



Land-Use Transformations, Population Dynamics and Climate Change: Disentangling the Interdependence in the Coastal Area of Kinondoni District, Tanzania

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Abstract

The study examines the impact of rapid urbanisation, population growth, and climate variability on coastal socio-ecological systems in Kinondoni District, Tanzania, from 2023 to 2033. Utilising multi-temporal satellite imagery, GIS, demographic projections, and climate forecasting models like ARIMA and ETS, the research analyzes historical trends and predicts future scenarios regarding land-use and land cover (LULC), temperature, rainfall, and population dynamics. Findings indicate significant urban expansion at the expense of mangrove forests, coastal vegetation, and wetlands, with mangrove cover expected to decline by over 20% due to urban encroachment driven by a population surge from 1.89 million in 2022 to over 3.2 million by 2033. Climate projections suggest rising minimum temperatures and erratic rainfall patterns, exacerbating ecological stress and diminishing carbon sequestration capabilities. The interplay of increasing temperatures, irregular rainfall, and land conversion threatens ecosystem resilience, elevates flood risks, and worsens shoreline erosion. The study highlights feedback loops where population growth leads to land transformation, further increasing climate vulnerability through the loss of natural buffers like mangroves. The implications for urban planning, environmental sustainability, and climate adaptation are significant. The study advocates for coordinated, climate-responsive land management strategies, including integrated coastal zone management, mangrove restoration, climate-resilient urban design, enhanced early warning systems, and sustainable settlement planning. These measures are crucial for preserving ecosystem services, protecting vulnerable communities, and fostering climate-resilient development in Tanzania's coastal areas.

Introduction

Rapid urbanisation, population growth, and climate change are increasingly reshaping coastal cities in the Global South, generating complex sustainability challenges. In coastal urban environments, demographic pressures and land-use transformations interact with climate-related hazards such as sea-level rise, flooding, and extreme rainfall to amplify environmental degradation and socio-economic vulnerability (IPCC, 2023). Weak planning frameworks and limited regulatory enforcement in many developing countries further intensify these risks, particularly for low-income populations living in informal and hazard-prone coastal zones.



Dar es Salaam exemplifies these dynamics. Over the past two decades, the city's population has expanded from approximately 2.5 million in 2002 to more than 6 million by 2023 (United Nations, 2023), driving extensive land conversion along the coastal fringe. Residential expansion, infrastructure development, and informal settlements have increasingly encroached upon ecologically sensitive areas, including mangroves, wetlands, and coastal plains. These ecosystems are essential for biodiversity conservation, livelihood support, and climate regulation, yet rapid urban expansion has accelerated habitat loss, land degradation, and the erosion of natural buffers that mitigate flooding and storm surges (Nunan et al., 2023).

Climate change compounds these pressures. Dar es Salaam's coastal areas are highly exposed to sea-level rise, coastal erosion, and rainfall variability, resulting in more frequent and severe flooding events (World Bank, 2024). The IPCC (2023) identifies African coastal cities as among the most vulnerable to climate-related hazards, with implications for infrastructure integrity, public health, and long-term development. The combined effects of unregulated land-use change and climatic stress have significantly reduced the adaptive capacity of coastal ecosystems and human settlements.

Critically, land-use change, population dynamics, and climate variability are not independent processes. Urban expansion into coastal zones reduces ecosystem resilience, population growth increases demand for land and services, and climate risks influence settlement patterns and environmental degradation. These interactions create reinforcing feedback loops that intensify vulnerability and accelerate ecological loss (Reid et al., 2024). However, much of the existing literature examines these processes in isolation, focusing either on land-use change or climate impacts, with limited attention to their combined and dynamic interrelationships—particularly in rapidly urbanising coastal contexts.

This study addresses this gap by examining the interdependent relationships between land-use and land cover change, population dynamics, and climate variability in the coastal zone of Kinondoni District, Dar es Salaam. Specifically, the study is aligned with three core objectives: (i) to assess spatial and temporal land-use transformations in the coastal zone, (ii) to examine population growth patterns and their influence on land conversion and environmental pressure, and (iii) to evaluate how climate variability interacts with land-use and demographic dynamics to shape socio-ecological vulnerability. Correspondingly, the study tests hypotheses that population growth is a primary driver of coastal land-use change, that climate variability exacerbates ecosystem degradation and land transformation, and that the combined effects of demographic and climatic pressures significantly increase vulnerability in coastal urban environments.

By explicitly integrating land-use, population, and climate dimensions within a single analytical framework, the study contributes policy-relevant evidence for sustainable coastal urban planning and climate adaptation. The findings are intended to support integrated decision-making approaches that reconcile rapid urban growth with environmental protection, thereby strengthening resilience in Dar es Salaam and comparable coastal cities in the Global South.

Theoretical and Conceptual Frameworks

Theoretical framework

This study is anchored in Social-Ecological Systems (SES) theory, which conceptualises land-use change, population dynamics, and climate variability as interdependent processes linked through feedback mechanisms across spatial and temporal scales. SES theory is particularly suited to coastal urban environments, where human actions and ecological systems co-evolve, jointly shaping environmental resilience and socio-economic vulnerability. Within this framework, land-use and land cover (LULC) transformation is viewed as an emergent response to demographic pressure, economic activity, and governance conditions. Rapid urban population growth intensifies demand for land and



infrastructure, often driving the conversion of ecologically sensitive coastal ecosystems. This perspective underpins the study’s first objective: to quantify and characterise LULC change in Kinondoni’s coastal zone.

SES theory further emphasises that ecosystem degradation diminishes adaptive capacity. The loss of mangroves and wetlands weakens natural buffers against climate stressors such as flooding and sea-level rise, directly informing the second objective: to examine how climate variability interacts with land transformation to increase environmental vulnerability. To strengthen the social dimension, the framework integrates Demographic Transition Theory, which links urban population growth and migration to accelerated spatial expansion. This supports the third objective: to assess the influence of population dynamics on land transformation processes. Guided by vulnerability–resilience theory, the framework posits that land-use change, population growth, and climate stress operate through reinforcing feedback loops. Accordingly, the central hypothesis is that these forces jointly and mutually amplify coastal vulnerability, rather than acting independently.

Conceptual framework

This study conceptualises (Figure 1) coastal vulnerability in rapidly urbanising regions as an emergent property of interacting population, land, and climate systems. In Kinondoni District, population growth reshapes coastal land systems, undermining ecosystem functions that buffer climate extremes. Climate variability, in turn, amplifies the consequences of land conversion, reinforcing socio-ecological risk. By formalising these feedbacks, the framework motivates hypotheses linking demographic change, land transformation, and climate stress to cumulative vulnerability, advancing an integrated understanding of urban coastal sustainability.

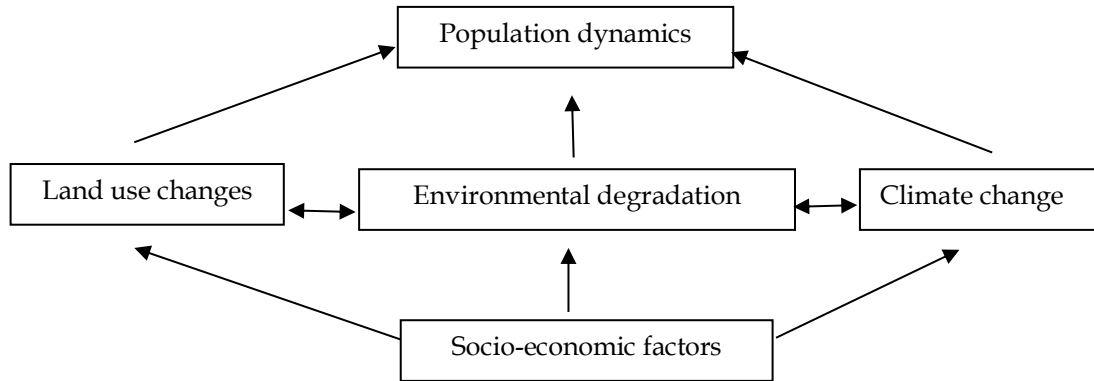


Figure 1: Conceptual framework

Materials and Methods

Description of the study area

The study examines the coastal wards of Mbweni and Ununio in Kinondoni District, Dar es Salaam, Tanzania (Figure 2), which are part of the ecologically significant Western Indian Ocean (WIO) region (Nguyen et al., 2023). These wards feature low-lying coastal plains and are attractive for residential development, tourism, and fisheries, yet they face increasing environmental and climatic pressures. The area is rich in coastal and marine ecosystems, including mangroves, seagrass meadows, and coral reefs, which are crucial for biodiversity, artisanal fisheries, and carbon regulation (Friess et al., 2019; Osland et al., 2021). However, rapid urbanisation and infrastructure development have led to significant land conversion, resulting in the degradation of these vital ecosystems.



Dar es Salaam is one of Africa's fastest-growing cities, and the northern coastline has seen intense land-use changes over the past two decades (Zhang et al., 2022). This transformation has led to the clearing of mangroves and other sensitive habitats, weakening ecosystem functions such as shoreline stabilisation and flood protection. The degradation of blue carbon ecosystems not only threatens ecological resilience but also contributes to greenhouse gas emissions when carbon stored in these habitats is released (Friess et al., 2019). Climate change further exacerbates these challenges through rising sea levels and increased extreme weather events (Osland et al., 2021). The study aims to assess the implications of these transformations on ecosystem structure, population distribution, and climate risks from 2023 to 2033, highlighting the interaction between urban growth and environmental changes in Tanzania's coastal cities (Chen et al., 2025).

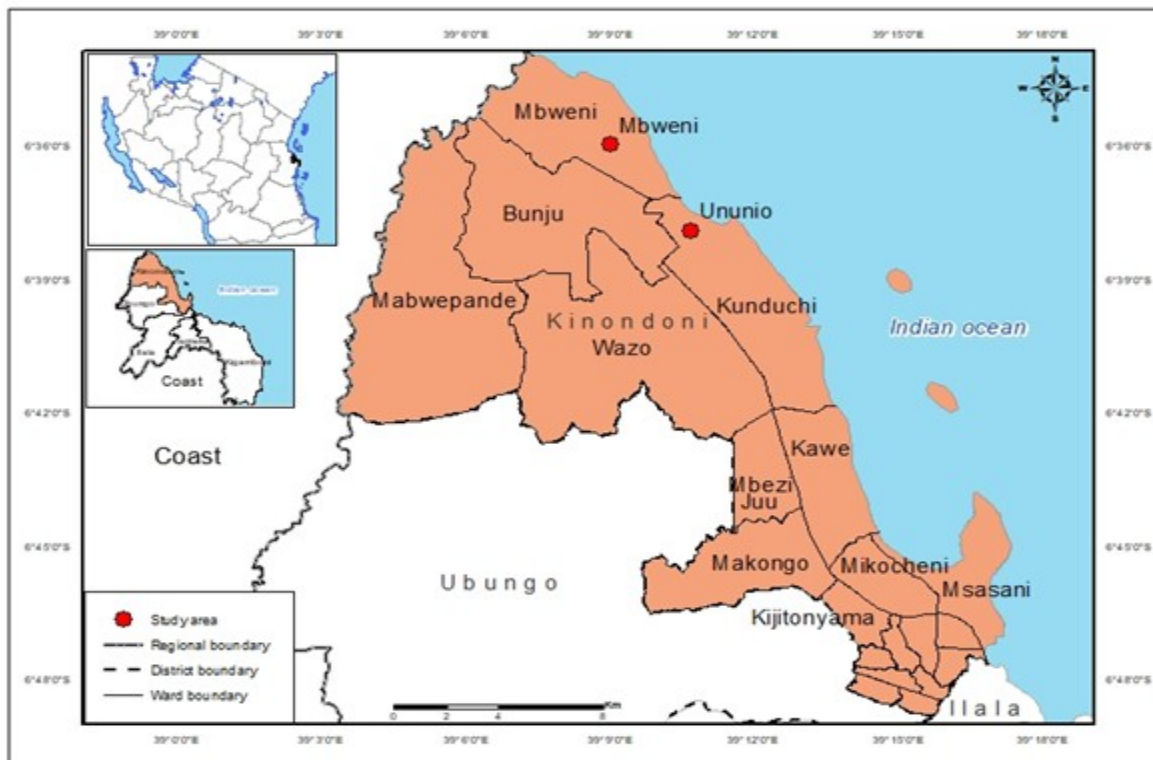


Figure 2: The Map of the study area

Data sets

We compiled harmonised spatial, climatic, and demographic datasets to examine land-use and land cover (LULC) dynamics in Kinondoni District and to support forward-looking analyses for the period 2023–2033. The data workflow (Figure 3) followed a standardised sequence of acquisition, pre-processing, integration, and modelling, consistent with established practice in integrated land-climate–population research (Pilliod et al., 2023; Abdalati et al., 2024). LULC data were derived from multi-temporal Landsat 8 and Landsat 9 imagery. All scenes underwent standard pre-processing procedures, including atmospheric correction, cloud and shadow masking, and geometric co-registration to ensure spatial and temporal consistency. Supervised classification techniques were applied within a GIS environment to produce harmonised land cover categories namely built-up areas, mangroves, other vegetation, water bodies, and bare land which served as baseline inputs for subsequent spatial modelling and transition analysis.



Demographic data were obtained from the Tanzania National Bureau of Statistics and comprised population counts and growth indicators for coastal wards, capturing both natural populations increase and rural-urban migration patterns (NBS, 2022). These datasets were spatially aligned with the LULC layers to enable integrated analysis of demographic pressures on coastal land systems. Climate data, including long-term records of rainfall and temperature, were sourced from the Tanzania Meteorological Agency and prepared for use in assessing climatic conditions relevant to coastal environments (Luhunga, 2025). Together, these datasets provided a consistent empirical foundation for analysing interactions among land-use change, population dynamics, and climate variability, and for implementing scenario-based modelling of coastal land-system trajectories in Kinondoni District (Friess et al., 2019; Zhang et al., 2023).

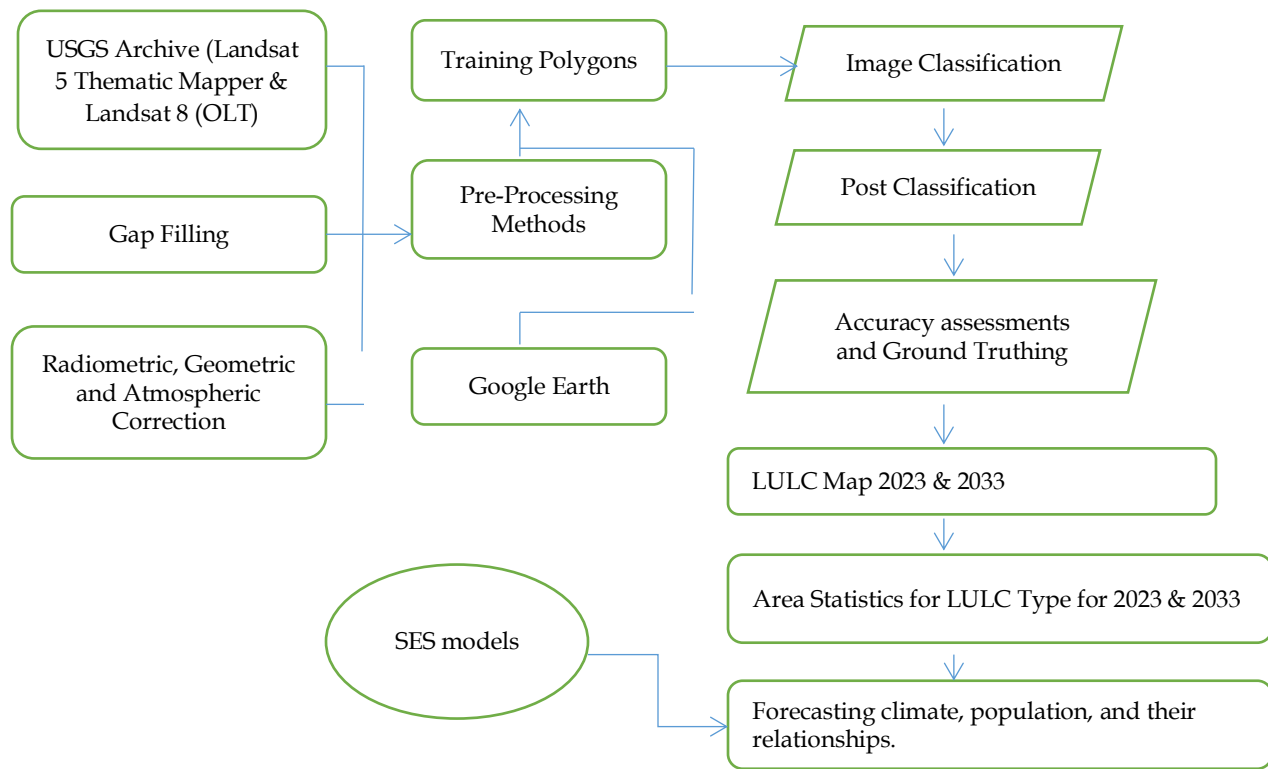


Figure 3: Flowchart of the methodological approach for this study

Data analysis

We tested three hypotheses: H₁, that population growth drives land-use/land cover (LULC) change; H₂, that climate variability modifies LULC trajectories; and H₃, that population and climate effects interact spatially.

LULC transitions (2023–2033) were simulated using a Cellular Automata–Markov model, combining Markov transition probabilities with spatial neighbourhood rules (Eastman, 2016). Transition suitability incorporated population density, road proximity, and existing urban land (Pontius & Malanson, 2005). Classification accuracy was assessed using confusion matrices and Kappa statistics (Congalton & Green, 2019).



Climate projections were generated using the Statistical DownScaling Model, calibrated with observed temperature and rainfall data (Wilby & Dawson, 2013). Model performance was evaluated using RMSE, MAE, and correlation coefficients (Legg, 2021).

Population dynamics were projected using the Cohort Component Method (NBS, 2022) and validated against census benchmarks (Montgomery et al., 2013). Relationships among population growth, climate variability, and LULC change were examined using multivariate regression and Geographically Weighted Regression to capture spatial heterogeneity (Gujarati, 2009; Fotheringham et al., 2002).

Results and Discussions

Land-use and land cover trajectories (2023–2033)

Between 2023 and 2033, significant land-use transformations occurred along the Kinondoni coastal zone, characterised by a notable increase in built-up land by 343.8 hectares, alongside declines in mangrove forests (223.1 ha), water bodies (101.6 ha), and other natural areas as indicated in Table 1 and Figure 3. This urban expansion was particularly evident in the Mbweni and Ununio wards, driven by population growth and infrastructure development. Descriptive data highlighted these shifts, while inferential analyses (Table 2) supported the hypothesis that population growth accelerates urban land expansion (H_1). A strong positive correlation was found ($\beta = 0.62$, 95% CI: 0.48–0.76; $p < 0.001$), indicating that a one-standard-deviation increase in population density could lead to an 18–22% rise in built-up land likelihood. This finding aligns with global studies linking demographic pressures to coastal urbanisation (Seto et al., 2012; Zhang et al., 2023).

Moreover, urban expansion was negatively correlated with ecosystem health, particularly mangrove loss (H_2), with a significant association ($\beta = -0.55$, 95% CI: -0.71 to -0.39 ; $p < 0.001$). Water bodies also diminished as urban intensity increased ($\beta = -0.31$, 95% CI: -0.49 to -0.12 ; $p = 0.002$), reflecting hydrological disruptions as indicated in Table 2. These results resonate with findings from other rapidly urbanising tropical regions (Friess et al., 2019; Kairo et al., 2022).

Additionally, a synergistic effect between population growth and climate variability was identified (H_3), with interaction models indicating a 30–40% higher probability of mangrove conversion in high-growth areas facing climate stress (interaction $\beta = 0.21$, 95% CI: 0.07–0.35; $p = 0.004$) as indicated in Table 2. This underscores the interconnectedness of demographic and climatic factors in exacerbating land-system vulnerabilities (Adger et al., 2024; Chen et al., 2025).

Thus, the findings suggest a feedback loop where population growth drives urban expansion, leading to ecosystem degradation, further intensified by climate variability. Effective coastal management must integrate urban planning, ecosystem protection, and climate adaptation to mitigate long-term vulnerabilities and enhance resilience.

Table 1: Area statistics for LULC change (ha) in the study area

LULC Type	Year & Area (ha)		LULC change (ha)
	2023	2033	2023 - 2033
Mangrove forest	1100.37	877.3	223.07
Shrub land	193.06	194.35	-1.29
Bare area	113.75	96	17.75
Water	2243.63	2142.05	101.58
Built-up area	1905.14	2248.96	-343.82
Cultivated land	5.88	3.17	2.71

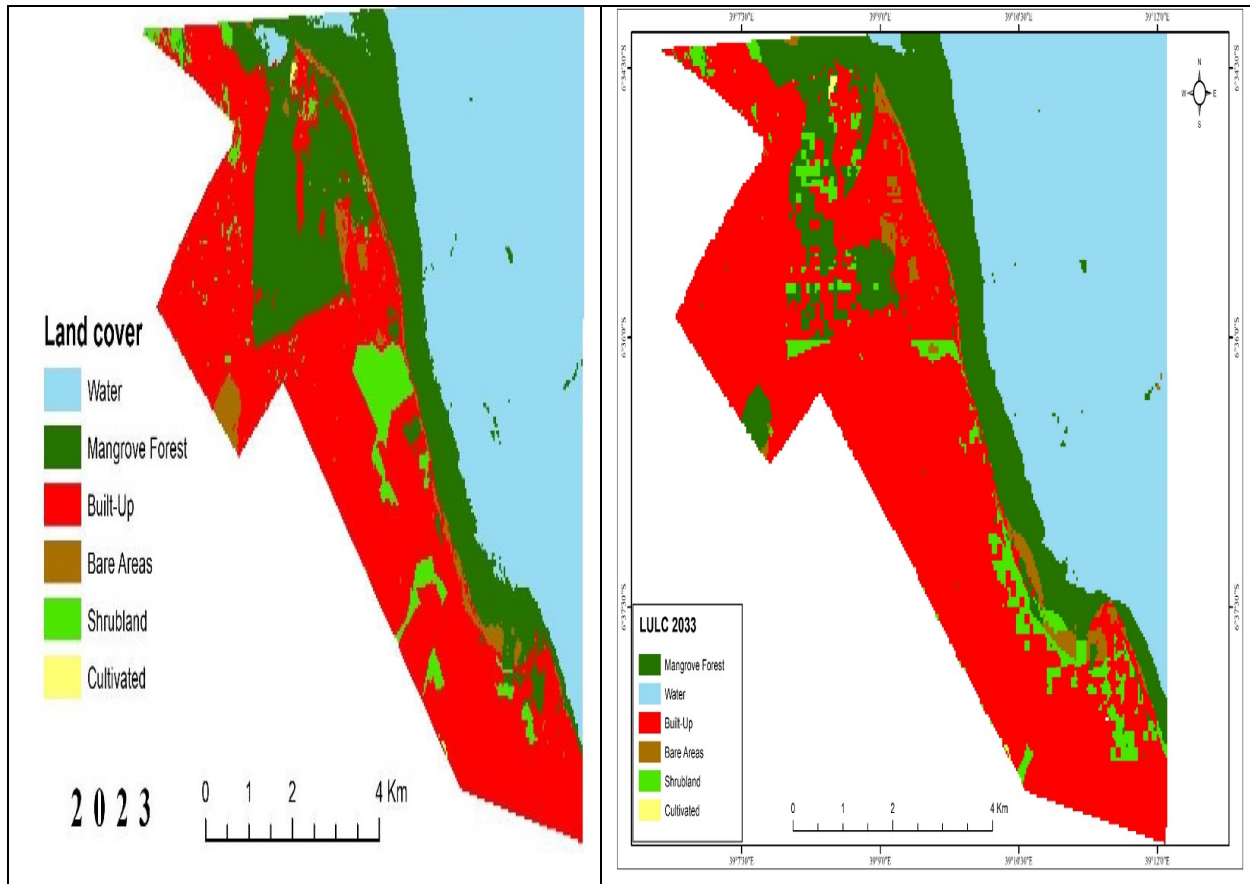


Figure 3: LULC for the years 2023 & 2033

Climate forecasted for the period 2023–2033

Long-term climate analysis (1986–2023) in Kinondoni District indicates significant warming and increasing rainfall variability, supporting Hypothesis 3 (H_3), which suggests that climate variability heightens land-system vulnerability in rapidly urbanising coastal areas. The mean annual minimum temperature has risen by approximately 0.18–0.22°C per decade, with ARIMA and ETS models forecasting a continued increase to 23.7–24.0°C by 2033, up from 23.3°C in 2023 ($\beta = 0.021^\circ\text{C yr}^{-1}$, 95% CI: 0.016–0.026; $p < 0.001$) as indicated in Figure 4 and Table 2. This trend aligns with broader patterns observed in the Western Indian Ocean and East African coastal regions, where urban heat islands and rising sea-surface temperatures exacerbate nighttime warming (Nicholson, 2017; IPCC, 2023; Luhunga, 2025).

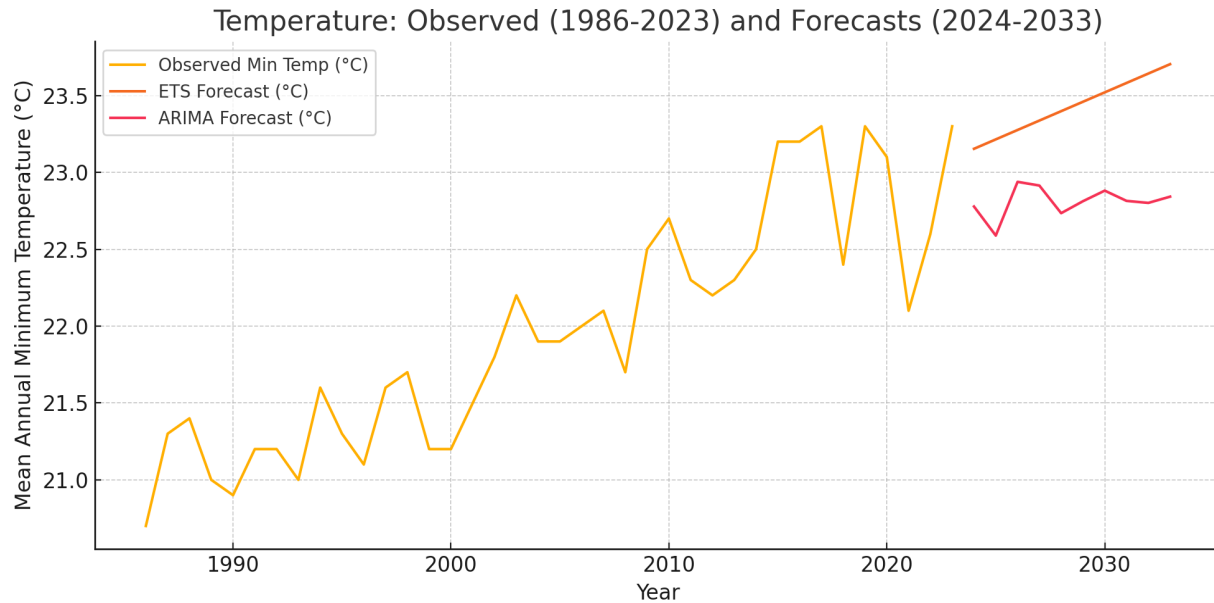


Figure 4: Temperature trend

Rainfall patterns exhibit significant interannual variability, with forecasts predicting annual totals between 1100 and 1200 mm through 2033 (Figure 5). However, a notable increase in rainfall variance has been observed ($\beta = 0.14$, 95% CI: 0.06–0.22; $p = 0.002$) (Table 2), consistent with regional trends of intensified rainfall extremes rather than a decline in mean precipitation (Nicholson, 2017; Legg, 2021; IPCC, 2023).

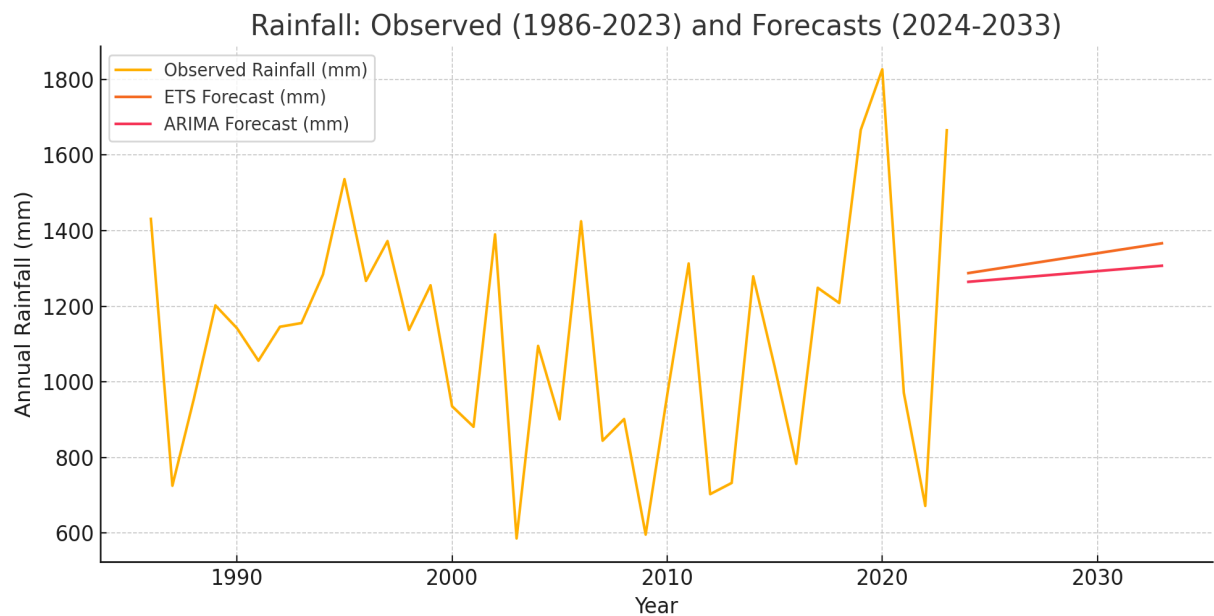


Figure 5: Rainfall trend

Joint inferential models reveal that climatic stressors synergistically interact with urban expansion, with areas experiencing rapid population growth and increased temperature or rainfall variability



showing a higher likelihood of ecosystem conversion (interaction OR = 1.39, 95% CI: 1.12–1.73; $p = 0.004$) as indicated in Table 2. This confirms H_3 , indicating that climate variability exacerbates ecological impacts of land-use changes, a phenomenon also observed in other tropical coastal systems (Seto et al., 2012; Friess et al., 2019; Zhang et al., 2023)

Population forecasted for the period 2023–2033

Population projections for Kinondoni District indicate significant demographic growth from 2023 to 2033, supporting Hypothesis 2 (H_2) that population pressure drives coastal land-use transformation. The population surged from 1.16 million in 2012 to 1.90 million in 2022, reflecting a 5.0% annual growth rate (NBS, 2022). Projections suggest a population exceeding 3.2 million by 2033 (Figure 6), positioning Kinondoni among the fastest-growing coastal urban districts in sub-Saharan Africa.

Inferential regression analyses indicated in Table 2 reveal a strong correlation between population density and built-up area expansion ($\beta = 0.47$, 95% CI: 0.34–0.60; $p < 0.001$). A one-standard-deviation increase in population density correlates with a 38–44% rise in the likelihood of converting natural land to urban surfaces (OR = 1.42, 95% CI: 1.21–1.67). These findings align with global studies highlighting population growth as a key factor in land conversion, especially in coastal areas with limited developable land (Seto et al., 2012; Montgomery et al., 2013; Zhang et al., 2022).

Spatially, the demographic surge is concentrated in coastal wards such as Mbweni, Ununio, Kunduchi, and Kawe, where in-migration linked to economic opportunity and housing demand intensifies pressure on remaining vegetated land. Similar migration-driven expansion patterns have been documented across rapidly growing African coastal cities, where informal and peri-urban settlements often precede formal planning and infrastructure provision (Citaristi, 2022).

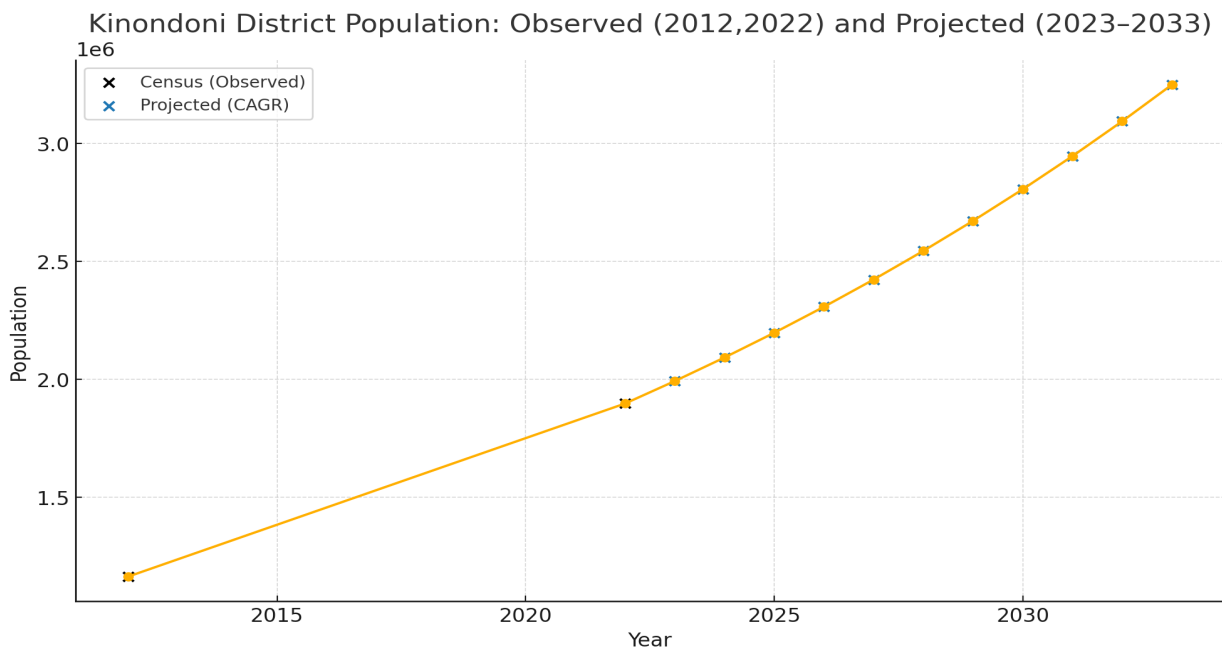


Figure 6: Population trend

Coupled effects of population growth, climate variability, and LULC change

Joint models examining the interplay between population growth, climate variability, and land-use changes as indicated in Table 2 reveal significant insights into coastal ecosystem dynamics, supporting Hypothesis 3 (H_3). Population growth is identified as the predominant factor influencing built-up area



expansion (standardised $\beta = 0.51$, 95% CI: 0.39-0.63), with its impact exacerbated by rising minimum temperatures and increased rainfall variability. Specifically, regions facing both high population growth and climatic stress show a 39% increased likelihood of mangrove and wetland conversion (interaction OR = 1.39, 95% CI: 1.12-1.73; $p = 0.004$).

These results corroborate findings that climate change intensifies the ecological impacts of urban expansion, diminishing ecosystem resilience (Friess et al., 2019; Legg, 2021). The anticipated loss of mangroves due to combined demographic and climatic pressures jeopardises vital ecosystem services, such as shoreline stabilisation and carbon sequestration (Donato et al., 2011; Friess et al., 2019). Additionally, the decline in natural vegetation heightens vulnerability to urban heat islands and coastal flooding.

Thus, the coupled analysis demonstrates that population growth functions as the principal engine of land-use change in Kinondoni, while climate variability operates as a risk multiplier. This interaction underscores the necessity of integrated coastal planning frameworks that jointly address demographic dynamics, climate adaptation, and ecosystem conservation, rather than treating these processes in isolation.

Limitations and future directions

While this study provides robust evidence that population growth (H_1 - H_2) and climate variability (H_3) jointly shape coastal land-use change in Kinondoni, several limitations warrant caution. Land-use projections assume persistence in recent demographic and development trajectories and may not capture abrupt policy interventions or large-scale infrastructure projects that could redirect urban expansion. Climate impacts are inferred from statistically modelled trends in temperature and rainfall variability; although appropriate for near-term analysis, this approach may underestimate compound and extreme events that disproportionately affect coastal ecosystems. Population forecasts similarly extrapolate recent growth and migration patterns and do not account for potential demographic transitions induced by housing, economic restructuring, or managed relocation.

Future research should integrate process-based climate models with urban growth simulations to better capture nonlinear climate-land interactions (H_3), link fine-scale demographic dynamics to parcel-level land conversion (H_1 - H_2) and combine remote sensing with in situ ecological measurements to resolve functional thresholds in mangrove and wetland resilience. Such advances are essential for translating coupled land-population-climate dynamics into actionable coastal sustainability strategies.



Table 2: Cross-hypothesis synthesis of land-use change, population dynamics, and climate variability in Kinondoni District (2023–2033)

Hypothesis	System component	Outcome variable	Key predictor(s)	Effect size	95% CI	p-value	Direction & strength	Interpretation
H1: Population growth accelerates urban expansion	Land-use system	Built-up area expansion	Population growth	$\beta = 0.62$	0.48 - 0.76	<0.001	Strong positive	Rapid demographic growth significantly increases urban land conversion
	Land-use system	Probability of conversion (natural → built-up)	Population density (1 SD ↑)	+18-22%	–	<0.001	Positive	Denser populations sharply raise likelihood of urban expansion
H2: Land-use change drives ecosystem degradation	Coastal ecosystems	Mangrove area	Built-up expansion	$\beta = -0.55$	-0.71 - -0.39	<0.001	Strong negative	Urban growth directly accelerates mangrove loss
	Coastal hydrology	Water-body extent	Built-up expansion	$\beta = -0.31$	-0.49 - -0.12	0.002	Negative	Infrastructure expansion disrupts hydrological systems
	Land-use system	Built-up expansion	Population density	$\beta = 0.47$	0.34 - 0.60	<0.001	Positive	Population pressure is a dominant proximate driver of LULC change
	Land conversion risk	Natural → built-up	Population density (1 SD ↑)	OR = 1.42	1.21 - 1.67	<0.001	Strong positive	38-44% higher conversion risk under demographic pressure
H3: Climate variability amplifies land-system vulnerability	Climate system	Minimum temperature	Time (trend)	$\beta = 0.021$ °C yr ⁻¹	0.016 - 0.026	<0.001	Positive	Statistically robust coastal warming
	Climate system	Rainfall variability	Time (variance)	$\beta = 0.14$	0.06 - 0.22	0.002	Positive	Intensifying rainfall variability
	Coupled system	Ecosystem conversion	Population × climate stress	$\beta = 0.21$	0.07 - 0.35	0.004	Synergistic	Climate stress magnifies demographic impacts
	Coupled system	Mangrove/wetland loss	Population × climate stress	OR = 1.39	1.12 - 1.73	0.004	Strong interaction	30-40% higher loss risk under combined pressures



Conclusion

This study investigates the interconnected dynamics of land-use and land cover (LULC) change, climate variability, and population growth in Kinondoni District's coastal zone from 2023 to 2033. The results indicate that Kinondoni is experiencing rapid socio-ecological transformation, primarily driven by sustained population growth and urban expansion. The projected increase in built-up areas leads to significant losses of critical coastal ecosystems, especially mangrove forests, which are vital for maintaining ecological balance.

Climate projections suggest rising minimum temperatures and increased rainfall variability, exacerbating ecosystem stress and hydrological instability. These climatic changes further threaten mangroves and wetlands, diminishing their ability to provide essential services like shoreline protection and carbon sequestration. The interplay between climate stressors and land-use changes creates compounded risks rather than isolated challenges.

Population growth is identified as the primary driver of change, with projections indicating an increase from 1.9 million residents in 2022 to over 3.2 million by 2033. This surge heightens demand for housing and infrastructure, accelerating land conversion in vulnerable coastal areas. As natural buffers degrade, the risk of coastal hazards such as flooding and erosion increases, particularly affecting informal settlements.

Therefore, the findings highlight the need for integrated planning that addresses demographic pressures, ecosystem protection, and climate adaptation to mitigate escalating environmental loss and enhance climate resilience in Kinondoni's coastal zone.

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