A GEOSPATIAL APPROACH TO ASSESS RIVER DIVERSION IMPACTS ON FLOODPLAINS: A CASE OF ULWE RIVER

Thesis submitted in partial fulfillment of the requirements for the award of the degree of

BACHELOR OF PLANNING

By

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Declaration

I **Kapil Shahaji Deshmukh**, Scholar No. **2021BPLN035**, hereby declare that the thesis entitled **"A Geospatial Approach to Assess River Diversion Impacts on Floodplains: A Case of Ulwe River"** submitted by me in partial fulfilment for the award of **Bachelor of Planning (Urban and Regional Planning)**, at School of Planning and Architecture, Bhopal, India, in the department of URP is a record of bonafide work carried out by me. The matter/result embodied in this thesis has not been submitted to any other University or Institute for the award of any degree or diploma.

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This is to certify that the declaration of **Kapil Shahaji Deshmukh** is true to the best of my knowledge and that the student has worked under my guidance for one semester in preparing this thesis.

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ABSTRACT

Urban rivers in India face escalating environmental stress due to rapid urbanization, unplanned land use, encroachment, and insufficient stormwater management infrastructure. The Ulwe River basin in Navi Mumbai exemplifies these challenges, with its floodplain undergoing significant transformation from natural wetlands and open water bodies to built-up urban areas. The thesis studies how such land use modifications during the period 2016–2024 have affected surface runoff processes and flood hazard in the Ulwe River floodplain.

The site and subject were selected for their strategic position in the Mumbai Metropolitan Region, susceptibility to mega-infrastructure projects (most notably the Navi Mumbai International Airport), and as a representative case of Indian urban floodplain change. The research aims to measure quantitatively surface runoff changes, evaluate the hydrological effects of urban expansion, and provide recommendations to inform sustainable urban planning and flood management. A robust methodology was used, combining high-resolution satellite imagery, field-based land use classification, and proven hydrological modeling. Land use mapping, grounded and verified by ground surveys, monitored changes in vegetation, wetlands, water bodies, and impervious surfaces over time. Soils in the area are characterized as sandy clay loam, which permitted the study to concentrate mainly on the influence of land cover change and rainfall variability on surface runoff. Surface runoff calculations were carried out using established hydrological processes, with soil and land use data normalized to ensure comparability between years.

The research established growth in impervious surfaces (roads and construction) compared to natural land uses (vegetation and wetlands). This has led to increased surface runoff and reduced infiltration and thus more monsoon flood hazard. Spatial analysis revealed unequivocally a loss of natural flood buffers and consequently more urban floods. The research demonstrates the causality of link between land use change in the urban area and the altered hydrologic response in the floodplain. The research has implications for urban planning and flood risk reduction. The increased surface runoff associated with urbanization implies that we require sustainable land use planning, green infrastructure, and wetland restoration to minimize flood risk. The research also demonstrates how geospatial analysis, and hydrological modeling can be integrated to analyze the effect of urbanization on floodplain processes.

In conclusion, this study offers a well-substantiated assessment of the impacts of high-rate urbanization and land cover modification that have led to rising surface runoff and flood vulnerability within the Ulwe River basin. Findings reveal the necessity of preventive planning strategies such as preservation and restoration of the natural floodplain features for establishing resilient and sustainable urban development. The results are intended to guide policymakers and urban planners in their policy and decision-making regarding flood risk management and ecological sustainability in rapidly growing urban river corridors.

Keywords: River Diversion, Hydrological Alteration, Flood Risk Assessment, Surface Runoff, Floodplain Dynamics, Geospatial Analysis,

सारांश

भारत में शहरी नदियाँ तीव्र शहरीकरण, अनियोजित भूमि उपयोग, अतिक्रमण और अपर्याप्त वर्षा जल प्रबंधन ढाँचे के कारण बढ़ते पर्यावरणीय दबाव का सामना कर रही हैं। नवी मुंबई में स्थित उलवे नदी जलग्रहण क्षेत्र इन समस्याओं का एक स्पष्ट उदाहरण प्रस्तुत करता है, जहाँ बाढ़ मैदान में प्राकृतिक आर्द्रभूमियों और खुले जलाशयों की जगह अब शहरी निर्माणों ने ले ली है। यह शोध वर्ष २०१६-२०२४ के बीच भूमि उपयोग में हुए परिवर्तनों का विश्लेषण करता है और यह समझने का प्रयास करता है कि इन परिवर्तनों ने सतही बहाव प्रक्रियाओं और बाढ़ के खतरों को किस प्रकार प्रभावित किया है।

इस अध्ययन के लिए उलवे नदी क्षेत्र का चयन इसके मुम्बई महानगरीय क्षेत्र में रणनीतिक स्थान, मेगा इन्फ्रास्ट्रक्चर परियोजनाओं (विशेष रूप से नवी मुंबई अंतरराष्ट्रीय हवाई अड्डा) की संवेदनशीलता और भारत के शहरी बाढ़ मैदान परिवर्तन के एक प्रतिनिधि उदाहरण के रूप में किया गया। इस शोध का उद्देश्य सतही बहाव में हुए परिवर्तनों का मात्रात्मक रूप से मूल्यांकन करना, शहरी विस्तार के जलवैज्ञानिक प्रभावों का विश्लेषण करना तथा सतत शहरी नियोजन और बाढ़ प्रबंधन के लिए सुझाव प्रदान करना है।

इस शोध में उच्च-रिज़ॉल्यूशन उपग्रह चित्रों, क्षेत्रीय सर्वेक्षण आधारित भूमि उपयोग वर्गीकरण, और स्थापित जलवैज्ञानिक मॉडलिंग का सशक्त संयोजन किया गया। भूमि उपयोग मानचित्रण को स्थल सर्वेक्षणों द्वारा सत्यापित किया गया, जिसमें वनस्पति, आर्द्रभूमि, जल निकायों और अभेद्य सतहों (जैसे सड़क और निर्माण) में हुए परिवर्तनों की निगरानी की गई। इस क्षेत्र की मिट्टी को 'सैंडी क्ले लोम' (रेतीली चिकनी दोमट) के रूप में वर्गीकृत किया गया, जिससे अध्ययन मुख्यतः भूमि आवरण परिवर्तन और वर्षा में परिवर्तनशीलता के सतही बहाव पर प्रभाव पर केंद्रित रहा। सतही बहाव की गणना स्थापित जलवैज्ञानिक प्रक्रियाओं के माध्यम से की गई, और वर्षों के बीच तुलनात्मकता सुनिश्चित करने हेतु मिट्टी और भूमि उपयोग डेटा को सामान्यीकृत किया गया।

शोध में यह स्पष्ट रूप से पाया गया कि प्राकृतिक भूमि उपयोग (जैसे वनस्पति और आर्द्रभूमि) की तुलना में अभेद्य सतहों (सड़क और निर्माण) का विस्तार हुआ है। इसके परिणामस्वरूप सतही बहाव में वृद्धि और जल का अवशोषण घटा है, जिससे मानसून के दौरान बाढ़ का खतरा बढ़ गया है। स्थानिक विश्लेषण ने स्पष्ट रूप से प्राकृतिक बाढ़ अवरोधों की हानि को दर्शाया और इसके परिणामस्वरूप शहरी क्षेत्रों में अधिक बाढ़ की संभावना पाई गई। यह शोध शहरी भूमि उपयोग

परिवर्तन और बाढ़ मैदान की जलवैज्ञानिक प्रतिक्रिया में आए परिवर्तनों के बीच कारणात्मक संबंध को सिद्ध करता है। इस शोध के निष्कर्ष शहरी नियोजन और बाढ़ जोखिम न्यूनीकरण के लिए महत्त्वपूर्ण हैं। शहरीकरण से जुड़ी सतही बहाव की वृद्धि यह संकेत देती है कि बाढ़ जोखिम को कम करने के लिए हमें सतत भूमि उपयोग नियोजन, हरित बुनियादी ढाँचे और आर्द्रभूमि पुनर्स्थापन की आवश्यकता है। यह शोध यह भी दर्शाता है कि किस प्रकार भू-स्थानिक विश्लेषण और जलवैज्ञानिक मॉडलिंग को एकीकृत कर शहरीकरण का बाढ़ मैदान प्रक्रियाओं पर प्रभाव विश्लेषित किया जा सकता है।

निष्कर्षतः, यह अध्ययन तीव्र शहरीकरण और भूमि आवरण परिवर्तन के प्रभावों का एक प्रमाणित मूल्यांकन प्रस्तुत करता है, जिसने उलवे नदी जलग्रहण क्षेत्र में सतही बहाव की वृद्धि और बाढ़ की संवेदनशीलता को बढ़ाया है। निष्कर्ष यह स्पष्ट करते हैं कि प्राकृतिक बाढ़ मैदान की विशेषताओं का संरक्षण और पुनर्स्थापन जैसे निवारक नियोजन उपायों की आवश्यकता है, ताकि लचीला और सतत शहरी विकास सुनिश्चित किया जा सके। यह परिणाम नीति निर्धारकों और शहरी योजनाकारों को तेजी से विकसित होते शहरी नदी क्षेत्रों में बाढ़ जोखिम प्रबंधन और पारिस्थितिकीय स्थिरता से संबंधित नीतियों और निर्णयों के निर्माण में मार्गदर्शन देने के उद्देश्य से प्रस्तुत किए गए हैं

कीवर्ड: नदी का मोड़, जल विज्ञान संबंधी परिवर्तन, बाढ़ जोखिम आकलन, सतही अपवाह, ग्रीनफील्ड परियोजना पर्यावरणीय प्रभाव, बाढ़ मैदान की गतिशीलता, भू-स्थानिक विश्लेषण

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List of Abbreviations

CIDCO	City and Industrial Development Corporation of Maharashtra
GIS	Geographic Information System
NMIA	Navi Mumbai International Airport
NAINA	Navi Mumbai Airport Influence Notified Area
KBRLP	Ken-Betwa River Linking Project
LULC	Land Use Land Cover
NDVI	Normalized Difference Vegetation Index
NRLP	National River Linking Project
SCS-CN	Soil Conservation Service Curve Number
CRZ	Coastal Regulation Zone
EIA	Environmental Impact Assessment
NDBI	Normalized Difference Built-up Index
MTHL	Mumbai Trans-Harbour Link
HSG	Hydrologic Soil Group
MCDA	Multi-Criteria Decision Analysis
URMP	Urban River Management Plan

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1. Introduction

River diversion is a significant hydrological intervention undertaken for infrastructure development, flood control, irrigation, and urban expansion. While these modifications are often essential for economic growth and urbanization, they can disrupt natural water flow patterns, leading to unintended environmental and hydrological consequences. River diversions typically involve altering a river’s natural course through channelization, damming, or inter-basin transfers. These alterations can significantly impact floodplain connectivity, sediment transport, and groundwater recharge, thereby increasing the vulnerability of surrounding regions to flooding and ecological degradation.

The consequences of river diversion are multifaceted. One of the most critical impacts is the reduction in the river’s capacity to absorb and manage excess rainwater, which increases the frequency and intensity of flooding. The loss of wetlands and mangroves, which serve as natural flood buffers, further exacerbates these risks. Additionally, river diversion can lead to soil erosion, sediment displacement, and reduced groundwater recharge, negatively affecting water availability for both human and ecological systems (Naidu, 2019). As cities continue to expand, the encroachment on floodplains and the construction of impermeable surfaces, such as roads and buildings prevent natural infiltration, resulting in increased surface runoff and urban flooding. This problem is further intensified in coastal areas, where rising sea levels pose additional hydrological challenges (Zope et al., 2017)

These effects are not merely theoretical but have been observed in several urban and peri-urban areas in India where river diversions have taken place. One of the most prominent examples is the Ken-Betwa River Linking Project in Madhya Pradesh and Uttar Pradesh, which aims to divert surplus water from the Ken River to the water-deficient Betwa basin. While the project is expected to support irrigation and drinking water supply, it has raised serious ecological concerns due to the potential submergence of nearly 9,000 hectares of the Panna Tiger Reserve, leading to large-scale biodiversity loss and alterations in natural hydrological regimes(Alagh et al., 2006) .

In Mumbai, the Mithi River is another example of river manipulation. The river’s channel was narrowed and altered due to the construction of the Bandra-Kurla Complex and the Chhatrapati Shivaji Maharaj International Airport. These interventions, coupled with the encroachment on adjoining wetlands and mangrove areas, significantly reduced the river’s flood-carrying capacity. The consequences became tragically evident during the 2005 Mumbai floods, where over 1,000 mm of rain fell in a single day, overwhelming the modified drainage system and causing widespread damage and fatalities (Kamath & Tiwari, 2022).

These case studies demonstrate that while river diversions are often justified as necessary for development, they can lead to unintended hydrological dysfunction and ecosystem collapse if not supported by adequate environmental assessments and long-term management plans.

The Ulwe River in Navi Mumbai has undergone significant modifications due to rapid urban development and infrastructure projects. One of the projects is the construction of the Navi Mumbai International Airport (NMIA), which requires the realignment of the river's natural flow. This diversion, combined with ongoing urban expansion, has significantly altered the region's hydrology, resulting in increased surface runoff, higher flood risks, and the loss of critical wetland ecosystems. The expansion of impervious surfaces has further compromised the region's natural flood management systems, making it increasingly difficult for excess water to be absorbed. In response, urban planners and policymakers must prioritize strategies that mitigate flood risks while promoting sustainable development.

Urbanization in Navi Mumbai has resulted in the degradation of mangrove ecosystems, which serve as essential buffers against coastal flooding and storm surges. The destruction of these natural barriers increases the vulnerability of low-lying areas to waterlogging and flood-related damage. Additionally, the rerouting of the Ulwe River has disrupted sediment transport processes, potentially resulting in alterations in river morphology and increased erosion in specific regions. Research indicates that the loss of mangroves not only increases flood vulnerability but also disrupts local biodiversity and diminishes the carbon sequestration capabilities of these coastal ecosystems (Singh & Jain, 2020). These factors highlight the need for a balanced approach that integrates ecological conservation into urban planning and infrastructure development.

The challenges posed by river diversion in Navi Mumbai are further intensified by the impacts of climate change. The region is experiencing unpredictable monsoon patterns, with more frequent and intense rainfall events contributing to increased flood risks. Rising sea levels add another layer of vulnerability, particularly for coastal cities like Navi Mumbai, where storm surges and high tides can worsen flooding. Infrastructure designed to manage flood risks, such as stormwater drainage systems and retention basins, is increasingly being pushed beyond its capacity due to these climatic changes. In many instances, the lack of integrated flood management policies leads to unplanned urban sprawl, further undermining the city's flood resilience. To mitigate these risks, a forward-looking approach that includes climate adaptation measures and resilient infrastructure planning is essential.

The financial and social consequences of urban flooding are significant. Damage to infrastructure, economic losses due to disrupted commercial activities, and the displacement of residents are some of the key issues associated with inadequate flood management. Recent studies indicate that urban flooding in Navi Mumbai has led to losses exceeding millions in property damages, in addition to disrupting essential services such as transportation and healthcare (*The World Bank Annual Report 2021*, n.d.). The inability of traditional flood mitigation strategies to address the root causes of flooding highlights the need for a more sustainable and integrated approach. Collaborative efforts between government agencies, urban planners, and environmental scientists can ensure long-term flood resilience in the region.

This study focuses on assessing the impact of the Ulwe River diversion on floodplain dynamics and urban flooding in Navi Mumbai. Through geospatial analysis and hydrological modelling, the study aims to identify high-risk flood zones, evaluate changes in land use and hydrology, and propose sustainable flood mitigation strategies. By leveraging advanced GIS techniques, remote sensing data, and hydrological models, the research seeks to provide a comprehensive assessment of urban flood risk. The findings will provide valuable insights for urban planners, policymakers, and environmental stakeholders, ensuring that future developments in Navi Mumbai align with principles of resilience and ecological conservation.

1.1 Background

Navi Mumbai, developed by CIDCO, is a planned extension of Mumbai designed to ease congestion and promote economic growth. However, rapid urbanization has led to significant environmental consequences. The replacement of natural flood management system such as wetlands, mangroves, and floodplain with concrete infrastructure has increased the city's vulnerability to flooding, particularly during the monsoon season. Several studies have indicated that unregulated urban expansion and inadequate drainage systems have intensified flood risks in the low-lying areas of Navi Mumbai (Dochartaigh et al., 2012; *The World Bank Annual Report 2021*, n.d.).

The Ulwe River, which originates in the Western Ghats, flows past Navi Mumbai before draining into the Arabian Sea. Historically, the river has played a crucial role in flood regulation, utilizing its natural floodplains to absorb and manage excess water during the monsoon season while supporting ecological sustainability (*Earth Surface Processes and Landforms | Geomorphology*

Journal | Wiley Online Library, n.d.). However, the construction of the Navi Mumbai International Airport (NMIA) required a major realignment of the river's course. As a result, the original width of the river, which ranged from 25 to 30 meters, has now been expanded to 200 meters in the diverted section, and its depth has been increased by 2.5 to 3 meters along a 3.1 km section. These modifications were implemented to accommodate airport infrastructure and improve drainage efficiency, but they have drastically altered the hydrological and ecological balance of the region.

The diversion of the Ulwe River poses several risks to the region.

1. Floodplain Disconnection: The diversion of the Ulwe River has disrupted its natural floodplain connectivity, reducing its ability to absorb and release excess water during heavy rainfall. This disconnection has weakened the area's natural flood resilience, rendering it more vulnerable to waterlogging and urban flooding.
2. Increased Surface Runoff: The rapid urbanization around the Ulwe River has introduced extensive impermeable surfaces, including roads, buildings, and airport infrastructure. This development has significantly reduced infiltration, resulting in increased surface runoff. Consequently, stormwater accumulates more rapidly, overwhelming drainage systems and increasing flood risks in low-lying areas.
3. Hydrological Alterations: The diversion of the Ulwe River has altered sediment transport processes, affecting groundwater recharge and river morphology. These alterations have led to noticeable changes in river morphology, including shifts in channel depth, width, and flow velocity, ultimately destabilizing the river's structural integrity and ecological balance.

Floodplains and mangroves play a vital role in maintaining ecological and hydrological balance. Floodplains help regulate water levels by absorbing excess rainfall, reducing the intensity of flood events, and providing habitat for microorganisms and aquatic species. Similarly, mangroves serve as natural storm barriers, stabilizing coastlines and mitigating the effects of sea-level rise. They also enhance water quality by filtering pollutants and supporting rich biodiversity (Singh et al., 2017). However, ongoing urbanization and river diversion projects in Navi Mumbai, driven by real estate expansion and large-scale infrastructure initiatives, have significantly threatened these critical ecosystems.

Figure 1 Image of Ulwe River. 2016, Before construction of NMIA

Figure 2 Image of Ulwe River. 2024, After the diversion of original river flow.

The following are the statements from the officials. “The diverted river can easily discharge heavy to very heavy rainwater. The rainfall range for the last 100 years has been considered while executing the diversion,” said Priya Ratambe, PRO, CIDCO.

The locals presented their own thoughts, “Modifying the river was the biggest mistake as now it is just 1 km away from sea, leading to reverse flow of seawater during high tides regularly. Earlier the river was almost 5 km away from the sea. No amount of expansion work will avert floods because the size of the riverbed is now reduced to a channel, which during rainfall will certainly overflow.” (“Cidco Diverts Ulwe River from Navi Mumbai International Airport,” 2022)

1.2 Need for study

Increased Flood Vulnerability Due to Urbanization and River Diversion

Rapid urbanization and large-scale river diversion projects have significantly altered natural hydrological systems, leading to increased surface runoff and a reduced capacity of floodplains to manage excess water. In many urbanizing regions, these changes disrupt natural flood regulation mechanisms, exacerbating flood risks in densely populated and low-lying areas (Pathak et al., 2020a). The diversion of rivers alters their natural courses, affecting drainage patterns and reducing groundwater recharge. Consequently, even in areas equipped with flood control infrastructure, flooding persists due to the loss of natural buffers such as wetlands and floodplains. In Navi Mumbai, hydrological changes surrounding urbanized floodplains have heightened flood exposure, necessitating updated flood management strategies for the city (Sansare & Mhaske, 2020) . The combined effects of intensified rainfall, unregulated development, and drainage overload contribute to recurrent urban flooding, especially in monsoon-prone coastal cities like Navi Mumbai.

Effect of Land Use Changes on Floodplains

Land-use changes, particularly the expansion of built-up areas and the reduction of open natural spaces, have exacerbated flood risks by impeding natural infiltration, shortening runoff times, and increasing water volumes during rainfall events. The proliferation of impermeable surfaces, such as roads, buildings, and paved areas, prevents water absorption, causing excess runoff to accumulate rapidly in urbanized floodplains (Zope et al., 2017). Additionally, many lower-order streams that once facilitated localized drainage have been lost to urbanization, disrupting natural water pathways and increasing the likelihood of localized flooding in developed areas. The disappearance of natural stream networks has resulted in poor drainage efficiency, leading to excessive water retention in urban basins. These disruptions necessitate a re-evaluation of land-use planning strategies to incorporate sustainable urban drainage systems and green infrastructure for effective flood mitigation.

Integrated Approach Involving Geospatial Enrichment

To generate accurate flood risk predictions, it is essential to use an integrated hydrological model alongside geospatial technologies such as Geographic Information Systems (GIS) and remote sensing. These geospatial tools enable a detailed spatial assessment of land-use changes, terrain characteristics, and hydrological alterations, providing crucial insights into flood-prone areas. An integrated, data-driven methodology allows for the precise identification of high-risk zones while facilitating simulation-based scenario analyses for effective mitigation planning ((Aishan et al., 2013; Jain & Kumar, 2014). By incorporating historical flood data, terrain elevation models, and hydrological simulations, GIS-based flood models significantly enhance disaster preparedness and response strategies. Furthermore, the integration of real-time monitoring systems with GIS applications can improve flood forecasting capabilities, enabling early warning measures and efficient urban drainage management.

Focus on Sustainable Flood Management

This research will work on developing flood risk mitigation strategies that consider both hydrological and ecological impacts, promoting a balance between development and natural flood management. This will be done by analyzing high-risk zones and land use, hence promoting sustainable flood management practices, which are crucial for cities facing both natural and anthropogenic flood risks (Pathak et al., 2020b).

Supporting Urban Planning and Policy Development

The project's findings will be actionable for urban planners and policymakers to improve flood risk management and resilience in urban areas. The geospatial analysis of the study will inform policy recommendations on zoning, green infrastructure, and land-use planning, ensuring that cities can grow sustainably while minimizing flood risks (Das, 2018). This support is crucial for developing policies that adapt to future climate challenges and growing urban demands.

1.3 Aim

"To develop a geospatial framework to quantitatively assess the impacts of river diversion on floodplains, focusing on hydrological alterations, land-use dynamics, and flood risk in the Ulwe River basin."

Focusing on the Ulwe River basin, this framework aims to assist urban planners in developing sustainable flood risk mitigation strategies. The Ulwe River has been significantly altered due to rapid urbanization and large-scale infrastructure projects, such as the Navi Mumbai International Airport, making it an ideal case study for analyzing the impacts of river diversion on hydrology, ecology, and urban flood vulnerability. Additionally, the Ulwe River’s proximity to coastal and estuarine systems increases its sensitivity to tidal influences and flooding related to climate change.

While the Ulwe River is a critical case for understanding urban flood risks, other rivers in Mumbai, such as the Mithi, Dahisar, Poisar, and Oshiwara Rivers, also face similar challenges due to encroachment, pollution, and altered drainage patterns. The Mithi River, for example, has experienced severe flooding events in recent decades as a result of unregulated construction, loss of floodplains, and inadequate drainage infrastructure. The Dahisar and Poisar Rivers have similarly suffered from encroachment and pollution, reducing their capacity to manage floodwater effectively. By incorporating lessons from multiple river systems, this study will provide comprehensive insights into floodplain management and urban resilience strategies for the Mumbai Metropolitan Region.

The framework will establish assessment criteria for conducting hydrological analyses in urbanizing river basins. This will enable the identification of high-risk flood zones, assessment of ecological impacts, and the development of actionable insights for sustainable floodplain management and land-use planning. By integrating geospatial technologies, hydrological modelling, and policy recommendations, this study will support policymakers in balancing infrastructure development with ecological preservation, thereby ensuring long-term urban resilience against both natural and human-induced flood risks.

1.4 Objectives

1. To analyze the historical and contemporary impacts of river diversion on hydrology and environment

This objective aims to examine the past and present-day changes in the Ulwe River due to diversion, evaluating their impacts on hydrological flow patterns and environmental parameters, such as wetland degradation and floodplain disruption. By conducting a comprehensive baseline study, the research will assess how river diversions have transformed the river-floodplain system over time, influencing flood risks, sediment transport, and ecological stability. Historical data, remote sensing imagery, and hydrological records will be used to reconstruct changes and establish long-term trends in river modifications.

2. To conduct a spatial analysis of hydrological and environmental factors associated with river diversion

This objective involves spatially assessing the extent of environmental and hydrological changes caused by river diversion using GIS and remote sensing techniques. Key analyses will include mapping land-use changes, floodplain connectivity, water flow distribution, and river morphology to visualize and measure the spatial impact of river modifications. By integrating geospatial datasets with hydrological modelling, the study will generate insights into how alterations in river systems influence urban flood risks and ecosystem health.

3. To quantify the extent of changes and establish linkages between hydrological and environmental changes

This objective focuses on measuring the degree of hydrological and environmental changes identified in Objectives 1 and 2, with an emphasis on statistical modelling and comparative assessments. The research will quantify shifts in flood frequency, sediment deposition, groundwater recharge, and wetland loss due to river diversion. By analyzing correlations between land-use changes, floodplain alterations, and ecological degradation, the study will establish clear linkages between river modifications and their cascading effects on flood risks and ecosystem dynamics in the Ulwe River basin.

4. To develop targeted mitigation strategies for high flood risk areas

Based on findings from spatial analysis and quantitative assessments, this objective aims to propose sustainable and data-driven mitigation strategies for managing flood risks and preserving ecological balance. The strategies will focus on high-risk and environmentally vulnerable areas along the Ulwe River and emphasize resilient urban planning, wetland restoration, and flood risk reduction measures. Key recommendations will include green infrastructure solutions, nature-based flood mitigation techniques, and policy interventions to integrate ecological preservation with urban development, ensuring long-term resilience against flood hazards and environmental degradation.

1.5 Scope of the study

This study aims to develop a geospatial framework to assess the impacts of river diversion on the flood plains of the Ulwe River basin. The focus is on understanding hydrological alterations, land-use dynamics, and flood risks resulting from urbanization and large-scale infrastructure projects, such as the Navi Mumbai International Airport. By integrating Geographic Information Systems (GIS), remote sensing technologies, and quantitative methodologies, the research will provide a comprehensive understanding of floodplain dynamics. The insights gained will help balance infrastructure development with ecological conservation, forming a scientific foundation for policymaking and sustainable floodplain management.

Hydrological impact analysis is an important part of the study. It looks into how diversion from rivers has affected the natural regimes of the river flow in the basin, making surface runoff altered, the hydraulic dynamics of flow changed, and the flood hazards increased. Hydrological modelling technologies will be utilized to calculate those impacts and zone out areas as high-risk for flooding. This analysis will offer valuable insights into the altered hydrological regimes caused by the river's diversion and urban encroachments, providing a foundation for effective flood management strategies.

Urbanization has changed the LULC characteristics of the Ulwe River basin, thereby significantly altering its floodplains. This study will analyze the influence of such changes, particularly the replacement of natural ecosystems with urban infrastructure, using satellite imagery and GIS tools. By assessing the temporal changes in LULC, the research will evaluate how these transformations have disrupted floodplain connectivity and increased the vulnerability of the region to flood events.

This ecological study includes the effects of river diversion on flood plains, especially their critical ecosystems, including wetlands, vegetation, and biodiversity. Changes in sedimentation patterns and hydrological processes will be evaluated in terms of impacts on ecological stability and groundwater recharge. This part underlines the significance of maintaining the ecological importance of floodplains, which are important for biodiversity, regulating water quality, and natural flood mitigation.

A scenario-based flood risk analysis will simulate multiple scenarios, such as extreme rainfall events and continued urban expansion, which will predict the future risks from flooding. Simulations will form the basis of developing spatial flood risk maps that mark vulnerable areas in the floodplain. These will be crucial tools for urban planners to proactively reduce flood risks and institute mitigation measures.

The study will develop sustainable floodplain management and land-use strategies to mitigate flooding risk, while enabling urban development. These will focus on low-impact development support, green infrastructure integration and floodplain ecosystem protection recommendations. The results are meant to be actionable inputs for policymakers: allowing for the integration of flood risk management into regional planning frameworks.

1.6 Limitations

One of the key limitations of this study is the availability and accuracy of data. The research study heavily relies on historical hydrological and ecological datasets, which could be incomplete, inconsistent, or outdated. For instance, variation in the resolution and accuracy of satellite imagery or inconsistencies in historical rainfall and discharge data may lead to an error in the precision of the analysis (Suriya & Mudgal, 2012). Although remote sensing and GIS techniques give a general spatial overview of floodplain changes, the methods may fail to capture real-time alterations or highly localized phenomena, which are critical for accurate flood management planning (Kulkarni et al., 2014).

Modelling uncertainties also pose a significant challenge. Hydrological and ecological models applied in this study rely on a range of input parameters, such as rainfall intensity, land-use changes, and river discharge rates. These models run on assumptions that simplify real world complexities, potentially leading to inaccuracies. Besides, external factors such as extreme weather events, unregulated urban development, and unexpected ecological disturbances can introduce variability, making it difficult to account for all the possible outcomes (Zope et al., 2017)As such, the models may not fully represent the intricate interactions between hydrology, land use, and floodplain dynamics.

The Ulwe River basin is experiencing rapid urban transformation, which presents significant challenges for effective floodplain management. In particular, the area surrounding the Navi Mumbai International Airport has become a focal point for large-scale infrastructure development, intensifying pressure on the region's natural hydrological systems. The dynamic nature of land use, infrastructure expansion, and construction activities creates a constantly evolving scenario, making it difficult to design static, long-term strategies for floodplain management (Pathak et al., 2020b). These rapid changes necessitate adaptive and flexible planning approaches that can accommodate future uncertainties.

Despite these limitations, the research forms a valuable framework for assessing the impacts of river diversion on floodplains and offers insights for development in sustainable urban flood management. The findings, therefore, form part of a nascent body of knowledge that identifies the importance of geospatial tools and adaptive planning in rapidly urbanizing regions.

1.7 Methodology

The first phase consists of baseline data collection via field reconnaissance and satellite imagery analysis. Ground surveys captured physical changes in the river, while remote sensing data (Landsat and Sentinel) supplied hydrological parameters like rainfall and discharge, which allowed for the determination of pre- and post-diversion conditions.

Land cover and land use (LULC) analysis was done with GIS-based urban, vegetated, marshland, barren, and water body category classification. Temporal images were utilized to identify patterns of urban sprawl, wetland degradation, and vegetation degradation. The expansion of impervious surfaces, particularly in the airport area, was observed to relate to increased flood hazards with increasing surface runoff.

Surface runoff was quantitatively determined using the SCS-Curve Number (CN) approach, which considers rainfall amount, land use types, and soil properties. This computation enabled a spatial analysis of runoff volume changes by land cover types, verifying that urban spaces produce considerably more runoff compared to natural conditions.

Hydrological assessment entailed the examination of river flow variation, sediment transport disruption, and changed channel morphology due to diversion activities. Historical and present-day flow conditions compared showed a reduction in floodplain connectivity along with enhanced erosion hazards.

An ecological analysis further analyzed changes in wetlands, mangroves, and riparian buffers through NDVI analysis. Buffer zone degradation was found to diminish the natural flood absorption capacities and jeopardize biodiversity. The results guided nature-based interventions and zoning suggestions towards supporting sustainable floodplain management in the fast-growing Ulwe River basin.

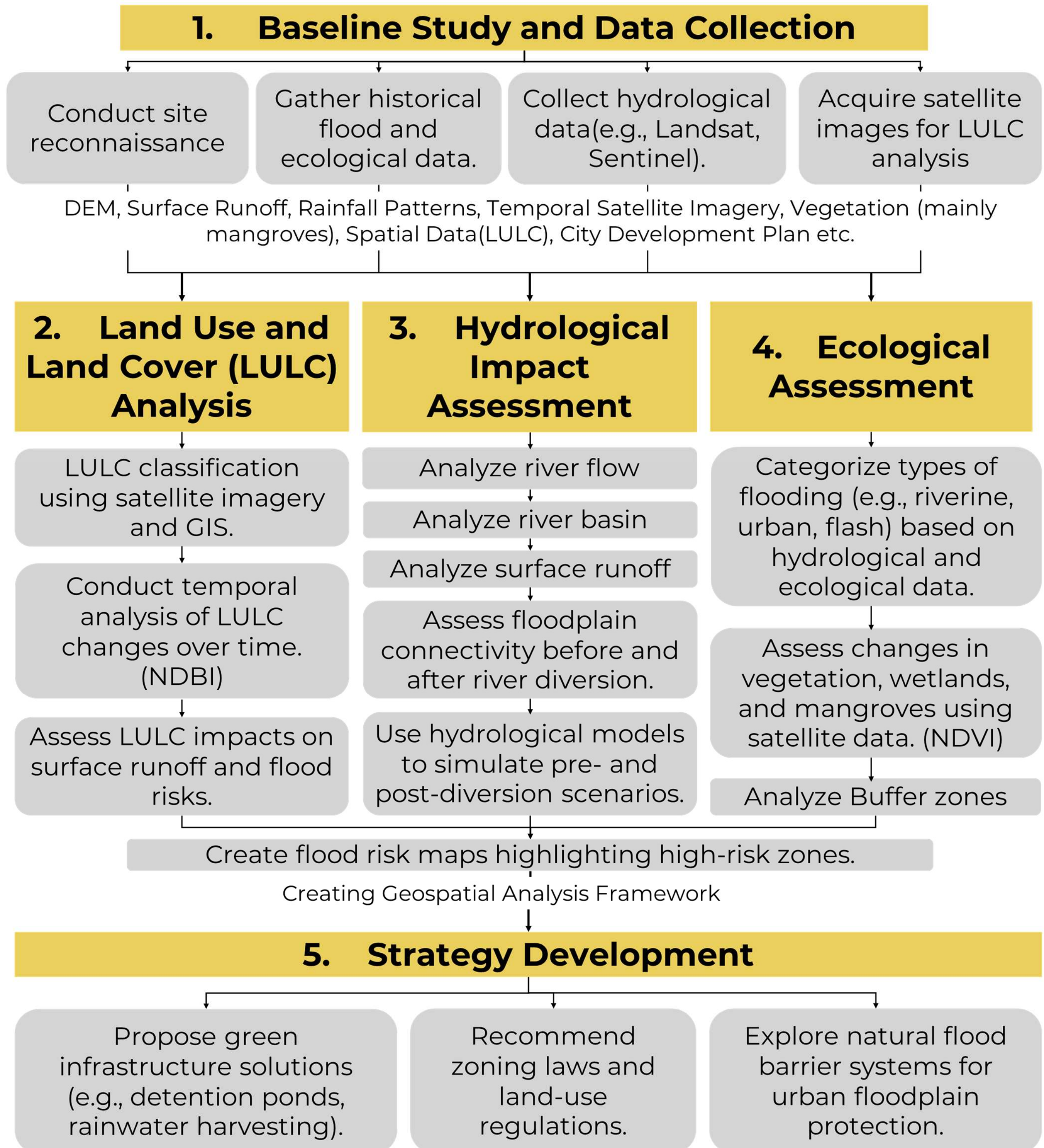

Figure 3 Methodology.

2 Literature review

2.1 Introduction

Urban floodplains and wetlands are being increasingly valued as key elements of metropolitan hydrological systems, but they are under serious threat from accelerated urbanization. These wetlands and floodplains have a key function in regulating floods in cities, supporting biodiversity, and sequestering carbon. They facilitate important ecological processes like nutrient cycling, sediment trapping, and groundwater recharge, thus contributing to the climate variability and extreme weather resilience of cities. Operating at the interface of land and water, urban wetlands also offer services such as water cleansing, connectivity between habitats, and local temperature regulation.(Pathak et al., 2020b)

In rapidly urbanizing areas such as Navi Mumbai, however, the spread of large-scale infrastructure developments-such as the Navi Mumbai International Airport has resulted in systemic degradation and fragmentation of wetland ecosystems. This is mainly because of unsustainable land-use transformations, encroachment, and large-scale hydrological interventions, such as river diversion and channelization. (Sansare & Mhaske, 2020) To address these challenges, contemporary research underscores the necessity of integrating geospatial modelling, hydrodynamic simulations, and evidence-based policy frameworks to formulate sustainable wetland conservation strategies. Additionally, the restoration of degraded wetland systems through strategic ecological engineering and sustainable water resource management is increasingly being recognized as a critical intervention for mitigating urban flood risks and preserving biodiversity.

This study, on the Ulwe River basin and its related urban floodplains, underscores the imperative to strike a balanced approach that reconciles infrastructural development with ecologically sensitive preservation. Urban floodplain management must, on a priority basis, restore and conserve wetland systems, not only to provide flood mitigation but also to promote urban biodiversity, water quality, and climate resilience. The conclusion promotes data-based planning, engagement with communities, and the application of nature-based solutions as central strategies for urban development that is resilient and sustainable. This research contributes to the wider discourse on sustainable urban planning by advocating for data-driven decision-making, community engagement, and the adoption of nature-based solutions. It underscores the critical role of urban wetlands in enhancing urban resilience and ensuring the long-term sustainability of rapidly growing cities.

2.2 Impacts of Urbanization on Wetlands

Urban expansion profoundly reconfigures hydrological regimes, fundamentally altering watershed equilibrium, floodplain integrity, and groundwater recharge dynamics. The proliferation of impervious surfaces manifested through asphalted roads, high-density residential areas, and engineered drainage systems impedes natural infiltration processes, amplifies stormwater runoff, and intensifies peak discharge rates. Moreover, the anthropogenic modification of riverine corridors through channelization, embankments, and diversions distorts sediment transport mechanisms, leading to increased erosion, hydrodynamic instability, and ecological degradation. These disruptions not only impact surface hydrology but also lead to significant long-term groundwater depletion, altering subsurface hydrological balances.

2.2.1 Disruption of Hydrological Connectivity

Urbanization-induced fragmentation of hydrological networks disrupts the continuity of surface and subsurface water movement, significantly impairing wetland function. The installation of artificial barriers—including embankments, levees, and roads—reduces the ability of wetlands to act as hydrological buffers, exacerbating flood vulnerabilities and diminishing aquifer recharge potential. This disruption fosters localized water stagnation, alters seasonal flow patterns, and escalates the risk of both flash floods and prolonged droughts. Moreover, the disruption of connectivity between upstream and downstream systems results in an altered hydrological cycle, reducing wetland resilience to seasonal variations and extreme climatic events.

2.2.2 Increased Surface Runoff and Flood Risk

The expansion of built environments markedly reduces percolation capacity, escalating surface runoff volumes and overloading stormwater infrastructure. The rapid accumulation of runoff heightens flood magnitudes, causing recurrent urban inundation and exacerbating socio-economic disruptions.

Studies in the Poisar River Basin, Mumbai, demonstrate a strong correlation between increasing urban footprint and heightened flood susceptibility, necessitating the integration of hydrological models in urban planning to mitigate environmental risks (Zope et al., 2017).The increasing reliance on stormwater drainage systems rather than natural infiltration mechanisms further exacerbates urban water management challenges, increasing dependence on artificial flood mitigation infrastructure.

2.2.3 Alterations in Sediment Transport and Deposition

Anthropogenic land-use transformations have fundamentally disrupted sediment transport mechanisms, leading to spatial heterogeneity in sediment deposition patterns. Construction activities, deforestation, and hydrological re-engineering have induced erosional hot spots while simultaneously increasing sediment load in wetland catchments. This disruption results in channel instability, floodplain constriction, and diminished floodwater attenuation capacity, further exacerbating hydrological stress within urban wetlands. Additionally, the alteration of sediment transport impacts nutrient cycling and aquatic habitat structures, contributing to the decline of wetland-dependent species.

2.3 Case Studies

2.3.1 Ken-Betwa River Linking Project (KBLP)

Ken-Betwa River Linking Project (KBLP) is India's first interlinking of rivers initiative under the National Perspective Plan (NPP) of the 1980s, executed by the Ken-Betwa Link Project Authority. The project seeks to transfer excess water from the Ken River in Madhya Pradesh to the Betwa River in Uttar Pradesh, both rivers of the Yamuna, to meet water shortages in the arid Bundelkhand region. The KBLP is conceived in two stages: Phase I involves the construction of the Daudhan Dam complex, related tunnels, a 231-kilometer connecting canal, and powerhouses, and Phase II involves development of the Lower Orr Dam, Bina Complex Project, and Kotha Barrage. The expected dividends are considerable, including irrigation of 6.3 lakh hectares, supply of drinking water to 62 lakh people, and the generation of 103 MW of hydropower. (Alagh et al., 2006; Amarasinghe et al., 2008)

Even with these advantages, the project has been seriously questioned and put under controversy. Environmentalists and communities have objected to the flooding of more than 8,000 hectares of forest land-part of the Panna Tiger Reserve-wildlife habitat loss possibilities, and more general ecological implications. Others raise questions about lack of transparency in data, public participation, and environmental impact assessment sufficiency. However, after decades of controversy and successive rounds of governmental clearance, the project has progressed, with state agreements between Uttar Pradesh and Madhya Pradesh and fresh cabinet approvals in recent times. The Ken-Betwa case therefore highlights the potential as well as the pitfalls of large-scale river diversion in balancing regional water deficits, while emphasizing the need to incorporate ecological protection and participatory governance into such initiatives.(Avtar et al., 2011)

Socio-Economic and Ecological Consequences
The changes in hydrological regimes have directly impacted local communities, with increased flood risks affecting property values, infrastructure resilience, and public health. Moreover, the loss of wetland habitat has led to a decline in biodiversity, particularly in fish populations that are crucial for sustaining local livelihoods. The ecological consequences extend beyond habitat loss, as altered water quality dynamics have increased the prevalence of waterborne diseases, exacerbating health risks for vulnerable populations.

2.3.2 Caernarvon Freshwater Diversion Project

The Caernarvon Freshwater Diversion Project in southeastern Louisiana, USA, represents an internationally recognized example of river diversion for wetland restoration and flood risk reduction. Authorized under a series of U.S. federal acts and constructed between 1988 and 1991, the Caernarvon structure is located on the east bank of the Mississippi River and is designed to reintroduce up to 8,000 cubic feet per second of freshwater, sediments, and nutrients into the marshes and bays of the Breton Sound estuary. The primary objectives are to enhance emergent marsh vegetation, reduce marsh loss, and boost the productivity of commercial and recreational fisheries, particularly oysters, which have suffered from saltwater intrusion.

The project operates through controlled diversions, especially during high-flow periods, to mimic natural flood pulses and maintain salinity gradients beneficial for marsh and estuarine ecosystems. Extensive monitoring-including pre- and post-construction ecological assessments and long-term tracking of vegetation, fisheries, and water quality-has demonstrated positive outcomes. These include increased marsh stability, improved oyster production, and the mitigation of saltwater intrusion, supporting both ecological health and local livelihoods. The Caernarvon experience is frequently cited as a model for nature-based solutions in coastal restoration, emphasizing adaptive management, stakeholder engagement, and the integration of ecological objectives into river management. (Wu et al., 2023)

2.3.3 Inferences

Together, these case studies reflect the evolving goals and methodologies of river diversion projects. While the Ken-Betwa project is primarily engineered for irrigation and water supply in a semi-arid context, the Caernarvon diversion exemplifies ecosystem restoration and flood management in a coastal delta. Both underscore the need for balancing infrastructural benefits with environmental stewardship, robust monitoring, and community involvement to ensure long-term sustainability and resilience.

2.4 Ecological Impacts of Mangroves Degradation

Mangroves are one of the most ecologically valuable and productive wetland ecosystems, offering critical services like habitat for a variety of species, shoreline protection, water filtration, carbon storage, and flood control. Yet extensive mangrove degradation, fueled by urbanization, industrialization, land use change, and hydrological modifications, has resulted in serious ecological impacts along India's coastlines and worldwide.

Evidence shows that mangrove degradation leads to high biodiversity loss, with research recording up to a 20% reduction in benthic species richness and local phyla extinction in disturbed habitats. This biodiversity loss is followed by a drastic decline in ecosystem functioning: disturbed mangrove sediments have up to 80% reduced microbial decomposition rates and a marked reduction in faunal biomass relative to undisturbed habitats. Such losses compromise the nutrient-cycling, carbon-sequestration, and fishery-support functions of mangroves, diminishing the resilience of coastal ecosystems against environmental stressors.

In India, approximately 50% of the mangrove cover has been lost since the 1950s, with Sundarbans-a world-important mangrove eco-region-undergoing acute stress from both human activities and natural stressors like salinity increase, anoxia, and cyclonic storms. Urbanization and infrastructure use, such as conversion for settlement, aquaculture, and agriculture, have fragmented mangrove habitats, limited species movement, and caused sensitive species like Heritiera fomes and Phoenix paludosa to decline. Fragmentation not only disrupts ecological connectivity but also exposes mangrove-dependent communities to coastal risk and diminishes the ecosystem's ability to regulate climate.(Bhomia et al., 2016)

Removal of mangrove buffers in fast-growing cities such as Navi Mumbai has increased vulnerability to storm surges, tidal erosion, and saline intrusion, leading to ecological imbalances that impact fisheries, aquatic productivity, and socio-economic well-being of the people. Loss of vegetation cover also reduces carbon sequestration potential, leading to enhanced greenhouse gas emissions and changing local climate conditions. Moreover, the loss of intertidal wetlands destroys important breeding habitats for marine and avian species, resulting in population declines and changes in species distributions.

Industrial effluent, untreated sewage, and agricultural runoff pollute mangrove and freshwater wetland ecosystems further, enhancing eutrophication, hypoxia, and the spread of invasive species that compete with native vegetation. These transformations destabilize trophic regimes, lower ecosystem services, and exacerbate the urban heat island effect by lowering evapotranspiration and moisture holding capabilities.

In view of the extent and complexity of mangrove loss, adaptive and integrated management strategies are called for. Restoration activities like replanting indigenous vegetation, reconnecting isolated habitats, and instituting sustainable land-use planning can restore ecosystem function and improve climate resilience. Policy measures such as the declaration of biosphere reserves and more effective enforcement of conservation legislation are also essential to protect existing mangrove cover and promote the livelihoods of supporting communities.

In conclusion, mangrove degradation results in cascading ecological effects such as loss of biodiversity, compromised ecosystem functioning, and enhanced susceptibility to climate risks. Conservation and restoration of mangroves are critical in ensuring the ecological and socio-economic stability of coastal urban areas.(Carugati et al., 2018)

2.5 The Role of GIS and Remote Sensing in Wetland Management

Advancements in geospatial technologies have significantly enhanced wetland conservation methodologies, allowing for precise and systematic monitoring of ecological and hydrological parameters. Geographic Information Systems (GIS) and remote sensing facilitate multi-temporal assessments of wetland loss, hydrological alterations, and land-use transitions, providing valuable insights for conservation planning and policy implementation.

The study demonstrated the effectiveness of GIS-based risk mapping in identifying vulnerable zones in the Kalamboli catchment area, emphasizing the role of detention basins in mitigating flood-related hazards. Similarly, GIS-integrated flood hazard assessments in the Oshiwara River Basin have informed urban resilience strategies, leading to the optimization of stormwater management infrastructure and flood mitigation planning. Additionally, the integration of hydrological modelling with GIS-based mapping has provided urban planners with real-time decision-making tools to forecast flood risks and design adaptive infrastructure that mitigates climate-induced hydrological variability. (Shahapure et al., 2011)

The incorporation of LiDAR technology, AI-driven object classification, and drone-based ecological surveillance has further revolutionized wetland assessment. These advanced tools enable high-resolution mapping of topographical changes, vegetation health indices, and hydrodynamic fluctuations. The fusion of GIS with real-time hydrological data enhances predictive modelling capabilities, facilitating proactive interventions for climate-induced wetland changes. Such integrations improve the accuracy of wetland conservation efforts by enabling real-time responses to habitat degradation. Furthermore, GIS-driven simulations of climate change impacts on wetlands can inform conservationists about potential vulnerabilities and enable them to design pre-emptive mitigation strategies.

Furthermore, GIS applications extend beyond ecological monitoring to include socio-economic analyses, which provide insights into human-wetland interactions, land-use conflicts, and the efficacy of conservation initiatives. Hydrodynamic modelling has been employed to simulate urbanization impacts on wetland hydrology, improving the development of adaptive wetland management frameworks. Strengthening regulatory compliance through GIS-based monitoring ensures that conservation policies are informed by empirical data, thereby enhancing decision-making processes. The real-time monitoring of wetland parameters using satellite technology also facilitates the enforcement of environmental regulations and the early detection of ecosystem stressors, allowing for swift remedial actions. Additionally, GIS-based participatory mapping initiatives have proven to be effective in engaging local communities in wetland conservation efforts by integrating indigenous knowledge with scientific data to develop holistic conservation strategies.

2.6 Policy Frameworks and Conservation Strategies

The conservation and management of wetlands necessitate a robust, multi-tiered policy framework that effectively integrates ecological preservation with sustainable urban development. Wetlands, as vital ecological assets, require stringent legislative protections to mitigate the deleterious effects of anthropogenic pressures such as industrialization, urban sprawl, and climate-induced environmental changes. The implementation of comprehensive policies is crucial for preserving their hydrological and ecological functions, which include carbon sequestration, groundwater recharge, flood regulation, and biodiversity conservation.

India’s Wetlands (Conservation and Management) Rules, 2017, constitute a structured legal framework aimed at protecting wetlands through the delineation of ecologically sensitive zones, the prohibition of environmentally detrimental activities, and the promotion of sustainable wetland utilization. These regulations underscore the importance of scientific methodologies in wetland delineation and management, advocating for adaptive strategies that align with regional ecological requirements.

Despite the existence of this legal framework, enforcement remains an arduous challenge. The dual imperatives of economic development and environmental conservation frequently come into conflict, exacerbated by bureaucratic inefficiencies and limited public engagement. Enhancing institutional capacities through inter-agency cooperation, the deployment of geospatial monitoring tools, and the integration of wetland policies into national climate adaptation strategies can facilitate more effective governance. Remote sensing technologies, coupled with real-time ecological data analysis, can offer precise insights into wetland health, enabling proactive conservation measures.

On the international front, the Ramsar Convention provides a globally recognized framework for wetland conservation, advocating for sustainable ecosystem management practices. Aligning national and regional policies with Ramsar guidelines can strengthen wetland resilience, ensuring their long-term ecological sustainability and socio-economic viability. Effective governance must be predicated on stringent regulatory enforcement, increased financial investments in wetland restoration projects, and multi-sectoral collaborations among governmental agencies, environmental organizations, academic institutions, and local communities (Pathak et al., 2020). Public participation in conservation initiatives can further bolster compliance, ensuring that policy interventions are contextually relevant and widely accepted.

Additionally, integrating wetland conservation policies within broader climate resilience frameworks is imperative, given the growing threat of climate change. Wetlands play a crucial role in mitigating the impacts of rising sea levels, extreme weather events, and ecological disruptions. Governments should prioritize research and innovation in wetland restoration methodologies, such as bioengineering solutions for shoreline stabilization and ecosystem-based climate adaptation measures.

2.6.1 Coastal Regulation Zone (CRZ)

Coastal ecosystems, including wetlands, mangroves, estuaries, and tidal marshes, are increasingly threatened by rapid infrastructural expansion, industrial pollution, and climate-induced stressors. Recognizing the ecological and socio-economic significance of coastal regions, the Government of India established the Coastal Regulation Zone (CRZ) framework in 1991, which was revised in 2019 to address emerging environmental challenges. The CRZ framework categorizes coastal zones based on ecological sensitivity and permissible developmental activities, aiming to balance conservation objectives with economic priorities.

The four designated CRZ categories include:

- **CRZ I:** Highly ecologically sensitive areas, including mangroves, coral reefs, and estuarine ecosystems, where developmental activities are strictly prohibited to prevent habitat destruction and ecosystem degradation.

- **CRZ II:** Urbanized coastal areas within existing municipal limits where regulated development is permitted, ensuring that infrastructural expansion does not compromise coastal biodiversity.
- **CRZ III:** Relatively undisturbed rural coastal stretches where controlled development is allowed beyond a specified buffer zone. Sustainable tourism and eco-sensitive development models are encouraged in this zone.
- **CRZ IV:** Marine waters extending up to 12 nautical miles from the shoreline, with a primary focus on pollution control, sustainable fisheries management, and marine biodiversity conservation.

The CRZ framework plays a crucial role in regulating human activities in coastal regions, ensuring that fragile ecosystems receive adequate protection. However, enforcement challenges persist due to jurisdictional overlaps, inconsistent monitoring, and insufficient compliance mechanisms. Leveraging advancements in geospatial technologies, such as GIS mapping and AI-driven real-time monitoring using satellite imagery, can enhance regulatory efficacy, enabling timely interventions to mitigate environmental degradation.

A critical aspect of CRZ enforcement is the integration of local communities into the conservation process. Sustainable resource management strategies, such as community-based conservation initiatives and participatory coastal governance, can complement regulatory mechanisms by fostering a sense of environmental stewardship. Mangrove restoration projects, sustainable aquaculture, and eco-friendly tourism ventures are potential avenues for integrating conservation with economic development, ensuring long-term ecological and financial sustainability.

2.6.1.1 CRZ IV and Marine Wetland Protection

CRZ IV is particularly significant in the context of marine and tidal-influenced wetland conservation, as it provides a regulatory framework for mitigating industrial pollution, preventing oil spills, and curbing the overexploitation of marine resources. The effective conservation of marine wetlands is not only critical for biodiversity preservation but also essential for sustaining key ecological services, such as nutrient cycling, sediment stabilization, and oceanic carbon sequestration. (*Earth Surface Processes and Landforms | Geomorphology Journal | Wiley Online Library*, n.d.)

The key provisions under CRZ IV include:

Stringent regulations on industrial waste disposal: The discharge of untreated sewage, hazardous industrial effluents, and municipal waste into marine and estuarine waters is strictly prohibited.

Biodiversity conservation measures: The establishment of Marine Protected Areas (MPAs), mangrove afforestation projects, and sustainable aquaculture initiatives are promoted to restore and conserve estuarine and marine ecosystems.

Mandatory Environmental Impact Assessments (EIA): Any proposed industrial, tourism, or infrastructural project within CRZ IV zones must undergo a rigorous environmental evaluation to assess its potential ecological impact and compliance with sustainability criteria.

Regulation of coastal and deep-sea fisheries: Sustainable fishing practices, aquaculture monitoring, and biodiversity conservation programs are enforced to prevent overexploitation of marine resources and habitat destruction.

Despite the regulatory framework established under CRZ IV, enforcement remains inconsistent due to institutional fragmentation, regulatory loopholes, and lack of inter-agency coordination. Strengthening enforcement through satellite-based marine pollution tracking, blockchain-enabled regulatory compliance mechanisms, and AI-driven ecosystem monitoring can enhance accountability in marine wetland conservation efforts. Additionally, increasing governmental investments in marine restoration projects and fostering transboundary collaborations in coastal conservation can improve the efficacy of CRZ IV regulations.

2.6.1.2 Strengthening CRZ Enforcement for Wetland Conservation

Given the ecological significance of coastal and marine wetlands, enhancing CRZ enforcement mechanisms is imperative for ensuring long-term conservation outcomes. The following strategic interventions can improve CRZ implementation:

- **Integration of Emerging Digital Technologies:** AI-driven satellite monitoring, geospatial analytics, and blockchain-based environmental tracking can enhance regulatory transparency, ensuring that compliance frameworks are data-driven and enforceable.
- **Community-Centric Conservation Models:** Engaging local fishing communities, coastal settlers, and indigenous groups in conservation initiatives can foster sustainable resource management and strengthen regulatory compliance.
- **Institutional Strengthening and Inter-Sectoral Collaboration:** Establishing clear mandates for regulatory bodies, fostering cooperation between environmental agencies,

urban planning authorities, and private stakeholders, and allocating targeted funding for coastal conservation can ensure more effective policy execution.

- **Public Awareness and Environmental Advocacy:** Promoting awareness about CRZ regulations, wetland conservation imperatives, and sustainable coastal practices can build public support for environmental policies, facilitating participatory conservation.

2.7 Morphometric Parameters

Hydrological parameters are essential for understanding watershed dynamics, river basin characteristics, and water resource management. These parameters influence surface and subsurface hydrology, stream behavior, and the overall functioning of drainage basins. To comprehensively assess hydrological systems, these parameters are broadly categorized into three groups: **linear aspects, areal aspects, and relief aspects**. Each category provides crucial insights into the geomorphological and hydrological behavior of drainage basins, aiding in effective flood control, water resource planning, and environmental management.

2.7.1 Linear Aspects

Linear aspects refer to the morphological features associated with the length and connectivity of drainage networks within a watershed. These parameters are key to understanding stream organization, runoff response times, and sediment transport efficiency.

Stream Order: A hierarchical classification of streams based on the Strahler or Horton method, where higher-order streams exhibit greater discharge, longer flow paths, and increased drainage influence. Lower-order streams are more numerous and contribute significantly to basin hydrology.

Stream Length (L): The cumulative length of all streams within a drainage basin, directly affecting runoff velocity, water retention time, and sediment transport dynamics.

Drainage Density (Dd): Defined as the total length of streams per unit basin area, calculated as:

$$Dd = \frac{L}{A}$$

where **L** is total stream length and **A** is basin area. Higher drainage density signifies well-drained basins with reduced infiltration, while lower values indicate higher permeability and water retention.

Bifurcation Ratio (Rb): The ratio of the number of streams of one order to the next higher order, reflecting stream branching efficiency and drainage network complexity. Higher values suggest structural controls and geological influences on drainage patterns.

Stream Frequency (Fs): The total number of streams per unit area, which indicates watershed dissection and the potential for infiltration versus surface runoff. High stream frequency suggests rapid hydrological response and surface water dominance.

Length of Overland Flow (Lg): The average distance that water travels over the land surface before reaching a defined stream channel. It is inversely related to drainage density and influences runoff generation and erosion processes.

2.7.2 Areal Aspects

Areal aspects define the spatial extent, shape, and runoff characteristics of a drainage basin. These parameters provide insight into how effectively precipitation is collected, stored, and transported through a watershed.

Basin Area (A): The total surface area contributes to runoff, influencing water yield, flood potential, and sediment load.

Form Factor (Ff): The ratio of basin area to the square of its length, expressed as: $Ff = \frac{A}{L^2}$

where **L** is the basin length. Elongated basins exhibit lower peak discharge rates, while more circular basins tend to produce flashier flood responses.

Elongation Ratio (R_e): A measure of basin shape. Higher values indicate elongated basins with extended hydrological response times, reducing flood hazards compared to compact basins.

Circularity Ratio (R_c): A shape parameter indicating how closely a basin resembles a circle, calculated as: $R_c = \frac{4\pi A}{P^2}$

where **P** is the basin perimeter. A lower circularity ratio suggests an elongated basin with prolonged runoff duration, while higher values indicate compact basins with a rapid response to rainfall events.

Compactness Coefficient (Cc): Represents the efficiency of a basin's shape in conveying runoff, influencing drainage efficiency and flood response potential.

Drainage Texture (Dt): The ratio of total number of streams to basin area, providing an indication of surface dissection and geological resistance to erosion. Fine drainage textures suggest well-developed stream networks in impermeable terrains, whereas coarse textures indicate permeable conditions.

2.7.3 Relief Aspects

Relief aspects define the vertical characteristics of a watershed, including elevation variation, gradient, and slope complexity. These parameters govern runoff velocity, erosion susceptibility, and the overall drainage behavior of a basin.

Basin Relief (H): The difference in elevation between the highest and lowest points in the basin, directly affecting Stream Energy, sediment transport capacity, and erosion potential.

Relief Ratio (Rr): The ratio of basin relief to basin length, calculated as:

$$Rr = \frac{H}{L}$$

where **H** is basin relief and **L** is basin length. Higher relief ratios indicate steeper watersheds with greater erosion risks and flashier runoff responses.

Ruggedness Number (Rn): A composite measure of terrain ruggedness, given by: $Rn = Dd \times H$ where **Dd** is drainage density and **H** is basin relief. Higher ruggedness numbers suggest greater potential for mass wasting events, landslides, and high sediment yield.

Hypsometric Integral (HI): A dimensionless parameter representing the distribution of elevation within a basin. It is calculated by integrating the area-elevation curve and helps classify drainage basins as young (high HI values), mature (moderate HI values), or old (low HI values).

Slope (S): The average gradient of the basin's surface, influencing runoff speed, infiltration capacity, and erosion intensity. Steeper slopes generate faster runoff and higher erosion rates, while gentle slopes promote infiltration and groundwater recharge.

Dissection Index (Di): A measure of the extent of vertical erosion relative to total relief, indicating how much a basin has been dissected by streams and river channels.

2.8 Surface Runoff

Surface runoff is a fundamental process in hydrology, representing the portion of precipitation that flows over the land surface and eventually enters streams, rivers, or other water bodies. Its estimation is crucial for water resource management, flood forecasting, and the planning of hydraulic structures. The generation of surface runoff is influenced by several factors, including rainfall intensity and duration, soil characteristics, land use, topography, and the antecedent moisture condition of the catchment.(*Earth Surface Processes and Landforms* | *Geomorphology Journal* | *Wiley Online Library*, n.d.)

Among the various empirical methods developed for runoff estimation, Strange's Table method is widely recognized, particularly in India and other regions with monsoonal climates. Developed by W.L. Strange in the early 20th century, this approach provides a straightforward means of estimating runoff from rainfall data, especially in ungauged or data-scarce catchments. The method is based on the observation that the proportion of rainfall contributing to runoff varies with the physical and hydrological characteristics of the catchment, as well as its current moisture status.

Strange's Table classifies catchments into three categories-Good, Average, and Bad-according to their runoff-producing potential. A "Good" catchment yields a higher percentage of runoff for the same rainfall compared to "Average" or "Bad" catchments, reflecting differences in factors such as soil permeability, vegetation cover, and slope. The table assigns runoff coefficients as percentages of total rainfall for each catchment type, providing a simple lookup for practitioners.

A key theoretical underpinning of the method is its consideration of the antecedent moisture condition, which is the soil's wetness prior to a rainfall event. Strange's method incorporates the "Dry, Damp, Wet" classification, recognizing that a catchment's recent rainfall history significantly affects its runoff response. For instance, a catchment that has experienced substantial rainfall in the preceding days will have higher soil moisture, leading to greater runoff generation during subsequent events. The transitions between dry, damp, and wet states are defined by specific rainfall thresholds over set time intervals, allowing for dynamic adjustment of runoff estimates based on real-time or historical rainfall data.(Srinivas G et al., 2020)

The simplicity and practicality of Strange's Table have made it a standard tool for preliminary runoff estimation in small to medium-sized catchments, particularly for irrigation planning, tank and pond management, and flood risk assessment in India. It is especially useful where direct flow measurements are unavailable, as it relies primarily on accessible rainfall data and basic catchment classification. Despite its empirical nature, studies have shown that Strange's Table method produces runoff estimates comparable to more data-intensive approaches, such as the SCS Curve Number method, especially when applied to monsoon-dominated regions. In summary, Strange's Table method remains a widely used, empirically grounded approach for estimating surface runoff in monsoonal and ungauged catchments. Its enduring relevance lies in its ease of use, minimal data requirements, and reasonable accuracy for preliminary water resource assessments and planning.

2.9 Terminologies and definitions

River Flow

River flow refers to the movement of water through a river channel, primarily influenced by precipitation, groundwater inflow, and anthropogenic interventions such as dam constructions, diversions, and irrigation. It is typically quantified as discharge, measured in cubic meters per second (m^3/s), and is critical for maintaining ecological health, sediment transport, and water availability for human consumption and agriculture. Variations in river flow impact flood risks, water quality, and biodiversity.

River Basin

A river basin is a geographical area drained by a river and its tributaries, where all surface water converges into a single outlet such as an ocean, lake, or another river. River basins form the fundamental unit for hydrological studies and are essential for water resource management. Sustainable river basin management integrates flood control, biodiversity conservation, and water allocation to balance ecological integrity with human demands.

Watershed

A watershed is a land area that channels precipitation to streams, rivers, or lakes, encompassing both surface and subsurface water flows. Watersheds are classified based on size and drainage patterns, influencing localized hydrology, groundwater recharge, and ecosystem dynamics. Effective watershed management involves soil conservation, afforestation, and pollution control to maintain water quality and prevent erosion.

Surface Runoff

Surface runoff is the portion of precipitation that flows over land rather than infiltrating into the soil. It occurs when rainfall intensity exceeds soil infiltration capacity, contributing to urban flooding, erosion, and water contamination. Factors influencing surface runoff include soil type, land use, slope gradient, and rainfall duration.

Normalized Difference Built-Up Index (NDBI)

NDBI is a remote sensing index used to identify and quantify urban expansion by analyzing the spectral differences in the shortwave infrared (SWIR) and near-infrared (NIR) bands. It is calculated as: $NDBI = \frac{(SWIR+NIR)}{(SWIR-NIR)}$

A higher NDBI value indicates a greater presence of built-up areas. This index is instrumental in assessing urban sprawl, land-use changes, and their environmental impacts, including heat island effects and loss of vegetation cover.

Normalized Difference Vegetation Index (NDVI)

NDVI measures vegetation health and density by analyzing the contrast between near-infrared (NIR) and red-light reflectance. It is calculated as: $NDVI = \frac{NIR+Red}{NIR-Red}$

NDVI values range from -1 to +1, with higher values indicating healthier vegetation. This index is extensively utilized in environmental monitoring, precision agriculture, drought assessment, and land-cover classification.

Hydraulic Gradient

The hydraulic gradient refers to the slope of the water table or potentiometric surface, driving groundwater flow. It is calculated as the difference in hydraulic head per unit distance. A steeper hydraulic gradient results in faster groundwater movement, affecting aquifer recharge, contamination transport, and water extraction efficiency.

Base Flow

Base flow is the portion of river discharge that originates from groundwater seepage rather than direct surface runoff. It sustains streamflow during dry periods and plays a crucial role in maintaining aquatic ecosystems. Base flow is influenced by soil permeability, aquifer storage capacity, and land-use changes.

Infiltration Capacity

Infiltration capacity is the maximum rate at which soil can absorb rainfall or irrigation water. It is affected by soil texture, vegetation cover, compaction, and antecedent moisture conditions. High infiltration capacity reduces surface runoff and enhances groundwater recharge, while low infiltration contributes to erosion and flooding.

Hydrograph

A hydrograph is a graphical representation of river discharge over time, depicting variations in flow due to precipitation events, snowmelt, and other hydrological factors. Hydrographs are critical tools in flood forecasting, watershed management, and water resource planning.

Interflow

Interflow, also known as subsurface stormflow, is the lateral movement of water through the soil layer above the water table. It occurs when infiltration exceeds percolation capacity, contributing to streamflow between storm events. Interflows play a significant role in maintaining river discharge during dry conditions.

3. Study Area Description

3.1 Introduction

The Navi Mumbai International Airport (NMIA) and the Navi Mumbai Airport Influence Notified Area (NAINA) are among the most ambitious infrastructure and urban development initiatives in Maharashtra, India. These projects aim to redefine regional connectivity, stimulate economic growth, and promote sustainable urban expansion. NMIA, designed as a state-of-the-art international airport, seeks to alleviate congestion at the overburdened Chhatrapati Shivaji Maharaj International Airport (CSMIA) while positioning Mumbai as a global aviation hub. Conversely, NAINA is conceptualized as a strategically planned satellite city that will integrate residential, commercial, and industrial zones, fostering economic diversification and addressing the escalating demand for structured urbanization.

As integral components of the Mumbai Metropolitan Region (MMR) expansion strategy, the Navi Mumbai International Airport (NMIA) and the Navi Mumbai Airport Influence Notified Area (NAINA) are expected to reshape the region's infrastructure landscape by enhancing multimodal connectivity and catalyzing large-scale investments. However, these transformative projects also pose complex challenges, particularly regarding environmental sustainability, socio-economic equity, and land-use planning. Understanding these dynamics is essential for ensuring a balanced approach that prioritizes long-term resilience and responsible development.

3.2 Location and Regional Context

NMIA is strategically located in the Raigad district of Maharashtra, along the banks of the Ulwe River. Covering approximately 1,160 hectares, the airport site is positioned between the rapidly urbanizing areas of Panvel and Uran. The project falls under the jurisdiction of the City and Industrial Development Corporation (CIDCO), which is responsible for its master planning and phased implementation. This location offers significant logistical advantages, significantly enhancing both domestic and international trade and travel capabilities.

NMIA is seamlessly integrated into a network of transport corridors, including the Mumbai Trans Harbour Link (MTHL), Navi Mumbai Metro, and key national highways such as NH-4 and NH-17. This strategic positioning ensures efficient connectivity between Mumbai, Pune, and other vital economic zones, making NMIA as a pivotal infrastructure node. Furthermore, its proximity to the Jawaharlal Nehru Port Trust (JNPT), India’s largest container port, enhances its role as a multimodal transport hub, facilitating cargo movement and improving global supply chain efficiencies.

Encompassing an extensive area of 370 square kilometers, NAINA surrounds NMIA and is envisioned as an integrated urban agglomeration that promotes sustainable development through a focus on transit-oriented growth, industrial innovation, and climate-responsive infrastructure. Strategically located near Mumbai, NAINA aims to reduce development pressures on the Mumbai Metropolitan Region while promoting a decentralized urbanization model. The city's planning approach prioritizes mixed land-use developments, smart mobility solutions, and green infrastructure, ensuring its long-term ecological and economic viability.

Infrastructure development in NAINA includes a robust network of arterial roads, metro rail connectivity, and intelligent urban transit corridors that significantly enhance accessibility. The zoning regulations within NAINA incorporate eco-sensitive development strategies aimed at conserving critical natural habitats, including wetlands and mangrove ecosystems, which play a fundamental role in flood mitigation and biodiversity conservation. Additionally, NAINA's vision aligns with global smart city initiatives by integrating renewable energy solutions, digital governance frameworks, and advanced waste management systems to create a resilient urban environment.

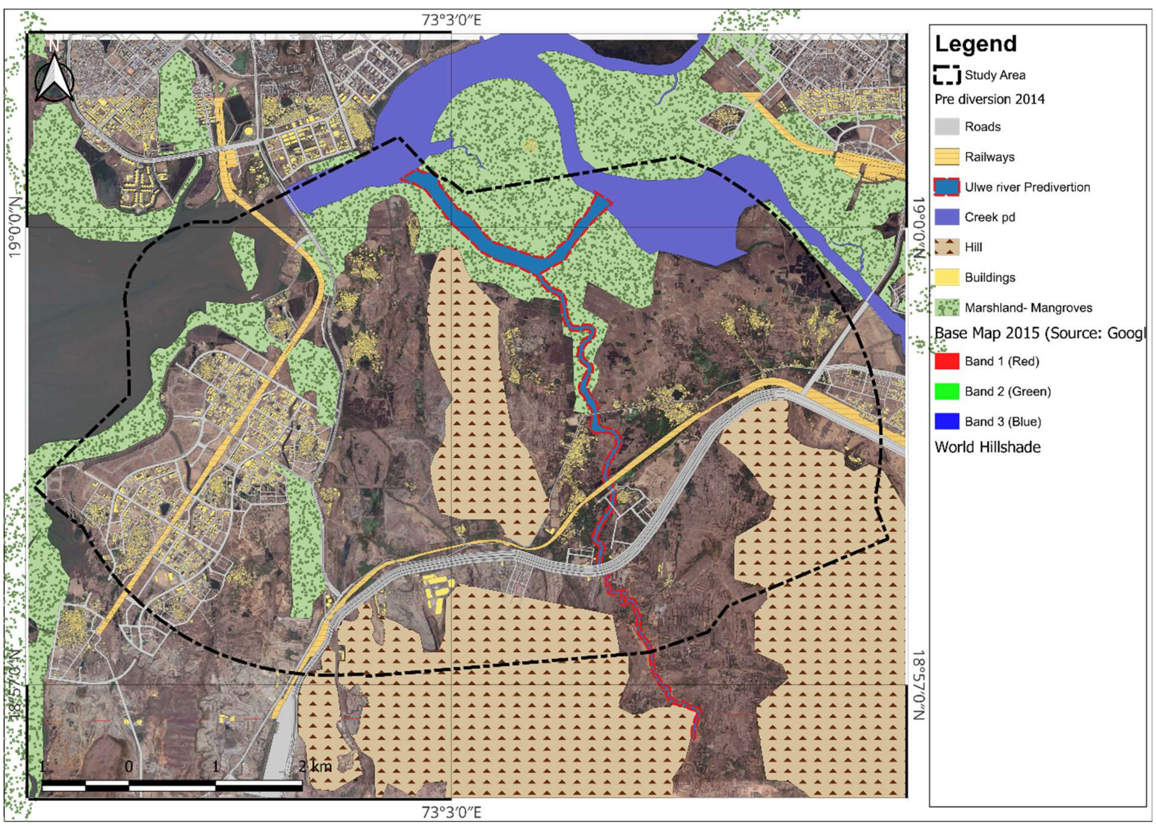

Figure 4 Map of Ulwe River Basin Pre Diversion (based on 2015 satellite imagery)

3.3 Environmental and Hydrological Considerations

3.3.1 Impacts on Wetlands and Floodplains

The development of the Navi Mumbai International Airport (NMIA) is taking place within an ecologically sensitive region characterized by extensive wetlands, tidal mudflats, and mangrove ecosystems. Historically, these wetlands have served as critical natural flood buffers, effectively regulating excess rainfall during monsoons and mitigating urban flood risks. However, the extensive land reclamation required for NMIA has significantly disrupted these hydrological functions, leading to increased surface runoff, increased flood risks, and compromised water filtration systems.

The floodplain of the Ulwe River, which once served as a natural spillover zone for excess water, has been significantly altered due to embankments and land reclamation activities. These modifications have disrupted the hydrological balance, leading to increased peak flood discharge levels and reduced groundwater recharge capacities. Furthermore, the degradation of mangrove forests, which act as vital coastal bio-shields, has heightened the region's vulnerability to storm surges, sea-level rise, and saltwater intrusion. The subsequent loss of wetland-dependent biodiversity, including both avian and aquatic species, presents long-term ecological threats that require urgent conservation efforts.

3.3.2 River Diversion and Hydrological Alterations

A significant hydrological modification within the NMIA project is the large-scale diversion of the Ulwe River. Originally, the river had a width of 25 to 30 meters, but engineering interventions have expanded it to 200 meters, with an increased depth of 2.5 to 3 meters. These large-scale changes have had significant effects on the flow regime of the river, with consequences for both floodplain response and fluvial stability.

The urban expansion has caused higher flow velocities, resulting in more severe bank erosion and sediment redistribution along the river corridor. Such morphological modifications have upset the equilibrium states of the river, decreasing its capacity to act as a naturally adaptive hydrological system. This is of concern in the context of the increased urbanization of the adjacent Navi Mumbai Airport Influence Notified Area (NAINA), where land cover modifications—trending toward more impervious cover—have exacerbated surface runoff.

In addition, the changed sediment transport regime and riparian buffer zone loss could intensify flood hazards in downstream and low-lying areas. Specifically, changes in deposition patterns risk clogging natural drainage channels, leading to localized flood hotspots. The higher volume and velocity of surface water flow, as determined in the surface runoff analysis, also add to these hazards. These results emphasize the need to embrace nature-based erosion control and incorporate ecological buffers into future development strategies in order to regain some of the lost hydrological resilience of the river and preserve regional floodplain function.

3.3.3 Climate Resilience and Adaptive Strategies

Given its coastal location, the NMIA-NAINA region is inherently vulnerable to climate-induced hazards, including rising sea levels, extreme rainfall events, and increasing cyclonic activity. To mitigate these risks, urban planners must integrate robust climate-resilient design principles. The incorporation of green infrastructure, such as constructed wetlands, permeable pavements, and riparian buffer zones, can significantly enhance flood attenuation and hydrological stability.

A nature-based urban planning approach that emphasizes mangrove restoration, afforestation programs, and sustainable water management practices is essential for long-term climate resilience. Additionally, the implementation of Sustainable Urban Drainage Systems (SuDS) can effectively regulate stormwater flow, minimize runoff, and enhance groundwater infiltration. The use of Geographic Information Systems (GIS) and remote sensing technologies for real-time monitoring of hydrological variables can further strengthen adaptive capacity, enabling data-driven decision-making for disaster risk reduction and infrastructure resilience.

3.4 Socio-Economic Impacts

The development of the Navi Mumbai International Airport (NMIA) is going to spur urbanization in Navi Mumbai, fueling huge residential, commercial, and industrial development, especially along the NAINA corridor. This fast development will bring in a huge number of skilled and semi-skilled manpower, putting additional pressure on housing, healthcare, education, and civic infrastructure. Though these trends hold out the promise of economic progress, they also threaten to widen socio-economic disparities, with uncontrolled growth potentially resulting in informal settlements, increasing real estate costs, and displacement of the vulnerable. It is thus essential to ensure fair access to affordable housing and basic services, and this can be facilitated by inclusive zoning regulations and incentives for affordable housing projects.

NMIA's strategic position in the Mumbai Metropolitan Region is supplemented by large-scale infrastructure developments like the Mumbai-Pune Expressway, Navi Mumbai Metro, and Mumbai Trans-Harbour Link. These connectivity upgrades are anticipated to spur economic growth, draw investment, and make Navi Mumbai a globally competitive metropolitan city. Enhanced transportation networks will ensure efficient mobility, lower travel times, and improve business logistics. However, this rapid expansion must be balanced with sustainability, prioritizing integrated public transport, electrified transit systems, and pedestrian-friendly planning to mitigate congestion and emissions. Smart city technologies and intelligent traffic management will further optimize urban mobility and energy efficiency.

Large-scale land acquisition for NMIA and NAINA has significantly impacted local communities, particularly those dependent on agriculture and fishing. Even with compensation and rehabilitation schemes, issues persist regarding the effectiveness of such interventions for affected groups. An overall resettlement framework encompassing skill upgradation, employment transition, and social reintegration is required, complemented by participatory governance so that displaced groups can be included in urban development processes. Land acquisition procedures with openness and effective grievance redress mechanisms are crucial to prevent conflict and promote social cohesion.

3.4.1 Policy Interventions for Equitable and Sustainable Growth

For NMIA and NAINA to fulfill their potential as models of sustainable urbanization, an integrated policy framework must be established that balances economic growth with environmental sustainability and social equity. Key policy recommendations include:

- Strengthening Environmental Governance: Implementing stringent enforcement of ecological conservation laws to protect wetlands, mangroves, and floodplains from unregulated development.
- Enhancing Climate Adaptation Strategies: Mandating the adoption of climate-resilient infrastructure, flood mitigation measures, and nature-based solutions in urban planning.
- Promoting Inclusive Urbanization: Implementing policies that ensure equitable access to affordable housing, social services, and economic opportunities for diverse demographic groups.
- Advancing Sustainable Mobility Solutions: Expanding electrified public transit networks, integrating last-mile connectivity initiatives, and incentivizing non-motorized transport options.
- Encouraging Investment in Knowledge-Based Industries: Establishing innovation hubs, research clusters, and high-tech industrial corridors to drive long-term economic resilience.

3.5 Study Area Selection Criteria

The selection of the study area for assessing urban wetland and water body management is guided by the Urban Wetland Water Bodies Management Guidelines, which emphasize the ecological significance of riparian zones and their role in maintaining hydrological balance. A critical factor in defining the study area is the 1 km buffer from the riverbank, as this zone lies within the hydrological and ecological zone of influence.

3.5.1 1 km Buffer as the Zone of Influence

The creation of a 1 km buffer zone from the riverbank is widely acknowledged as an essential management measure for urban river corridors due to its direct impact on riverine processes, flood behavior, and wetland ecology. National standards and urban river management systems endorse this influence zone, highlighting its significance in maintaining hydrological connectivity, flood hazard reduction, and biodiversity conservation.

Hydrologically, water bodies and wetlands in this buffer have a critical role in regulating river flow, facilitating groundwater recharge, and reducing flood peaks. Alterations in this zone-including land use change, drainage modification, or encroachment-have the potential to change the natural hydrological regime considerably, causing more urban flooding and less efficient natural water retention systems. The buffer generally includes floodplains and lowlands that function as natural sponges during monsoonal flows and hence are critical to urban flood management.

Ecologically, the riparian buffer provides habitat for varied flora and fauna such as aquatic plants, migratory birds, and fish, and helps provide larger ecosystem services like water purification and connectivity of habitats. Encroachment or degradation in this area results in loss of ecosystem services, reduced biodiversity, and greater exposure of urban dwellers to environmental risks. The effects of de-reserving plots under protected waterbodies, for instance, have become topical controversies in Navi Mumbai, revealing threats to species and livelihoods depending on the wetlands.

Urbanization and infrastructure growth place immense pressure on the buffer zone, frequently leading to the conversion of open spaces and wetlands into built-up land. The land use alteration not only loses ecological functions but also increases surface runoff and flood risk, as seen in fast-growing cities such as Navi Mumbai. National guidelines, including the River Centric Urban Planning Guidelines and Urban River Management Plan (URMP) framework, advise strict zoning rules within this buffer to limit or exclude construction and high-impact activities, particularly within 500 meters from the riverbank and up to 1 km for restricted activities. These plans promote the declaration of river sections and floodplains as River Conservation Zones, clearly demarcating areas where activities are prohibited, restricted, and regulated to achieve urban development and wetland as well as river conservation.

In conclusion, the 1 km buffer zone is a scientifically and policy-supported zone of influence crucial for maintaining riverine health, flood risk management, and urban biodiversity conservation. Proper management of the buffer, through coordinated urban planning and stringent enforcement of conservation rules, is pivotal to the attainment of resilient and sustainable river cities

3.5.2 Application to the NMIA and NAINA Regions

For the Navi Mumbai International Airport (NMIA) and the Navi Mumbai Airport Influence Notified Area (NAINA), the 1-kilometer riverbank buffer is particularly significant due to:

- The diversion and channelization of the Ulwe River have altered the natural dynamics of the floodplain.
- The presence of ecologically sensitive mangrove ecosystems that require conservation efforts to maintain coastal resilience.
- The risk of increased surface runoff and sedimentation due to ongoing construction activities.

By implementing the Urban Wetland Water Bodies Management Guidelines, it is essential to incorporate nature-based solutions, such as wetland restoration, green infrastructure, and strict buffer zone regulations, into urban planning policies for NMIA and NAINA.

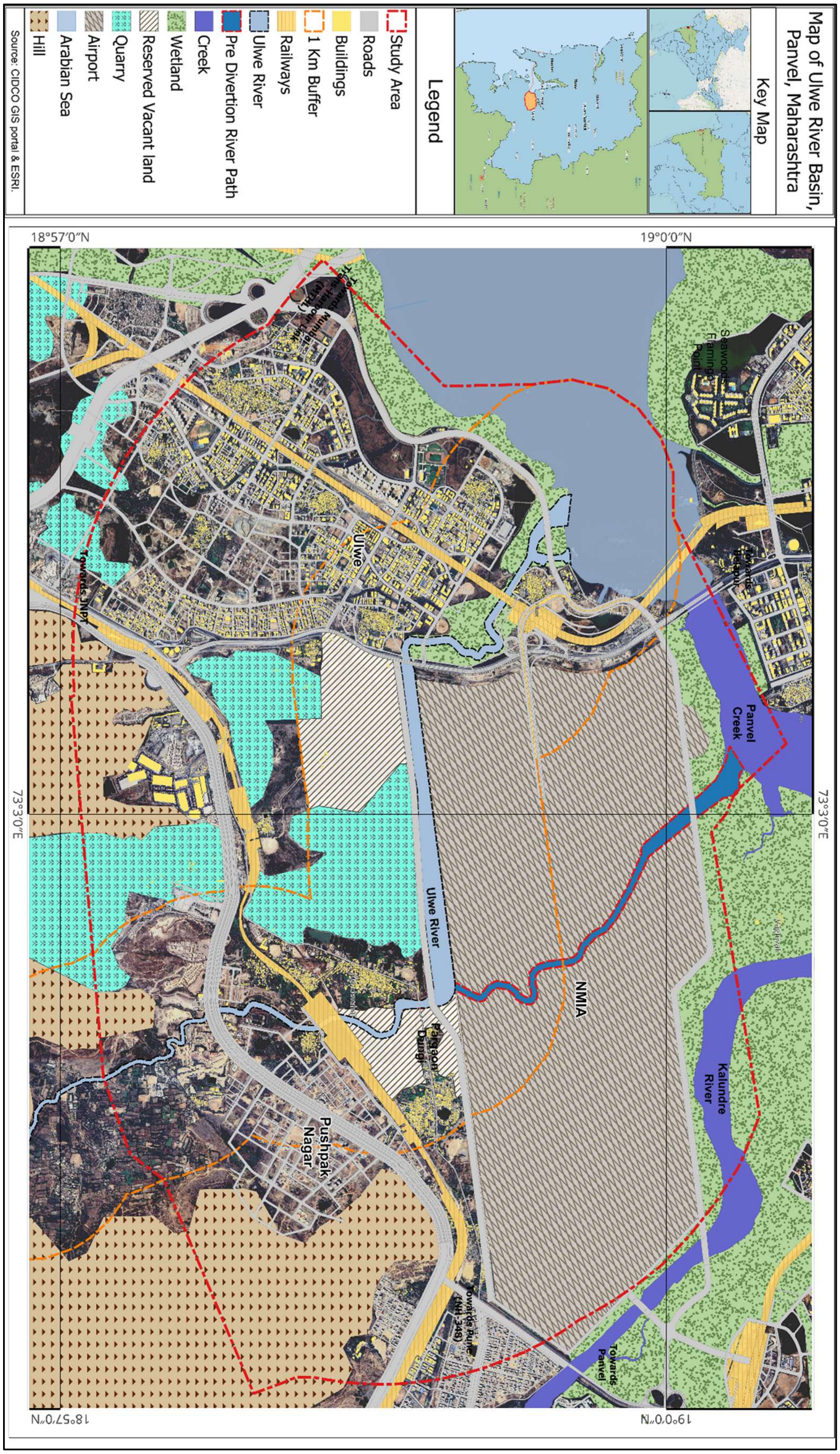

Figure 5 Study Area Map of Ulwe River Basin

4. Analysis

1. Land Use and Land Cover (LULC) Analysis

LULC dynamics are the prime concerns in comprehending changed floodplain processes. Land cover types were mapped into major groups such as urban, agriculture, marshland, vegetation, and bare land using remote sensing and GIS. Multi-year satellite image analysis over time facilitated monitoring the rate and area of urban expansion and the resultant displacement of natural land cover, especially wetlands and vegetated land.

The expansion of impervious surfaces like buildings and roads has impacted surface hydrology directly. As infiltration capacity reduces, surface runoff increases, especially in lowlands. The link between enhanced imperviousness and increased flood hazards was estimated, confirming land transformation as the leading cause of floodplain degradation.

2. Hydrological Assessment

The hydrological analysis targeted assessing the effects of river diversion and urbanization on the flood regime and surface runoff characteristics of the Ulwe River catchment. Spatial analysis to study river flow changes, and channel morphology. Concern was put on surface runoff, which has increased considerably following decreased vegetative cover and loss of flood-absorbing wetlands.

Connectivity of the floodplain was evaluated using pre- and post-diversion comparisons. Disruption of lateral hydrologic linkages between the river and its floodplain has changed natural water dispersion and enhanced the risk of flooding in urban areas. This disconnection also extends to sedimentation, channel stability, and ecological productivity.

3. Ecological Assessment

The ecological survey tested the health of riparian vegetation, mangroves, and wetlands, which act as natural flood buffers and reservoirs of biodiversity. Remote sensing indices like the Normalized Difference Vegetation Index (NDVI) were employed to measure vegetative health and spatial distribution.

Special focus was given to buffer zones along the floodplain and river, as these are important in reducing flood effects. Mangrove and marshland degradation have lowered the basin's hydrological stress resilience. Further, this analysis gave information on biodiversity changes, wetland fragmentation, and loss of ecosystem services due to land use change and river diversion.

4. Strategy Development

With reference to the empirical data, the research recommends an integrated floodplain management approach based on nature-based solutions and policy change. Emphasis is placed on the building of detention ponds, green infrastructure improvement, and riparian buffer restoration as inexpensive and environmentally friendly measures for managing surplus runoff and mitigating flood risks.

Urban zoning bylaws are to be put in place to limit development in at-risk zones, encourage the application of permeable surfaces, and implement construction-free buffer zones along the river. Mangrove and wetland conservation are listed as a high-priority measure to achieve long-term flood resilience and ecological sustainability.

This multi-level strategy, which incorporates hydrological modelling, ecological analysis, and spatial planning, enables a shift toward sustainable, climate-resilient urban growth in the Ulwe River basin.

4.1 Land Cover Analysis

Land cover analysis plays a crucial role in understanding environmental changes, urban expansion, and ecosystem sustainability. Image classification techniques utilizing remote sensing data are essential for mapping and quantifying these changes over time. This study employs satellite-based image classification to assess Land Use and Land Cover (LULC) changes between 2014 and 2024 within the designated study area. The analysis focuses on key land cover classes: Water, Marsh Land, Vegetation, Built-up Areas, and Barren Land.

By examining the land use and land cover (LULC) transitions over the past decade, this study aligns with the following objectives:

- Assessing Trends in Wetland Degradation and Urbanization
- Identifying the extent of vegetation loss and urban expansion.
- Understanding the Implications of Land Cover Changes in Water Bodies

The findings are based on NASA's Landsat Collection Level 2 data, utilizing supervised classification techniques, including Maximum Likelihood Classification (MLC).

Methodology: Image Classification Approach

The image classification process involved the following steps:

- Data Collection – Landsat images from 2014 and 2024 were acquired and preprocessed to eliminate noise and atmospheric distortions.
- Training Samples – Representative pixels for each Land Use/Land Cover (LULC) category were selected based on their spectral signatures.

- The Supervised Classification technique, specifically the Maximum Likelihood method, was employed to categorize land cover into five distinct classes.

1. Water (Blue)
2. Marsh Land (Light Green)
3. Vegetation (Dark Green)
4. Built-up (Red)
5. Barren (Yellow/Beige)
6. Accuracy Assessment – Post-classification validation was conducted using ground truth data and historical imagery.

4.1.1 Land Cover Change Analysis (2014-2024)

The classified maps and statistical analysis show significant land cover transformations over the last decade. And results are as follows in the land cover distribution table.

Table 1 Land Cover Classification

Classes	Area 2014	Percentage (%age)	Area 2024	Percentage (%age)
Water	1371.14	16.81	873.47	10.71
Marsh Land	2316.49	28.41	2082.26	25.53
Vegetation	1840.12	22.56	1718.11	21.07
Built up	1793.03	21.99	2588.66	31.74
Barren	834.21	10.23	892.49	10.94
Total	8154.99	100	8154.99	100

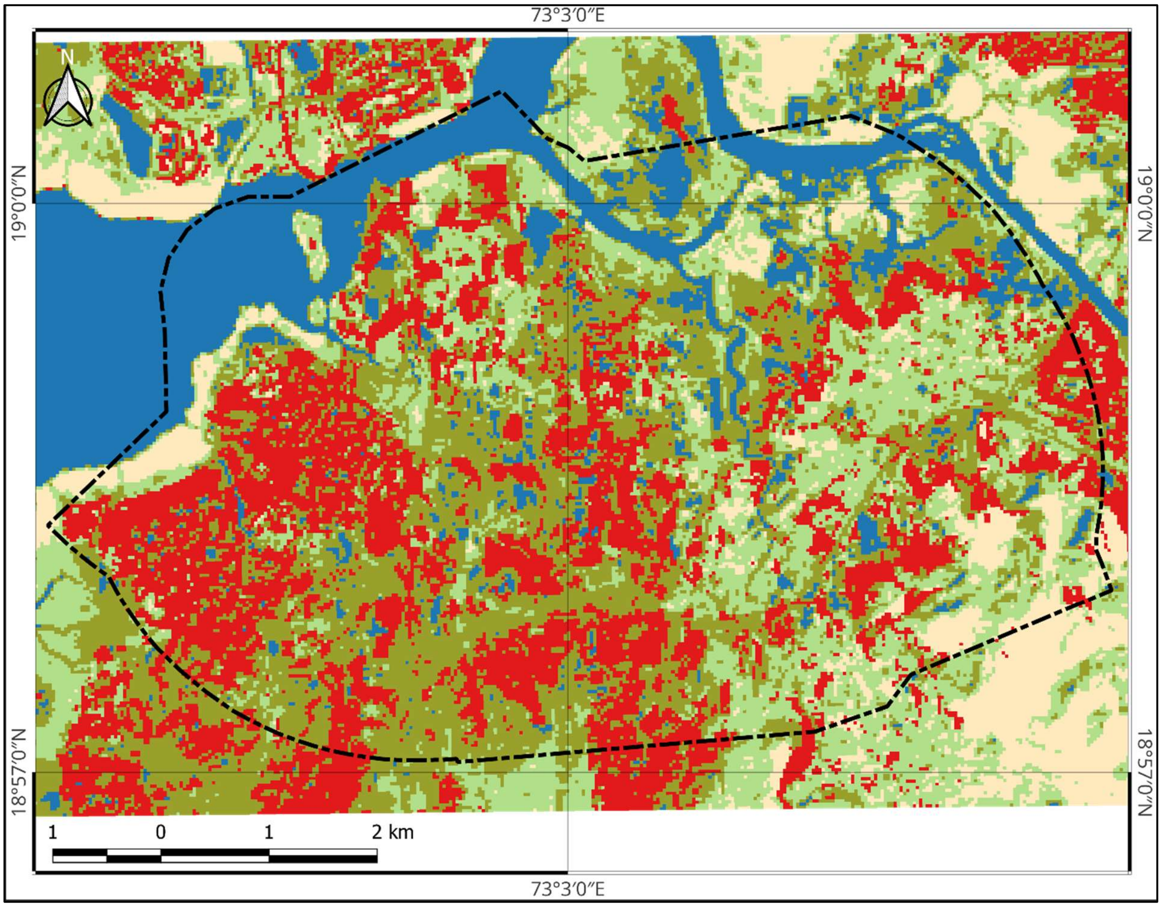

Figure 6 Landcover classification 2014.

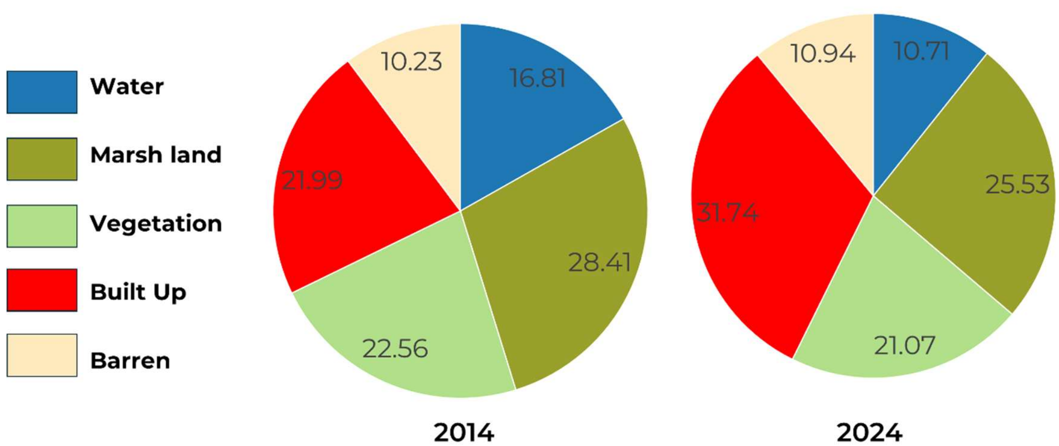

Figure 7 Distribution of landcover in %age during the year 2014 and 2024.

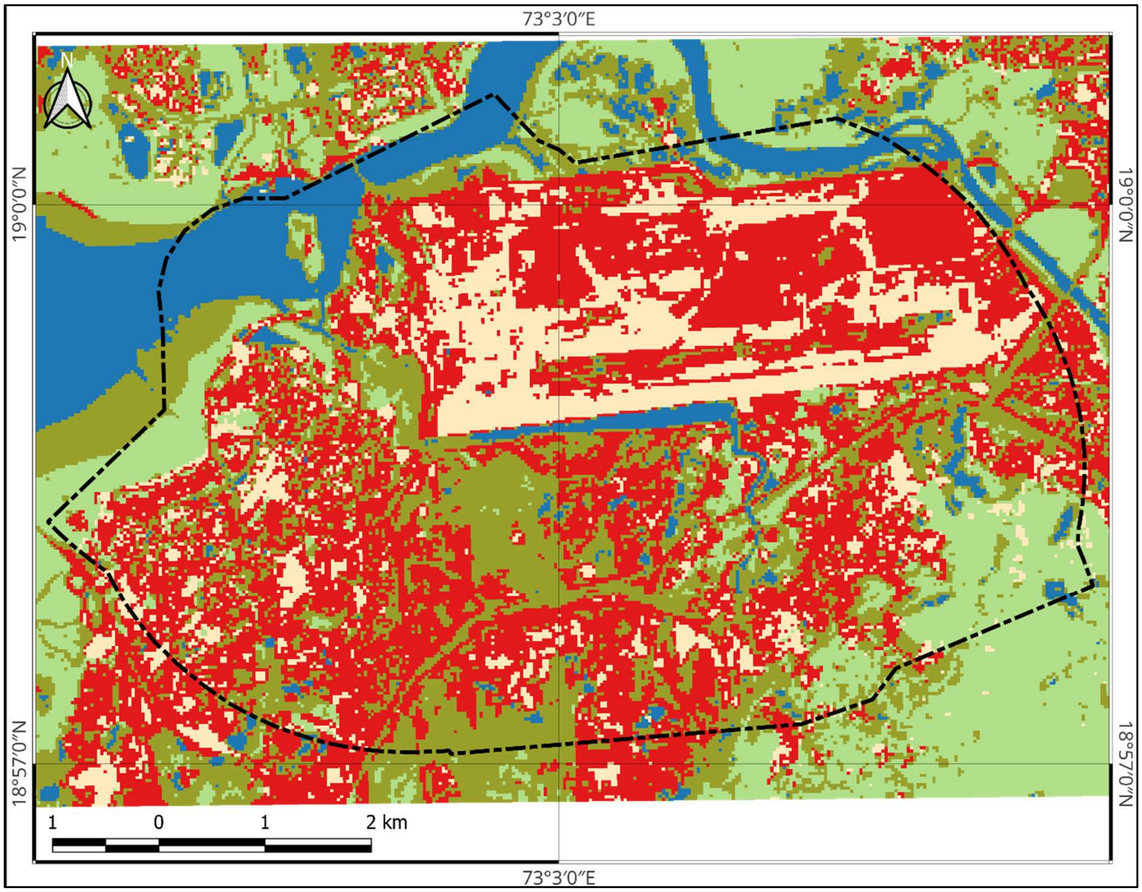

Figure 8 Landcover Classification of 2024

4.1.1.1 Changes in Land Cover Categories

Table 2 Change in Land Cover

Sr. no.	Change	Area Change	Class_2014	Class_2024	%age
1	Barren - Barren	28.07	Barren	Barren	0.34
2	Barren - Built	59.07	Barren	Built up	0.72
3	Barren - Marsh Land	44.82	Barren	Marsh Land	0.55
4	Barren - Vegetation	698.30	Barren	Vegetation	8.56
5	Barren - Water	3.95	Barren	Water	0.05
6	Built up - Barren	336.65	Built up	Barren	4.13
7	Built up - Built	1030.42	Built up	Built up	12.64
8	Built up - Marsh Land	321.93	Built up	Marsh Land	3.95
9	Built up - Vegetation	72.59	Built up	Vegetation	0.89

10	Built up - Water	31.44	Built up	Water	0.39
11	Marsh Land - Barren	270.61	Marsh Land	Barren	3.32
12	Marsh Land - Built	890.87	Marsh Land	Built up	10.92
13	Marsh Land - Marsh Land	908.82	Marsh Land	Marsh Land	11.14
14	Marsh Land - Vegetation	165.77	Marsh Land	Vegetation	2.03
15	Marsh Land - Water	80.42	Marsh Land	Water	0.99
16	Vegetation - Barren	192.97	Vegetation	Barren	2.37
17	Vegetation - Built	419.83	Vegetation	Built up	5.15
18	Vegetation - Marsh Land	463.47	Vegetation	Marsh Land	5.68
19	Vegetation - Vegetation	742.51	Vegetation	Vegetation	9.11
20	Vegetation - Water	21.33	Vegetation	Water	0.26
21	Water - Barren	64.20	Water	Barren	0.79
22	Water - Built	188.46	Water	Built up	2.31
23	Water - Marsh Land	343.23	Water	Marsh Land	4.21
24	Water - Vegetation	38.93	Water	Vegetation	0.48
25	Water - Water	736.32	Water	Water	9.03
	Total	8154.99			100

4.1.2 Key Findings and Observations

1. **Significant Decline in Water Bodies**
    a. Water bodies have reduced from 16.81% (1371.14 ha) in 2014 to 10.71% (873.47 ha) in 2024, a net loss of 497.67 ha (-6.10%).
    b. Major contributing factors include urban expansion, wetland degradation, and encroachments.
    c. The reduction in water area impacts aquatic biodiversity, groundwater recharge, and local climate regulation.
2. **Decline in Marsh Land and Vegetation**

a. Marsh land has decreased by 234.23 ha (-2.88%), demonstrating wetland degradation due to urban sprawl.
b. Vegetation has decreased by 122.01 ha (-1.49%), indicating deforestation and reduction in green cover.
c. The loss of natural vegetation and marshes affects flood control, carbon sequestration, and ecosystem services.

3. **Rapid Expansion of Built-up Areas**
   a. Built-up areas surged from 21.99% (1793.03 ha) to 31.74% (2588.66 ha), an increase of 795.63 ha (+9.75%).
   b. Urban growth is a direct cause of wetland loss, water body shrinkage, and vegetation degradation.
   c. The transformation reflects rising population density, infrastructure development, and industrialization.
4. **Increase in Barren Land**
   a. Barren land increased slightly by 58.28 ha (+0.71%), likely due to land clearing and soil degradation.
   b. Land degradation may result from unsustainable land use practices, climate variability, and deforestation.

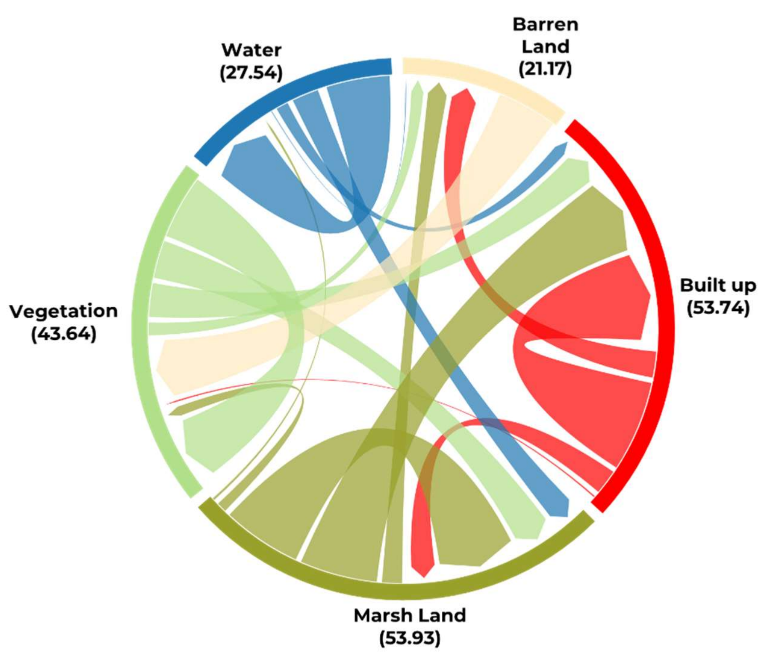

Figure 9 Chord Chart depicting change in landcover between 2014 and 2024.

4.1.3 Implications of Land Cover Changes

4.1.3.1 Environmental Impact

Water loss and wetland degradation reduce natural flood buffering capacity, increasing urban flooding risks.
The decline in vegetation leads to higher temperatures, reduced carbon sequestration, and loss of biodiversity.
The expansion of impervious surfaces increases surface runoff, reducing groundwater recharge.

4.1.3.2 Socioeconomic Consequences

The loss of wetlands affects livelihoods, particularly for fisheries and agricultural communities. Urban expansion demands better land-use planning, drainage management, and environmental policies.
An increase in barren land and deforestation may reduce agricultural productivity and contribute to food insecurity.

4.2 Normalized Difference Vegetation Index (NDVI) Analysis

The Normalized Difference Vegetation Index (NDVI) is a crucial remote sensing metric used to assess vegetation health and coverage over time. It is derived from the spectral reflectance of vegetation in the red and near-infrared bands, allowing researchers to analyze changes in land cover and detect environmental trends. NDVI values range from -1 to +1, where higher values indicate healthy vegetation, while lower values signify barren land, water bodies, or urbanized regions. This analysis focuses on NDVI changes in the study area between 2014 and 2024 to assess the ecological impact of land-use transformations, urbanization, and environmental degradation. The findings highlight the need for sustainable land management and conservation efforts to mitigate the negative impacts of anthropogenic activities on the environment.

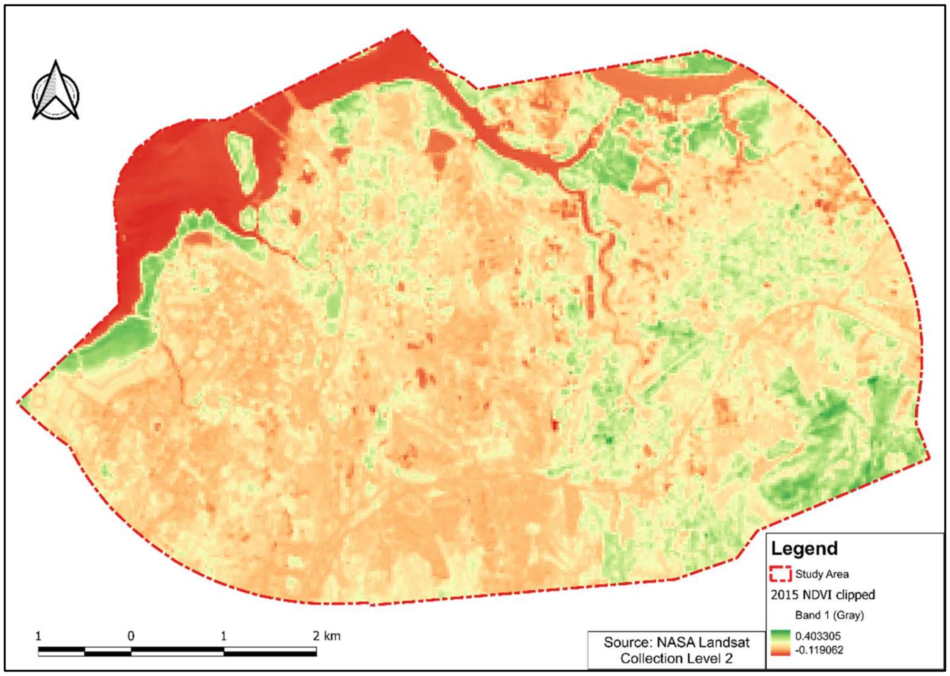

Figure 10 Normalized Difference Vegetation Index (NDVI) of 2014

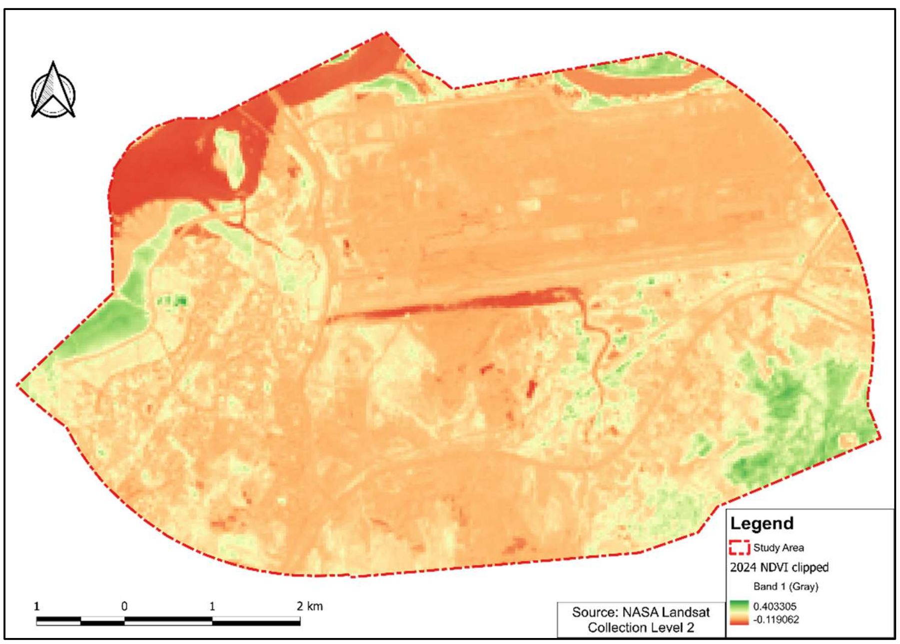

Figure 11 Normalized Difference Vegetation Index (NDVI) of 2014

4.2.1 NDVI Values and Observations

Overall NDVI Shift

- In 2014, NDVI values ranged between **-0.1 and 0.4**, with a peak frequency around **0.12-0.15**.

- In 2024, NDVI values predominantly ranged between **0 to 0.3**, with a peak at **0.05**.
- The downward shift in NDVI values suggests a decline in vegetation cover over the years, indicating potential environmental stress or land-use changes that negatively impact greenery.
- This trend highlights the progressive decline in vegetation density, which could have implications for climate regulation, carbon sequestration, and local biodiversity.

Table 3 NDVI values distribution

Values 2014	Area (in ha.)	Values 2024	Area (in ha.)
<0	432.67	<0	300.89
0-1	2121.54	0-1	3281.49
1-2	1648.01	1-2	899.17
2-3	473.65	2-3	236.52
3-4	52.84	3-4	10.88

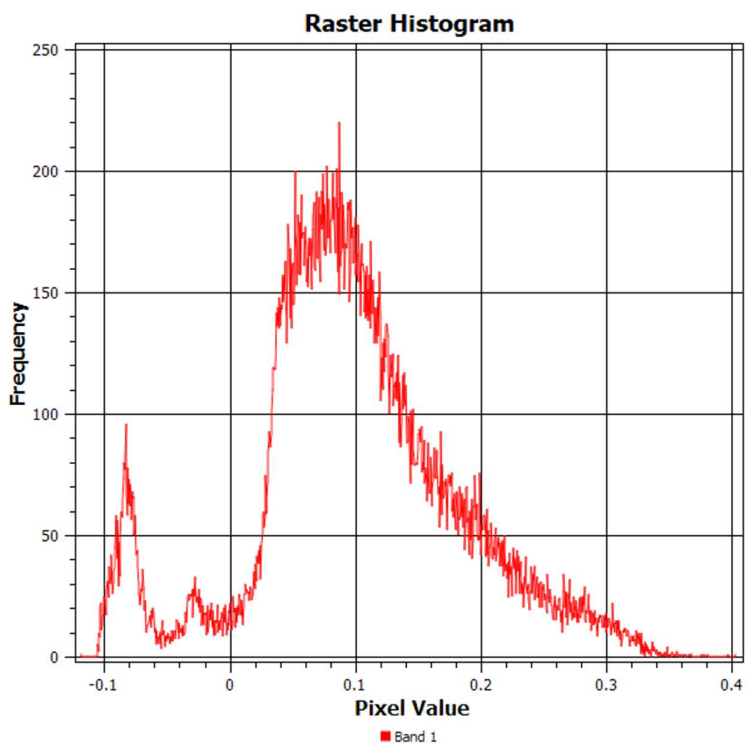

Figure 12 Histogram distribution of NDVI values for 2014.

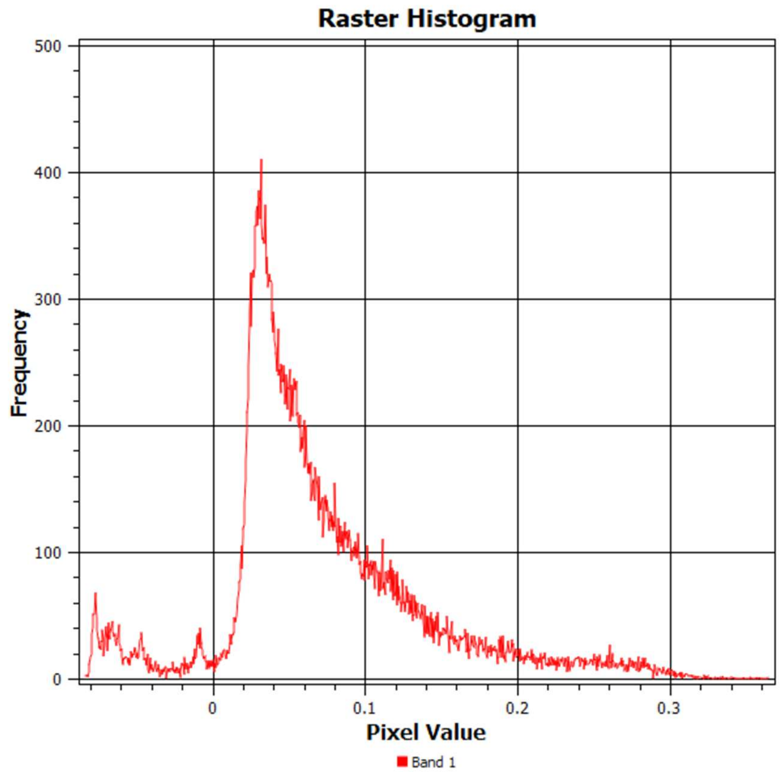

Figure 13 Histogram distribution of NDVI values of 2024.

Peak NDVI Value Reduction

- The highest frequency of NDVI values in **2014** was above **200 pixels**, indicating a prevalence of healthy vegetation.
- By **2024**, the peak frequency shifted significantly higher, exceeding **400 pixels**, but was concentrated at lower NDVI values.
- This shift suggests that more land areas have lower vegetation density than before, reflecting possible deforestation, urban expansion, or land degradation.
- The reduction in peak NDVI values implies a shift in the land cover composition, with a growing dominance of less vegetated or non-vegetated surfaces, potentially altering local microclimates and exacerbating land degradation.

Low NDVI Values in 2024

- In **2014**, negative NDVI values (around **-0.1**) were observed in some areas, representing barren land or water bodies.

- By **2024**, negative NDVI values were almost absent, but a sharp peak near **0** indicates an increase in **barren land or built-up areas**.
- The disappearance of negative NDVI values and the sharp peak at **0** suggest extensive land modifications, including urbanization and soil exposure.
- This pattern underscores the increased anthropogenic footprint in the region, highlighting the shift from vegetated landscapes to constructed environments that lack the ecological functions of natural ecosystems.

Vegetation Loss Indicators

- In **2014**, a significant proportion of land (i.e. 526.49 ha.) had NDVI values exceeding **0.2**, representing healthier vegetation.
- In **2024**, fewer areas (247.40 ha.) exceeded the **0.2** threshold, suggesting vegetation loss due to deforestation, urbanization, or land degradation.
- The declining trend in NDVI values points to large-scale environmental modifications that might require mitigation measures.
- Such reductions in vegetation cover can have profound effects on ecosystem services, including reduced air quality, increased land surface temperatures, and altered hydrological cycles.

4.2.2 Interpretation of Changes

1. **Urbanization and Infrastructure Development**
    - The increase in barren land or built-up areas indicates extensive urban expansion, possibly due to population growth, industrialization, or infrastructure projects.
    - Loss of green spaces could result in reduced ecological resilience and increased susceptibility to urban heat islands.
    - Urban expansion, if not carefully managed, could lead to worsening environmental conditions, affecting both human and ecological health.
2. **Deforestation and Land Use Change**
    - A sharp reduction in high NDVI values suggests tree loss or conversion of vegetated land to non-vegetated surfaces.

- This could be attributed to agricultural expansion, logging, or other land-use changes reducing vegetation density.
- Without reforestation efforts or strict land-use planning, these trends could lead to long-term environmental degradation and loss of habitat for wildlife.

3. **Environmental Degradation and Soil Exposure**
    - Lower NDVI values may indicate increased soil exposure due to erosion, overgrazing, or unsustainable agricultural practices.
    - Reduction in vegetative cover can accelerate land degradation, leading to loss of soil fertility and increased susceptibility to desertification.
    - Increased soil exposure not only reduces the land's productivity but also contributes to dust storms, erosion, and a decline in water retention capacity.
4. **Climate and Hydrological Changes**
    - Changes in precipitation patterns, prolonged droughts, or altered water availability could affect vegetation health.
    - Hydrological disruptions due to infrastructure projects or land-use modifications might have contributed to the declining NDVI values.
    - Variations in water availability could exacerbate vegetation stress, particularly in regions dependent on consistent rainfall or groundwater sources.

4.2.3 Environmental and Planning Implications

1. **Impact on Biodiversity**
    - Reduced NDVI values indicate habitat loss, which could threaten native flora and fauna.
    - Fragmentation of green spaces might disrupt ecological corridors, reducing wildlife movement and biodiversity sustainability.
    - Preserving green infrastructure and maintaining ecological connectivity can help mitigate biodiversity loss and maintain ecosystem stability.
2. **Increased Flood Risk**

- Vegetation loss can reduce natural water infiltration, increasing surface runoff and the likelihood of flooding.
- Proper land-use planning should integrate green infrastructure to mitigate hydrological imbalances.
- Implementing permeable surfaces, reforestation, and wetland restoration can enhance flood resilience and maintain natural water cycles.

3. **Need for Sustainable Urban Planning**
    - With increasing built-up areas, sustainable urban planning approaches should prioritize green spaces and ecosystem conservation.
    - Strategies like urban afforestation, green roofs, and protected conservation zones can help maintain ecological balance.
    - Integrating green infrastructure into urban planning can enhance climate resilience, improve air quality, and support human well-being.

4.2.4 Inferences

- The NDVI analysis between 2014 and 2024 indicates significant vegetation loss, urbanization, and land degradation.
- To mitigate these impacts, it is essential to adopt integrated water and land management strategies, enforce afforestation initiatives, and promote sustainable urban development.

4.3 Hydrological Impact Assessment

Flooding remains one of the most devastating natural disasters affecting communities worldwide. This study aims to analyze hydrological factors influencing flood risks using digital elevation models (DEMs), slope analysis, basin and stream mapping, shaded relief visualization, and contour analysis. By focusing on hydrological components such as watershed delineation, streamflow patterns, and runoff characteristics, this research provides an in-depth understanding of flood dynamics and their implications for flood management and mitigation. The study also examines how variations in precipitation, infiltration rates, and soil permeability influence surface runoff and water retention, further impacting flood occurrence and severity. An integrated approach using hydrological models and GIS techniques ensures a comprehensive assessment of flood susceptibility, offering valuable insights into mitigation strategies and disaster preparedness.

Hydrological analysis plays a critical role in flood risk assessment by examining water movement across landscapes. The interaction between precipitation, terrain features, drainage networks, and surface water accumulation determines the likelihood and severity of flooding. This study employs GIS-based hydrological tools to evaluate watershed characteristics, stream connectivity, and runoff distribution to develop a flood risk framework tailored to varying hydrological conditions. Additionally, the analysis considers hydrological cycle components, including evapotranspiration, infiltration, and groundwater recharge, to assess their influence on surface water distribution and flood intensity. By integrating multi-temporal hydrological data, this research provides a dynamic perspective on flood risks, enabling more accurate flood prediction and effective management strategies. (CWPRS Report, 2016)

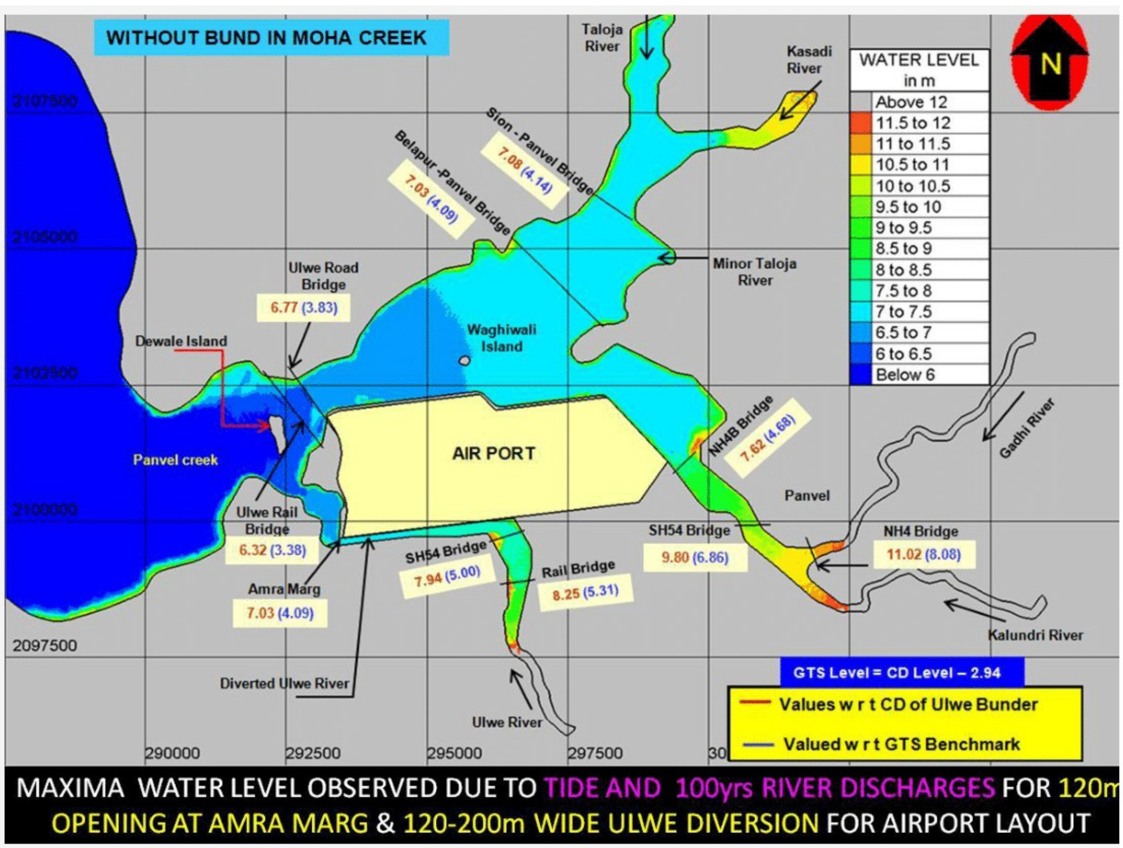

Figure 14 CIDCO CWPRS Report: mathematical model studies for the modified layout of proposed international airport at Panvel. (2017) Source: CWPRS Report 2016

This section provides a comprehensive analysis of hydrological processes influencing surface runoff and flood susceptibility, integrating advanced geospatial tools and modelling techniques.

The assessment leverages high-resolution data and empirical insights to evaluate terrain characteristics, watershed dynamics, and climatic interactions.

4.3.1 Flood Plain Delineation

1. Digital Elevation Model (DEM) and Hydrological Characteristics

DEMs are foundational for quantifying hydrological processes, enabling the delineation of flow directions, accumulation patterns, and drainage networks. High-resolution DEMs (e.g., 20–30 m) improve accuracy in identifying low-lying areas, drainage divides, and flood-prone zones. For instance, studies demonstrate that coarser DEMs (e.g., 500–1,000 m) underestimate runoff on high-rainfall days and overestimate it during low precipitation, leading to biased flood predictions.

Flow Accumulation Analysis: Flow accumulation grids derived from DEMs highlight areas where water converges, critical for predicting flash floods.

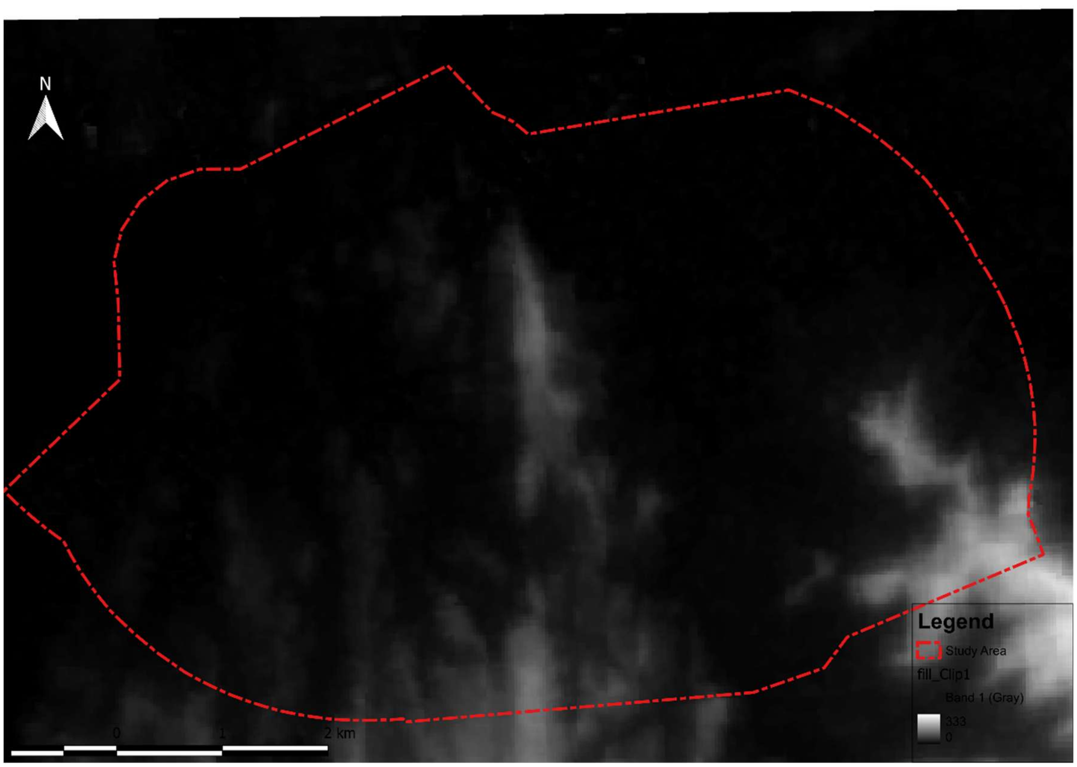

Figure 15 Digital Elevation model.

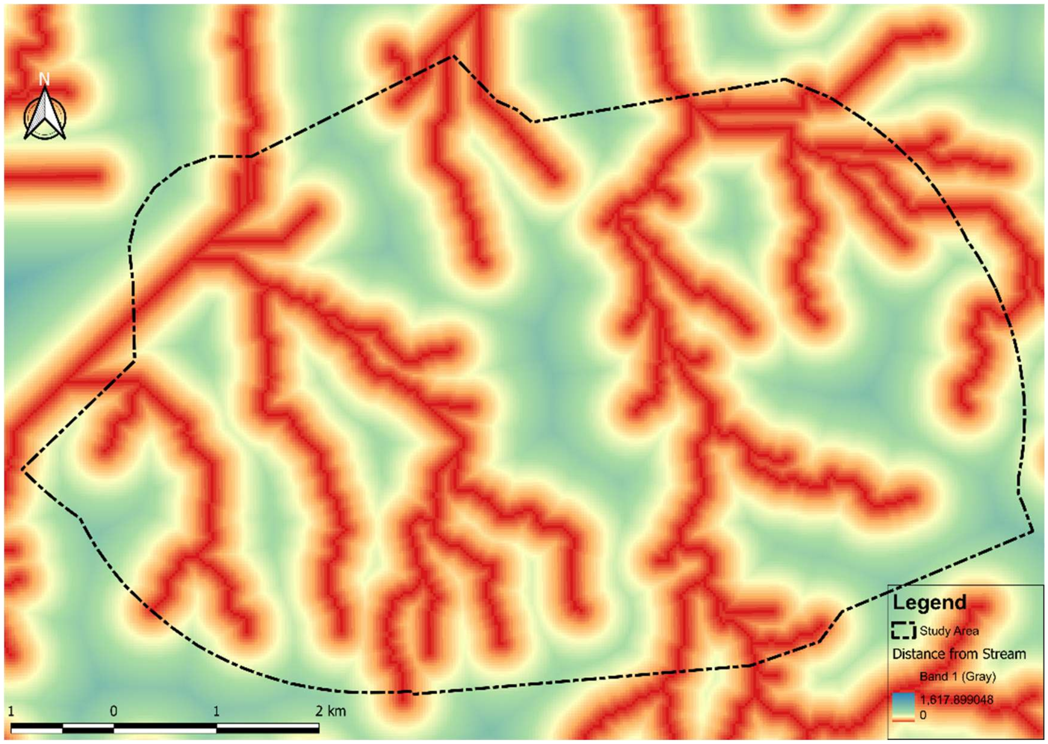

Figure 16 Distance from steam (Euclidian) Map

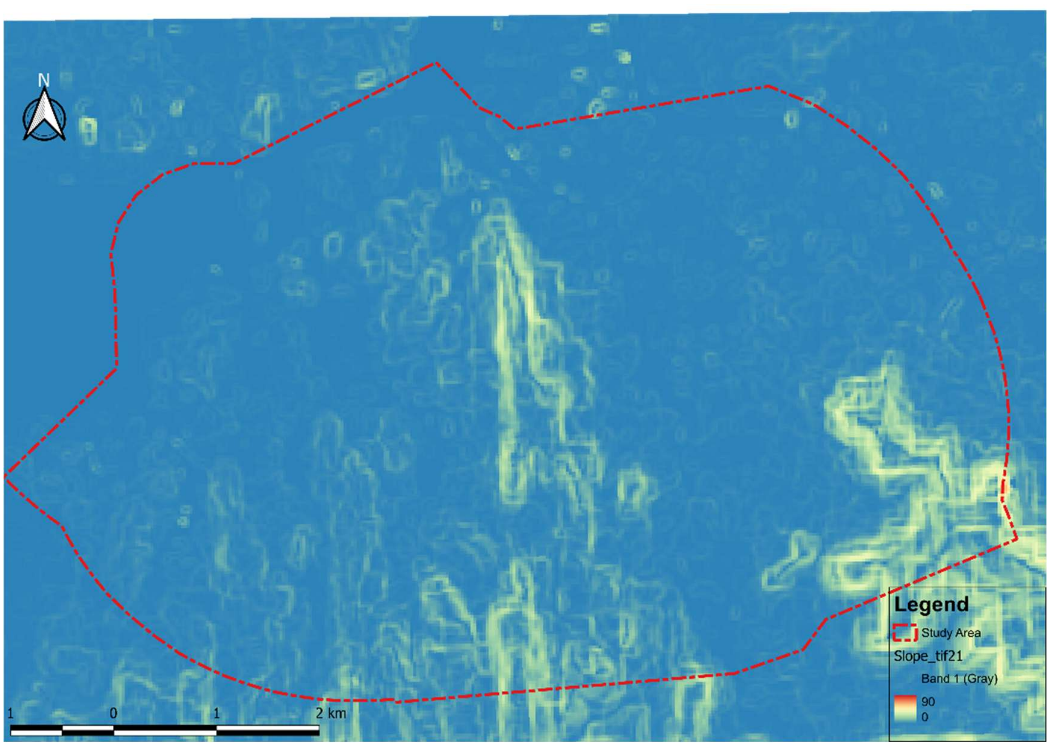

Figure 17 Slope Map

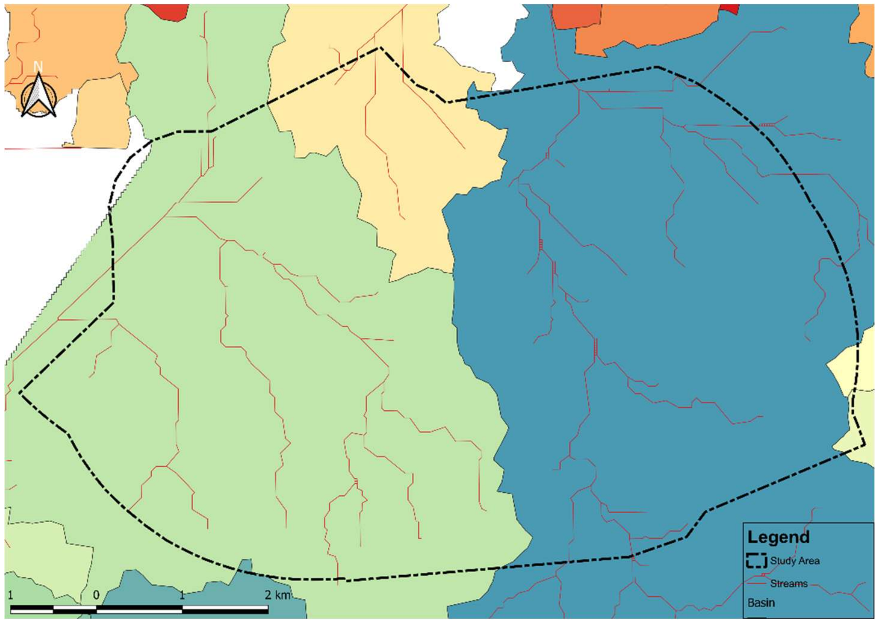

Figure 18 Streams and Watershed map.

2. Slope and Hydrological Flow Analysis

Slope gradients directly influence runoff velocity, infiltration capacity, and flood propagation.

- **Steep Slopes**:

Runoff Acceleration: Slopes >5% reduce infiltration, increasing surface runoff. The Sharpley-William's equation adjusts curve numbers (CN) for slopes: CN2α=CN2×[1+0.006×(S−5)]$CN2\alpha=CN2\times[1+0.006\times(S-5)]$
where S*S* is slope (%) [Nature: GCN250].

- **Gentle Slopes**:

Promote water stagnation and prolonged inundation, particularly in clay-rich soils (HSG C/D).

Mitigation: Contour trenching and terracing reduce erosion in low-slope agricultural areas.

3. Watershed Delineation and Streamflow Mapping

Watershed partitioning into sub-basins and hydrologic response units (HRUs) is critical for modelling runoff dynamics.

- DEM resolution affects HRU delineation, with finer grids (≤90 m) yielding reliable runoff estimates,

- **Stream Order Classification**:

Strahler's method identifies primary (1st-order) and higher-order streams, aiding in flood risk prioritization.

Drainage Efficiency: Poorly connected networks (e.g., discontinuous streams) exacerbate flooding in urbanized basins.

4. Shaded Relief and Contour Analysis for Hydrological Interpretation

Advanced terrain visualization enhances flood susceptibility mapping.

Multi-Scale Topographic Parameters:

Curvature Analysis: Concave regions (negative curvature) indicate water convergence zones.

Flow Accumulation Indices: Highlight potential debris flow channels in mountainous regions.

Contour Mapping:

10 m interval contours reveal micro-topographic depressions prone to waterlogging.

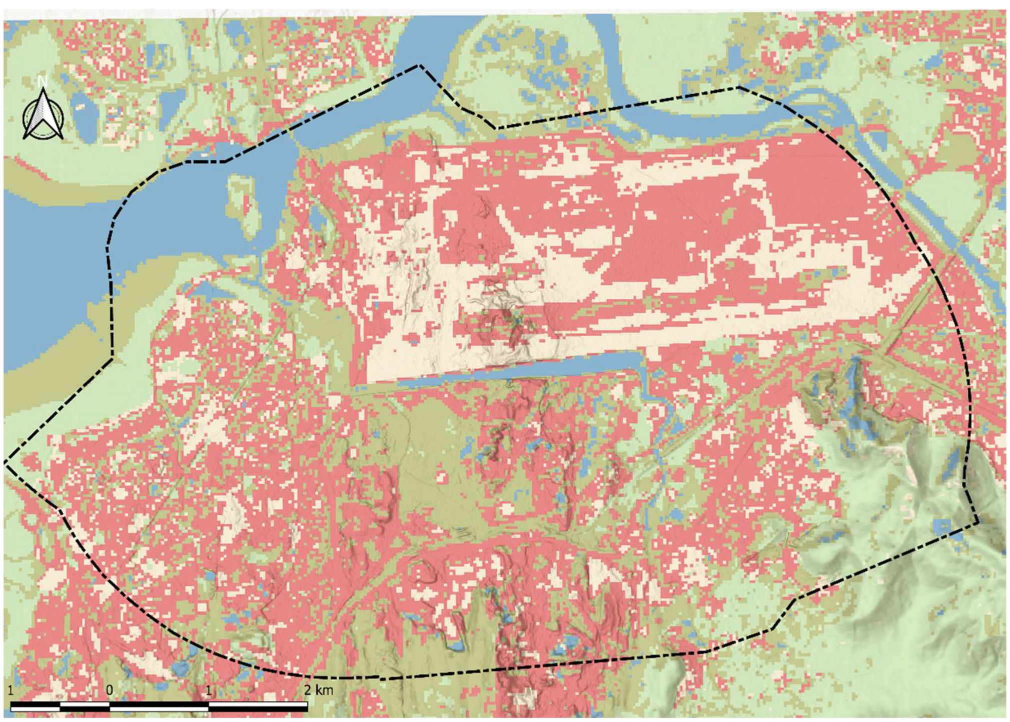

Figure 19 Shaded relief overlayed on land cover.

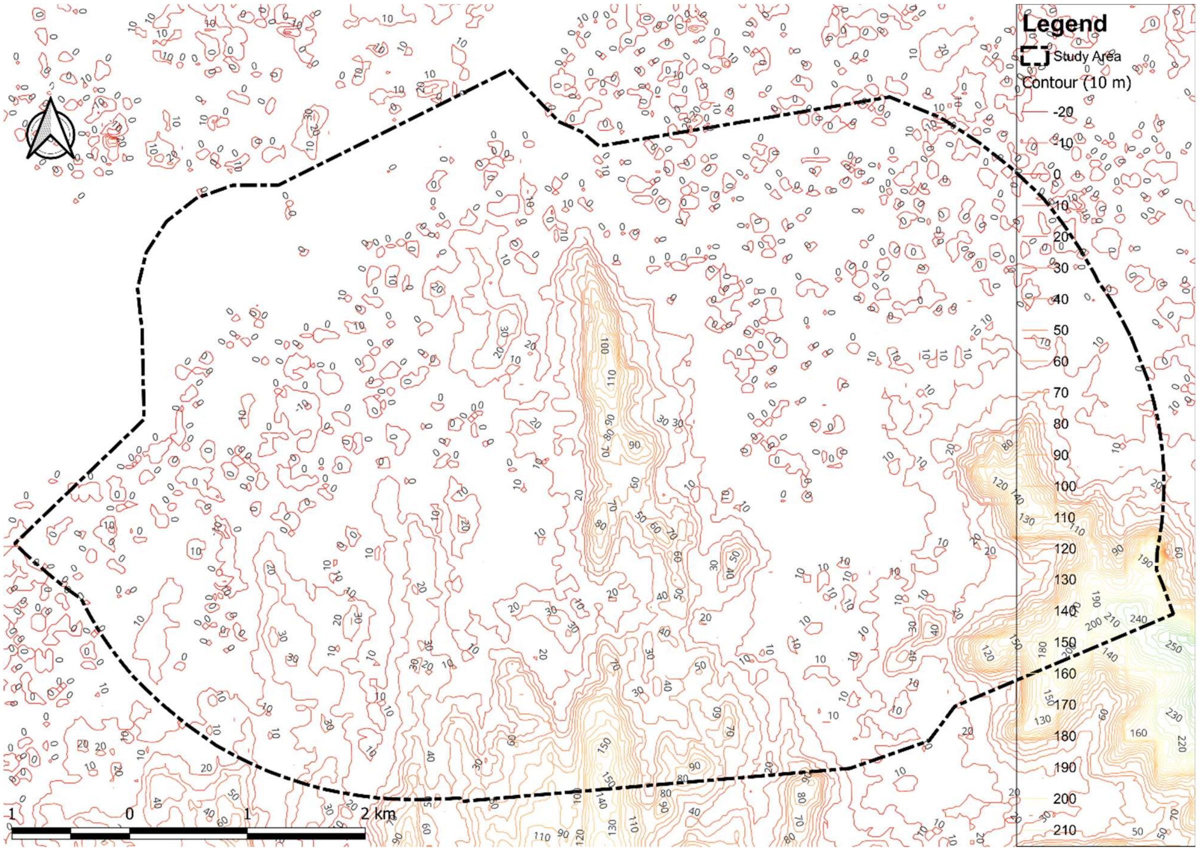

Figure 20 Contour 10 m interval.

4.3.2 Surface Runoff

Estimation of surface runoff is a fundamental aspect of hydrological evaluation, guiding water resource planning, flood hazard analysis, and engineering design. Runoff in this research was estimated based on the Strange's Table method, a standard empirical method used extensively in Indian catchments, especially where it is not possible to measure direct runoff.

Surface runoff estimation was carried out using the Strange’s Table method with the support of GIS-based analysis. The following key datasets were used:

- Land Use Land Cover (LULC) maps for 2016 and 2024.
- Monthly rainfall data (July 2016 and July 2024)
- Soil type map (FAO classification)
- Watershed boundary
- DEM (Digital Elevation Model) for terrain-based watershed delineation

5.1 Soil Types in the Study Area

The study catchment consists of three major soil types according to the FAO soil classification system:

Ne – Eutric Nitosols: Red, well-drained, tropical soils with high base saturation, usually occurring in sub-humid to humid environments.

Bc – Chromic Cambisols: Soils with a clear cambic horizon and medium weathering, commonly used for agriculture in semi-arid to sub-humid areas.

Je – Eutric Fluvisols: Young, alluvial river and floodplain soils with high fertility and irregular texture.

According to their physical properties and infiltration rates, all three soils fall under Hydrologic Soil Group C (HSG C), which is described as having moderate infiltration capacity and moderate potential to produce surface runoff in response to a rain event.

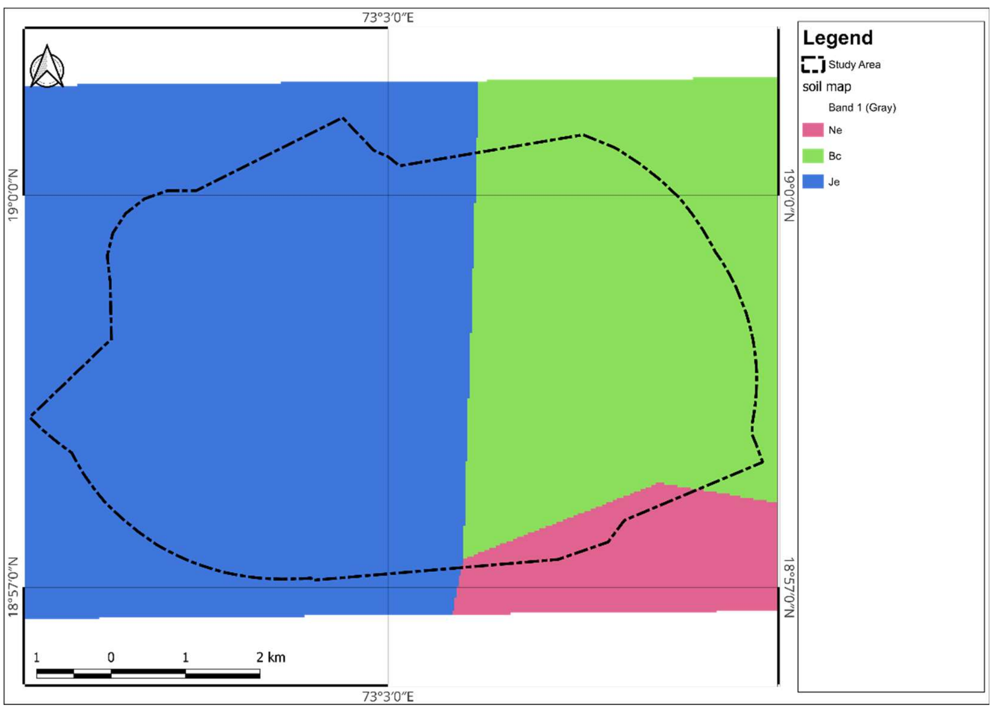

Figure 21 Soil Map

GIS Steps for Runoff Mapping:

1. **LULC Reclassification**: Each land cover class was assigned a corresponding runoff potential class based on catchment characteristics (e.g., water body, marshland,

vegetation, barren, built-up).

2. **Hydrologic Soil Grouping**: Soil data revealed three dominant soil types — *Ne, Bc, and Je*, all of which fall under **Hydrologic Soil Group C**, indicating moderate to high runoff potential.

3. **Rainfall Integration**: Rainfall values for July 2016 (Max: 280 mm, Min: 266 mm) and July 2024 (Max: 243 mm, Min: 207 mm) were considered for runoff estimation.

4. **Raster Calculation**: Using reclassified LULC and rainfall data, raster layers were computed to represent potential surface runoff.

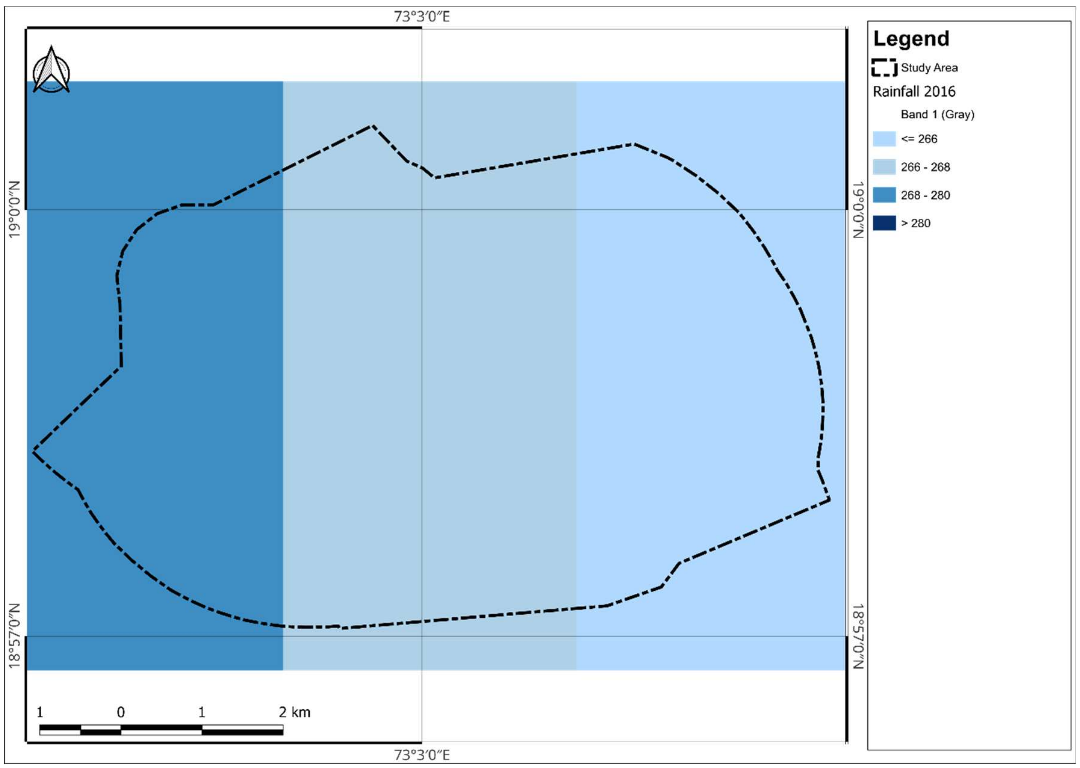

Figure 22 Rainfall Map (July 2016)

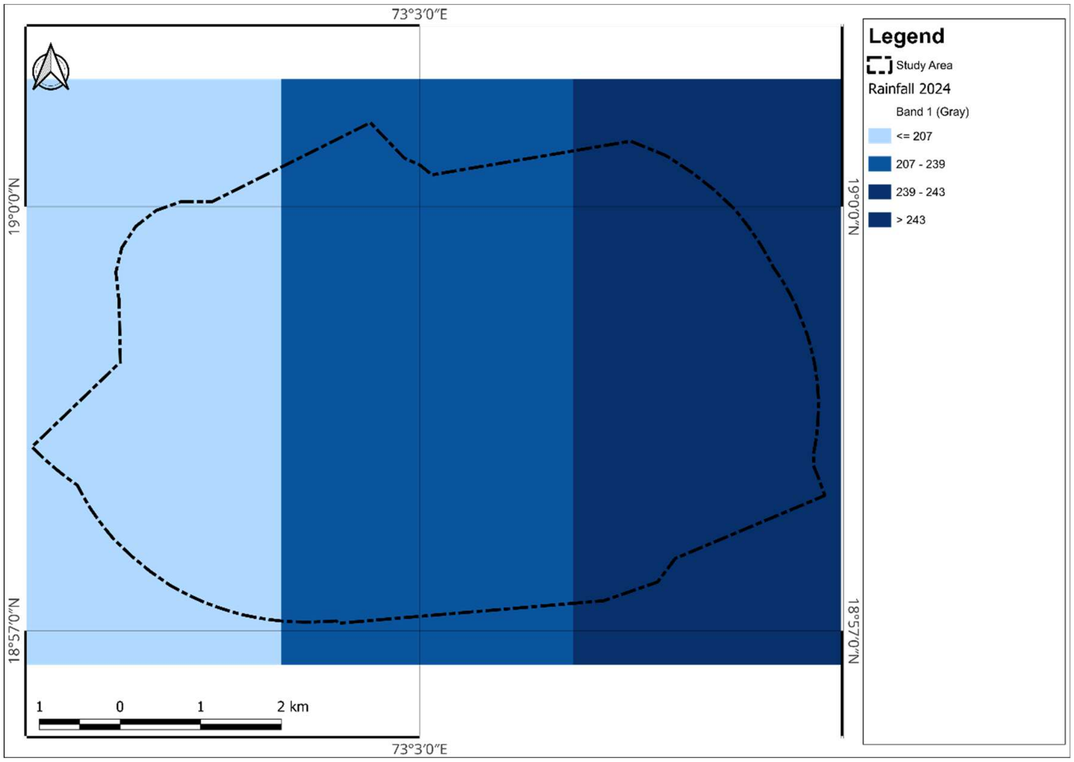

Figure 23 Rainfall Map (July 2024)

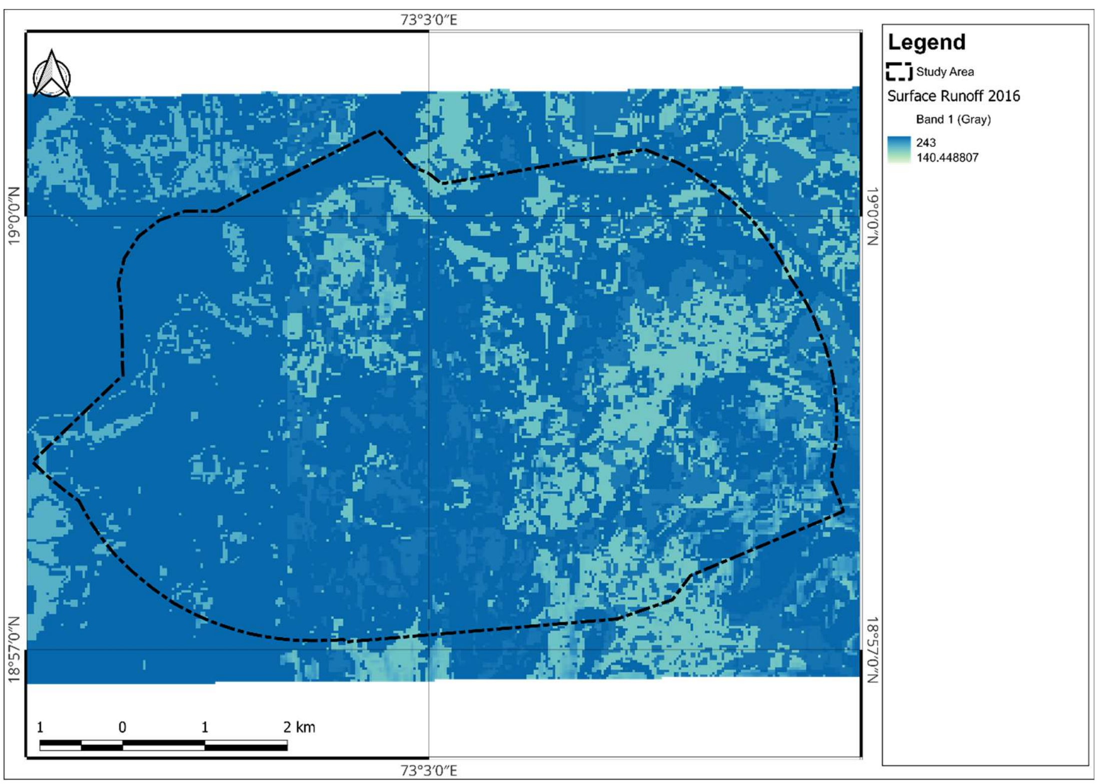

Figure 24 Surface Runoff (2016)

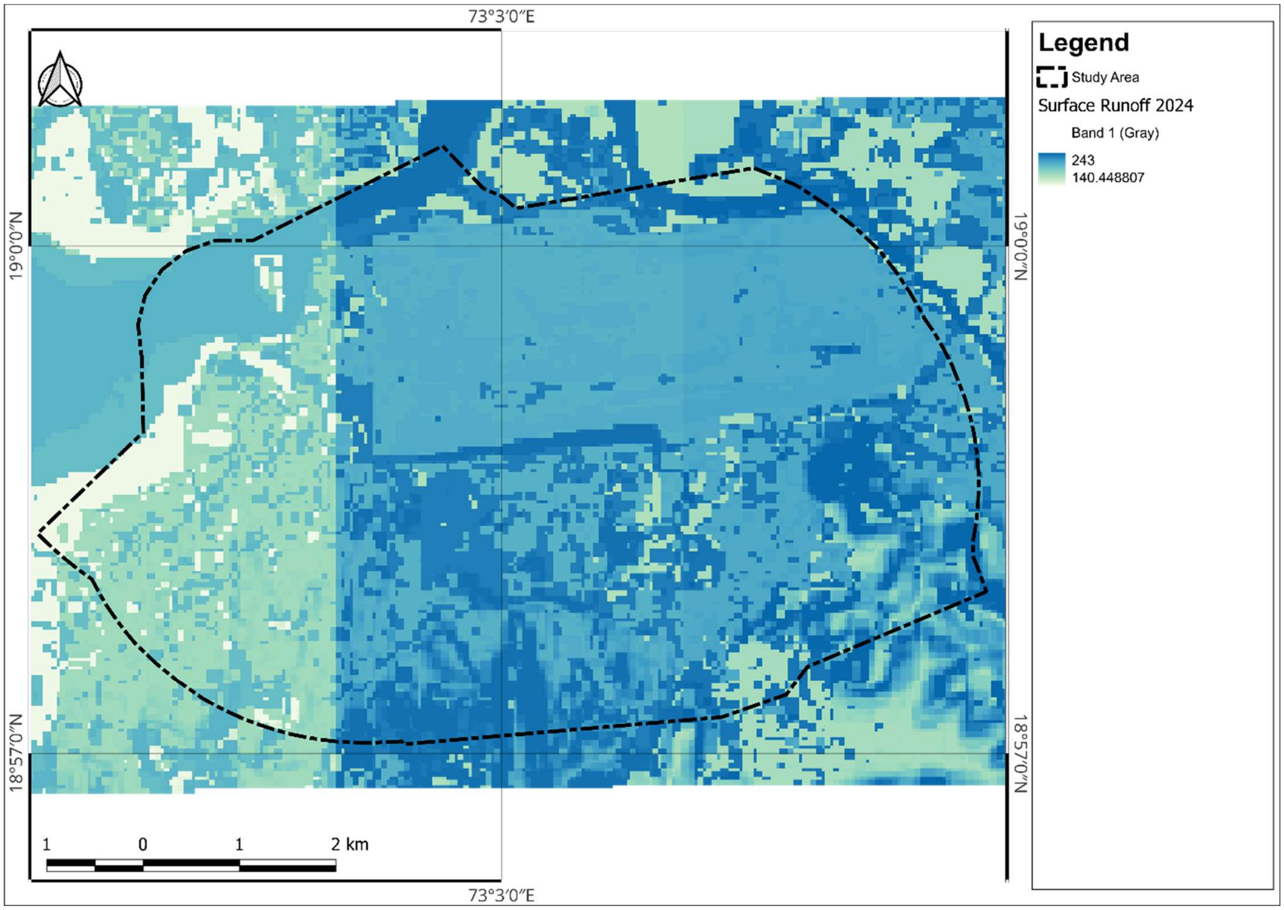

Figure 25 Surface Runoff (2024)

Application of Strange's Table

Strange's Table provides runoff as a percentage of rainfall based on the catchment condition. It classifies land into **Cultivated**, **Uncultivated**, and **Impervious/Rocky** types. The percentage of rainfall converted into runoff increases with rainfall depth and imperviousness of the land.

Based on the LULC classes:

- **Vegetation** was considered *Cultivated.*
- **Marshland and Water** were treated as *Uncultivated.*
- **Built-up and Barren land** as *Impervious or Rocky*

Runoff Estimation for July 2016:

Table 4 Runoff Estimation for July 2016

Land Use Type	Area (Ha)	Rainfall (mm)	Runoff Coeff. (%)	Runoff (mm)	Runoff Volume (m³)	Q (m³/s)
Marsh Land	2316.49	280	75	210	4,865,997	56.29
Vegetation	1840.12	280	65	182	3,348,021	38.74
Built-up	1793.03	280	85	238	4,267,417	49.39
Barren	834.21	280	85	238	1,985,427	22.97

Runoff Estimation for July 2024:

Table 5 Runoff Estimation for July 2024

Land Use Type	Area (Ha)	Rainfall (mm)	Runoff Coeff. (%)	Runoff (mm)	Runoff Volume (m³)	Q (m³/s)
Marsh Land	2082.26	243	72	174.9	3,644,561	42.16
Vegetation	1718.11	243	60	145.8	2,506,273	28.99
Built-up	2588.66	243	84	204.1	5,281,659	61.44
Barren	892.49	243	84	204.1	1,821,677	21.08

As Built-up area increase from 2016 to 2024 led to a notable rise in urban runoff, as urban areas have higher impervious surfaces. Vegetative and marshland areas declined, which generally provide more infiltration, contributing to reduced groundwater recharge and higher surface runoff. The dominance of **Hydrologic Soil Group C** across the watershed further amplifies runoff due to its moderate infiltration capacity.

2016: Runoff discharge of **201.61 m³/s** indicates **very high runoff**, attributed to both intense rainfall (280 mm) and a number of impervious surfaces.

2024: Despite lower rainfall (243 mm), the discharge remains high at **171.53 m³/s** due to increased urbanization (built-up area increased by ~800 ha).

This depicts the land use change is driving urban flood potential, even when rainfall decreases.

Runoff Ratio from 2016 to 2024:

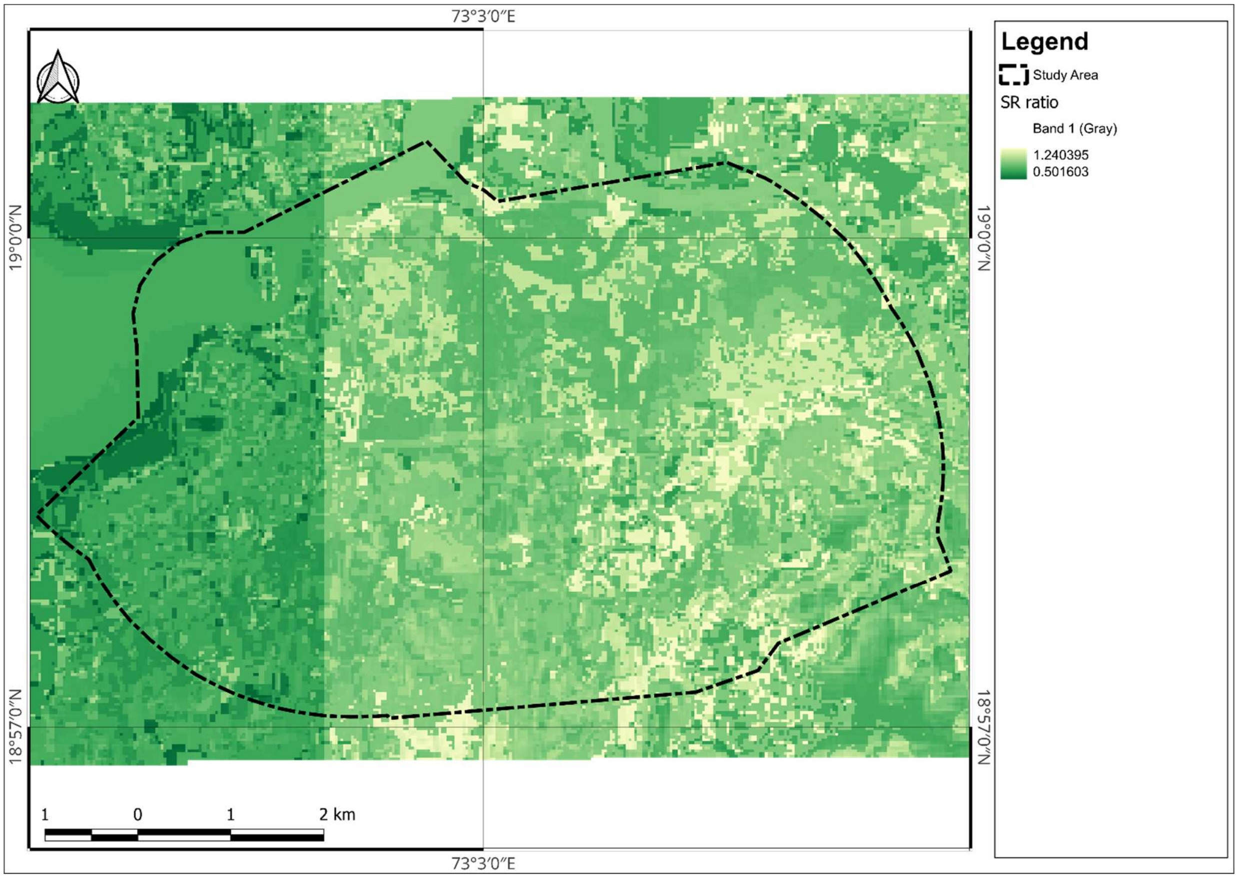

Figure 26 Surface Runoff ration from 2016 to 2024.

In this study, the spatial analysis revealed runoff ratio values ranging from **0.5 to 1.24** across different land cover types within the watershed from the year 2016 to 2024.Values between 0.5 and 0.75 were primarily observed in areas with dense vegetation, marshlands, and water bodies, where a significant portion of rainfall is absorbed, stored, or infiltrated into the ground. These lower runoff ratios are indicative of natural attenuation, higher infiltration, and reduced flood risk.

Values from 0.76 to 1.00 were recorded in **mixed-use zones** such as sparsely vegetated lands and suburban areas, suggesting **moderate runoff** behaviour with partial infiltration and partial overland flow.

Values exceeding 1.0, up to **1.24**, were found in **dense built-up and impervious areas**. These abnormally high values may be attributed to:

- Localized rainfall concentration,

- Surface sealing due to urban expansion,
- Minimal infiltration capacity, and
- Possible runoff contributions from adjacent upslope regions (spatial spillover).

Such high runoff ratios imply a **higher risk of flash flooding, low groundwater recharge, and increased surface flow velocity**. These values are critical indicators for urban flooding and infrastructure planning, especially in areas undergoing rapid land use change.

The presence of runoff ratios above 1 indicates the need to refine catchment boundaries and considering **additional hydrological inputs** (like upstream flows or stormwater channels) that may be contributing extra runoff not directly accounted for by rainfall alone.

4.4 Flood risk assessment

The increasing frequency and intensity of floods due to climate change further emphasize the necessity of robust flood risk assessment methodologies. Accurate evaluation of flood risk is critical for disaster management, urban planning, and environmental conservation. This study employs advanced hydrological analysis techniques, integrating remote sensing data, geographic information systems (GIS), and multi-criteria decision analysis (MCDA) to assess flood-prone areas. The primary factors analyzed include precipitation, elevation, slope, land use/land cover (LULC), and proximity to water bodies. The results provide valuable insights into flood vulnerability and highlight potential mitigation strategies to enhance resilience and reduce disaster impacts.
Flood risk assessment is an essential component of hydrological studies, offering critical insights into vulnerable areas and supporting proactive disaster preparedness. Various factors contribute to flooding, including rainfall intensity, topography, land use patterns, soil permeability, and proximity to water bodies. The rapid urbanization and deforestation occurring in many regions exacerbate flood risks, making the assessment even more vital. Modern GIS and remote sensing technologies significantly improve our ability to analyze and predict flood hazards by providing high-resolution spatial data. This study focuses on a flood-prone region, employing multiple hydrological variables and advanced modeling techniques to deliver a comprehensive flood vulnerability analysis.

4.4.1 Study Area and Data Sources

Study Area

The study is conducted in a region known for recurring flooding events, characterized by a complex hydrological system and diverse land use patterns. The analysis incorporates topographical variations, hydrological flow patterns, and urban expansion trends. The study area is classified into different flood risk levels, ranging from very low to very high risk, providing a detailed understanding of spatial flood distribution.

Data Sources

To ensure accurate assessment, data is collected from multiple sources, including:

- **Satellite Imagery**: NASA Landsat Collection Level 2 for land use classification and hydrological features.
- **Topographic Data**: Digital Elevation Model (DEM) for slope and elevation analysis.
- **Hydrological Data**: Stream networks, flow accumulation models, and Euclidean distance calculations.
- **Meteorological Data**: Long-term precipitation records for seasonal and annual rainfall patterns.
- **Land Use/Land Cover (LULC)**: Classification of vegetation, urban, agricultural, and water bodies to assess flood vulnerability.

4.4.2 Parameters Chosen for Assessment

1. Hydrological Factors Considered

Flood risk assessment incorporates multiple hydrological and environmental parameters. The main variables used in this study include:

- **Precipitation**: Determines the amount of water input into the system, influencing flood probability.
- **Elevation**: Low-lying areas are naturally more prone to flooding due to water accumulation.
- **Slope**: Steep slopes facilitate rapid water runoff, whereas flat terrains retain water, increasing flood risks.
- **Distance from Streams**: Proximity to river networks significantly impacts flood susceptibility.
- **LULC**: Urban regions with impervious surfaces are at higher risk compared to vegetated or agricultural areas due to reduced infiltration capacity.

2. GIS-Based Multi-Criteria Decision Analysis (MCDA)

A GIS-based framework integrates multiple flood risk factors using MCDA techniques. The

Analytical Hierarchy Process (AHP) is utilized to assign weighted importance to each factor, based on their influence on flooding. The weighted layers are combined using an overlay analysis to create an integrated flood risk map.

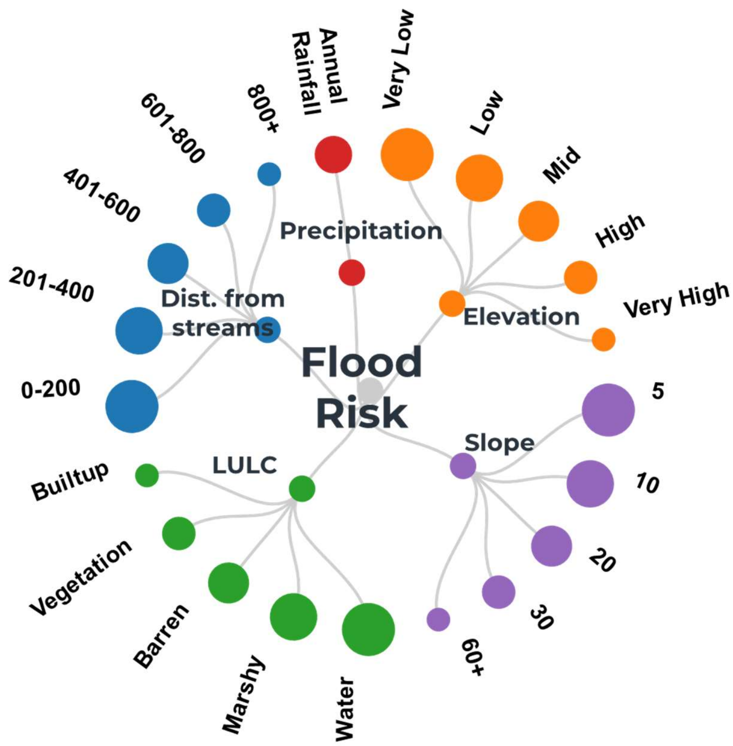

Figure 27 Weightage of parameters in Flood risk map generation.

3. Flood Risk Mapping

The final flood risk map is generated through GIS-based spatial analysis, categorizing regions into five flood risk levels: very low, low, moderate, high, and very high. The spatial distribution of risk levels provides a valuable tool for local authorities and disaster response teams.

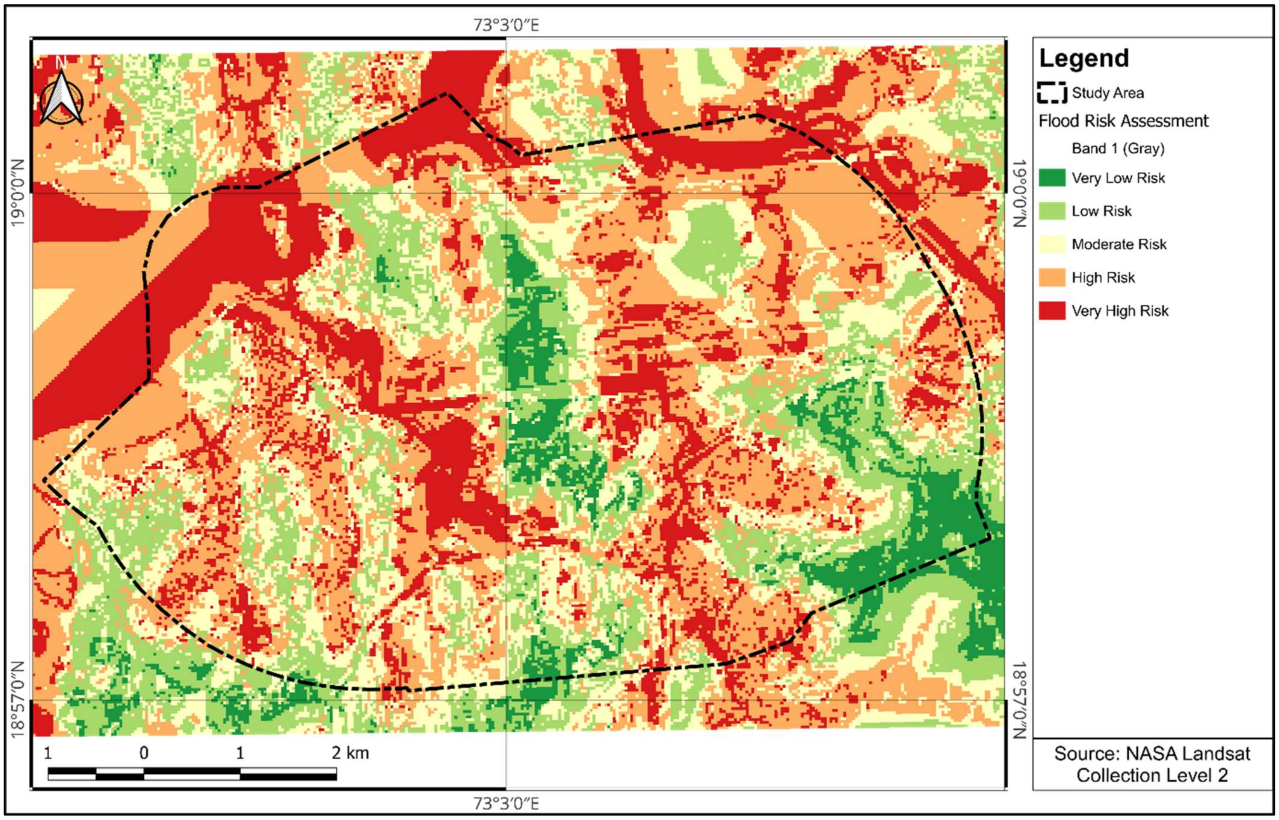

Figure 28 Flood Risk Map

4.4.3 Results

1. Spatial Distribution of Flood Risk

The developed flood risk map reveals:

- **High-Risk Zones**: Predominantly found in low-lying areas adjacent to river networks with intense precipitation.
- **Moderate-Risk Zones**: Located in regions with mixed land use, moderate slopes, and seasonal flood exposure.
- **Low-Risk Zones**: Found in elevated terrains with dense vegetation and efficient drainage.

2. Influence of Individual Factors

- **Precipitation**: High rainfall regions exhibit greater flood vulnerability, necessitating effective water management strategies.
- **Elevation and Slope**: Areas with lower elevation and minimal slope gradients are more prone to prolonged water accumulation.

- **Distance from Streams**: The farther from a river, the lower the likelihood of flood exposure, highlighting the role of proximity in flood risk.
- **LULC**: Urban development has drastically increased flood risks due to reduced infiltration, poor drainage systems, and excessive runoff.

3. Comparison with Historical Flood Events

The model's accuracy is validated by comparing results with historical flood data. The generated flood risk zones generated with previous flood occurrences, confirming the reliability and predictive capabilities of the methodology.

4.4.4 Flood Mitigation Strategies

1. Structural Measures

- **Construction of Flood Barriers**: Levees, embankments, and flood walls help reduce floodwater intrusion into urban areas.
- **Improved Drainage Systems**: Expansion and modernization of drainage infrastructure prevent urban flooding.
- **Retention Basins**: These structures temporarily store excess water, reducing peak flow and mitigating flood impacts.

2. Non-Structural Measures

- **Sustainable Urban Planning**: Implementing zoning regulations that restrict development in flood-prone zones.
- **Afforestation and Reforestation**: Increasing tree cover to enhance water retention and prevent soil erosion.
- **Community-Based Disaster Management**: Raising awareness, conducting flood drills, and implementing real-time monitoring systems for early warnings.
- **Flood-Resilient Infrastructure**: Encouraging the development of buildings designed to withstand flood conditions.

4.4.5 Inferences

This study presents a detailed flood risk assessment using advanced hydrological and GIS-based methodologies. The integration of multiple flood-contributing factors allows for a comprehensive evaluation of flood vulnerability and supports effective mitigation planning. The findings emphasize the importance of integrating spatial data analysis into disaster risk management. Future research should focus on real-time flood prediction models, climate change impacts, and the role of land use planning in flood mitigation to enhance resilience and adaptability in flood-prone regions.

4.5 Flood Susceptibility Assessment

A comprehensive susceptibility analysis conducted to identify and assess areas at risk due to river diversion and associated land transformations near the Ulwe River. Using multi-criteria evaluation (MCE) in a geospatial environment, the analysis integrates five critical factors—**Land Ownership, Land Use, Flood Risk, Land Cover**, and **Distance from River**—each assigned weightages based on their relative influence on flood susceptibility. The scoring system incorporates expert judgment, field knowledge, and literature-backed risk gradation for each sub-class within the factors.

4.5.1 Methodology

The susceptibility index was computed using a weighted overlay analysis in a GIS platform. Each thematic layer was reclassified based on the assigned **risk values (scale 0–9)**, with higher values indicating higher susceptibility. The layers were then weighted and overlaid using the formula:

$$Susceptibility\ Index\ (SI) = \sum (W_i \times R_i)$$

Where:

W_i = Weightage of the i-th factor

R_i = Reclassified risk score of the i-th factor

The final output delineates zones of varying susceptibility across the study area, enabling spatial prioritization for flood risk mitigation and sustainable planning.

4.5.2 Factor-Based Analysis

4.5.2.1 Land Ownership (Weightage: 30%)

Land ownership significantly determines the potential for intervention and development. Newly acquired government lands and those yet to be transferred show high risk scores (9), indicating intense developmental pressure without existing ecological buffers. Mangroves scored 7 due to their vulnerability despite protective regulations. Private non-acquired and excluded areas scored the lowest, reflecting minimal immediate risk from development.

- **High-risk classes**: Under New Acquisition (9), Government Not Transferred (9)
- **Moderate risk**: Mangroves (7), Private Acquired (5), Govt. Transferred (4)
- **Low risk**: Excluded from Acquisition (0), Others/Private Not Acquired (1)

4.5.2.2 Land Use (Weightage: 25%)

Land use types indicate functional exposure and development sensitivity. "Future Development" areas scored the highest (9), followed by open spaces and RPZs (4). Established uses such as residential, public utility, and water bodies presented minimal risk due to either lower alteration potential or protective status.

- **High-risk**: Future Development (9)
- **Moderate risk**: Open Space, RPZ (4), Non-developable Areas (3)
- **Low risk**: Water Body (0), Residential, SEZ, Social Facilities (1)

4.5.2.3 Flood Risk (Weightage: 20%)

This layer was derived from hydrological modelling and historical flood event mapping. Areas with high and moderately high flood risk were scored 9 and 7, respectively. Low and moderately low risk zones scored 2 and 4. This criterion directly informs planning restrictions and protection priorities.

- **High-risk**: High Risk Zone (9), Moderately High (7)
- **Moderate risk**: Moderate (5), Moderately Low (4)
- **Low risk**: Low (2)

4.5.2.4 Land Cover (Weightage: 15%)

Land cover informs the hydrological behaviour of the terrain. Marshlands (score 9) and barren lands (8) are most vulnerable due to low permeability and ecological sensitivity. Vegetated areas scored moderately (7), while built-up (1) and water bodies (0) showed low flood susceptibility due to existing impermeability or non-occupiable nature.

- **High-risk**: Marsh Land (9), Barren (8)
- **Moderate risk**: Vegetation (7)
- **Low risk**: Built-up (1), Water (0)

4.5.2.5 Distance from River (Weightage: 10%)

Proximity to the river is a fundamental driver of susceptibility. Areas classified as "Very Close" and "Close" scored 9 and 7, respectively, indicating higher risk due to immediate exposure to overflow and erosion processes. Risk decreases with distance, reaching minimal levels at "Very Far" (1).

- **High-risk**: Very Close (9), Close (7)
- **Moderate risk**: Medium (5)
- **Low risk**: Far (3), Very Far (1)

Table 6 Land Susceptibility Weightage

Factor	Weightage	Scale	Risk (scale of 1-9)
Land Ownership	30	Under New Acquisition	9
		Mangroves	7
		Excluded From Acquisition	0
		Government Not Transferred	9
		Government Transferred	4
		Others	1
		Private Acquired	5
		Private Not Acquired	1
Land use	25	Future Development	9
		Gaothan Area	2
		Non-Developable Area	3
		Open Space	4
		Public Utility	1

		Residential	1
		Water Body	0
		Transportation	1
		Special Economic Zone	1
		Social Facilities	1
		Rpz	4
		Commercial	1
Flood Risk	20	High Risk	9
		Moderately High	7
		Moderate	5
		Moderately Low	4
		Low	2
Land Cover	15	Water	0
		Marsh Land	9
		Vegetation	7
		Built up	1
		Barren	8
Distance From River	10	Very Close	9
		Close	7
		Medium	5

		Far	3
		Very Far	1

4.5.3 Composite Susceptibility Index and Zoning

By integrating all factors, a composite susceptibility index map was created, classifying the area into five categories:

- Very High Susceptibility
- High Susceptibility
- Moderate Susceptibility
- Low Susceptibility
- Very Low Susceptibility

The zones with very high and high susceptibility were predominantly characterized by:

- Newly acquired government lands intended for development.
- Proximity to the river
- Marshland or barren land cover
- Future development or open space land use
- High flood risk overlays

These regions were mainly found along the Ulwe River's newly diverted course and adjacent floodplain fragments.

4.5.4 Interpretation of Susceptibility Map

The susceptibility map (Figure 29) synthesizes the weighted overlay of five critical factors influencing floodplain vulnerability near the Ulwe River. The spatial distribution of susceptibility zones highlights significant variation across the planning region:

- **Very High Susceptibility Zones (Red):** These areas are concentrated along the newly diverted river course and northern boundary of the region. They largely correspond to marshlands, newly acquired government lands, and areas earmarked for future development—often in close proximity to the river. These zones are at immediate risk from hydrological disruption and urban encroachment.

- **High to Moderate Susceptibility Zones (Orange and Yellow):** Spanning a majority of the central and eastern regions, these zones contain a mix of residential expansion, open spaces, and vegetated lands. Their moderate scores are attributed to mid-range river proximity and transitional land uses, such as RPZs and public utilities.
- **Low to Very Low Susceptibility Zones (Light to Dark Green):** These are primarily in the southern and southeastern extents, featuring established residential areas, forest buffers, and non-developable zones. Their distance from the river, lower development pressure, and protective land uses reduces their susceptibility significantly.

The circular buffer depicted in the central zone likely corresponds to a critical area of interest—possibly a development core or ecological hotspot—requiring detailed focus in planning.

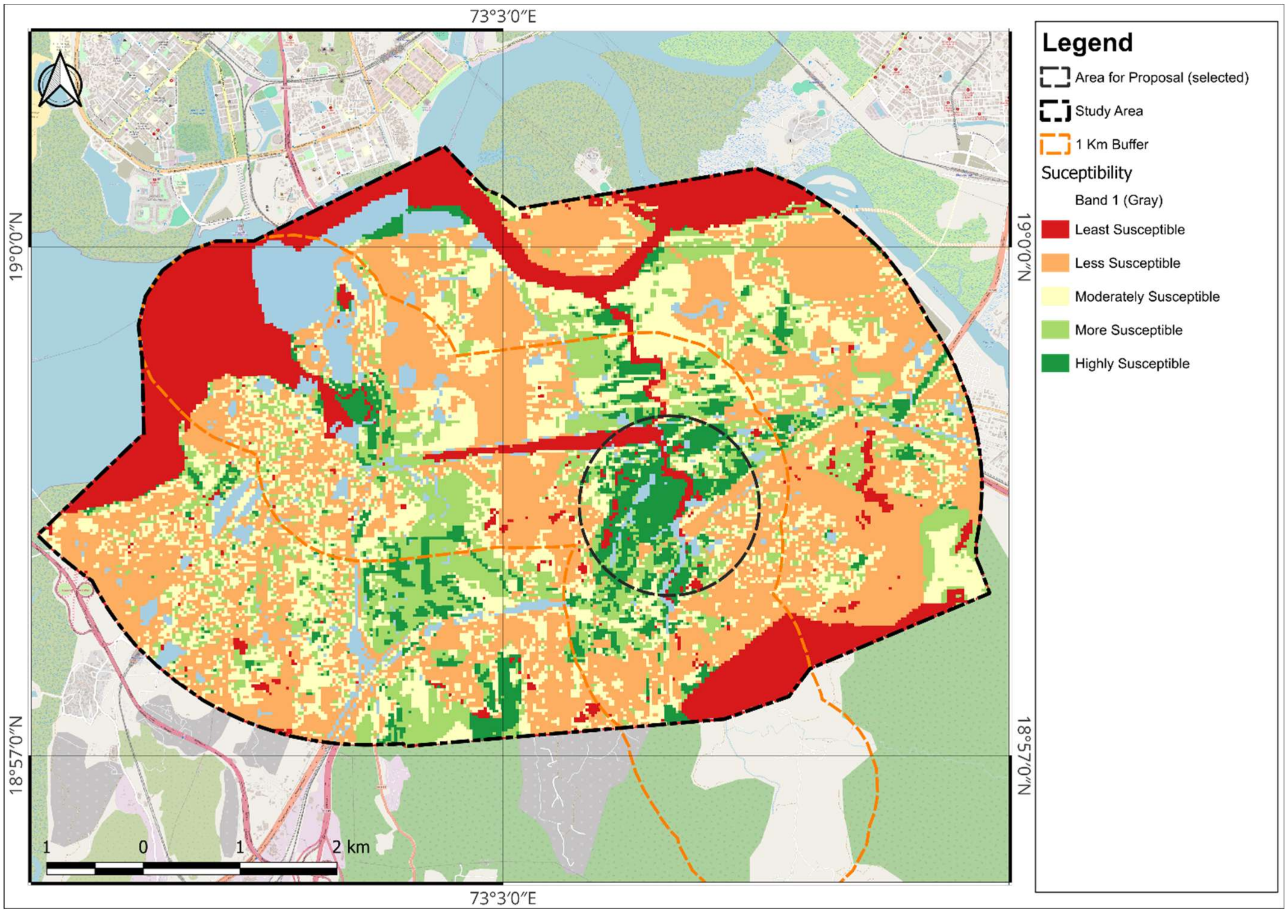

Figure 29 Composite Susceptibility Map of Study Area

5. Proposals

5.1 Introduction

The proposed site, as demarcated by the dashed line on the indicated map, forms a strategically important section of the Ulwe River floodplain. The site has been reported as a key interface where ecological sensitivity crosses with intensifying urban pressure. The configuration of land cover is characterized by a rich spatial mosaic, including dense vegetative areas, open wetlands, and scattered urbanization. High vegetation cover, symbolized by green patches, and light blue areas showing residual wetlands highlight the site's ecological value. Concurrently, the visibility of red-hued impervious surfaces and fragmented land holdings indicates the encroaching footprint of urban infrastructure. This contrast between ecological potential and urban vulnerability makes the site a prime target for focused floodplain management interventions.

Planning-wise, the location presents a special chance to bring together various nature-based and regulatory options. Its vegetated buffers and residual wetland systems offer a biophysical platform on which ecosystem services can be recovered and amplified. The surrounding riverbanks, however, show discernible signs of destabilization and erosion—especially in areas near unregulated construction and invasions—requiring immediate stabilization and protection. In addition, the patch mosaic of composite land-use categories, such as medium- to high-density developed land and unclassified development corridors, emphasizes the need for land-use zoning, policy implementation, and flood-risk-conscious planning.

Tailoring pilot interventions within this geospatial boundary makes it feasible to practically exemplify sustainable floodplain management. The region provides a suitable scale to pilot eco-sensitive urban planning, participatory governance, and sediment flow management. The findings emanating from such localized application can be methodically extrapolated to larger sections of the Ulwe River corridor, thus providing a replicable model for climate-resilient river management in cities.

The following sections describe specific interventions suggested for this site. These are organized around three central goals: controlling anthropogenic activity in the floodplain, restoring and improving the functionality of waterbodies and wetlands, and applying nature-based erosion control.

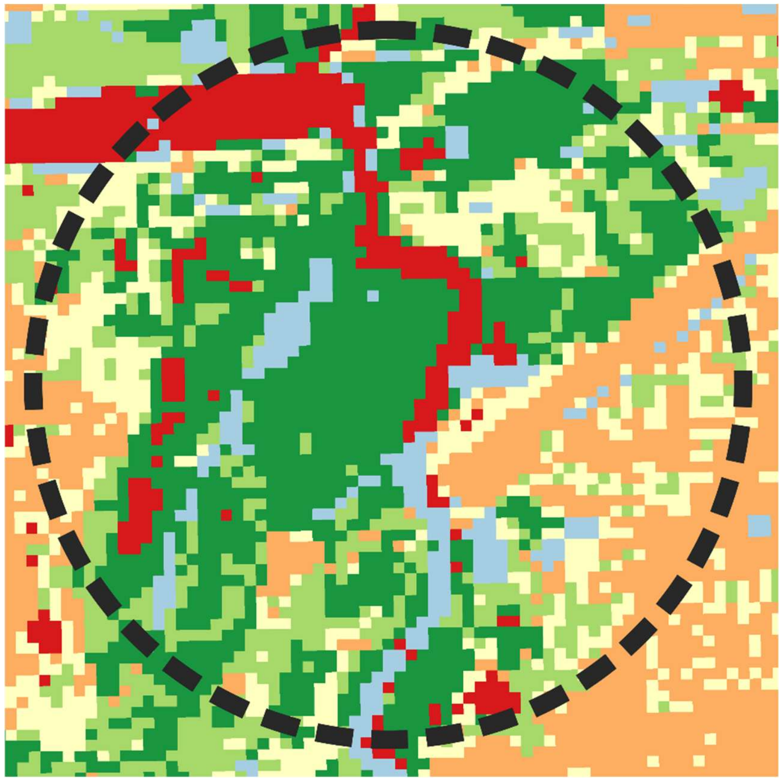

Figure 30 Area Selected for Proposal

5.2 URMP Objective 1: Ensuring Effective Regulation of Activities in Floodplains

Successful regulation of floodplain use is a necessity when constructing climate-resilient cities in rapidly urbanizing riverine environments such as the Ulwe River basin. Pilot area analysis by the study demonstrates a multi-faceted land-use pattern, with high-density vegetation, built-up clusters, and open spaces located within flood-prone areas. Urbanization in such sensitive regions without controls risks both human lives and long-term hydrological stability in local systems.

One of the major measures to overcome these problems is enforcing strict development control measures. A main suggestion is the prohibition of permanent structures within a radius of five hundred meters along riverbanks, particularly where the floodplain transitions immediately into the river channel. The buffer area aims at reducing exposure of the infrastructure to flood risk and conserving the river's natural overflow space during peak monsoons. The geographical analysis points out that the vicinity of the river, especially built-up areas, where flood prone areas have overlap, are most at risk.

In addition to construction controls, zoning regulations must be revised to set aside floodplain land for green infrastructure. Existing vegetated tracts offer scope for multifunctional landscapes like urban parks, wetlands, and community forests that can hold and store floodwater while adding to biodiversity and creating recreational space. Providing such areas with protective status in the city's master plan aligns ecological resilience with urban development priorities.

One of the transformative measures for the Ulwe basin is implementing the "Room for the River" principle, where river natural dynamics are favoured over controlling them with hard structures. The idea is to reserve sections of the floodplain to allow for river migration, deposition of sediment, and channel shifting, lowering the reliance on embankments and other engineered protection measures that have proven ineffective in the area. Such nature-based solutions are gaining international recognition for their capacity to buffer flood effects and restore resilient riverine ecosystems.

Participatory mapping and stakeholder involvement are also essential. GIS-based workshops involving local communities, environmental organizations, and planning authorities can produce spatial datasets that represent both technical evaluations and community realities. The collaborative processes identify the informal settlements, cultural values, and local priorities to make floodplain management transparent, fair, and responsive to the needs of people. These maps can be made part of statutory planning documents, like the City Development Plan, to enhance enforcement and minimize future land-use conflicts.

Where such encroachments are already identified, there arises a need for a socially just resettlement strategy. Residents in exposed areas should be provided dignified relocation alternatives in more secure, serviced sites, facilitated by housing and livelihood integration programs to become universally accepted in the long term. Abandoned lands can next be restored as payback green spaces, seeded with native plants such as bamboo and vetiver grass to act as bio-shields against erosion and subsequent floods. They can also be used as educational parks or public commons to promote environmental conservation.

Through incorporating regulatory controls, participatory planning, and ecosystem-based land management, the interventions intend to align urban development with floodplain natural functions. Expected outcomes are decreased flood damage, enhanced ecological functions, and the development of a replicable resilience model for riverine tropical cities. The approach not only reduces flood risk but also fosters sustainable urban development and community well-being.

5.3 URMP Objective 3: Rejuvenate Waterbodies and Wetlands

Urban wetlands and water bodies are critical ecological resources, functioning as natural buffers against flooding, maintaining biodiversity, and improving groundwater recharge and water quality. Nonetheless, accelerated peri-urban urbanization in areas such as the Ulwe River basin has caused degradation, fragmentation, and even loss of these systems. In the pilot site along the Ulwe River, a number of low-lying depressions and patches-once wetland function-are currently isolated remnants under threat from adjacent land use pressures.

The initial step in reviving these ecosystems is to develop a detailed GIS-based inventory of all the present and potential wetlands and waterbodies. The spatial database should record not just the location and extent of hydrological features but also ecological attributes like vegetation types, water quality, seasonal changes in water levels, and connectivity with the river network. Such a database facilitates the prioritization of restoration along ecological value and flood mitigation potential, maximizing urban investments in terms of environmental and social returns. In the Ulwe basin, vegetated or agricultural land bordering depressions are especially attractive targets for restoration because they are naturally rechargeable and have little existing infrastructure.

One of the main suggestions is to implement successful foreign models, like the Caernarvon Freshwater Diversion from Louisiana, which restored wetlands by diverting treated freshwater into depleted marshes. In the Ulwe scenario, this might include diverting treated effluent or excess stormwater into remaining wetlands during the monsoon, if the inflow is controlled and pre-treated. This strategy would rehydrate wetland soils, encourage native aquatic vegetation, and restore natural biogeochemical cycles, while highlighting the significance of hydrological connectivity for ecological recovery.

Incubating wetland restoration within urban planning instruments is essential for long-term conservation. Declaring restored wetlands Urban Natural Assets or Ecologically Sensitive Areas under the city's Development Plan can protect them against future encroachment and trigger opportunities for climate adaptation finance and biodiversity mitigation offsets. Community participation is also essential; local residents can be involved through stewardship programs that promote frequent maintenance, monitoring, and conflict resolution, which allows for a shared sense of responsibility and ownership.

Restored wetlands may also be multifunctional, being used as eco-parks or bio-retention areas that offer educational, recreational, and tourism uses. Infrastructures like pervious trails, boardwalks, and viewing platforms can be added in a sensitive manner to maximize public access and appreciation without sacrificing ecological integrity. These areas not only enhance urban resilience but also contribute to the health and quality of life of urban dwellers.

Wetland rejuvenation, integrated with regulatory and erosion-control provisions, creates a comprehensive strategy for flood risk management, climate resilience, and biodiversity preservation. The Ulwe River catchment, with its transitional environment and unused land pockets, is particularly well positioned to take advantage of such nature-based approaches. In the end, rejuvenating and reincorporating wetlands in urban settings is critical to ensuring resilient, sustainable city growth that supports both environmental well-being and community livelihoods.

5.4 URMP Objective 4: Control Bank Erosion

Bank erosion is a major problem in the Ulwe River basin that contributes significantly to enhanced flood risk, loss of agricultural land, and environmental degradation of riverine ecosystems. A study of the intervention zone identifies several vulnerable reaches, particularly along inner river bends and around habitation where vegetation cover has been removed and banks are subjected to direct hydraulic forces and bank erosion. These reaches make up particularly susceptible zones due to high gradients and high land use pressure.

Conventional hard engineering measures, including concrete embankments, tend to impair ecological connectivity and relocate erosion issues further downstream. Rather, this approach favors nature-based solutions (NbS) that integrate bioengineering and strategic structural interventions for environmentally friendly bank stabilization. One of the key methods is the cultivation of local, deep-rooted species such as bamboo and vetiver grass, which have been shown to strengthen soil, slow the velocity of runoff, and root banks against river flows. Such plant life stabilizes soil while also improving water quality and riparian habitat with time.

Where high-velocity or actively eroding areas require something more than just vegetation alone, bioengineering features like gabion walls and riprap are advocated as supplements. Locally sourced materials used to construct them, these structures dissipate hydraulic energy and create immediate support during the maturation period of planted vegetation. Hybrid solutions-a mix of engineered and nature-based methods-provide protection in layers, balancing immediate erosion control with long-term ecological strength.

Sediment management is also critical. Erosion quickens siltation in river channels, lowering flow capacity and disrupting natural rhythms. Silting sediment traps on drainage outlets-especially where stormwater or untreated effluent flows into the river-can catch coarse sediments and pollutants prior to their entry into the main channel, maintaining water quality and minimizing the need for frequent dredging. In cases where dredging is inevitable, the material should be reused in urban landscaping, land reclamation, or used as a green infrastructure base in line with the principles of the circular economy to avoid environmental wastage.

Long-term efficacy of erosion control is reliant on ongoing monitoring, adaptive management, and active community participation. Involvement of local stakeholders in monitoring and upkeep ensures that interventions are effective and responsive to emerging river dynamics. Periodic evaluation enables flexibility to adjust measures as river conditions change.

This integrated approach concurs with best practice for sustainable river management, as evidenced by how joining nature-based and engineered options has been seen to effectively prevent bank erosion, stabilize channels, and restore riparian ecosystems. For the Ulwe River basin, these will likely stop bank failure, protect people from floods, and build multifunctional riparian buffers to benefit people and ecosystems alike. Integrating these strategies into urban water governance systems will make erosion control an active, and not passive, part of resilient city planning.

5.5 Conclusion

The Ulwe River basin, especially its floodplain area adjacent to the Navi Mumbai International Airport, is threatened by a convergence of problems such as flood hazard, wetland degradation, urban encroachment, and bank erosion. These are compounded by fragmented planning and a deficiency of river-sensitive regulatory mechanisms, and hence integrative and ecologically guided interventions are crucial for sustainable management.

This study took on a systematic, multi-objective strategy to combat these challenges across four pillars of floodplain regulation, wetland rejuvenation, erosion control, and participatory governance. Utilizing geospatial analysis, hydrological modelling, field observations, and policy analysis, this study provides not only a justification but also an action plan to roll out meaningful interventions.

The first aim lies in regulating floodplain use via spatial zoning and development controls. Creation of a 500-meter construction-free buffer in statutory land-use plans are suggested to safeguard the floodplain from further deterioration and reduce flood risk. Implementation of the "Room for the River" strategy, which accepts natural river dynamics instead of trying to confine them, is suggested as an adaptive planning approach. Incorporation of participatory GIS mapping in this process increases transparency and allows for more equitable planning outcomes through the involvement of local stakeholders in decision-making.

The second goal focuses on rejuvenating wetlands and waterbodies. The research promotes the development of a GIS-based wetland inventory to inform restoration priorities. Taking cue from exemplary international models, such as the Caernarvon Freshwater Diversion, the research suggests rehydrating wetlands with controlled inflows of treated water. These measures not only re-establish hydrological equilibrium but also have co-benefits such as biodiversity protection, recreational use, and microclimate management.

For the third objective, the attention is given to managing riverbank erosion using nature-based solutions. The proposed interventions are vegetative bio-stabilization by utilizing native vegetation such as bamboo and vetiver grass, supported by low-impact bioengineering infrastructure such as gabion walls and riprap for high-risk sections. These practices are context-dependent, affordable, and environmentally self-sustaining. Sediment management systems and regular, ecologically friendly dredging-in which dredged sediment is reused-are also recommended, reflecting the transition from reactive to proactive hydrological management.

Together, these methods constitute a resilient floodplain restoration plan that harmonizes technical accuracy with ecological acumen. Prioritization of space ensures interventions in the zones of maximum risk and ecological worth. Composite susceptibility maps, hydrological modelling, and landscape analysis aid data-based decision-making and provide a model that can scale to other urban river basins in India.

The study also emphasizes that the effectiveness of these interventions is contingent upon socio-political will and active engagement by urban local bodies, planning authorities, and communities. Embedding nature-based solutions in city-level planning documents like Development Plans, Regional Plans, and Coastal Zone Management Plans will make them more effective and resilient in the long term.

The Ulwe River example illustrates how urban infrastructure construction, like that of the Navi Mumbai International Airport, can be integrated with river basin planning by a conscious, science-driven approach. The suggested framework is not a restriction on development but a steering mechanism towards resilience, sustainability, and equity.

In summary, floodplains are essential ecological systems that offer key hydrological, environmental, and social services. Their protection and restoration are a necessity, not a choice. The strategies and tools outlined in this research provide a pragmatic route for managing the intricacies of urban river basin management amidst accelerated urban change, making development and ecological stewardship go hand in hand.

5.6 Way Forward

Based on the findings and interventions identified for the Ulwe River floodplain, the path forward must place highest value on integrated, adaptive, and community-based responses in order to provide long-term resilience and sustainability to face ongoing urbanization and climate variability.

1. Institutionalized Nature-Based and Regulatory Solutions:

The ecological sensitivity of the Ulwe River floodplain and urban vulnerability necessitate integrating nature-based solutions and strong regulatory mechanisms into statutory planning. This involves institutionalizing construction-free buffers, green infrastructure zoning, and the "Room for the River" concept in the city's Development Plan and corresponding regulatory tools. Institutionalization will ensure protection of floodplain functions, minimize flood risk, and preserve ecological connectivity despite increasing urban pressures.

2. Increase and Sustain Wetland and Waterbody Restoration:

There should be an ongoing, GIS-based inventory and monitoring system for waterbodies and wetlands integrated into urban planning. Restoration should be prioritized for sites with high ecological value and flood mitigation potential. Based on international best practices, like the Caernarvon Freshwater Diversion, adaptive management of treated effluent and stormwater can be tested to rehydrate and reconnect fragmented wetlands, enhancing biodiversity and urban climate resilience.

3. Mainstream Participatory and Inclusive Governance:

Continuously active stakeholder participation is important for successful floodplain management. Frequent participatory GIS workshops and community care programs should become institutionalized such that local perspectives, priorities, and cultural practices are incorporated within planning and decision-making and execution. Clear-cut resettlement formats and livelihood consolidation must be had along with every relocation, as redeveloped lands are returned to public park space and common education space.

4. Advance Erosion Control and Sediment Management:

Nature-based bank stabilization with indigenous vegetation, augmented by context-sensitive bioengineering structures, must be expanded to at-risk reaches. Sediment traps and eco-friendly dredging must be combined with urban landscaping and green infrastructure, according to circular economy principles to achieve maximum resource efficiency and minimum ecological disturbance. Monitoring and adaptive management protocols must be developed to accommodate changing river dynamics and maintain long-term effectiveness.

5. Embed Data-Driven Decision Making and Monitoring:

The application of high-resolution geospatial data, hydrological modeling, and real-time monitoring should be amplified to support dynamic flood risk assessment and intervention prioritization. Composite susceptibility maps and scenario-based planning can be used to forecast future challenges, inform resource planning, and facilitate climate adaptation strategies.

6. Embed Policy Alignment and Multi-Agency Collaboration:

Successful floodplain management demands coordination among several agencies, such as urban planning, water resources, disaster management, and environmental protection authorities. Policy coherence at the city, regional, and state levels will be essential to align goals, prevent fragmented interventions, and guarantee the sustainability of resilience measures.

7. Encourage Research, Innovation, and Capacity Building:

Ongoing research in urban hydrology, wetland restoration, and nature-based solutions must be promoted, with pilot projects as learning platforms for upscaling successful interventions. Capacity building for municipal personnel, local communities, and technical staff will facilitate implementation and build a culture of adaptive, science-based management.

The Ulwe River floodplain provides a distinctive challenge to showcase the potential of mainstreaming how city infrastructure development may be integrated harmoniously with stewardship of natural ecosystems using comprehensive, participatory, and responsive management. Navi Mumbai, through the institution of nature-based solutions, rigorous regulation, and inclusive governance, can create an emulable model for the management of river systems under climate change in accelerating tropical urbanism. The future calls for not only policy and technical innovation but continued community involvement and inter-agency cooperation to ensure that urban expansion and environmental health move hand in hand.

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