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I have read the University's statement on Good Academic Practice; that the following work is my own work; and that significant academic debts and borrowings have been properly acknowledged and referenced.

Land Cover and Land Use Change in Nairobi from 1984-2023: A Study of Urban Growth, Development, and Informal Settlements.

1. Introduction:

Nairobi, Kenya is one of the world's quickest-growing urban centers, with a yearly growth rate of 4.06% in 2024 alone (Macrotrends 2024). From 1984 to 2023, the city's population increased by 432%, from 1.04 to 5.23 million residents (Macrotrends 2024). The first residents moved to Nairobi due to the construction of the Uganda Railway (Kingoriah 1983). Since, the city has grown into one of Eastern Africa's largest economic hubs. However, the population increase is too quick for the city's infrastructure to keep up, causing over 60% of residents to live in informal urban settlements, commonly known as slums (Wamukoya *et al* 2020). The term 'slum' is used to describe informal settlements that often lack access to clean water, sanitation, paved sidewalks and roads, and easy access to education. Slum growth is an outcome of population growth, contributing to urban sprawl and unorganized expansion into the outskirts of the city. Furthermore, slum populations often have high levels of poverty, disease, air pollution, and violence, contributing to unsustainable living conditions (CitiesAlliance, 2024). Slum conditions in Nairobi are no different; roughly 200 slums exist in the city, including Kibera, widely known as the "biggest slum in Africa" (Desgroppes and Taupin 2011). Roughly 40% of children living in this slum attend school each day, exemplifying the area's low education and reading levels (Chaffinch 2023). Rapid population growth, particularly in slums, contradicts the UN's Sustainable Development Agenda and forces residents into unsuitable and unsustainable living conditions.

Like many cities in Africa, Nairobi is experiencing exponential urban growth due to high levels of migration from rural areas, high birth rates, and an increase in urban settlements (Wamukoya *et al* 2020). Many Kenyans migrate to Nairobi in hopes of greater economic security and better quality of life, though this is hard to achieve (Oyvat and Githnji 2020). New immigrants often settle into informal settlements and slums, promoting an unsustainable quality of life. Increasing migration and urbanization leads to other structural and demographic changes within the city such as changes in sex and age structures, economic changes, and psychological changes (Wamukoya *et al* 2020). Rapid urbanization rates and changes prompt discourse about the city's sustainability and overall quality of living, because slum conditions are far below modern sustainable standards. This report will examine urban sprawl and development growth in Nairobi from 1984-2024 and its implications on residents using remotely-sensed imagery.

2. Methods:

2.1 Study Area

This study focuses on the Nairobi metropolitan region, with maps centered on Nairobi county. Nairobi serves as the capital city of Kenya and is home to roughly 5.2 million people, though the exact figure is unknown.

2.2 Data:

Landsat imagery downloaded from the United States Geological Survey (USGS) database was used in examining land change for the Nairobi region. Two separate scenes were used in land cover mapping: Landsat 9 OLI-2 and TIRS-2 for 2023 (Scene ID LC09_L1TP_168061_20230204_20230311_02_T1) and Landsat 5 TM for 1984 (Scene ID LM05_L1TP_168061_19841217_20200902_02_T2), both covering Path 168 and Row 61, as visualized below in *Table 1*.

Data type:	Sensor:	Acquisition Date:	Path:	Row:
Landsat-05	TM	17/12/1984	168	61
Landsat-09	OLI-2, TIRS-2	04/02/2023	168	61

Table 1: table with information about the scenes and imagery used.

Landsat imagery was utilized for a few reasons, specifically because of the availability of clear satellite imagery from 1984 and its 30-meter spatial resolution. Higher-resolution imagery would have been much more challenging to process because of the amount of data, and lower-resolution would not have provided enough detail for urban growth analysis. Furthermore, Landsat imagery has a number of spectral bands available for analysis.

2.3 Methods and Image Classification:

To examine land use/cover changes, data and image processing was completed in ArcGIS. First, the clip raster function was used to separate a 60 x 60 km section of the Landsat data focusing solely on Nairobi and the land directly surrounding it.

A false colour composite was then applied to both images to aid with visualization of built-up areas. on Landsat-09, the NearInfrared (Band 5, Wavelength 0.85-0.88um) and Shortwave Infrared bands (Bands 6 and 7, Wavelengths 1.57-1.65um and 2.11-2.29um respectively) are most important in differentiating built-up areas from surrounding vegetation and land use. This report used Band 6, SWIR 1. The NIR band reflects vegetation strongly while built-up areas have a lower reflectance. The SWIR 1 band reflects built-up areas less than natural surfaces such as vegetation or soil. In many cases, Red (Band 4, Wavelengths 0.64-0.67um) is most popular as the third band for distinguishing built-up land from surrounding land uses and did provide greater contrast between vegetation and built-up areas, however, using Green (Band 3, Wavelength 0.53-0.59um) provided greater contrast between Savannah and Developed areas. *Figure 1* depicts an aerial view of Nairobi in 2023 using the aforementioned false color composite to highlight built-up land.

The Landsat-5 imagery, however, only had four different bands available due to the sensor technology. The NearInfrared1 (Band 4, Wavelength 0.76-0.90um) and NearInfrared2 (Band 5, Wavelength 1.55-1.75um) bands are essential in differentiating built-up areas from vegetation as built-up areas will reflect far less than natural areas. Similarly to the Landsat-09 band combinations, the Green (Band 2, Wavelength 0.52-0.60 um) differentiated Savannah areas better than the Red band. *Figure 2* depicts an aerial view of Nairobi in 1984 using a false color composite that highlights built-up land.

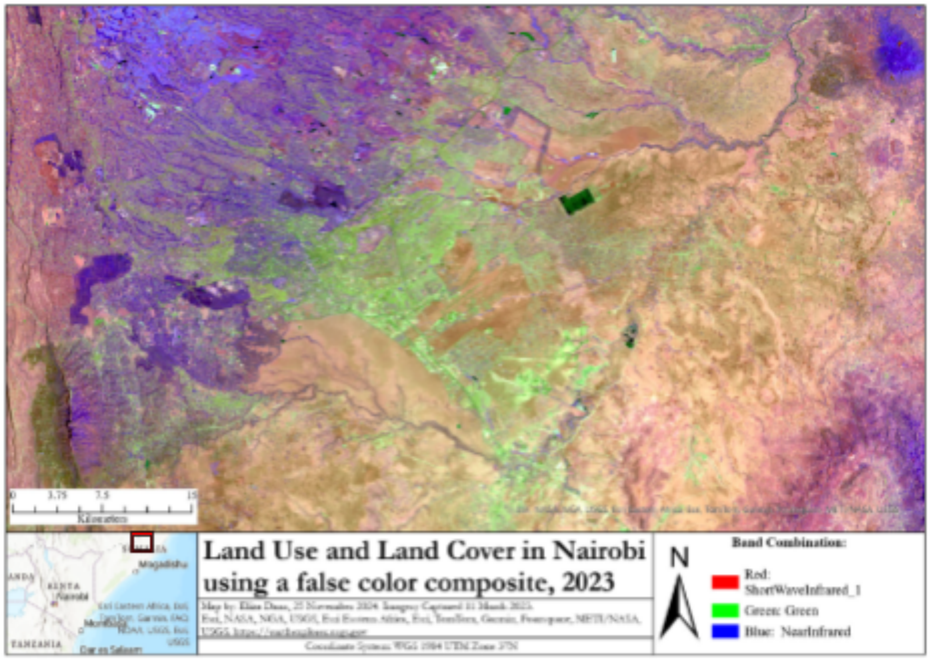

Figure 1: Aerial view of Nairobi in 2023 in a false color composite highlighting developed land. Green areas contain developed land, purple areas contain vegetated land, and brown colors contain savannah. Landsat-09 bands were utilized for this false color composite.

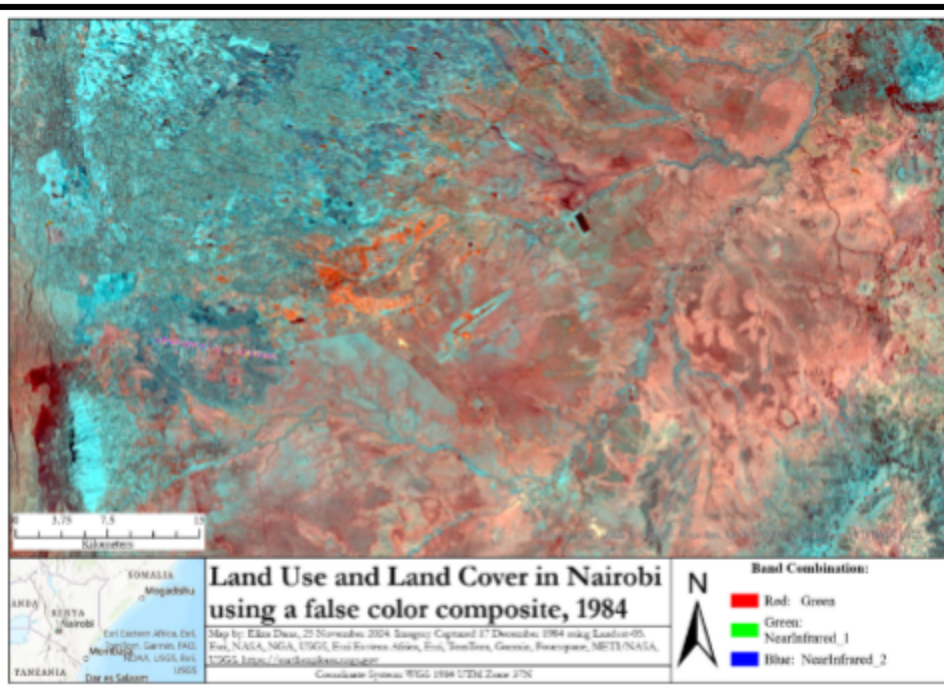

Figure 2: Aerial view of Nairobi in 1984 in a false color composite highlighting developed land. Bright orange areas contain developed areas, light blue areas represent vegetated land, and muted red and orange colors represent savannah. Landsat-05 bands were utilized.

Both images were then classified into 6 different land classes: Water, Developed, Savannah, Light Vegetation, Medium Vegetation/Forest, and Agriculture using a supervised classification method as shown in *Figure 3* and *Figure 4*. To classify the images, the Image Classification Wizard was used through isolating between 5-10 polygons of known areas within each class. These areas were then used to itemize the rest of the map, separating each pixel into one of the 6 aforementioned classes. Next, the classified image was converted to a vector format, cleaning up the image and creating multipart polygons using the Raster to Polygon tool.

Next, accuracy assessment was completed by manually-assessing 10 randomly generated points within each class. The points were compared to the Landsat files in both natural and false color composites as well as Google Earth imagery at times to assess whether or not the supervised classification was accurate.

Finally, change maps were created using the land classification outputs from the Landsat-05 and Landsat-09 rasters. Change detection was completed using the Change Detection Wizard, a function that used both map inputs to detect change between the different land types. These new groups of pixels were then reassigned colors to aid visualization.

3. Results:

After processing the image, post classification change analysis was used to analyze and interpret the changes. The classified study area was mapped, quantified, and analyzed.

3.1 Classification

The following images were classified into six different types of land cover: developed, savannah, water, forest, vegetation, and agriculture as shown in *Figure 3* and *Figure 4.* Pixels were grouped together based on their spectral characteristics, which were accurate in parts but also had some land type misclassification.

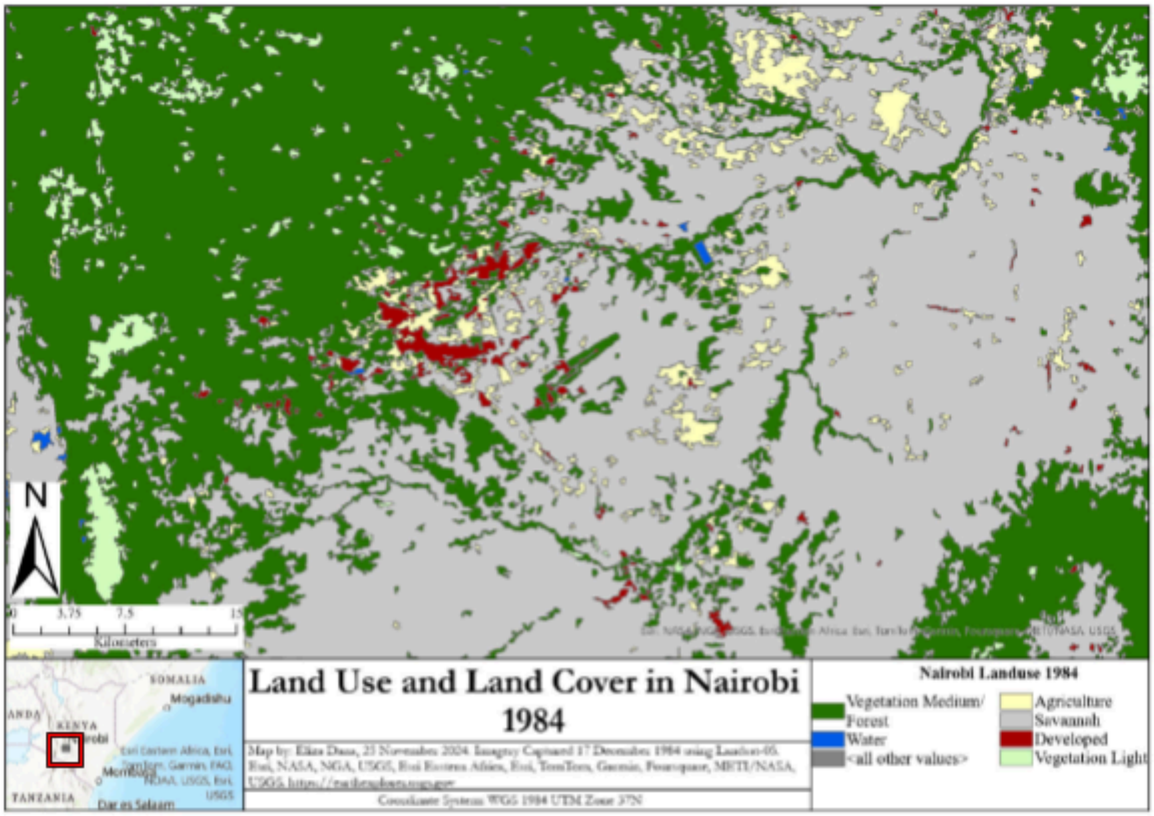

Figure 3: Land use and land cover in Nairobi and surrounding regions in 1984.

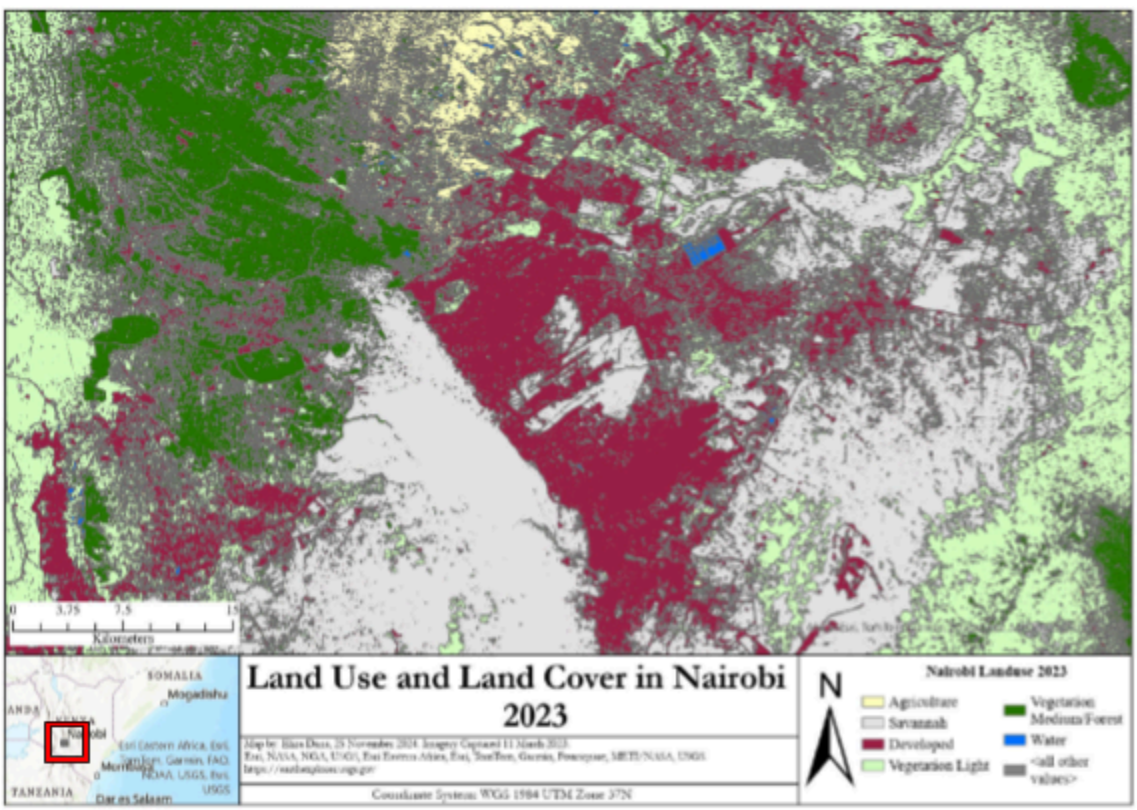

Figure 4: Land use and land cover in Nairobi and surrounding regions in 2023.

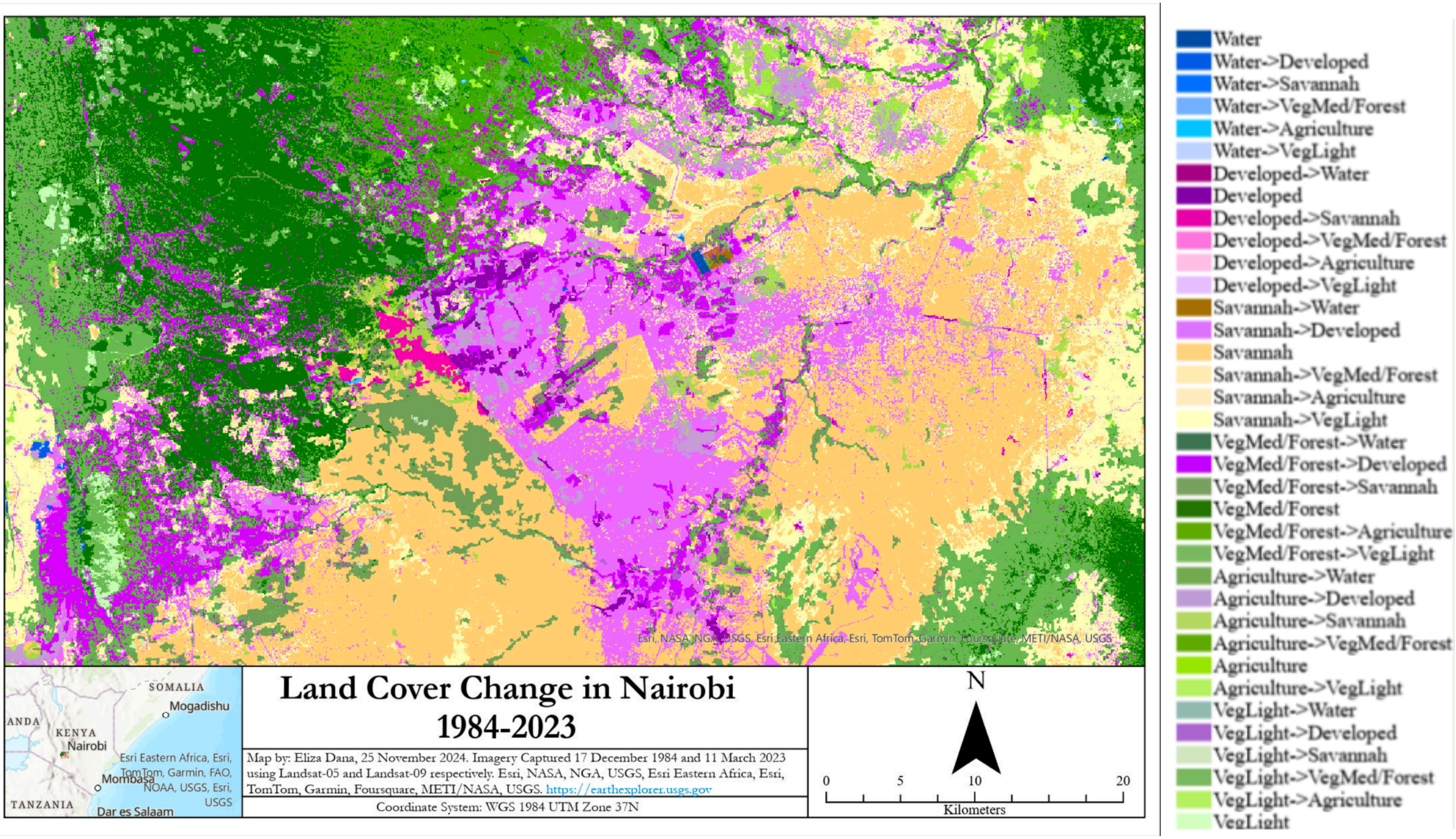

Figure 5: Land cover change in Nairobi and greater regions from 1984-2023. Urban developments have encroached on forested and savannah land, highlighting rapid urbanization that also poses sustainability issues.

3.2 Accuracy Assessment:

The following accuracy assessment shows the User, Producer, and Overall accuracy of the change detection.

As visualized in *Table 2,* the total accuracy for the accuracy assessment of the Landsat-05 land classification outputs was 65%, while the Kappa values was 58%. These are very low accuracy results: ideally these values would be much higher. However, this report focuses on urban and developed land classification and expansion. Much of our accuracy assessment was skewed by the misclassification of vegetation, agriculture, and savannah. When looking at developed land classifications (highlighted), the data is much more accurate.

Reference

Classified	Water	Developed	Savannah	VegMed/ Forest	Agriculture	VegLight	Total	User's Accuracy (%)
Water	**4**	0	0	2	1	3	10	40
Developed	0	**7**	3	0	0	0	10	70
Savannah	0	0	**8**	0	0	2	10	80
VegMed/Forest	0	0	1	**8**	0	1	10	80
Agriculture	0	0	3	0	**5**	2	10	50
VegLight	0	0	0	3	0	**7**	10	70
Total	4	7	15	13	6	15	**60**	
Producer's Accuracy (%)	100	100	53.3	61.5	83.3	46.7		65

Table 2: Confusion matrix and accuracy assessment for Landsat-05 satellite imagery.

Reference

Classified	Water	Developed	Savannah	VegMed/ Forest	Agriculture	VegLight	Total	User's Accuracy (%)
Water	**7**	0	0	1	0	2	10	70
Developed	0	**9**	0	0	0	1	10	90
Savannah	0	1	**9**	0	0	0	10	90
VegMed/Forest	1	1	0	**8**	0	0	10	80
Agriculture	0	0	0	1	**6**	3	10	60
VegLight	0	1	0	0	1	**8**	10	80
Total	8	12	9	10	7	14	**60**	
Producer's Accuracy (%)	87.5	75.0	100	80.0	85.7	57.1		78.3

Table 3: Confusion matrix and accuracy assessment for Landsat-09 satellite imagery.

As visualized in *Table 3,* the total accuracy for the Landsat-09 imagery was 78.3% while the Kappa value was 74%. While more accurate than the Landsat-05 imagery, these are still low accuracy results and would ideally be much higher. However, like the Landsat-05 imagery, much of the error comes from mislabelling vegetation, agriculture, and savannah, which this report is not as concerned about.

3.3 Class Area Change Detection

Land cover class area for the classified images was classified in square kilometers. *Table 4* and *Figure 5* show that the developed land cover increases from 64.7 km^2 to 927.2 km^2 from 1984 to 2023, an increase of 1,332.46 %. As to be expected, this aligns with Nairobi's estimated population increase from 1.04 to 5.23 million in the same time period. *Table 3* shows how 'Light Vegetation' also increased significantly, which may suggest that other types of significant land cover change occurred beyond built up area. However, classification accuracy for light vegetation was extremely low (*Tables 2* and *3* report 46.7 and 57.1% accuracy respectively for Light Vegetation). *Table 4* also demonstrates that 'Savannah' (53.3% and 100% accuracy in

Tables 2 and *3* respectively) and 'Vegetation Medium/Forest' (61.5 and 80.0% accuracy in *Tables 2* and *3* respectively) decreased considerably, suggesting that developed land has encroached on many of these native areas. The accuracy statistics are lower than researchers would hope for, however, visual interpretation of *Figures 1* and *2* confirm that savannah and native areas have been built on.

Land cover Class:	Landsat-05 Area (km2)	Landsat-05 % Area	Landsat-09 Area (km2)	Landsat-09 % Area	Area Change (%)
Water	10.7	0.2	17.1	0.3	59.7
Developed	64.7	1.3	927.3	18.3	1332.4
Savannah	2321.6	45.7	1547.7	30.5	-33.3
VegLight	117.1	2.3	1379.4	27.2	1077.5
VegMed/ Forest	2330.9	45.9	780.2	15.4	-66.5
Agriculture	236.8	4.7	425.6	8.4	79.7

Table 4: Land cover change in Nairobi from 1984-2023.

3.4 Urban Land Use Changes:

This report focuses primarily on the changes in developed land in Nairobi. Thus, while helpful in synthesizing results and supplementing evidence regarding development growth, land cover changes between agriculture, savannah, light vegetation, water, and forest are not as important to our study as land changes related to developed land. Per our classifications, developed land includes residential and commercial buildings, roads, and other infrastructural features. The rest of the land includes any vegetation, savannah, water, and any other type of natural feature.

4. <u>Discussion:</u>

This study's objective was to analyze urban sprawl and slum growth in Nairobi, Kenya and the implications that this growth has for its residents.

4.1 Population Growth in Nairobi:

A city with urbanization rates as quick as Nairobi's will struggle to expand sustainably. Already, the city was not built on strong, easily-expandable infrastructure. In 1984 slums, including Kibera, Korogocho, and Mathare, already had many residents. These slums served as "bus stops" for migrants, providing temporary housing for those migrating to Nairobi for better employment opportunities (Mukeku 2018, 26). This pattern is not dissimilar from those in many major cities in the global south. Slums provide cheap housing near the city center for migrants and residents who cannot afford to live anywhere else. As a result, roughly 60% of Nairobi's population lives in slums surrounding the city center (Ren *et al* 2020). Yet, these slums only take up 6% of the city's land, emphasizing their population density and alluding to dire living conditions. Rapid migration and urbanization in Nairobi have consistently contributed to urban sprawl, posing greater challenges for improving sustainability within the city. *Figure 6* highlights an area of urban growth in Nairobi, picturing areas that infrastructure has developed since 1984. This growth is enormous – almost all of the built-up area did not exist in 1984, highlighting Nairobi's growth. Recent studies display similar patterns of growth within the city, for instance, Katyambo and Ngigi (2017) claim that land cover increased from 408.99 km^2 to 763.79 km^2 to 2,187.82 km^2 from 1995-2000-2015. While the land cover classifications in this report were not the most accurate, growth results are still in line with other literature and studies.

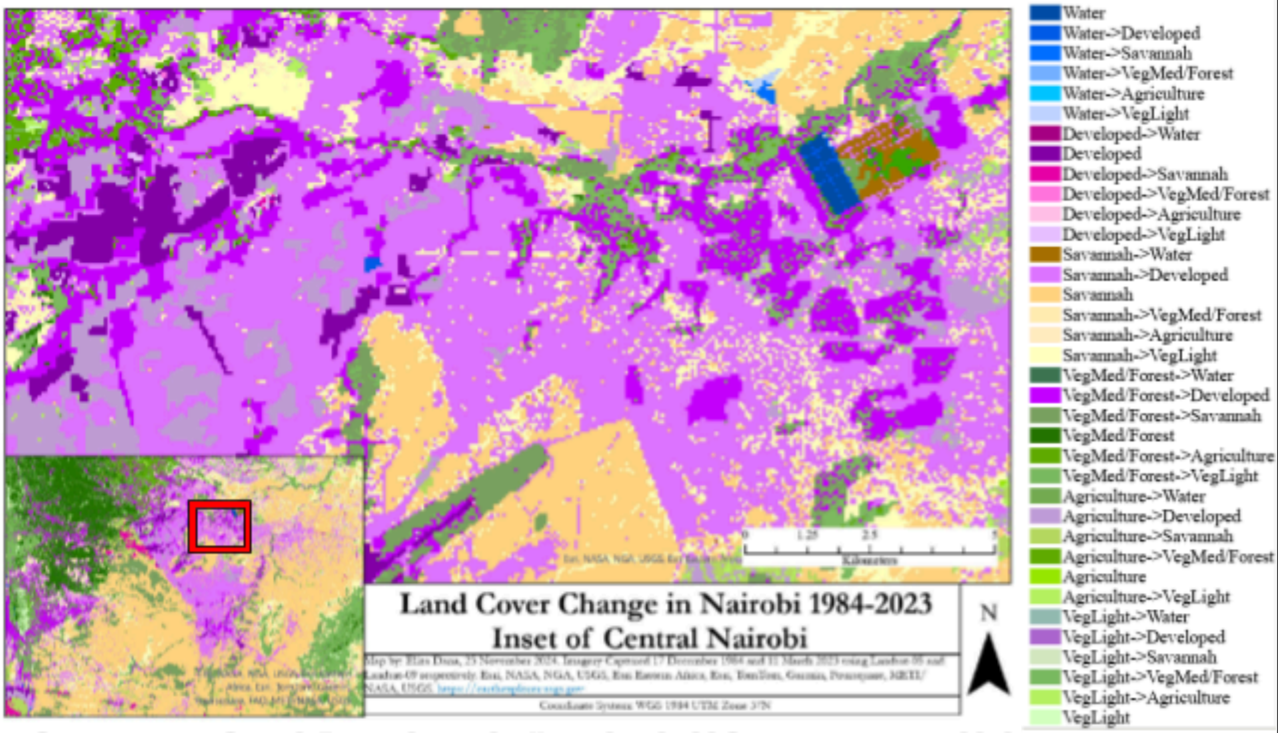

Figure 6: Map of Land Cover change in Central Nairobi from 1984-2023. This inset map provides a clear example of how urban growth has impacted land cover in Nairobi. Purple regions represent growth urban expansion from Forest and Savannah areas.

4.2 Case Study: Kibera

Mass-immigration to Nairobi began during the late 1970s and early 1980s – Kibera was a popular destination for new residents. Located close to the city center and near wealthy neighborhoods, there were plenty of opportunities for economic growth in Kibera, hence why many began flocking to the area. Kibera occupies roughly 225 hectares of land, down from 550 hectares in 1971, and construction of new structures have not legally occurred since the early 1990s (Smedt, 2011). Despite land in Kibera being mostly occupied by the 1990s, the slum's population has continued to grow exponentially. The slum's total population is unknown, and sources cite varying estimates. The Kenyan National Census lists 170,000 residents, however, other estimates range from 500,000 to 1,000,000 (Mukeku 2018). Regardless of what the slum's population is, Kibera's population increase in the past four decades is unprecedented. *Figure 7* attempts to visualize land use change in Kibera, although it is not as accurate as other map subsects. While Kibera has not grown much in physical size due to lack of space and construction limitations, it has grown in population (Smedt, 2011). The slum's condition and population density growth implies that many live in unsustainable conditions. *Figure 8,* however, visualizes Kwangware, a slum with very similar demographics to Kibera. This imagery clearly highlights areas where the slum has expanded since 1984 and provides a clearer

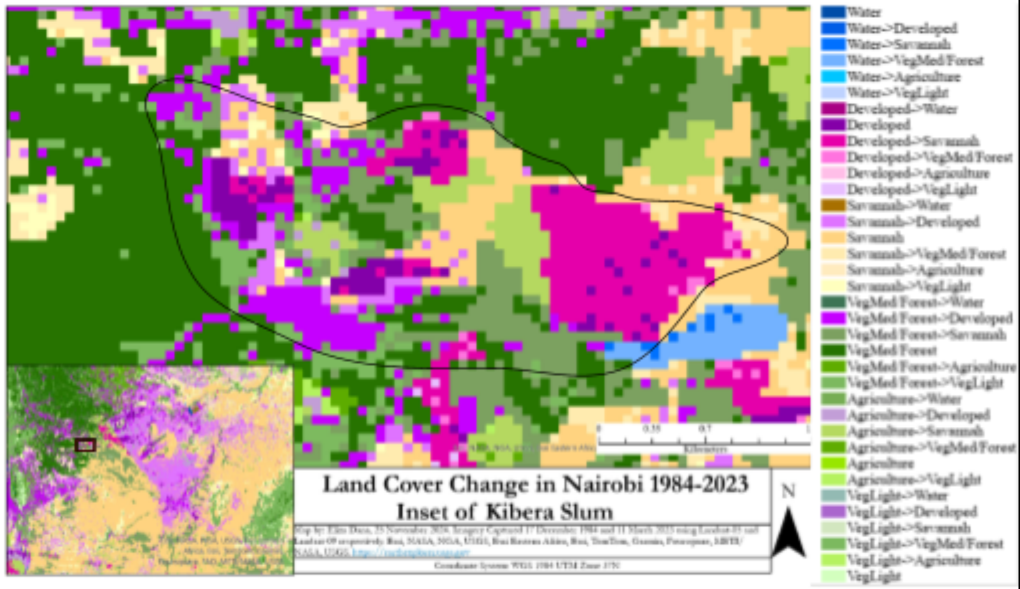

Figure 7: Land Cover Change in Kibera Slum from 1984-2023. The land cover change in this inset map is unclear, potentially due to spectral inaccuracies, however, when looking at imagery from both 1984 and 2023, the slum has not changed much in size, partially due to building regulations, even if it has grown in population.

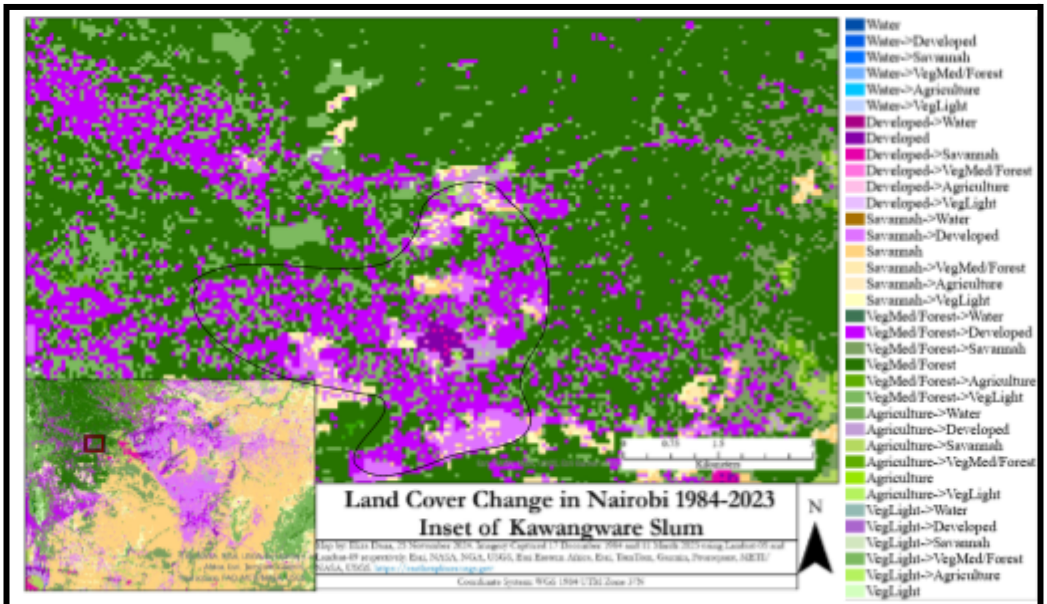

Figure 8: Land Cover Change in Kawangware Slum, Nairobi, Kenya from 1894-2023. While not Kibera, Kawangware is not far from Kibera and provides a much clearer and expected change map for what slum growth looks like. Here, you can see clusters of 'developed' pixels that have taken over forested and savannah areas.

visualization of a densely-populated slum on land cover change maps than Kibera.

4.3 Limitations:

Despite clearly exemplifying developed land expansion in Nairobi, there were many limitations to land classification in this report.

Firstly, the Landsat-05 imagery only contained four spectral bands: NearInfrared1, NearInfrared 2, Red, and Green, which provided fewer options for land classification analysis. As we had NearInfrared1 and NearInfrared2 (which functions similarly to SWIR bands in Landsat-09), classification was still successful, though accuracy may not be as high as it may have been with more band combinations to choose from. For the Landsat-05 classifications, differentiating developed land from undeveloped land was successful, however, other land use classifications, such as separating agricultural use from vegetation from forest provided more challenging, infringing on the overall accuracy of the classification.

The Landsat-09 imagery was easier to classify than the Landsat-05 imagery, increasing accuracy of land classifications from 65% to 78%. However, there were still many inaccuracies in land classification due to the nature of urban sprawl in Nairobi and the high NearInfrared reflectance of savannah and built up areas.

Furthermore, accuracy could have been improved by subsetting a smaller area than 60 x 60 km. Our images contained some urban and vegetated areas that were not relevant to our analysis of growth and urban sprawl in Nairobi. Most of the growth in Nairobi has occurred within 10 km of the city center, allowing residents to walk into the city for work. If anything, including these outside areas takes away from our analysis by decreasing the accuracy of the expansion that this report focuses on: expansion within walking distance of the city center.

4.4 Infrastructure and Sustainability

While a lot of Nairobi's population growth occurs in slums, most of its land cover expansion was not a result of slum growth (as aforementioned, slums only sit on 6% of Nairobi's land). Higher-income neighborhoods and increased built up infrastructure contribute to most of the city's physical growth (Oyugi 2017). These neighborhoods provide more sustainable living conditions for residents, however, they have expanded into savannah and forested areas, changing wildlife corridors and impacting wider surroundings (Oyugi 2017). Additionally, much of Nairobi's infrastructure cannot keep up with the city's rapid urbanization, compromising housing, water supply, security, education, and health throughout the city (Asoka *et al* 2013). These infrastructural issues create demand for even more expansion, highlight how urbanization and growth as rapid as Nairobi's have wide implications on the city, while posing challenging national sustainability issues.

5. Conclusion

To conclude, population growth, urban sprawl, and increased areas of developed land are clearly evident in Nairobi's metropolitan area. Nairobi has gone through many land cover changes in the past four decades, encroaching on land previously classified as savannah or forest in the 1980s. As a result, our calculations state that built-up land has increased by 1,330% from

1984-2023. This population growth and urban expansion has not just occurred in Nairobi. It is a pattern common throughout many cities in Sub-Saharan Africa such as Lagos, Kinshasa, Luanda, Dar es Salaam, Addis Ababa, and many more. While many migrate in hopes of a better lifestyle, very few will achieve this due to slum living conditions, disease, and lack of work, highlighting the sustainability issues within the city. Nairobi's urbanization rates are too high to be sustainable: the city's infrastructure is not built to sustain the increased number of people living in the city and its outskirts.

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