentration levels of Chloride (180–220 mg/L) and Sulphate (120–195 mg/L), which are significant parameters in assessing salinity intrusion and anthropogenic effects in groundwater systems, were observed to be within the BIS-permissible limits of 1000 mg/L and 400 mg/L, respectively, although Chloride levels at some locations exceed the BIS desirable limit of 250 mg/L. The results assume more significance in the context of Mumbai city being located in the coastal region. The presence of moderate Chloride levels, consistent with the coastal setting, indicates limited but measurable saline intrusion into the groundwater system, while Sulphate levels well within acceptable limits indicate minimal contamination from industrial and chemical sources.

Moreover, the comparative analysis of the present EIA results with the previously recorded EIA results for the metro rail projects in the Mumbai region indicates the absence of significant changes in the groundwater quality due to the construction activities [20]. The results indicate that if adequate engineering controls and mitigation measures are put in place in the underground metro rail tunnel construction, the effects of the underground metro rail construction on the groundwater systems can be minimized.

The environmental parameters evaluated in this case are similar to the parameters considered in metro sustainability studies. The air quality parameters such as PM_{10}, $PM_{2.5}$, NO_2 and SO_2 had similar values to the values obtained from Mumbai Metro Line 3, Delhi Metro and Bengaluru Metro projects. The noise levels observed during this analysis had similar values to other metropolitan corridors, with the exception of some localized exceedances above the residential standards of the CPCB. The groundwater quality parameters observed showed consistent results compared to acceptable limits. This means that the environmental impact assessment of Metro Line 11 shows consistency with earlier metro projects.

Overall, the results indicate the low probability of the groundwater systems becoming unsuitable for potable use and undergoing adverse environmental changes due to the metro rail development. However, in the context of the hydrogeological conditions in the Mumbai region, it is recommended to constantly monitor the groundwater parameters to observe any changes in the long term.

4.4. Results of GIS-based CRZ Interaction

The spatial interaction between the proposed Metro Line 11 infrastructure and designated Coastal Regulation Zone (CRZ) categories, within the broader framework of coastal environmental assessment, has been evaluated. This has been achieved utilizing a geographic information system (GIS)-based overlay technique. As per the analysis, there are no major infrastructure elements of Metro Line 11 intersecting with the CRZ-I zone. Typically, the CRZ-I zone comprises features like mangroves, mudflats, and so on, which are considered sensitive from an environmental perspective. It is noteworthy that Metro Line 11 does not have any direct interface with the CRZ-I zone, which is heavily regulated in terms of environmental constraints and permissible activities within the zone as per the coastal regulation norms.

The spatial overlay analysis has shown that some of the auxiliary infrastructure of Metro Line 11, like ventilation shafts, access structures, and buildings, fall within the CRZ-II zone. Typically, the CRZ-II zone comprises stretches of the coastal area that have already been developed and are considered suitable for infrastructure development within the framework of regulated conditions. This is because Metro Line 11 passes through stretches of the metropolitan area, where land availability constraints are high.

The nature of the interaction in the context of the CRZ-II zones also does not come as a surprise, considering the fact that such zones have been earmarked for development in consonance with the regulatory requirements. As per the guidelines issued by the Ministry of Environment, Forest and Climate Change, infrastructure development projects of public utility value, such as urban transport infrastructure, can be permitted in the context of the CRZ-II zones while satisfying the requirements of environmental regulations and planning.

The spatial analysis undertaken using the GIS also establishes the fact that the infrastructure in the context of the CRZ-II zones is limited in nature. Such infrastructure has been developed in the context of the metro project and has been restricted to the functional requirements necessary to enable the smooth operation of the metro. Such infrastructure has been developed to enable the connection of different sections of the metro corridor. However, the spatial statistics derived also indicate the fact that the infrastructure has not been extended in a manner to cause undue spatial encroachment. Such a situation has been derived based on the spatial statistics, which indicate the fact that the infrastructure has remained within the acceptable limits. It also establishes the fact that while there has been a certain degree of interaction in the context of the metro infrastructure and the CRZ-II zones, the same has been within the acceptable limits and has been characteristic of the infrastructure development in the context of the urban environment.

5. Limitations

5.1. Limitations of Work

The study makes use mainly of secondary data available in the public domain in the form of DPRs, EIAs, regulatory documents, and published literature. Hence, no site-level data collection was undertaken. The GIS assessment made use of available spatial data and georeferenced data layers developed based on such information. In light of this, it can be said that the results obtained through this study have to be seen as indicative and not conclusive indicators of environmental performance.

5.2. Future Research

Building on the limitations identified above, future research should prioritise primary field measurements, including on-site air quality monitoring, noise dosimetry, and groundwater sampling along the Metro Line 11 corridor to validate the secondary-data-based findings reported here. A weighted composite sustainability index, informed by expert elicitation or stakeholder consultation, could also be developed to build on the equal-weighting approach used in this study. Future work would further benefit from higher-resolution GIS layers (e.g., LiDAR-based terrain and updated land-use maps) to refine the CRZ overlay analysis, from extending the benchmarking framework to additional under-construction Indian metro corridors to test its generalisability, and from incorporating longitudinal monitoring data to assess how environmental performance evolves across the construction-to-operation lifecycle of underground metro projects in coastal cities.

6. Conclusion

From the analysis, it is evident that there is environmental performance in Metro Line 11 similar to other metro line projects in urban cities using the selected criteria for evaluation. The study indicates that air quality and groundwater baselines remained in compliance throughout the evaluation period. This is consistent with other metro lines in Mumbai. However, it is also clear that baseline noise levels in both residential and commercial zones exceeded the limits set by the CPCB. In addition, the present study makes use of secondary sources of information to a large extent, which are easily available in the public domain through DPRs, EIAs, regulations, and literature. Data collection has not taken place on a ground-level basis in connection with this research.

The process of GIS analysis has made use of geographic information, along with georeferenced information from available geographic information. It is essential to mention at this point that the results obtained from the present research are just indicative in nature and not definitive results themselves. The study indicates that using a comparative approach that is enhanced using GIS is beneficial in identifying sustainability risks, which is beyond what is normally available. The study's main contribution is that it offers a methodology that is applicable to other studies using models that can be applied to assess metro projects in environmentally sensitive cities along coastlines using secondary data. The approach is applicable to future studies that involve data monitoring, life cycle analysis, and evaluation.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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