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Geospatial Assessment of Urban Expansion and Green Infrastructure Dynamics for Sustainable Urban Planning in Kabul, Afghanistan

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Abstract

Rapid urbanization in conflict-affected cities often occurs with limited planning capacity and inadequate spatial information, creating challenges for sustainable urban management. This study assessed urban expansion and green infrastructure dynamics in Kabul, Afghanistan, between 2013 and 2023 using multi-temporal Landsat imagery and an integrated geospatial framework. Landsat data were processed through atmospheric correction, spectral index extraction, supervised Support Vector Machine (SVM) classification, and GIS-based change detection analysis. Vegetation dynamics were evaluated using the Normalized Difference Vegetation Index (NDVI), while urban expansion was characterized using the Normalized Difference Built-up Index (NDBI). Land use/land cover maps were generated for four classes, including built-up land, vegetation, bare land, and water bodies. Classification performance was assessed using confusion matrices, overall accuracy, and the Kappa coefficient. The results revealed substantial urban expansion, primarily concentrated in the northern, western, and southern sectors of Kabul. Although localized improvements in vegetation density were observed, urban growth exerted increasing pressure on surrounding open lands and green infrastructure. Overall classification accuracy improved from 92.02% in 2013 to 99.28% in 2023, demonstrating the reliability of the proposed methodology. The integrated geospatial framework provides a practical, transparent, and transferable decision-support tool for monitoring urban growth, prioritizing green infrastructure conservation, and supporting sustainable urban planning in rapidly growing cities with limited spatial information.

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1. Introduction

Urbanization is one of the most significant drivers of environmental and socio-economic transformation in the twenty-first century. According to global projections, the proportion of the world's population living in urban areas will continue to increase, with most future growth occurring in developing countries (United Nations Department of Economic and Social Affairs [UN DESA], 2025). Although urbanization can stimulate economic development and improve access to services, rapid and unplanned urban growth often creates substantial challenges for sustainable urban planning, particularly in cities where planning capacity, land governance, and infrastructure development are limited.

Accelerated urban expansion is frequently associated with extensive land-use conversion, increasing impervious surfaces, and degradation of natural environments. These processes may alter local hydrological and energy balances, intensify urban heat accumulation, increase flood susceptibility, deteriorate air quality, and reduce overall urban livability (Seto et al., 2012). In many developing cities, the pressure exerted by rapid urbanization often exceeds the capacity of urban infrastructure systems, making evidence-based planning essential for achieving sustainable urban development.

In recent years, green infrastructure has emerged as a fundamental component of sustainable urban planning. Green infrastructure refers to interconnected networks of natural and semi-natural areas, including urban parks, gardens, street trees, riparian corridors, and other vegetated spaces that provide multiple ecological, environmental, and social benefits. Besides supporting biodiversity and ecosystem functions, urban green spaces contribute to temperature regulation, carbon sequestration, stormwater management, and improved urban resilience (Wolch et al., 2014). Consequently, preserving and enhancing urban green infrastructure has become an important priority for urban managers and decision-makers worldwide (Mirzade et al., 2023).

Sustainable urban planning requires a comprehensive understanding of the interactions between urban expansion and green infrastructure dynamics. As urban areas expand, the distribution, fragmentation, and quality of vegetated spaces often change considerably. Understanding these processes is particularly important in cities experiencing rapid population growth, informal settlements, and limited institutional planning capacity. Conventional field-based monitoring approaches are often expensive, time-consuming, and difficult to implement at large spatial scales. Therefore, reliable and repeatable monitoring systems are needed to provide long-term and spatially explicit information that can support evidence-based planning and urban management.

Kabul, the capital city of Afghanistan, represents a prominent example of these challenges. During recent decades, Kabul has undergone substantial demographic growth, conflict-induced migration, and rapid urban expansion, resulting in extensive land-use transformations and increasing pressure on urban infrastructure and environmental resources (World Bank, n.d.). Much of this expansion has occurred in an unplanned manner, leading to competition between built-up areas and green spaces and increasing the vulnerability of the urban environment. Consequently, decision-makers require robust analytical tools to identify urban growth corridors, monitor green infrastructure changes, and prioritize sustainable development interventions.

Geospatial technologies, particularly remote sensing and Geographic Information Systems (GIS), have become powerful tools for addressing these challenges. These technologies enable continuous monitoring of urban dynamics over large spatial extents and long temporal periods while minimizing the need for extensive field surveys. More importantly, geospatial technologies can function as practical decision-support tools that provide objective and consistent information for evidence-based urban planning and urban management.

Among the available Earth observation datasets, the Landsat program has become one of the most widely used resources for long-term urban studies due to its global coverage, multi-decadal archive, and freely accessible standardized products (USGS, 2021). Recent improvements in radiometric calibration and the introduction of Landsat Collection 2 products have further enhanced the consistency and reliability of multi-temporal analyses (USGS, 2021). Consequently, Landsat imagery has become an effective data source for monitoring urban growth and environmental changes, particularly in data-constrained regions.

Several geospatial approaches have been developed to characterize urban expansion and vegetation dynamics. Spectral indices are among the most commonly used methods because they provide simple and interpretable representations of land surface conditions. The Normalized Difference Vegetation Index (NDVI) has long been used to assess vegetation presence, density, and vigor (Rouse et al., 1974; Pordel et al., 2017;), whereas the Normalized Difference Built-up Index (NDBI) has proven effective for identifying built-up surfaces and urban development patterns in medium-resolution imagery (Zha et al., 2003). Although these indices may present limitations in arid and semi-arid environments due to spectral similarities between bare soil and urban areas, they remain transparent and reproducible indicators when integrated with appropriate classification procedures.

Machine-learning approaches have also become increasingly important for land-use and land-cover (LULC) mapping because they can effectively capture complex and nonlinear relationships within heterogeneous urban environments. Among these methods, Support Vector Machine (SVM) has demonstrated robust performance in remote sensing applications owing to its ability to handle high-dimensional datasets and achieve reliable classification results using limited training samples (Cortes & Vapnik, 1995; Habibi Razi et al, 2026). The integration of spectral indices, machine-learning algorithms, and GIS-based change detection therefore provides a comprehensive geospatial framework for evaluating urban expansion and green infrastructure dynamics.

Despite the growing number of urban remote sensing studies, several challenges remain. Existing studies often address individual components of urban systems separately, such as land-use change, vegetation dynamics, or thermal environments, without integrating them into a unified framework that directly supports urban planning decisions. Furthermore, methodological differences in preprocessing procedures, classification strategies, and temporal coverage frequently limit the comparability and practical applicability of previous findings.

According to studies conducted by Ghaderi et al. (2023), using satellite images and vegetation and soil salinity indices, they obtained a vegetation and soil salinity map of the study area to classify the soil with classification algorithms. Alemi Safaval et al. (2026) extracted LST of the study area in order to investigate land use changes caused by human activities using Landsat satellite images and NDVI index algorithms, brightness temperature and using thermal bands. These temperature changes have been strongly related to the reduction of vegetation and the expansion of impervious surfaces due to the increase in demand for housing, trade and tourism in the free zone.

Therefore, there is a need for a transparent, transferable, and repeatable geospatial framework that can serve as a decision-support tool for sustainable urban planning, urban resilience assessment, and urban management in rapidly growing cities with limited spatial information. Such a framework should simultaneously quantify urban expansion and characterize changes in green infrastructure to generate actionable information for urban planners and policymakers.

Accordingly, this study develops a geospatial assessment framework to evaluate urban expansion and green infrastructure dynamics in Kabul, Afghanistan, using multi-temporal Landsat imagery, spectral indices, Support Vector Machine classification, and GIS-based change detection. Specifically, the objectives of this study are to: (1) quantify and map the spatial expansion of built-up areas between 2013 and 2023; (2) characterize the spatial patterns of vegetation dynamics; and (3) provide evidence-based information that can support sustainable urban planning, green infrastructure management, urban resilience, and urban decision-making in Kabul. The proposed framework offers a practical and transferable approach that can be readily applied to other rapidly growing cities facing similar environmental and planning challenges.

2. Materials and Methods

2.1. Study Area

This study was conducted in Kabul, the capital city of Afghanistan, located in the central part of the country (Figure 1). Kabul has experienced rapid population growth, conflict-induced migration, and extensive urban expansion during recent decades, resulting in substantial changes in land use patterns and increasing pressure on urban infrastructure and environmental resources.

The urban landscape of Kabul consists of densely built-up areas, bare lands, scattered vegetation, and limited water bodies. Rapid urbanization combined with insufficient planning capacity has intensified the need for evidence-based urban management strategies. Therefore, Kabul represents an appropriate case study for evaluating urban expansion and green infrastructure dynamics using geospatial technologies.

2.2. Satellite Data Acquisition and Pre-processing

Multi-temporal Landsat imagery was utilized to evaluate urban expansion and green infrastructure dynamics between 2013 and 2023. Satellite images were acquired from the United States Geological Survey (USGS) EarthExplorer archive and processed using ENVI and ArcGIS software environments. A standardized preprocessing workflow was implemented to ensure spectral consistency and comparability between study periods.

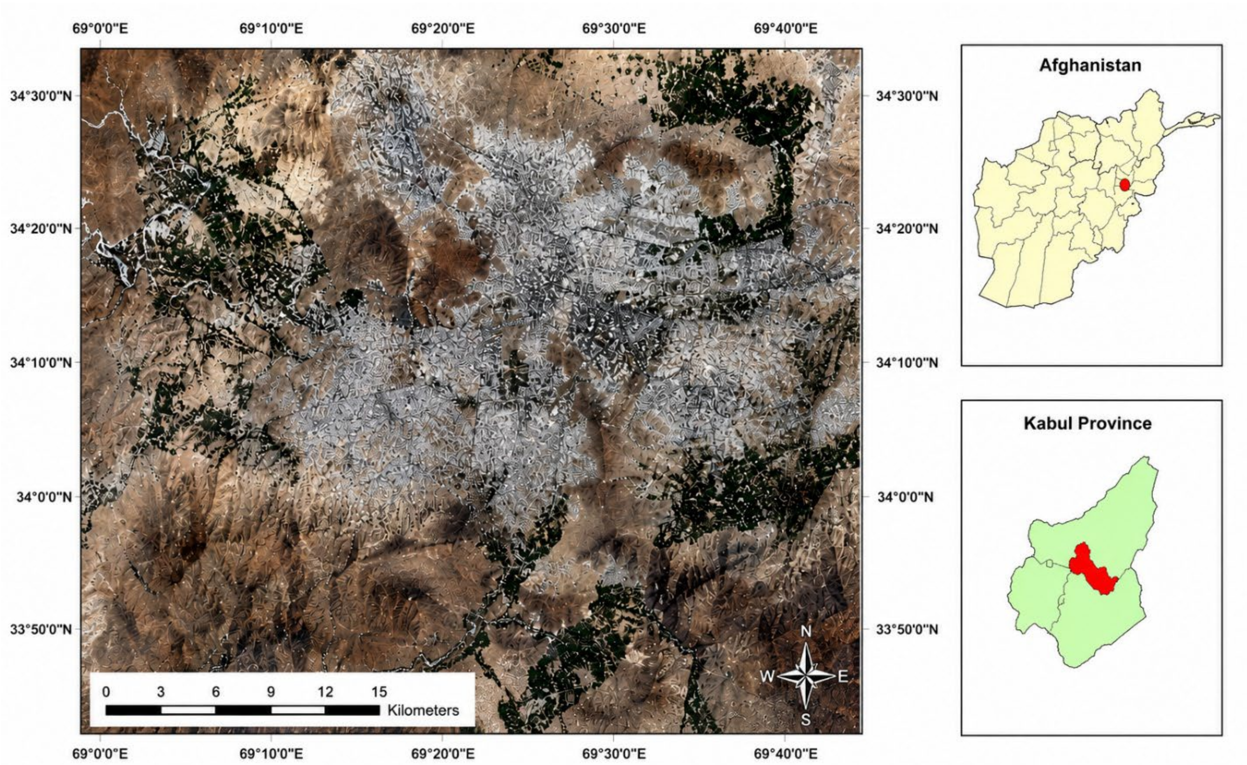


Figure 1. Study area and geographical location of Kabul

The preprocessing procedure consisted of the following steps:

1. Geometric verification: Landsat Collection 2 Level-2 products were already geometrically corrected; therefore, no additional geometric correction was required.
2. Radiometric calibration: Digital numbers were converted into physically meaningful surface reflectance values using the calibration parameters provided by USGS.

3. Atmospheric correction: Atmospheric effects were minimized using the Quick Atmospheric Correction (QUAC) algorithm to improve inter-temporal comparability.
4. Image subsetting: Images were clipped according to the Kabul administrative boundary.
5. Image visualization: True-color (4-3-2) and false-color (5-4-3) composites were generated to facilitate visual interpretation and training sample selection.

The standardized preprocessing workflow established a consistent geospatial database suitable for long-term urban growth assessment.

2.3. Spectral Analysis of Green Infrastructure and Built-up Areas

Spectral indices were used to characterize vegetation dynamics and built-up development patterns across the study area.

The Normalized Difference Vegetation Index (NDVI) was employed to evaluate vegetation presence and density (Rouse et al., 1974). NDVI has been extensively used as a reliable indicator for assessing vegetation conditions in urban environments and supports the identification of green infrastructure distribution.

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

Built-up development was evaluated using a built-up index referred to as NDBI within the study workflow. This indicator was used to identify urbanized areas and characterize the spatial expansion of impervious surfaces. The implemented formula used in this study should be explicitly reported to ensure methodological transparency.

The integration of spectral indices enabled simultaneous assessment of urban expansion and green infrastructure dynamics, supporting evidence-based urban management.

$$NDBI = \frac{SWIR - NIR}{SWIR + NIR}$$

2.4. Land Use and Land Cover Classification

Land use and land cover (LULC) maps were generated using a supervised classification approach based on the Support Vector Machine (SVM) algorithm.

SVM is a robust machine-learning algorithm that has been widely applied in remote sensing studies due to its ability to classify complex and heterogeneous landscapes while requiring relatively limited training samples (Cortes & Vapnik, 1995).

The Landsat images were classified into four major classes:

- Built-up (urban) land
- Vegetation
- Bare land

Water bodies

Training samples were selected through visual interpretation of multi-band imagery and supported by Google Earth imagery. Particular attention was given to representing the spectral variability within each class to minimize classification uncertainty.

The resulting classification maps were subsequently used to evaluate urban growth patterns and green infrastructure changes.

2.5. Accuracy Assessment

Classification performance was evaluated using a confusion matrix approach by comparing classified pixels with reference data. Two standard accuracy metrics were employed:

Overall Accuracy (OA): The proportion of correctly classified samples relative to the total number of reference samples.

Kappa Coefficient: A statistical measure that quantifies the agreement between classified and reference data while accounting for chance agreement (Congalton, 1991).

Accuracy assessment provides a quantitative evaluation of map reliability and ensures the suitability of the generated LULC maps for subsequent urban growth analyses.

2.6. Urban Growth and Change Detection Analysis

Urban expansion and land-use transitions were quantified using a post-classification comparison approach. This method compares classified maps from different years to identify spatial changes and determine transitions among land-cover classes.

The generated transition information was used to identify urban growth corridors, evaluate vegetation changes, and assess the interactions between built-up areas and green infrastructure.

The resulting geospatial information provides a practical decision-support framework for sustainable urban planning by identifying areas experiencing rapid urbanization and areas requiring green infrastructure conservation.

The proposed workflow offers a transparent and transferable methodology that can be readily applied in other rapidly growing cities facing similar urban management challenges.

3. Results

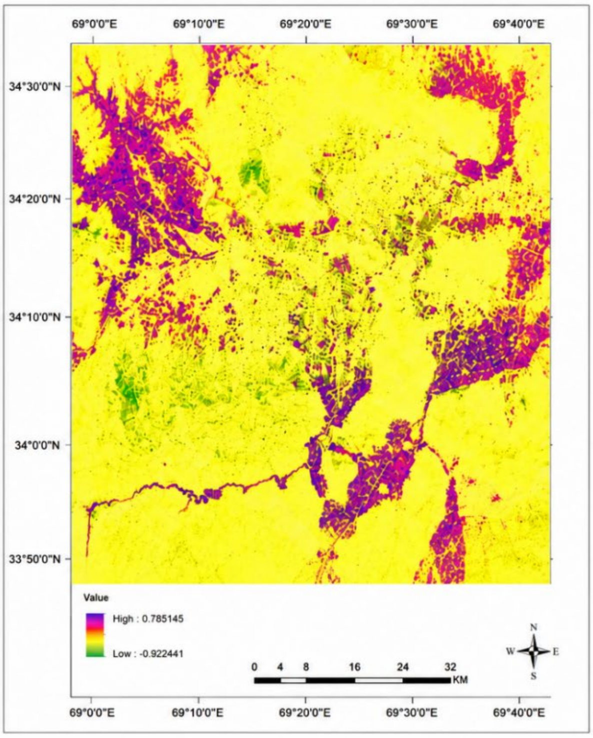
3.1. Spatial Patterns of Green Infrastructure Dynamics

Vegetation dynamics exhibited considerable spatial heterogeneity between 2013 and 2023. The NDVI maps (Figures 2 and 3) indicate that although Kabul experienced substantial urban growth during the study period, localized improvements in vegetation density were also observed.

NDVI values were categorized into five classes representing water or non-vegetated surfaces, bare soil, low-density vegetation, moderate vegetation, and high-density vegetation. The extent of high-density vegetation increased from 10,800 m² in 2013 to 1,002,180 m² in 2023, indicating that vegetation enhancement occurred in selected areas despite ongoing urbanization.

However, these improvements were unevenly distributed across the city and were concentrated in specific districts. This spatial heterogeneity suggests that urban expansion and green infrastructure development occurred simultaneously rather than as mutually exclusive processes.

The NDVI maps presented in Figures 2 and 3 provide spatially explicit information that can assist in identifying priority areas for vegetation preservation and future greening interventions. These findings can directly support green infrastructure conservation and evidence-based urban management.



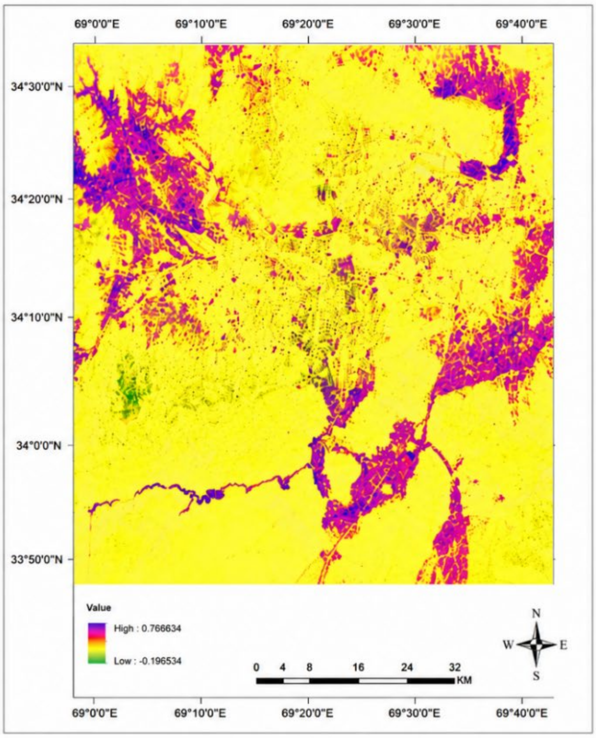


Figure 2. NDVI map 2013 **Figure 3. NDVI map 2023**

3.2. Spatial Assessment of Urban Expansion

Urban development increased substantially between 2013 and 2023, with expansion predominantly occurring toward the northern, western, and southern sectors of Kabul. The spatial patterns derived from NDBI analysis are illustrated in Figures 4 and 5.

The results indicate a clear outward expansion of the urban footprint accompanied by increasing encroachment into surrounding open lands. Additional urban growth was also detected in eastern districts, suggesting multi-directional expansion across the metropolitan area.

The identified urban growth corridors represent zones that may experience increasing pressure on transportation systems, public services, and future infrastructure provision. Consequently, these areas should be considered priority zones for land-use regulation and infrastructure development.

Overall, the NDBI analysis provides a spatial basis for identifying future development corridors and can support sustainable urban planning and infrastructure investment prioritization.

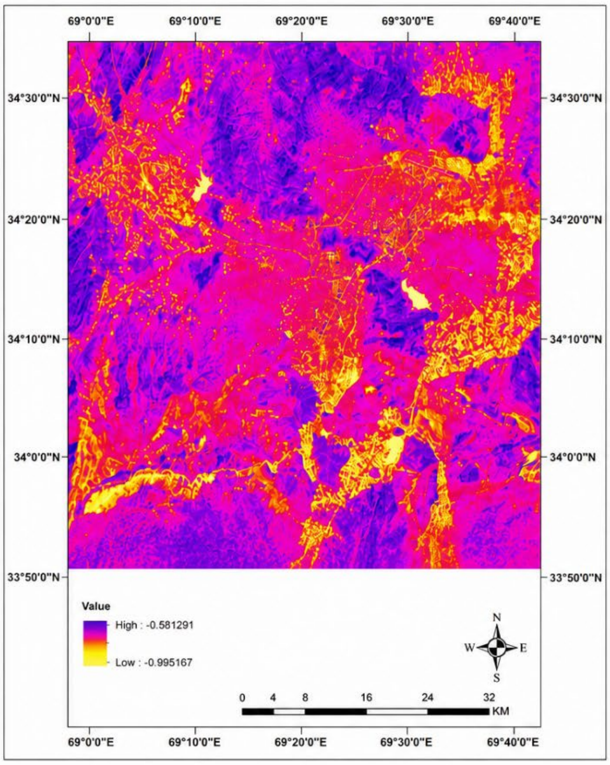


Figure 4. NDBI map 2013

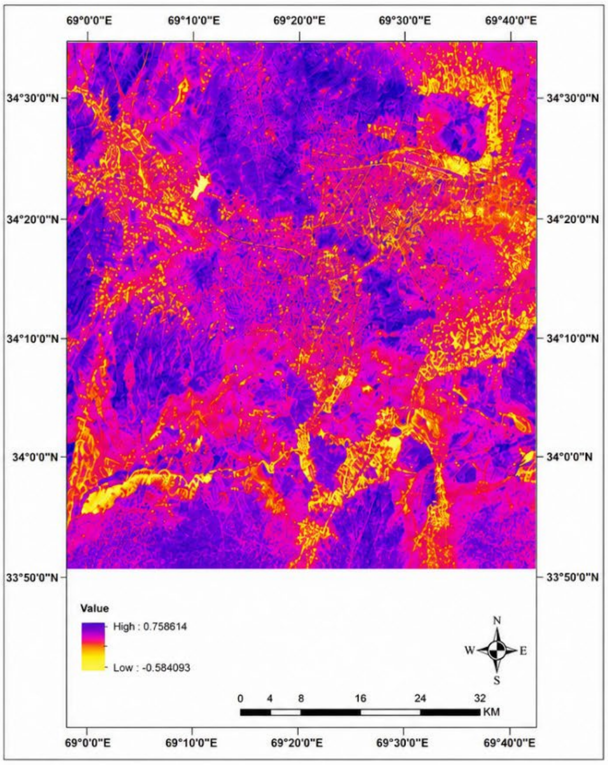


Figure 5. NDBI map 2023

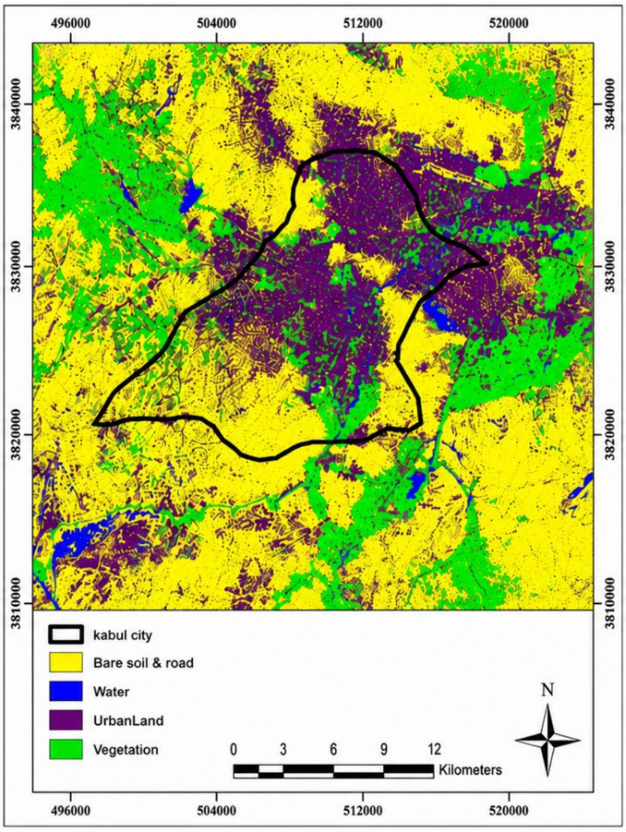
3.3. Land Use and Land Cover Mapping

The SVM classifier successfully generated land use and land cover maps for both study years (Figures 6 and 7). Four major classes were identified, including built-up land, vegetation, bare land, and water bodies.

The classified maps reveal substantial urban transformation during the study period. Built-up areas expanded considerably, while portions of bare land and vegetated areas were converted into urban land. Water bodies occupied only a limited proportion of the study area throughout both years.

The spatial patterns obtained from the classification outputs are consistent with the NDVI and NDBI analyses, confirming the reliability of the integrated geospatial assessment framework.

The resulting maps establish a spatial baseline for future monitoring activities and can function as a decision-support tool for sustainable urban planning and long-term urban management strategies.



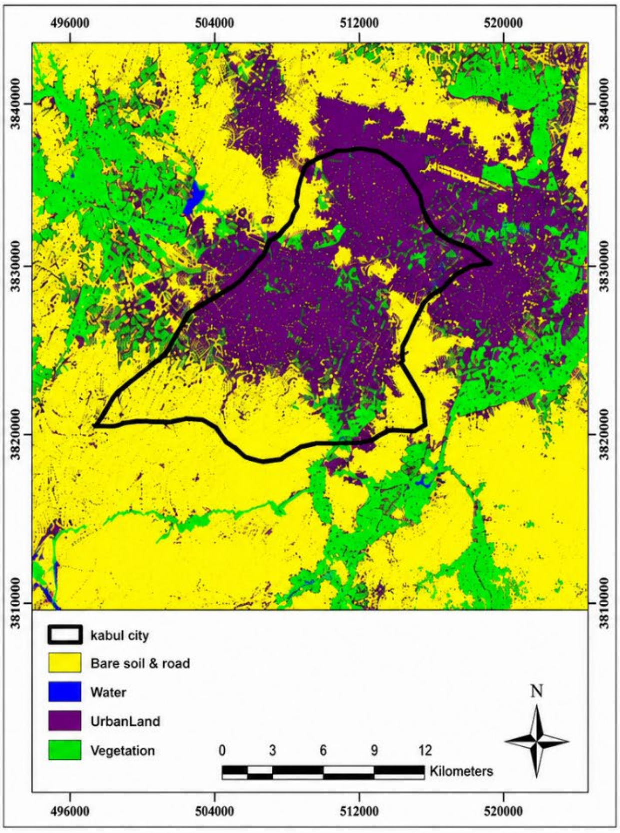


Figure 6. LULC classification map of Kabul in 2013

Figure 7. LULC classification map of Kabul in 2023

3.4. Classification Accuracy Assessment

The classification outputs demonstrated high levels of agreement with the reference data (Tables 1 and 2). For 2013, the overall classification accuracy reached 92.02%, with a Kappa coefficient of 88.31%. For 2023, overall accuracy increased to 99.28%, while the Kappa coefficient reached 98.93%.

The improvement in classification performance in 2023 may be attributed to enhanced image quality and improved spectral separability among land-cover classes.

These results indicate that the generated land-use maps provide a reliable basis for evaluating urban growth and green infrastructure dynamics. Furthermore, the high classification accuracies demonstrate that the proposed geospatial framework can serve as a robust decision-support tool for evidence-based urban management.

3.5. Land Use Transitions and Urban Growth Dynamics

The post-classification comparison revealed substantial land-use transitions between 2013 and 2023 (Table 1). The results indicate considerable interactions among urban, vegetated, and bare land classes during the study period.

Table 1. Land-use transition matrix between 2013 and 2023 (%)

2013 / 2023	Bare land	Vegetation	Urban land	Water	Total (%)
Bare land	80.35	2.47	16.12	1.06	100
Vegetation	6.91	69.04	23.08	0.97	100
Urban land	4.27	10.31	83.96	1.46	100
Water	12.84	3.52	8.16	75.48	100

Approximately 69.04% of vegetated areas remained unchanged, whereas 23.08% were converted into urban land. Similarly, 16.12% of bare land transitioned into urban areas. In contrast, 83.96% of existing urban areas remained stable over time, indicating strong persistence of urban land use.

The spatial distribution of these transitions confirms that the northern, western, and southern sectors of Kabul constitute the primary urban growth corridors.

These findings demonstrate that urban expansion is not only spatially extensive but also structurally transformative, with direct implications for future land-use allocation and environmental sustainability. Therefore, the transition analysis can support sustainable urban planning, green infrastructure conservation, and future infrastructure investment decisions.

4. Discussion

The findings of this study reveal substantial urban expansion in Kabul between 2013 and 2023, with development primarily concentrated in the northern, western, and southern sectors of the city. These results are consistent with previous studies that reported rapid urbanization and extensive land-use transformation in Kabul during recent decades (Hekmat et al., 2023; Ahmadi et al., 2023). The observed spatial patterns indicate that urban growth is occurring through horizontal expansion, increasing pressure on surrounding open lands and green infrastructure. Such expansion patterns highlight the urgent need for evidence-based planning strategies that can balance urban development with environmental sustainability.

Rapid urbanization is a common characteristic of many developing cities where population growth often exceeds the capacity of urban planning systems and infrastructure provision. Similar trends have been observed globally, where unregulated urban growth leads to land-cover transformation, environmental degradation, and increasing demands on urban infrastructure systems (Seto et al., 2012). The identified urban growth corridors in Kabul therefore represent areas that may experience increasing future demands for transportation networks, public services, and infrastructure investments. Similar studies have also shown that integrating urban growth assessment into planning scenarios can support long-term conservation strategies and improve urban management decisions (Ashjaee et al., 2025).

The results also demonstrate that urban expansion and vegetation dynamics are closely interconnected processes. Although urban growth intensified during the study period, localized increases in vegetation density were observed in some parts of the city. This finding suggests that urban development and green infrastructure improvement can occur simultaneously when appropriate management interventions are implemented. However, the uneven distribution of vegetation gains indicates that these improvements are insufficient to compensate for the broader pressure exerted by rapid urbanization. Therefore, preserving existing green infrastructure should be considered a fundamental component of future urban development policies.

From an urban planning perspective, maintaining green infrastructure is becoming increasingly important for supporting urban resilience and improving environmental quality. Urban green spaces contribute to more sustainable urban environments and should be strategically integrated into long-term development plans (Wolch et al., 2014). Consequently, future development policies should prioritize the protection of vegetated areas located within urban expansion corridors and promote the creation of interconnected green networks.

The identified growth patterns have several practical implications for urban management. First, urban growth corridors should be considered priority zones for future infrastructure investments. Second, land-use regulations should be strengthened to minimize uncontrolled expansion into environmentally sensitive areas. Third, urban greening initiatives should be incorporated into future development plans, particularly in rapidly expanding districts. Similar GIS-based studies have highlighted the importance of identifying both opportunities and constraints associated with physical urban expansion to support future urban development planning (Safari et al., 2021;).

One of the main contributions of this study is the integration of multiple geospatial techniques into a unified framework that can support evidence-based urban planning. Rather than assessing urban expansion or vegetation dynamics independently, the proposed approach simultaneously evaluates both components and translates the results into actionable information for urban managers and decision-makers. The generated spatial information can assist in identifying future development corridors, prioritizing green infrastructure conservation, and supporting long-term urban management strategies. Integrating geospatial information into decision-support systems has been identified as a key component for enhancing land-use planning and sustainable urban development (Faraji et al., 2023).

Another advantage of the proposed framework is its operational simplicity. Because the methodology relies on freely available satellite imagery and widely accessible geospatial tools, it can be implemented in cities with limited financial and technical resources. This is particularly important for developing countries where urban growth often occurs faster than the establishment of comprehensive monitoring systems. Consequently, the proposed framework offers a practical and transferable solution that can be adapted to other rapidly urbanizing cities facing similar environmental and planning challenges.

Several limitations should nevertheless be acknowledged. First, the analysis was performed using two observation years, which may not fully capture intermediate urban development dynamics. Second, medium-resolution Landsat imagery may introduce uncertainty when delineating small urban features and fragmented green spaces. Third, this study focused primarily on physical land-cover changes and did not explicitly incorporate socio-economic variables, transportation networks, demographic characteristics, or urban infrastructure indicators. Integrating such datasets could provide a more comprehensive understanding of urban growth processes and strengthen future planning recommendations.

Despite these limitations, the proposed geospatial framework provides a transparent, transferable, and practical decision-support tool for sustainable urban planning. The resulting maps and spatial indicators can support infrastructure investment prioritization, green infrastructure conservation, and evidence-based urban management. Continuous monitoring of urban growth patterns will be essential for balancing future development with environmental sustainability and improving urban resilience in Kabul and other rapidly growing cities facing similar challenges.

5. Conclusion

This study presented an integrated geospatial framework for assessing urban expansion and green infrastructure dynamics in Kabul, Afghanistan, between 2013 and 2023 using multi-temporal Landsat imagery, spectral indices, Support Vector Machine (SVM) classification, and GIS-based change detection analysis. The results revealed substantial urban growth, particularly in the northern, western, and southern sectors of the city, accompanied by increasing pressure on surrounding open lands and vegetated areas. Although localized improvements in vegetation density were observed, urban expansion remained the dominant spatial process throughout the study period. The high classification accuracies obtained for both years (92.02% in 2013 and 99.28% in 2023) demonstrate the reliability and robustness of the proposed methodology for long-term urban monitoring. Beyond quantifying land-cover changes, this study provides a unified analytical framework that simultaneously evaluates urban growth and green infrastructure dynamics and translates them into actionable information for planners and decision-makers. The use of freely available Landsat imagery and accessible geospatial tools also makes the proposed approach transferable to other rapidly growing cities with limited financial and technical resources. The findings emphasize the necessity of integrating green infrastructure conservation into future urban development strategies and prioritizing urban growth corridors for infrastructure investments and land-use regulation. Overall, the proposed framework offers a practical, transparent, and scalable decision-support tool that can contribute to evidence-based urban management, urban resilience, and sustainable urban planning in Kabul and other developing cities facing similar urbanization challenges.

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