Advanced Land Management
https://publish.mersin.edu.tr/index.php/alm
e-ISSN 2822-7050

Land use/land cover change detection and prediction for sustainable urban land management in Kigali City, Rwanda

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Cite this study: Gilbert, K. M., & Shi, Y. (2023). Land use/land cover change detection and prediction for sustainable urban land management in Kigali City, Rwanda. Advanced Land Management, 3 (2), 62-75

Keywords
Built-up areas
Remote sensing
GIS-based planning
Land cover changes
Urban land management

Research Article
Received:15.06.2023
Revised: 27.08.2023
Accepted: 20.09.2023
Published: 29.09.2023

Abstract

Rapid urbanization and population growth have significantly transformed land use and land cover (LULC) in cities worldwide, including Kigali City. This research aims to analyze the changes in urban population growth from 2002 to 2022, to measure LULC changes in Kigali over twenty years from 2003 to 2023, and projections for 2033, and to find the correlation between population growth and LULC changes in Kigali. The study employs remote sensing imagery and supervised classification, an accurate GIS-based technique to assess the change in built-up and non-built-up. In the preprocessing stage for correcting image stripes in Landsat7, the Fill Nodata tool, a spatial analyst tool, was utilized. The results show that the population of Kigali City has grown significantly over the past two decades, with an increase from 608,141 in 2002 to 1,132,686 in 2012 and 1,745,555 in 2022. As a result of urbanization, there have been changes in land use. In 2003, built-up areas covered 48.59 km^2, while non-built-up areas were 681.41 km^2. By 2013, built-up areas expanded to 85.24 km^2 and by 2023, it reached 238.07 km^2. On the other hand, non-built-up areas decreased to 596.17 km^2 in 2013 and further to 491.93 km^2 in 2023. Projections for 2033 suggest that built-up areas will cover 265.06 km^2, while non-built-up areas will decrease to 464.94 km^2. Therefore, the corresponding decline in non-built-up areas indicates the conversion of natural landscapes and the challenges arising from urban sprawl. These transformations underscore the need for proactive urban management and strategic planning to effectively control expansion and mitigate the consequences of uncontrolled growth. When considering the future in 2033, the anticipated data indicates that urban growth will continue, with an upward trend in built-up areas and a corresponding downward trend in non-built-up areas. It is recommended that to manage the influence of urban growth in Kigali on land cover change, planners should develop policies for compact and mixed-use areas, clear boundaries for growth, and preservation of green spaces. Comprehensive land use planning and zoning regulations are necessary for sustainable urbanization that balances development, environment, and socio-economic well-being.

1. Introduction

At present, people in cities that have developed, as well as those that are still in the process of developing, have a close connection to the land because the land provides the physical space for human settlement, infrastructure, and economic activities [1–3]. Land provides the basis for housing, places of employment, and public spaces, influencing the overall quality of life [4] and social interactions in urban areas [5–7]. The availability and accessibility of land in cities directly influence the affordability of housing, access to services, and overall well-being of urban residents. This highlights the crucial interaction between people and land in urban contexts.

Because so many activities relating to the economy [6,7], society, and the environment take place on land, the component of sustainable development is very important [8]. One definition of sustainable land use is to make the most of a piece of land's resources while doing the least damage possible to the surrounding environment, the community, and the people of the future [9]. It involves applying measures that are beneficial to the preservation of land, the protection of biodiversity, the efficient management of resources, and the guaranteeing of fair access to land for all people [9,10]. Societies can strike a balance between economic expansion, improvements in social conditions, and preserving the natural environment if they use sustainable land use policies such as land zoning, agriculture conservation, and urban planning [11–13]. This ensures that ecosystems and communities will continue to exist for a long time and can adapt to any changes.

Several authors have pointed out that contemporary cities are facing a multitude of environmental difficulties, some of which include noise, water, and air pollution [3,6,7], the loss of biodiversity [5,14], and the usage of resources that are not sustainable [5]. Cities have a variety of tools at their disposal that they can use to accomplish the SDGs (Sustainable Development Goals) in the context of land management sustainability [8]. To begin, promoting urban greening projects [15], like establishing parks, green spaces, and urban forests, can improve air quality, increase biodiversity, and create opportunities for recreational activities [11,13]. Second, implementing environmentally friendly transportation systems that precede public transport, walking, and cycling can help reduce CO^2 emissions, improve mobility, and diminish the impact of congestion [3,10]. In addition, implementing environmentally friendly building methods and promoting energy efficiency [16,17] in urban infrastructure can help reduce negative environmental impacts and contribute to the transition toward low-carbon cities. Engaging communities through education [18] and awareness initiatives, encouraging citizen engagement [19], and integrating sustainable land management concepts into urban planning and policy are all critical components for achieving SDGs and maintaining the environment and ecology in urban areas.

The rapid increase in urban expansion in cities [1,20,21] like Kigali [3,10] is primarily influenced by population growth and population migration [22]. This phenomenon significantly impacts non-built-up areas [20,23,24], as natural and undeveloped land faces increasing pressure. The areas that change from non-built-up to built-up areas to meet the growing demand for housing [5], infrastructure, and economic activities, have disadvantageous effects, including land degradation, habitat fragmentation, and biodiversity loss [20]. These challenges necessitate adopting urban planning and land management strategies prioritizing smart growth, compact development [16], and preserving green spaces to balance urban expansion and conserving non-built-up areas [5]. Moreover, implementing effective land use policies, promoting sustainable urban design, and fostering public participation can mitigate the negative influences of urban expansion on non-built-up land.

Detecting and predicting LULC changes are recently found to be important tools for achieving sustainable development [21,23,25–33], particularly in urban areas such as Kigali. It is possible to examine the dynamic transformations in the city's land use patterns by applying advanced remote sensing techniques, such as satellite imaging and GIS analysis [22]. This can contribute to developing effective urban planning and sustainable land management practices. Remote sensing and GIS are helpful techniques for detecting and monitoring changes built-up over multiple years [29,30,34]. This allows for identifying patterns, drivers, and potential future situations [24,26,29–39]. In the context of Kigali and other cities, remote sensing makes it easier to detect urban expansion, built-up growth, and land-use changes [40–42]. This facilitates informed decision-making, land governance, and policies that respect sustainable land management principles, human rights, and environmental protection. It makes it possible to anticipate the requirements of future generations by anticipating and planning for sustainable urban expansion, ensuring that land resources are utilized effectively and the atmosphere is safeguarded for the needs of current and upcoming people.

The leading objective of the study is to conduct a comprehensive analysis of LULC change in Kigali City from 2003 to 2023. The analysis will draw upon evidence-based data and incorporate insights from multiple academic disciplines, fostering a holistic understanding of the subject. Furthermore, particular attention will be given to the projected changes in LULC, specifically within the built-up areas, from 2023 to 2033. It is anticipated that these alterations will have negative implications for the residents of Kigali, necessitating careful consideration and proactive measures to mitigate adverse effects.

2. Material and Method

The following diagram design (Figure 1) encompasses a comprehensive analysis of LULC changes in Kigali. The investigation incorporates qualitative and quantitative methods to examine these changes' spatial patterns, causes, and consequences. Three Landsat satellite images from 2003, 2013, and 2023 were downloaded from the USGS (United States Geological Survey) website, focusing on the built-up areas. Spatial locational data for the wetland and Kigali City boundary were sourced from reliable platforms. The analysis utilized spatially referenced techniques and involved interpreting and comparing LULC maps. Additionally, the study explores the anticipated alterations in LULC in the built-up areas from 2023 to 2033. The findings are interpreted within the context of the research objectives and aligned with sustainable land management principles.

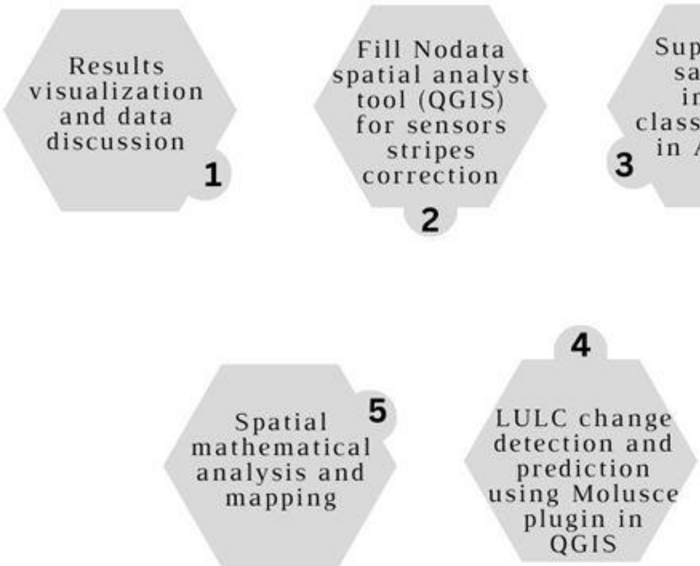

Figure 1. The flow chart design.

The research design employed in the study provides a comprehensive framework to assess the dynamics of LULC changes in Kigali City and their implications for sustainable development.

2.1. Study Area

Kigali, the capital city of Rwanda, is located in East Africa at latitude -1° 56' 22.79" S and longitude 30° 03' 20.40" E. As shown in Figure 2, it serves as the focal point of this study, representing a vibrant and rapidly developing urban center. For crediting the "2023 World Imagery base map" used in ArcGIS 10.8.2 for mapping the Figure 2, the source is Esri, Maxar, Earthstar Geographics, and the GIS User Community.

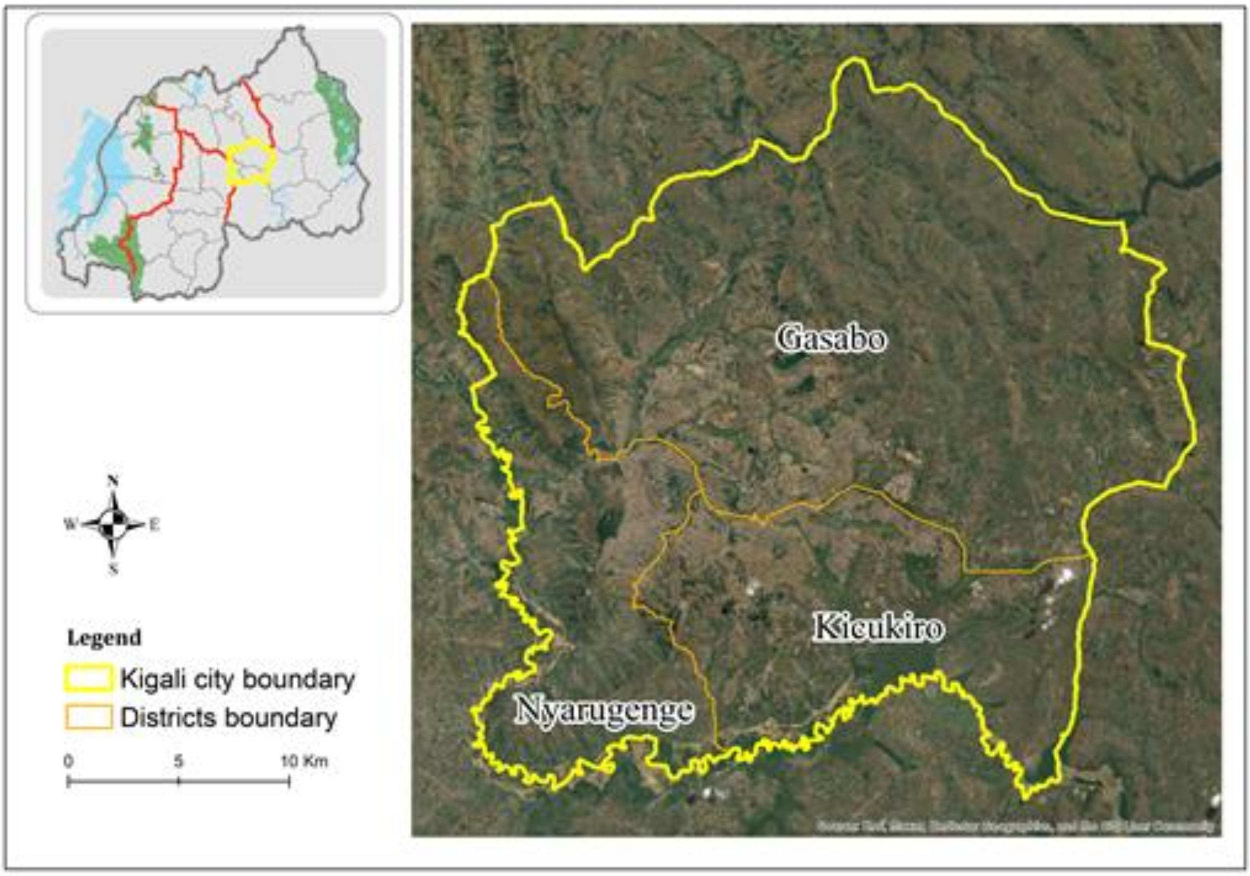

Figure 2. Location map of the study area.

The city, located within the embrace of undulating hills, offers pretty landscapes with 730km^2 [10] and is well-known as Rwanda's capital and largest city. Kigali thrives as a bustling hub of economic, political, and cultural activities, showcasing a harmonious blend of modern infrastructure, historical landmarks, and lush green spaces.

The city's population has experienced remarkable growth, surging from 358,200 in 1996 [41], 608,141 in 2002, 1,32,686 in 2012, and 1,745,555 in 2022 [43], consequential of 2,401 individuals per km^2 (Figure 3).

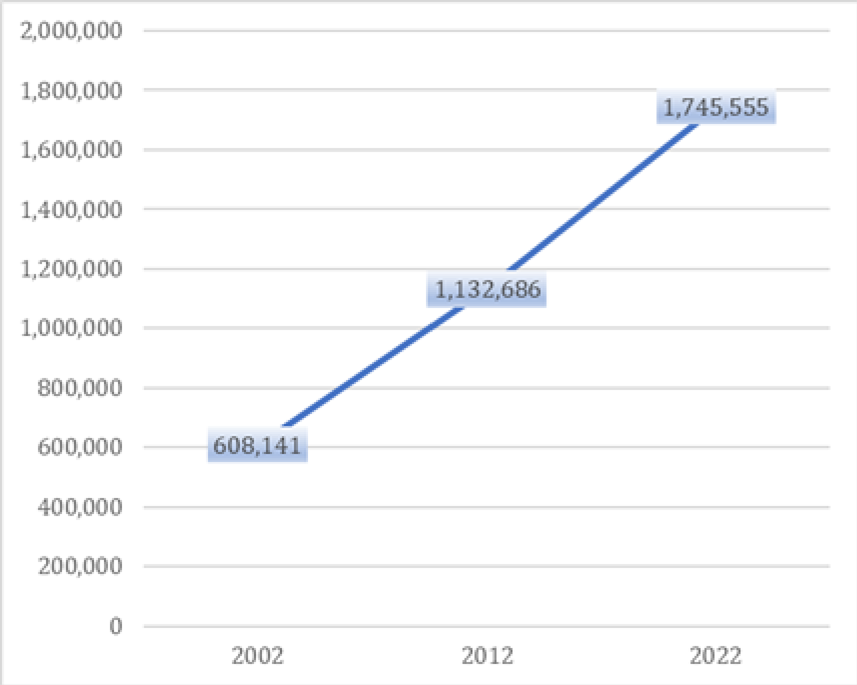

Figure 3. Population growth 2002-2022.

Kigali has three districts, "Nyarugenge, Kicukiro, and Gasabo", which comprise 35 sectors, 161 cells, and 1,061 villages [41]. With the ongoing urbanization challenges, such as increased housing demand, infrastructure development, and land use changes, understanding the dynamics of LULC in Kigali becomes crucial for operative urban planning and sustainable urban land management.

2.2. Data Description

Three Landsat images were obtained from the USGS to examine changes in LULC in Kigali City. The dataset consisted of Landsat 7 images captured in 2003 and 2013 and a Landsat 8 image from 2023 (Table 1). These images shared a consistent grid cell size of 30 meters and were acquired using the same World Reference System (WRS) path/row combination of 172/161. The projection of spatial reference was established using UTM 36.

Table 1. Landsat data from 2003 to 2023.

Landsat name	Pixel	Bands	Path/Row	Date
LE07_L1TP_172061_20030817_20200916_02_T1	30 m	8	172/161	26/12/2003
LC08_L1TP_172061_20130722_20200912_02_T1	30 m	11	172/161	02/07/2013
LC08_L1TP_172061_20230123_20230207_02_T1	30 m	11	172/161	23/01/2023

To enhance the analysis, supplementary spatial locational data for Kigali City were sourced from reliable platforms like the Rwanda Spatial Data Hub and DIVA-GIS. The resulting analysis outcomes were then interpreted and discussed within the framework of the research objectives. To illustrate the methodology employed, a workflow chart was created, presenting a visual representation of the sequential steps undertaken during the analysis.

2.3. LULC classification and prediction method

Image preprocessing for the Landsat 7 image sensor stripes was corrected using the "Fill Nodata" tool in QGIS for Raster analysis. We corrected the satellite image bands one by one and utilized the "fill no-data" function to correct and fill the missing gaps. This was achieved through the interpolation of values from other pixels. Then, the process of LULC using supervised classification involved image preprocessing through radiometric and atmospheric correction using ArcGIS 10.8.2 software. The images were then classified into two categories, built-up and non-built-up, for 2003, 2013, and 2023. A standard color combination was implemented, and approximately 45 training samples were used for the classification. For LULC change detection and predicting the 2030 LULC distribution, the MOLUSCE plugin tool in the QGIS software was used. This tool is recognized as one of the best prediction models. The LULC maps of 2013 and 2023 were used to simulate the 2033 LULC. Finally, before prediction analysis, a standardization approach was applied to convert all images to a 30 m x 30 m spatial resolution. Finally, this method was used for calculating LULC transitions between different years.

2.4. Correlation between urban population growth and changes in LULC

Researchers have studied the correlation between urban population growth and Rwanda's LULC changes. They analyzed National Institute of Statistics Rwanda data [44] from the third, fourth and fifth Population and Housing Census (PHC) conducted in 2002, 2012 and 2022, respectively. Spatial Land Use / Land Cover data from 2003 to 2013 and 2023 were extracted from supervised satellite image classification. This analysis aimed to comprehend how population growth has led to urbanization and affected land use patterns. By examining both datasets, researchers determined the impact of population growth on urban development and land use changes, including the expansion of built-up areas and the reduction of non-built-up areas. They also made projections for potential future trends. The population data provides information on the rate and scale of urban population growth in Kigali City, while LULC data reveals changes in land use, which are both important factors in understanding the relationship between population growth and urbanization.

3. Results

3.1 Landsat image 2003

The satellite image captured on 26/12/2003 was meticulously analyzed and classified using ArcMap, a widely used GIS software. The classification process involved identifying and categorizing various land cover classes within the image. The results of this classification process have been represented in a map, which effectively portrays the distribution and extent of each classified land cover class. The map derived from the classification process reveals valuable insights into the composition and characteristics of the study area. Among the classes classified, two main categories are "built-up" and "non-built-up" areas (Figure 4). These classifications are crucial for assessing the region's urbanization and land development patterns.

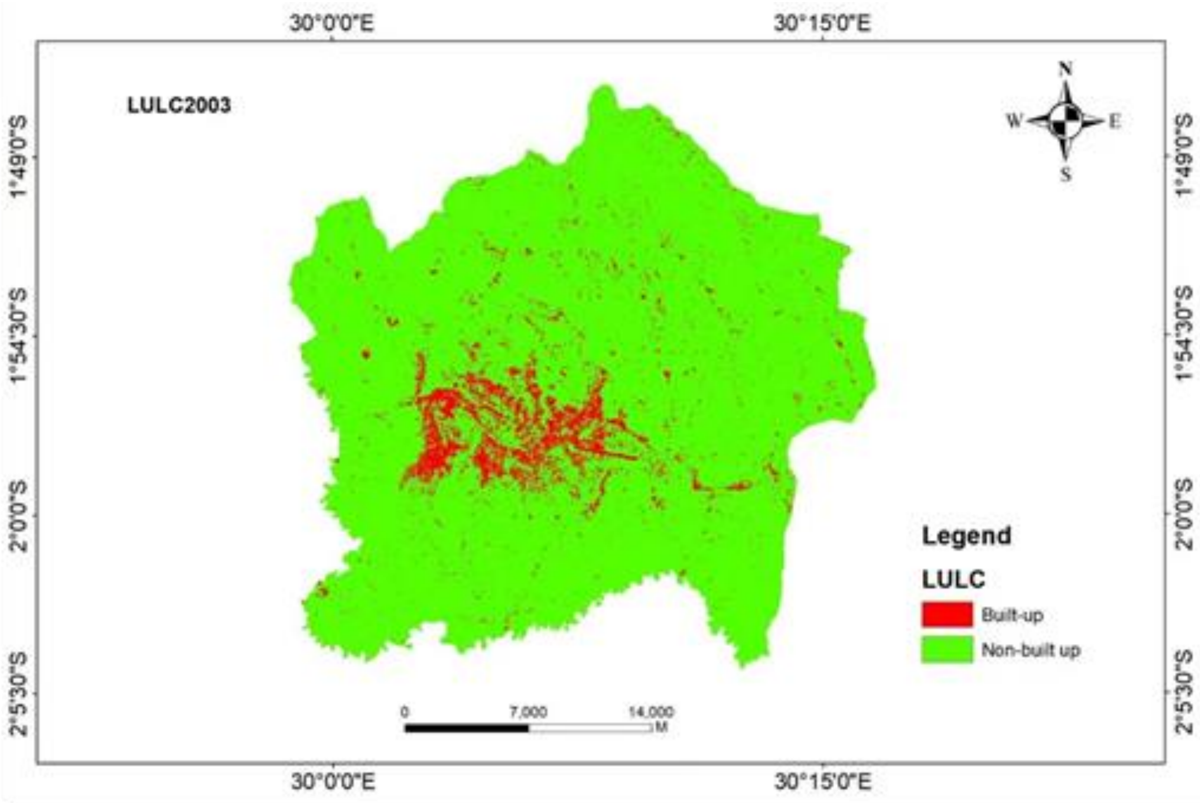

Figure 4. The classified map of 2003.

According to the classification results, the built-up area in the year 2003 covered approximately 48.59 km^2. This category represents the land that has undergone significant human-induced development and construction activities, such as residential, commercial, or industrial buildings, infrastructure, and other artificial structures. In contrast, the non-built-up areas in the year 2003 encompassed a much larger expanse, totaling 681.41 km^2. By comparing the above classes in 2003, it is possible to analyze the rate and magnitude of urban expansion, identify areas of concentrated advance, and monitor changes in LULC patterns over time.

3.2 Landsat image 2013

The satellite image captured on 02/07/2013 was processed and classified using ArcMap, a powerful geographic information system (GIS) software. The classification process involved analyzing the image data and assigning different areas into distinct classes based on their characteristics (Figure 5). The results of this classification provided valuable insights into the land cover distribution during that period.

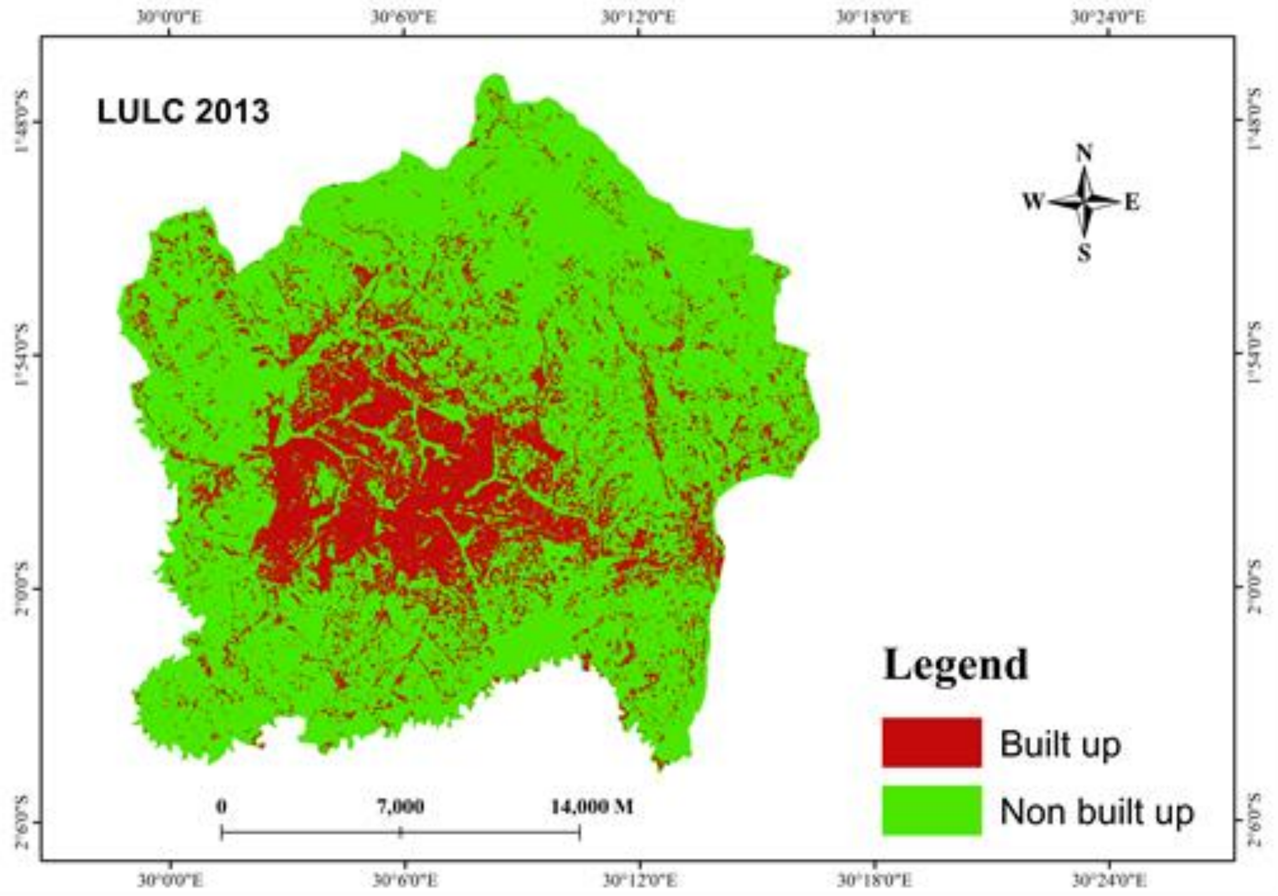

Figure 5. Classified map of 2013.

According to the classified map, the land cover in the year 2013 was predominantly categorized into two classes. The built-up areas, which encompassed urban and developed regions, occupied a total of 184.88 km^2. These areas typically comprised residential, commercial, and industrial zones with main human activities. On the contrary, the non-built-up areas covered a much larger extent, totaling 545.12 km^2. These non-built-up areas encompassed a variety of land cover types, such as forests, agricultural fields, water bodies, and natural landscapes, where human development and infrastructure could have been improved.

3.3. Landsat image 2023

The satellite image captured on January 23, 2023, underwent classification in ArcMap, leading to a classified map representing different land cover classes. The analysis revealed two main categories: built-up and non-built-up areas, each encompassing different extents of land (Figure 6).

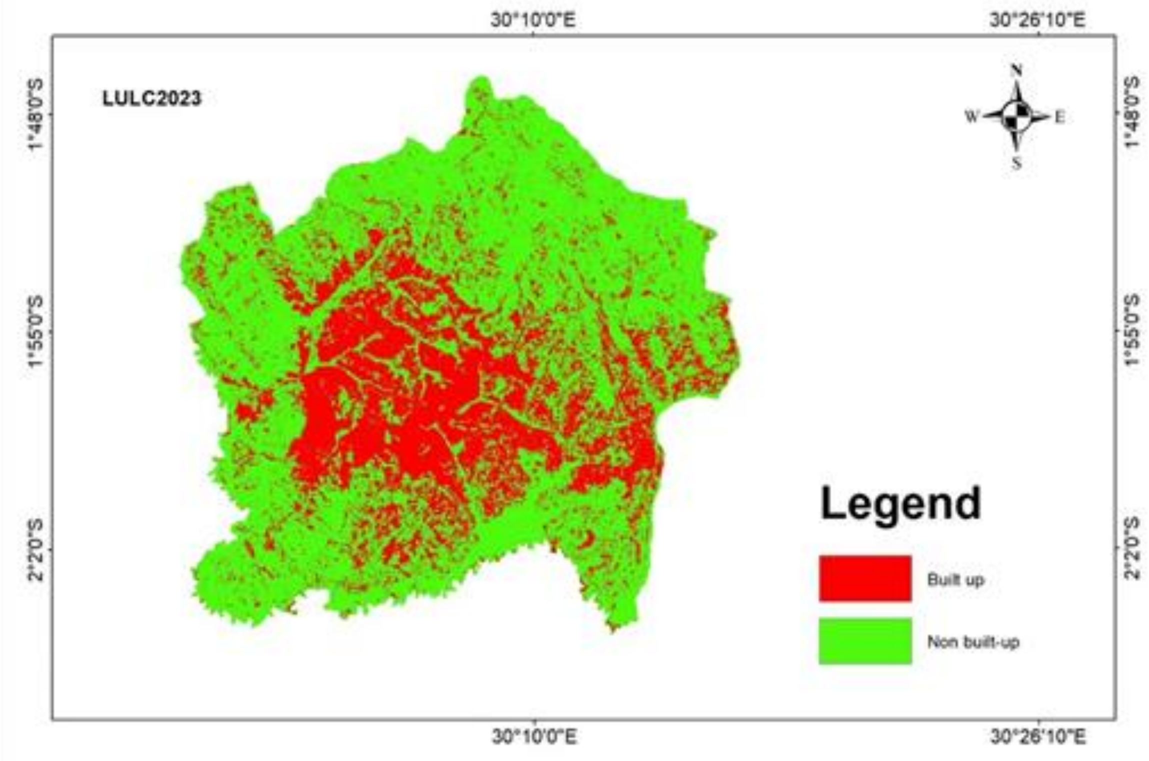

Figure 6. Classified map of 2023.

Notably, in 2023, the total built-up area identified through the classification process amounted to 238.07 km^2, indicating the presence of urbanized and developed regions. On the contrary, the non-built-up areas encompassed a decreasing portion, measuring 491.93 km^2, signifying the persistent decrease of natural landscapes, open spaces, and non-urbanized regions. This information provides valued considerations into the spatial distribution and structure of land cover types, aiding in assessing and monitoring urbanization trends, environmental changes, and land management practices.

Table 2. Percentage of LULC from 2003 to 2023.

Class	2003%	2013%	2023%
Built-up [km^2]	6.6	25.3	32.6
Non-Built-up [km^2]	93.3	74.6	67.3

Table 3. Percentage change of LULC between two last decades.

Class	Change (2003-2013) %	Change (2013-2023) %
Built-up [km^2]	18.7	7.3
Non-Built-up [km^2]	-18.7	-7.3

In 2003, the built-up area was observed to be lower compared to both 2013 and 2023. Over the decade from 2003 to 2013, there was an interval change in which the built-up area experienced an increase (Table 2). This suggests a gradual process of urbanization and development during that period (Table 3). Furthermore, between 2013 and 2023, another interval change occurred, with the built-up area further expanding. This indicates ongoing urban growth and potential land conversion for infrastructure and human settlements. In contrast, the non-built-up areas exhibited a greater extent in 2003 than in subsequent years. However, from 2003 to 2013, there was an interval change where the non-built-up area decreased, suggesting a conversion of natural or undeveloped land into built-up areas. This trend continued between 2013 and 2023, with a further reduction in non-built-up areas. The decreasing non-built-up areas could indicate the loss of natural habitats, deforestation, or agricultural land conversion due to expanding urbanization and human activities.

3.4 Change detection 2003-2023

The change detection map of Kigali, depicting the land cover changes between 2003 and 2023, is visually represented in Figure 7. This map provides a comprehensive overview of the spatial transformations and highlights the city's dynamic urban growth and development nature. By comparing the LULC classes identified in 2003 and 2023, the change detection map reveals the areas that have experienced substantial LULC changes in twenty years.

It visually illustrates the expansion of built-up areas and the corresponding reduction in non-built-up areas, indicating the progressive urbanization and conversion of natural landscapes.

Table 4. LULC converted between 2003-2023.

LULC change	Area change in km^2
Non-built-up to built-up [km^2]	142.4
Built-up to non-built-up [km^2]	8.6

Table 4 presents the calculated and extracted areas of Kigali city that have undergone conversion into different land uses and covers, expressed in km^2. This tabular representation provides a concise and quantitative overview of the extent of changes within the city's boundaries. By specifying areas in km^2, the table facilitates a comprehensive understanding of LULC transformations' size and spatial distribution. Figure 7 also shows the case.

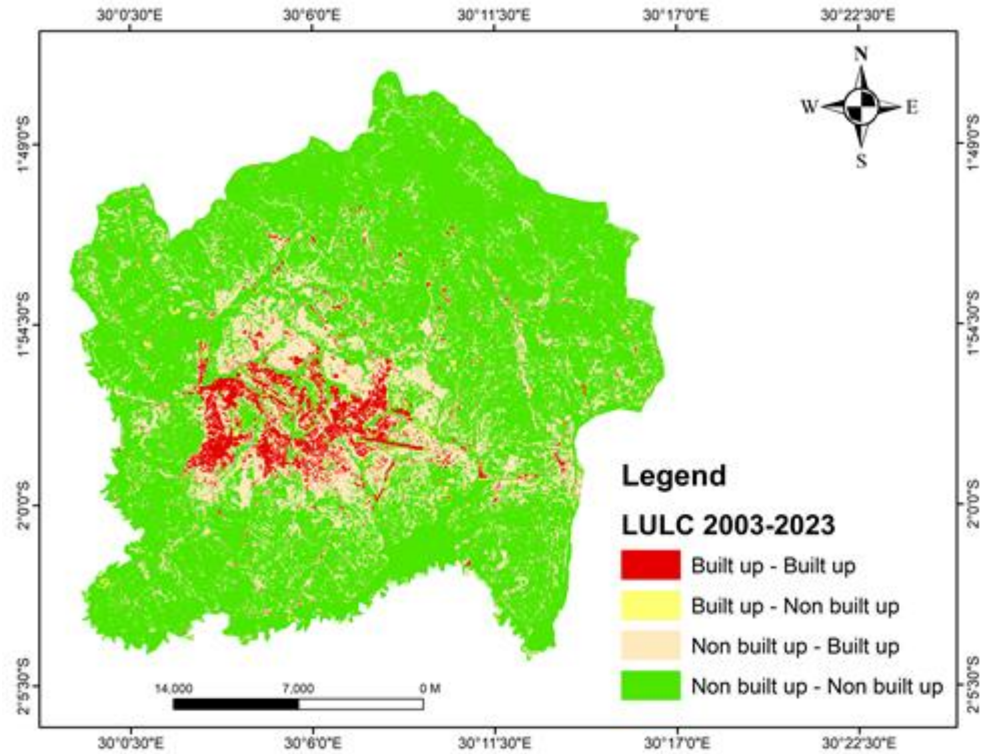

Figure 7. Change detection map 2003-2023

The change detection map employs a color-coded scheme to differentiate between the various land cover categories, enabling a clear understanding of the magnitude and spatial distribution of changes that have taken place. The use of distinct colors or symbols for built-up and non-built-up areas provides a visual contrast, emphasizing the extent of urban growth and the shrinking of non-urbanized regions.

4. Discussion

The comparison of both classes between 2003, 2013, and 2023 provides a valued understanding of urbanization and land development dynamics over two decades. Analyzing the interval changes in these land cover categories illuminates the spatial transformations and their implications.

4.1 Correlation between population growth and LULC change over the two decades

Census data analyzed by the Rwanda National Statistics confirms that the population of Kigali has been steadily increasing from 2002 to 2022, and there is no indication of a slowdown. The data also reveals a strong correlation between population growth and changes in land cover, as evidenced by the rise in built-up areas from 2003 to 2023. Teguh et al.'s research from 2021 [43] reinforces this trend, linking it to the high rate of population growth in the Kuranji watershed, like changes observed in Kigali. Graphs depicting this correlation over the past two decades are presented in Figure 8 and Figure 9.

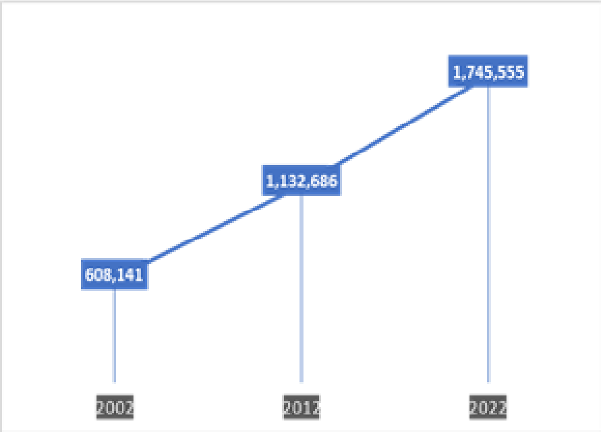

Figure 8. Population growth from 2002 to 2022

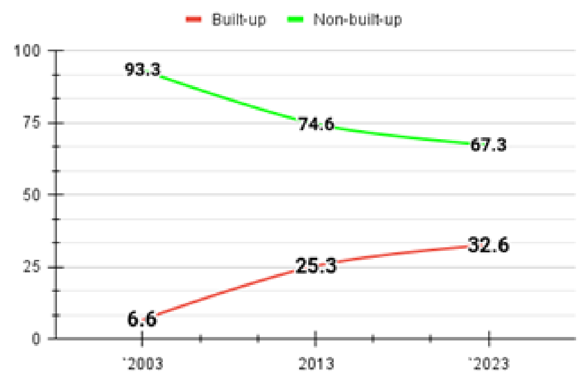

Figure 9. LULC change in percentage of Kigali over two decades

The analysis of Rwanda censuses carried out over twenty years, from 2002 to 2022, reveals a striking correlation between population increase and Land Use/Land Cover (LULC) changes in Kigali. The city's population surged from 608,141 in 2002 to 1,132,686 in 2012 and further to 1,745,555 in 2022 [45]. Simultaneously, LULC underwent significant transformations. From 2003 to 2013, built-up areas expanded by 18.6%, while non-built-up areas decreased by the same percentage. Similarly, the comparison between 2013 and 2023 showed a 7.2% increase in built-up areas and a corresponding decrease in non-built-up areas. This pattern of change underscores the profound impact of population growth on urbanization dynamics.

Mathematically, the percentage changes in population and built-up areas reinforce this relationship. Population growth was substantial – 86.24% from 2002 to 2012 and 53.87% from 2012 to 2022. Correspondingly, the percentage expansion of built-up areas during the same periods exhibited significant magnitudes – 280.73% from 2003 to 2013 and 28.81% from 2013 to 2023. These parallel trends validate the direct link between population increase and urban sprawl, with population growth necessitating the conversion of non-built-up areas into built-up regions. In essence, Kigali's rapid urbanization is a tangible manifestation of the intricate interplay between demographic shifts and resultant alterations in Land Use/Land Cover patterns.

4.2 LULC change and sustainable development

These comparisons demonstrate the trends in classified classes over two decades. The rise in built-up areas and the decrease in non-built-up areas indicate the expansion of urbanized regions and the transformation of natural landscapes. These changes can have significant implications for various aspects, such as land management, environmental sustainability, and urban planning, highlighting the need for effective measures to balance urban development with preserving non-built-up areas and ecosystems. The Figure 10 show a predicted change in 2033.

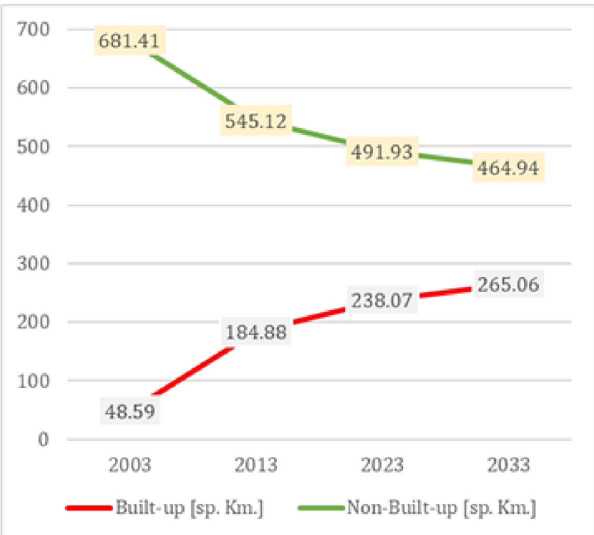

Figure 10. LULC trend between 2003 and 2033.

Based on the predicted values for 2033, where the built-up area is projected to be approximately 265.06 km^2, and the non-built-up area is estimated to be 464.94 km^2, it is crucial for urban managers in Rwanda, particularly in the city of Kigali, to proactively anticipate and plan for future urban growth needs.

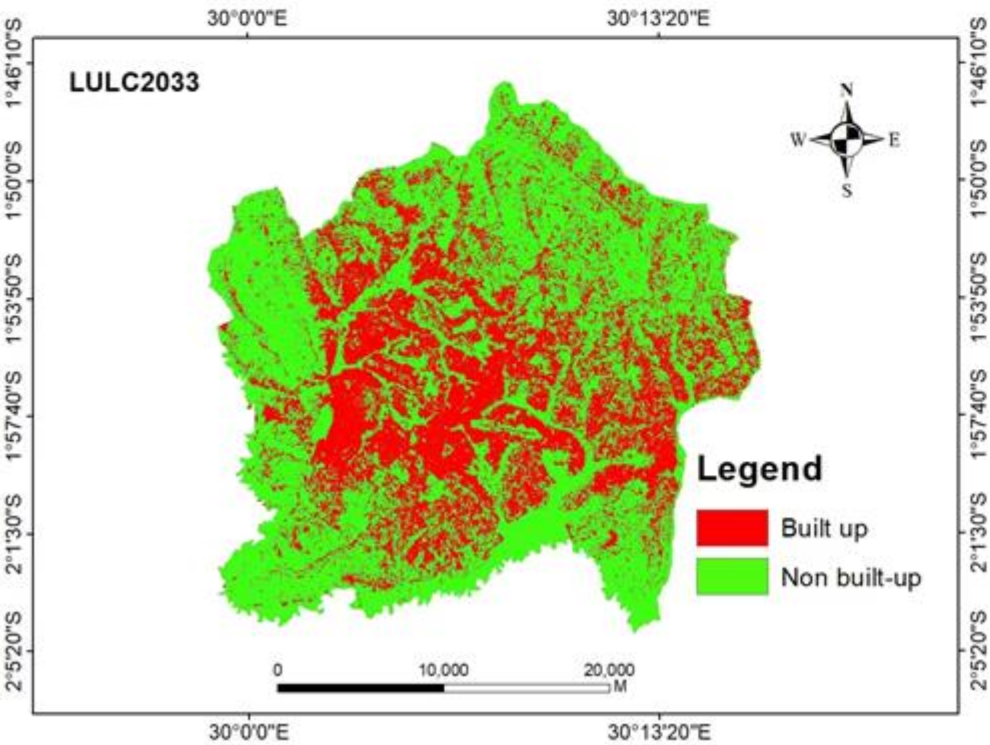

Figure 11. Predicted map of 2033

The data in Figure 10 and Figure 11 highlight a concerning trend of increasing urban sprawl and its impact on the built-up coverage of settlements. The projections indicate that without significant measures, the built-up area is predicted to enlarge from 238.07 km^2 in 2023 to 265.06 km^2 in 2033 (Table 5). This represents a substantial increase of 26.99 km^2 over the ten years. In terms of percentage change, this projected increase corresponds to a 3.7% growth in built-up areas. Such growth can have various implications for urban environments, including increased infrastructure demands, greater strain on resources, and potential negative effects on residents' environment and quality of life. Conversely, the data indicates that the non-built-up area is anticipated to decrease from 491.93 km^2 in 2023 to 464.94 km^2 in 2033. This implies a reduction of 26.99 km^2 in the non-built-up area over the same period. This reduction could be attributed to the encroachment of urban development into previously undeveloped or natural areas. The decrease in non-built-up areas raises concerns about losing open spaces, green areas, and potentially valuable ecological habitats. It may also indicate challenges in preserving natural environments and maintaining a sustainable balance between urbanization and environmental conservation. These projections underscore the urgent need for implementing serious measures and comprehensive urban planning strategies to manage and mitigate the adverse effects of urban sprawl.

Table 5. LULC converted between 2003-2023.

Class	2023	2033	Change	2023%	2033%	Change %
Built-up [km^2]	238.07	265.06	26.99	32.6	36.3	3.7
Non-Built-up [km^2]	491.93	464.94	-26.99	67.3	63.6	-3.7

The study's findings significantly contribute to the existing body of literature in the realm of urban sustainability by providing empirical evidence of the relationship between population growth, land use changes, and their implications for sustainable development. The data underscores the urgency of effective urban planning strategies to control and manage urban sprawl, aligning with previous research in this field. Urban planners and stakeholders are vital in curbing urban sprawl's adverse effects and promoting sustainability through well-crafted environmental and socio-economic policies and planning regulations.

One key alignment with the literature is the proposed strategy of limiting outward expansion and prioritizing high-rise building development. This strategy resonates with the sustainable urbanization discourse, as it optimizes land use by accommodating population growth vertically and diminishes the ecological footprint associated with horizontal expansion. As recommended by the study, the notion of establishing urban growth boundaries and delineating built-up areas corresponds with the prevailing understanding that controlled urban growth is essential to maintain ecological balance and safeguard non-built-up areas. This approach concurs with prior research advocating for comprehensive land use planning, zoning regulations, and urban development plans to foster compact and sustainable growth while deterring uncontrolled sprawl.

Moreover, the study's emphasis on safeguarding urban green areas aligns with the literature's acknowledgment of the importance of preserving green spaces for ecological integrity and residents' well-being. The research underscores these areas' crucial role in biodiversity conservation, recreation, and overall quality of life. The call to balance urban development with environmental sustainability by protecting green spaces reflects a shared understanding in the field that urban planning should consider ecological factors alongside human-centric development. Ultimately, the study bolsters the existing literature by offering tangible insights into how urban planners and stakeholders can effectively navigate the complex interplay between urbanization, land use, and sustainability, ultimately contributing to more resilient and ecologically sensitive urban futures.

5. Conclusion

The rapid urbanization and population growth observed in cities worldwide, including Kigali City, have profoundly impacted LULC patterns. In the context of Kigali City, the population has experienced significant growth, rising from 608,141 in 2002 to 1,745,555 in 2022. This rapid urbanization has driven substantial changes in the way land is utilized. To understand these changes, satellite images captured in 2003, 2013, and 2023 were analyzed to track the evolution of built-up and non-built-up areas over two decades. In 2003, the extent of built-up areas was measured at 48.59 km^2, while non-built-up areas covered 681.41 km^2, indicating the dominance of natural landscapes. However, by 2023, the land cover patterns had transformed significantly. The built-up areas expanded to cover 238.07 km^2, signifying a substantial increase over the two-decade period. Simultaneously, the non-built-up areas witnessed a reduction, covering 491.93 km^2. This comparison highlights the conversion of natural landscapes into urbanized regions, a consequence of population growth and urban expansion in Kigali. Looking ahead to 2033, the projected values indicate a continuation of this urban growth trend. The built-up areas are estimated to increase to approximately 265.06 km^2, while the non-built-up areas are projected to expand to 464.94 km^2. These projections underline the persistence of urbanization and the ongoing conversion of natural areas into built-up regions. These findings underscore the need for proactive urban management and strategic planning approaches in Kigali. Addressing the challenges of urban sprawl and its ramifications requires adopting effective actions to reach sustainable development, preserve natural landscapes, and enhance the city's livability. By implementing proactive urban planning strategies, Kigali can effectively manage the impacts of urban growth, promote sustainable land use practices, and foster a balanced and resilient urban environment for its residents.

Kigali's urban managers must predict future urban growth needs and devise appropriate environmental and socio-economic policies and planning regulations to manage urban growth effectively. The city can achieve sustainable urbanization by implementing strategies such as limiting outward expansion and promoting compact and mixed-use (mid-rise or high-rise apartments) areas. This approach would optimize land use and preserve non-built-up areas, contributing to a more balanced and environmentally conscious development. Moreover, strategies should focus on adapting sprawling cities by encouraging higher densities and delineating built-up areas and urban growth boundaries. By doing so, urban managers can effectively control the city's expansion and prevent uncontrolled sprawl into non-built-up areas. Simultaneously, efforts should be made to limit development in urban green areas, ensuring the preservation of ecological integrity.

Acknowledgement

The authors obtained spatial information data by downloading them from various sources, including the websites of USGS, DIVA-GIS, and the Rwanda Spatial Data Hub. Additionally, they acquired population growth data from the National Institute of Statistics of Rwanda.

Funding

This research received no external funding.

Author contributions

Katabarwa Murenzi Gilbert.: Methodology, formal analysis, visualization, and draft writing. **Yishao Shi** Conceptualization, supervision, and draft review and editing.

Conflicts of interest

The authors declare no conflicts of interest.

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