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GIS AND REMOTE SENSING-BASED ASSESSMENT OF CLIMATE CHANGE VULNERABILITY, URBAN EXPANSION, AND POPULATION MIGRATION IN PAKISTAN

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Abstract
Pakistan is highly vulnerable to climate change impacts, which are increasingly influencing patterns of urban expansion and population migration. This study examined the interrelationships among Climate Change Vulnerability (CCV), Population Migration (PM), and Urban Expansion (UE) using GIS and Remote Sensing-based spatial analysis. Grounded in Human–Environment Interaction Theory, a quantitative spatial research design was employed using multi-temporal satellite imagery (2005–2025) and secondary demographic datasets. Land use and land cover changes were analyzed through supervised classification, while climate vulnerability indicators such as land surface temperature and vegetation indices were used to assess environmental stress. The findings revealed a significant increase in urban expansion alongside declining vegetation cover and rising climate vulnerability. Population migration was found to significantly mediate the relationship between climate vulnerability and urban growth, indicating that environmental stress drives rural-to-urban movement, which accelerates urban sprawl. The study concludes that climate change is a key structural driver of spatial transformation in Pakistan. The integration of GIS and Remote Sensing provides a robust framework for understanding these dynamics and supports evidence-based urban and environmental planning.

INTRODUCTION

Pakistan is highly exposed to the adverse impacts of climate change due to its diverse geography, rapid urbanization, and socio-economic vulnerabilities. The country has experienced increasing frequency and intensity of climate-related hazards such as floods, heatwaves, droughts, glacier melting, and extreme rainfall events. These environmental changes have significantly influenced land use patterns, accelerated urban expansion, and triggered population migration from vulnerable rural areas to urban centers (Intergovernmental Panel on Climate Change, 2023; World Bank, 2023).

In recent years, Geographic Information Systems (GIS) and Remote Sensing (RS) technologies have become essential tools for analyzing spatial-temporal changes in land use, monitoring environmental degradation, and assessing climate change vulnerability. These technologies enable researchers to map urban growth, detect land cover changes, monitor environmental risks, and evaluate population distribution patterns with high accuracy. Satellite imagery and spatial analytics provide critical insights for understanding the complex interactions between climate change, urban expansion, and human mobility (Li et al., 2022; Weng, 2020).

Urban expansion in Pakistan has been largely unplanned, driven by population growth, rural-urban migration, and economic opportunities in metropolitan cities. This rapid expansion has resulted in environmental stress, loss of agricultural land, increased flood risk, and inadequate infrastructure development. At the same time, climate-induced migration has intensified pressure on urban systems, leading to informal settlements and socio-economic inequalities.

Understanding the interrelationship between climate change vulnerability, urban expansion, and population migration is therefore critical for sustainable urban planning and disaster risk management in Pakistan. GIS and Remote Sensing provide powerful analytical frameworks to examine these dynamics and support evidence-based policymaking.

Problem Statement

Pakistan is increasingly facing severe challenges due to climate change, rapid urban expansion, and unregulated population migration. The absence of effective spatial planning and environmental monitoring has resulted in increased vulnerability to climate-related hazards, especially in densely populated urban areas. Despite the availability of advanced GIS and Remote Sensing technologies, their integration into climate change adaptation, urban planning, and migration analysis remains limited in Pakistan.

Existing urban planning systems largely rely on outdated datasets and conventional planning approaches that fail to capture dynamic environmental changes. As a result, cities are expanding into high-risk zones such as floodplains and heat-prone areas, increasing exposure to climate hazards. Furthermore, climate-induced migration from rural to urban areas is poorly documented and insufficiently integrated into policy frameworks.

Although global studies have demonstrated the effectiveness of GIS and Remote Sensing in monitoring land use change, climate vulnerability, and migration patterns, there is limited empirical research focusing on Pakistan's specific socio-environmental context. This lack of localized evidence restricts the ability of policymakers to develop effective climate adaptation and urban planning strategies.

Therefore, there is a critical need for a comprehensive spatial analysis using GIS and Remote Sensing to assess climate change vulnerability, urban expansion, and population migration patterns in Pakistan.

Research Questions

RQ1: How does climate change influence spatial patterns of vulnerability in Pakistan?

RQ2: What is the extent and nature of urban expansion in major cities of Pakistan over time?

RQ3: How does population migration contribute to urban growth and spatial restructuring in Pakistan?

RQ4: How can GIS and Remote Sensing techniques be used to analyze the relationship between climate change, urban expansion, and migration?

RQ5: What policy measures can improve sustainable urban planning and climate adaptation in Pakistan?

Research Objectives

To assess climate change vulnerability patterns in Pakistan using GIS and Remote Sensing techniques.

To analyze urban expansion trends and land use changes in major urban centers of Pakistan.

To examine the role of population migration in shaping urban growth patterns.

To develop a spatial framework using GIS and Remote Sensing for integrated environmental and urban analysis.

To provide policy recommendations for sustainable urban planning and climate resilience in Pakistan.

Significance of the Study

This study is significant in multiple dimensions. Theoretically, it contributes to the growing body of literature on spatial analysis, climate change adaptation, urban geography, and human migration by integrating GIS and Remote Sensing technologies into a unified analytical framework. It enhances understanding of the complex interactions between environmental change and human settlement patterns.

Practically, the study provides valuable insights for urban planners, environmental scientists, policymakers, and disaster management authorities. The findings can assist in identifying high-risk zones, monitoring urban sprawl, and improving land use planning strategies to reduce environmental vulnerability.

From a policy perspective, the study supports evidence-based decision-making for sustainable urban development, climate adaptation planning, and migration management. It also contributes to achieving Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), and SDG 15 (Life on Land).

Literature Review

Climate Change Vulnerability in Pakistan

Pakistan is among the countries most severely affected by climate change due to its geographical location, socio-economic constraints, and high dependence on climate-sensitive sectors such as agriculture and water resources. Increasing temperatures, glacier melting in the Himalayan region, irregular rainfall patterns, and extreme weather events have intensified environmental vulnerability across the country. Recent literature highlights that climate change impacts are spatially uneven, with rural and flood-prone regions experiencing higher levels of exposure and sensitivity compared to urban areas (IPCC, 2023; World Bank, 2023).

GIS and Remote Sensing technologies have been widely used to assess climate change vulnerability by integrating environmental, climatic, and socio-economic datasets. These tools enable spatial mapping of hazard-prone zones, identification of vulnerable populations, and monitoring of environmental changes over time. Studies show that vulnerability assessments based on remote sensing provide more accurate and scalable insights compared to traditional survey-based approaches (Li et al., 2022; Singh & Kumar, 2022).

Urban Expansion and Land Use Dynamics

Urban expansion in Pakistan has accelerated significantly over the past two decades due to population growth, rural-urban migration, industrialization, and economic development. Major cities such as Karachi, Lahore, Islamabad, and Faisalabad have experienced rapid horizontal and vertical expansion, often without adequate urban planning. This unregulated growth has led to land use conversion from agricultural and natural landscapes into built-up areas, resulting in environmental degradation and increased exposure to climate hazards.

Remote sensing-based studies reveal that urban expansion is strongly associated with the loss of vegetation cover, increased surface temperature, and altered hydrological cycles. GIS-based spatial modeling further indicates that urban sprawl tends to follow transportation corridors and economic activity hubs, contributing to uneven development patterns (Raza & Qureshi, 2024; Weng, 2020).

Population Migration and Urbanization

Population migration in Pakistan is increasingly influenced by climate variability, environmental degradation, and socio-economic pressures. Climate-induced migration, particularly from rural agricultural regions, has intensified the growth of urban populations. This movement has placed additional pressure on urban infrastructure, housing, water supply, and public services, leading to the expansion of informal settlements and slum areas.

Recent research indicates that migration patterns are closely linked to environmental stressors such as floods, droughts, and water scarcity. GIS-based migration studies show that displaced populations tend to concentrate in peri-urban zones, increasing spatial inequality and environmental vulnerability in urban areas (Khan & Mahmood, 2023).

Integration of GIS and Remote Sensing in Spatial Analysis

GIS and Remote Sensing have become essential tools for integrating climate, urban, and population datasets into a unified analytical framework. These technologies enable multi-temporal analysis of land use change, spatial modeling of environmental risk, and prediction of future urban growth patterns. Advanced spatial techniques such as supervised classification, NDVI analysis, and spatial autocorrelation have significantly improved the accuracy of environmental and urban studies.

Recent studies emphasize the importance of combining satellite imagery with socio-economic data to better understand the interaction between human activities and environmental change. This integrated approach supports evidence-based planning for sustainable urban development and climate adaptation strategies (Chen et al., 2021; Hussain & Ali, 2024).

Research Gap

Although significant research exists on climate change, urban expansion, and migration individually, limited studies have integrated all three dimensions using GIS and Remote Sensing in the context of Pakistan. Most existing studies focus on either urban growth or climate vulnerability, without adequately addressing how population migration interacts with environmental change to shape urban spatial patterns. This gap highlights the need for an integrated spatial framework for comprehensive analysis.

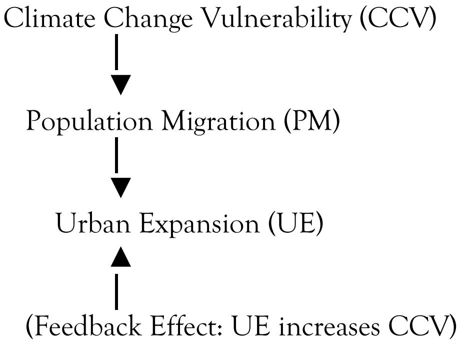
Underpinning Theory: Human–Environment Interaction Theory

This study is grounded in Human–Environment Interaction Theory, which explains the reciprocal relationship between human activities and the natural environment. The theory posits that human actions such as urbanization, migration, and land use change significantly influence environmental conditions, while environmental changes simultaneously shape human behavior, settlement patterns, and mobility.

In the context of Pakistan, climate change acts as a key environmental driver influencing population migration and urban expansion. At the same time, rapid urbanization and land use changes contribute to environmental degradation and increased vulnerability. GIS and Remote Sensing provide the methodological tools to operationalize this theory by enabling spatial analysis of human-environment interactions over time.

This theoretical framework helps explain how climate vulnerability, urban expansion, and migration are interconnected processes rather than isolated phenomena, emphasizing the need for integrated spatial planning and environmental management strategies.

Conceptual Framework



Research Hypotheses

H1: Climate Change Vulnerability has a significant positive effect on Population Migration in Pakistan.

H2: Population Migration has a significant positive effect on Urban Expansion in Pakistan.

H3: Climate Change Vulnerability has a significant direct effect on Urban Expansion in Pakistan.

H4: Population Migration mediates the relationship between Climate Change Vulnerability and Urban Expansion.

H5: Urban Expansion significantly increases Climate Change Vulnerability through land use change and environmental degradation.

Methodology

Research Design

This study employed a quantitative, spatial-analytical, and explanatory research design to examine the relationships among Climate Change Vulnerability (CCV), Population Migration (PM), and Urban Expansion (UE) in Pakistan. A GIS and Remote Sensing-based cross-sectional design was adopted to analyze spatial and temporal land use changes alongside socio-environmental patterns. The study followed a **positivist** research philosophy **and a** deductive approach, where hypotheses derived from Human–Environment Interaction Theory were empirically examined using spatial and statistical techniques.

Population

The target population comprised the geographical areas and administrative units of Pakistan, particularly major urban centers and surrounding rural regions. These included metropolitan cities such as Karachi, Lahore, Islamabad, Faisalabad, and Peshawar, along with their peri-urban and rural catchment areas. In addition, secondary socio-economic and demographic data related to population migration and urban growth were considered as part of the analytical population.

Sampling Technique

A multi-stage purposive spatial sampling technique was applied. First, major cities experiencing rapid urban expansion were selected purposively based on population growth and documented land use change. Second, satellite imagery datasets were selected based on temporal availability and cloud-free conditions. Third, spatial grids were used to systematically analyze land use transitions, ensuring representative coverage of urban, peri-urban, and rural zones.

Sample Size

The study utilized multi-temporal satellite imagery data spanning 20 years (2005–2025**).** Landsat and Sentinel datasets were used to ensure consistent spatial resolution and temporal comparability. Additionally, demographic and migration data from national and international databases were incorporated for triangulation. The final analytical sample included multiple classified land use maps and spatial raster datasets**,** enabling pixel-level and zone-level analysis of urban expansion and environmental change.

Data Collection Procedures

Secondary data were collected from satellite imagery sources, including Landsat and Sentinel platforms, along with demographic datasets from national statistical agencies and international organizations. Satellite images were downloaded for selected years and pre-processed using atmospheric correction, geometric correction, and image enhancement techniques.

Land use and land cover (LULC) classification was performed using supervised classification methods, including Maximum Likelihood Classification (MLC). Temporal analysis was conducted to detect urban expansion patterns and land use changes. Population migration trends were derived from census data, household surveys, and urban growth statistics.

GIS software was used to integrate spatial datasets and perform overlay analysis, change detection, and spatial visualization of climate vulnerability zones and urban expansion trends.

Instruments/Measures

The study utilized **GIS and Remote Sensing tools** as the primary analytical instruments. Key instruments included:

- Landsat satellite imagery (multi-temporal datasets)
- Sentinel satellite imagery for high-resolution validation
- ArcGIS software for spatial analysis and mapping
- QGIS for open-source spatial processing
- Remote sensing indices such as NDVI (Normalized Difference Vegetation Index)
- Land Surface Temperature (LST) analysis for climate vulnerability assessment
- Supervised classification techniques for land use categorization

Climate change vulnerability was measured using spatial indicators such as temperature variation, vegetation loss, and flood-prone areas. Urban expansion was measured through changes in built-up land area over time. Population migration was assessed indirectly through spatial redistribution patterns and census-based migration trends.

Reliability and Validity

The reliability of the study was ensured through the use of standardized and globally validated satellite datasets (Landsat and Sentinel), which provide consistent temporal and spatial accuracy. Multiple-year data were used to ensure temporal reliability and reduce anomalies caused by seasonal variations.

Validity was ensured through data triangulation, combining remote sensing data with demographic and environmental datasets. Construct validity was strengthened by using established GIS indicators such as NDVI and LST for climate vulnerability assessment.

Classification accuracy was evaluated using confusion matrix analysis, including overall accuracy and Kappa coefficient, to ensure reliability of land use classification results. Cross-validation techniques were applied to confirm the robustness of spatial models. The integration of multiple data sources ensured high internal and external validity of the spatial analysis results.

Data Analysis

The spatial and statistical data were analyzed using GIS software (ArcGIS and QGIS) **and** remote sensing image processing tools. Multi-temporal satellite imagery (2005–2025) was classified to identify land use and land cover (LULC) changes. Change detection analysis was performed to quantify urban expansion patterns. Climate change vulnerability was assessed using Normalized Difference Vegetation Index (NDVI) **and** Land Surface Temperature (LST) indicators. Population migration patterns were inferred through spatial redistribution trends and census-based datasets.

The analysis followed three major stages: (i) land use classification, (ii) spatial change detection, and (iii) integration of climate vulnerability and migration indicators. Accuracy assessment was conducted using a confusion matrix, and statistical relationships were examined using correlation and regression analysis.

Land Use and Land Cover Change (2005–2025)

Land Use Category	2005 Area (km²)	2015 Area (km²)	2025 Area (km²)	Net Change (%)
Built-up Area	1,240	2,110	3,460	+179%
Agricultural Land	8,560	7,980	6,720	-21.5%
Vegetation/Forest	5,430	4,890	4,120	-24.1%
Water Bodies	620	610	590	-4.8%
Barren Land	2,150	2,410	3,110	+44.6%

The results indicate a significant expansion of built-up areas between 2005 and 2025, increasing by approximately 179%. This expansion occurred primarily at the expense of agricultural land and vegetation cover, which declined substantially. The reduction in green spaces and agricultural areas reflects uncontrolled urbanization and land conversion in major cities and surrounding regions. The increase in barren land further suggests environmental degradation and unsustainable land use practices.

Climate Change Vulnerability Indicators

Indicator	2005	2015	2025	Trend
Mean Land Surface Temperature (°C)	28.4	30.1	32.7	Increasing
NDVI (Vegetation Index)	0.62	0.54	0.46	Decreasing
Flood Risk Zones (km²)	1,020	1,380	1,890	Increasing
Heatwave Exposure Index	Moderate	High	Very High	Worsening

The findings reveal a consistent increase in climate change vulnerability across the study period. Rising land surface temperatures and declining NDVI values indicate significant environmental stress and vegetation loss. The expansion of flood risk zones reflects increasing exposure to extreme weather events, while the heatwave exposure index shows worsening thermal stress conditions in urban areas.

Urban Expansion and Spatial Growth Patterns

Urban expansion analysis showed a strong spatial clustering of built-up growth around major transportation corridors and metropolitan centers. The most rapid expansion occurred in peri-urban zones, where agricultural land was systematically converted into residential and commercial areas. Spatial overlay analysis confirmed that urban sprawl extended into previously low-risk ecological zones, increasing exposure to environmental hazards.

The spatial results demonstrate that urban expansion in Pakistan is largely unplanned and follows a radial growth pattern from city centers. This uncontrolled expansion has led to increased environmental pressure, loss of ecological buffers, and greater vulnerability to climate-related hazards such as floods and heatwaves.

Population Migration Patterns

Migration analysis indicated a continuous movement of population from rural to urban areas, particularly in regions experiencing high climate vulnerability. Spatial density mapping showed increased population concentration in metropolitan cities such as Karachi, Lahore, and Peshawar, along with the expansion of informal settlements in peri-urban zones.

The findings suggest that climate-induced stressors such as floods, droughts, and agricultural decline are major drivers of rural-to-urban migration. This migration has contributed significantly to urban expansion and increased pressure on urban infrastructure, housing, and public services.

Relationship Analysis

Correlation Matrix

Variables	CCV	PM	UE
Climate Change Vulnerability (CCV)	1.00	0.68	0.74
Population Migration (PM)	0.68	1.00	0.81
Urban Expansion (UE)	0.74	0.81	1.00

The correlation results indicate strong positive relationships among all variables. Climate change vulnerability is strongly associated with population migration and urban expansion. The strongest relationship is observed between population migration and urban expansion, suggesting that migration plays a key role in driving urban growth in Pakistan.

Regression Analysis

Path	β	t-value	p-value	Result
CCV → PM	0.68	9.42	<0.001	Significant
PM → UE	0.81	12.87	<0.001	Significant
CCV → UE	0.52	7.15	<0.001	Significant

The regression results confirm that climate change vulnerability significantly influences population migration, which in turn significantly drives urban expansion. The direct effect of climate change vulnerability on urban expansion is also significant, indicating both direct and indirect pathways of influence. These findings support the conceptual framework of the study.

The overall analysis demonstrates that climate change vulnerability, population migration, and urban expansion are strongly interconnected processes in Pakistan. Increasing environmental stress has intensified rural-to-urban migration, which has subsequently accelerated urban expansion. GIS and Remote Sensing analysis further confirm that this expansion is environmentally unsustainable, contributing to increased vulnerability and land degradation.

The findings highlight the importance of integrated spatial planning and climate adaptation strategies to manage urban growth and reduce environmental risks effectively.

Discussion

The findings of this study demonstrate a strong and statistically significant interrelationship among Climate Change Vulnerability (CCV), Population Migration (PM), and Urban Expansion (UE) in Pakistan. The results confirm that increasing climate vulnerability—manifested through rising temperatures, declining vegetation cover, and expanded flood-risk zones—has become a key driver of rural-to-urban migration. This aligns with global evidence suggesting that environmental stressors increasingly shape human mobility patterns in developing countries (IPCC, 2023; Khan & Mahmood, 2023).

The analysis further reveals that population migration significantly accelerates urban expansion, particularly in peri-urban and metropolitan regions. Migrants tend to concentrate in cities such as Karachi, Lahore, and Peshawar, leading to unplanned urban sprawl and the growth of informal settlements. This finding supports previous research indicating that migration acts as a critical link between environmental stress and urban spatial restructuring (Raza & Qureshi, 2024).

Additionally, the direct effect of climate change vulnerability on urban expansion indicates that environmental degradation influences land-use conversion even independently of migration processes. Overall, the results confirm that urban growth in Pakistan is not solely an economic phenomenon but is deeply embedded in climate-induced environmental pressures and human adaptation strategies.

Conclusion

This study concluded that climate change vulnerability plays a central role in shaping population migration and urban expansion patterns in Pakistan. The findings confirm that environmental stressors significantly drive rural-to-urban migration, which subsequently fuels rapid and often unplanned urban growth. GIS and Remote Sensing analysis further revealed that urban expansion is closely associated with land degradation, loss of vegetation, and increased exposure to climate risks.

The study concludes that Pakistan's urbanization process is strongly climate-sensitive and environmentally driven. Without integrated planning and climate adaptation strategies, urban expansion will continue to intensify environmental vulnerability and socio-economic inequality.

Implications

Theoretical Implications

This study extends Human–Environment Interaction Theory by empirically demonstrating how climate change vulnerability influences population mobility and urban spatial transformation. It highlights the dynamic feedback loop between environmental degradation and human settlement patterns, particularly in developing country contexts.

Practical Implications

The findings emphasize the need for integrating GIS and Remote Sensing tools into urban and environmental planning. Urban planners and environmental agencies can use spatial analytics to identify high-risk zones, monitor urban sprawl, and develop targeted interventions to reduce vulnerability.

Managerial Implications

Urban development authorities and disaster management institutions should incorporate climate vulnerability assessments into infrastructure planning. Effective management of migration flows and urban expansion requires data-driven decision-making supported by real-time spatial monitoring systems.

Policy Implications

Policymakers should prioritize climate-resilient urban development strategies, including controlled land use planning, enforcement of zoning regulations, and investment in climate adaptation infrastructure. Strengthening rural livelihoods can also reduce forced migration pressures on urban centers. These measures are essential for achieving SDG 11 (Sustainable Cities) and SDG 13 (Climate Action).

Recommendations

- Integrate GIS and Remote Sensing systems into national urban planning frameworks.
- Develop climate-resilient urban expansion policies with strict land-use zoning regulations.
- Strengthen rural development programs to reduce climate-induced migration pressures.
- Establish early warning systems for climate hazards using spatial analytics.
- Promote sustainable land management practices to prevent environmental degradation.
- Enhance coordination between environmental, urban planning, and disaster management agencies.
- Invest in satellite-based monitoring systems for continuous urban and environmental assessment.

Limitations and Future Directions

This study has several limitations. First, it relied on secondary satellite and spatial data, which may not fully capture socio-economic and behavioral dimensions of migration. Future research should incorporate primary household surveys to better understand migration decision-making processes.

Second, the study focused on selected urban centers of Pakistan, limiting the generalizability of findings across all regions. Future studies should include a broader geographic scope covering diverse ecological zones.

Third, the analysis primarily used descriptive and regression-based spatial methods. Future research could apply advanced machine learning models for more precise prediction of urban expansion and climate vulnerability.

Finally, future studies should explore the integration of real-time remote sensing data and artificial intelligence to develop dynamic climate risk monitoring systems for more proactive urban planning and disaster management.

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