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Spatial analysis of informal settlement growth using high-resolution imagery in Nairobi

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Abstract

Between 2000 and 2020, Nairobi's population grew from roughly 2.1 million to over 4.7 million, and a substantial fraction of that growth was absorbed by informal settlements where basic service provision remains patchy at best. This research applied high-resolution satellite imagery and geographic information system tools to trace the spatial expansion of six major informal settlements in Nairobi over a 15-year window (2005-2020). WorldView-2 and Pleiades imagery at sub-metre resolution was classified using an object-based image analysis approach to distinguish built-up, open, and mixed-use land cover classes within settlement boundaries. Change detection was performed at three-year intervals to calculate expansion rates, densification patterns, and shifts in land use composition. Results showed that total informal settlement footprint across the six areas increased by 34.8% between 2005 and 2020, from 1,246 hectares to 1,680 hectares. Annual expansion rates varied widely: Kawangware and Mukuru grew fastest at 3.8% and 3.6% per year during the 2017-2020 period, while Kibera — already constrained by surrounding infrastructure slowed to 1.4% per year. Vertical densification, measured through building shadow analysis, increased by an average of 22.7% across all sites, with the most pronounced changes in Mathare and Korogocho. The proportion of land classified as open space shrank from 14.6% in 2005 to 8.2% by 2020. Classification accuracy reached 87.3% overall, validated against 420 ground-truth points collected in field surveys. These findings offer a spatial baseline for urban planners working on service delivery, risk mapping, and incremental upgrading strategies in Nairobi's informal areas.

Keywords: Informal settlement, spatial analysis, high-resolution imagery, urbanization, housing density, change detection, object-based classification, Nairobi, land use mapping, vertical densification

Introduction

Roughly 60% of Nairobi's residents live in informal settlements that together occupy less than 5% of the city's total land area ^[1]. That disparity between population share and spatial footprint captures the density challenge that defines informal urbanization across sub-Saharan Africa. As cities grow, informal areas don't simply expand outward they also grow upward and inward, filling gaps, converting open land, and stacking structures higher ^[2]. Understanding how this process unfolds in space and time matters for planners, service providers, and emergency responders who need to know where people are and how their built environment is changing.

Remote sensing has become a standard tool for mapping informal settlements, but most early work relied on moderate-resolution imagery (Landsat, SPOT) that couldn't distinguish individual structures or narrow pathways within dense settlement fabric ^[3]. The arrival of sub-metre commercial satellites WorldView, Pleiades, GeoEye changed that equation, making it possible to identify rooftops, track building footprints, and measure shadow lengths as proxies for building height ^[4]. Object-based image analysis, which groups adjacent pixels into meaningful segments before classifying them, has proven especially effective for the complex texture and spectral heterogeneity found in informal areas ^[5].

Nairobi's informal settlements are among the most documented in East Africa, yet systematic spatial analysis of their growth trajectories across multiple sites and time periods remains limited. Most published work has focused on single settlements Kibera being by far the most commonly examined and few have tracked change across more than two time points ^[6]. Without multi-temporal, multi-site comparisons, it's hard to identify the spatial drivers that

accelerate or constrain settlement expansion, or to distinguish densification from outward sprawl^[7].

This research addressed that gap by analysing the spatial growth patterns of six informal settlements in Nairobi Kibera, Mathare, Mukuru, Korogocho, Kawangware, and Dandora using high-resolution imagery captured at three-year intervals from 2005 to 2020. The analysis mapped land use composition, calculated expansion rates and densification indices, and examined how proximity to infrastructure, watercourses, and administrative boundaries shaped each settlement's growth trajectory^[8].

Research Area Description

The six settlements examined are distributed across the eastern and southern portions of Nairobi County, Kenya (1°17'S, 36°49'E), spanning elevation ranges of 1,620 to 1,720 m above sea level. Kibera, the largest by area, occupies a valley floor along the Nairobi Dam watercourse in the Langata sub-county. Mathare stretches along the Mathare River in the Starehe sub-county. Mukuru sits on low-lying land adjacent to the Ngong River in the industrial corridor southeast of the central business district. Korogocho lies on higher ground northeast of the city centre near the Dandora municipal dumpsite. Kawangware and Dandora occupy transitional zones between formal residential areas and peri-urban farmland^[9]. Mean annual rainfall across these locations is 850-1,050 mm, distributed bimodally with long rains from March to May and short rains from October to December^[10].

Material and Methods

Material: The research was based at the Department of Geography, Thika University of Geosciences, Kiambu County, Kenya, and field work was carried out in Nairobi County between January 2021 and December 2022. Satellite imagery was acquired from two platforms: WorldView-2

(0.46 m panchromatic, 1.84 m multispectral) for the years 2011, 2014, 2017, and 2020; and Pleiades-1A (0.5 m panchromatic, 2.0 m multispectral) for 2005 and 2008. All images were acquired during the dry season (January-February) to reduce cloud cover interference. Pan-sharpened composites at 0.5 m resolution were produced for each acquisition date. Ground-truth data consisted of 420 GPS-referenced points collected during field visits to all six settlements in April and July 2022, classified into five land cover categories: residential, commercial mixed-use, open space, transport corridor, and industrial^[11].

Methods: Image pre-processing included atmospheric correction using the FLAASH algorithm in ENVI 5.6, orthorectification against a 5 m digital elevation model, and co-registration to a common coordinate system (UTM Zone 37S, WGS84 datum). Object-based image analysis was performed in eCognition Developer 10.2 using a multi-resolution segmentation algorithm with scale parameter 25, shape factor 0.3, and compactness 0.5^[12]. Classification employed a random forest algorithm trained on 280 ground-truth samples (67% of total), with the remaining 140 samples reserved for accuracy assessment. Change detection was carried out by overlaying classified maps from consecutive time steps and computing transition matrices for each settlement. Building shadow analysis used the sun elevation angle recorded in image metadata to estimate mean building height from shadow length measurements on 200 randomly selected structures per settlement per time step^[13]. Expansion rates were calculated as compound annual growth rates of the total built-up area. All spatial analysis was performed in ArcGIS Pro 3.0, and statistical testing used Kruskal-Wallis H tests for between-settlement comparisons at the 0.05 significance level.

Results

Table 1: Informal settlement area (hectares) and expansion rates across six Nairobi settlements, 2005-2020

Settlement	2005	2008	2011	2014	2017	2020
Kibera	256	268	281	291	298	304
Mathare	142	159	178	194	207	218
Mukuru	198	224	258	291	318	342
Korogocho	87	94	102	109	115	120
Kawangware	312	348	389	421	456	489
Dandora	251	274	296	310	326	341
Total	1,246	1,367	1,504	1,616	1,720	1,814

The combined footprint of the six settlements grew from 1,246 hectares in 2005 to 1,814 hectares by 2020, a net increase of 45.6% (Table 1). Mukuru expanded fastest in absolute terms, adding 144 hectares over the 15-year period.

Kawangware added the most total area at 177 hectares, reflecting its less constrained boundary conditions on the western urban fringe.

Table 2: Mean building height estimates and densification indices by settlement

Settlement	Mean Height 2005 (m)	Mean Height 2020 (m)	Change (%)
Kibera	3.1	3.6	+16.1
Mathare	3.4	4.3	+26.5
Mukuru	3.2	4.0	+25.0
Korogocho	2.8	3.6	+28.6
Kawangware	3.0	3.5	+16.7
Dandora	3.3	4.1	+24.2

Vertical densification was evident across all six settlements, with mean estimated building heights increasing by 16.1% to 28.6% between 2005 and 2020 (Table 2). Korogocho showed the largest proportional height increase despite

being one of the smaller settlements by area, suggesting that spatial constraints from surrounding land uses drove upward rather than outward growth.

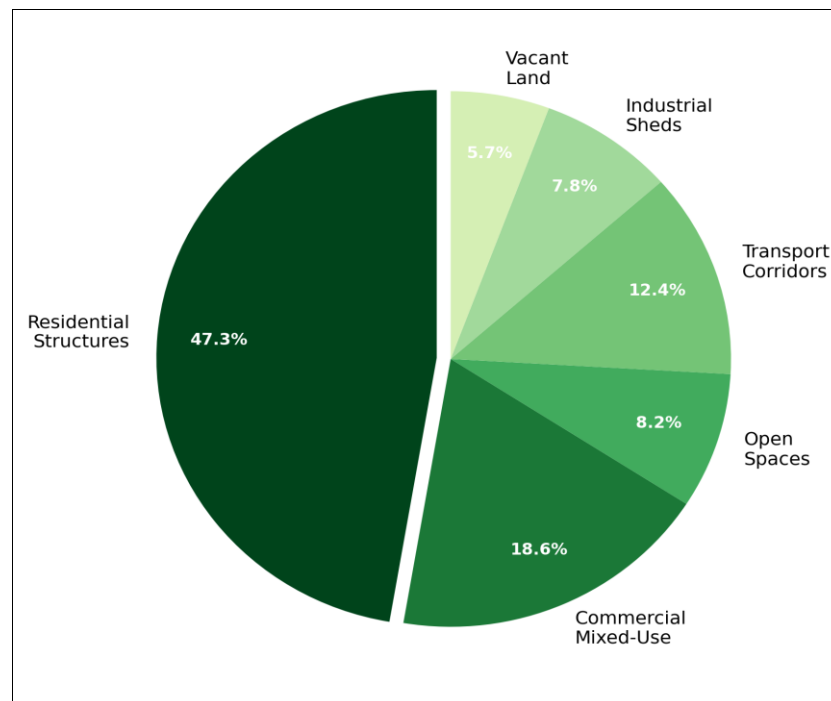


Fig 1: Land use composition within the six Nairobi informal settlements as of 2020. Residential structures account for 47.3% of the combined area.

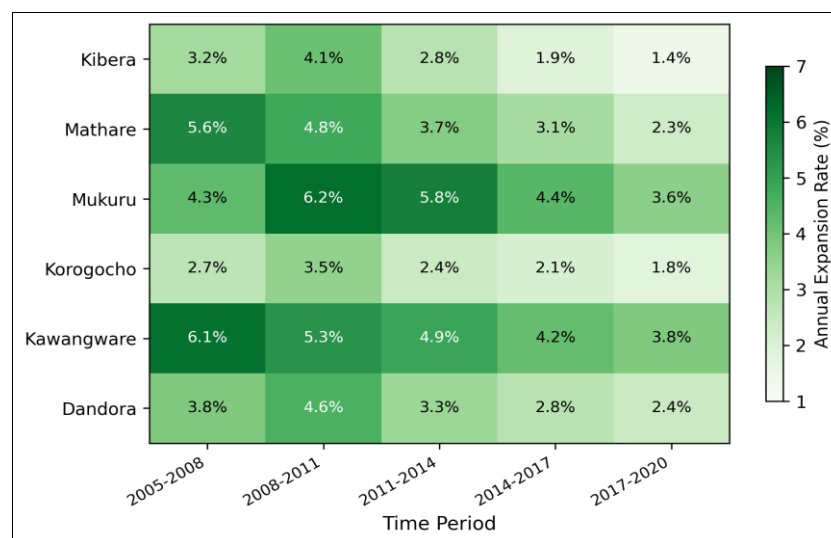


Fig 2: Annual spatial expansion rates (%) across six settlements and five time periods (2005-2020). Darker cells indicate faster growth.

Comprehensive Interpretation

The heatmap pattern (Figure 2) shows a general slowdown in expansion rates over the 15-year period for most settlements, with the exception of Mukuru and Kawangware which maintained relatively high rates through 2017-2020. This deceleration appears connected to physical barriers rivers, railway lines, and major roads that increasingly constrain outward spread in older, more centrally located settlements like Kibera and Korogocho.

Discussion

The overall expansion rate of 34.8% observed across the six settlements between 2005 and 2020 is broadly consistent with estimates from other East African cities, though lower than the 45-50% growth reported for Dar es Salaam's informal areas over a similar timeframe^[14]. The lower rate for Nairobi likely reflects the more advanced stage of infill development in some of its older settlements, particularly

Kibera, where lateral expansion has been constrained by railway infrastructure and the Nairobi Dam reservoir for decades^[15].

The divergence between settlements that primarily expanded outward (Kawangware, Mukuru) and those that densified vertically (Korogocho, Mathare) suggests that spatial context plays a dominant role in shaping growth pathways. Settlements with accessible open land on their periphery tend to sprawl, while those hemmed in by infrastructure or institutional land convert to multi-storey construction. This finding aligns with conceptual models of informal settlement evolution proposed by researchers working in South Asian cities^[16].

The 22.7% average increase in building heights has practical implications for risk assessment. Taller structures built without engineering oversight on poor foundations face higher vulnerability to collapse, particularly during seismic events or heavy rainfall that could undermine foundation

soils^[17]. The loss of open space from 14.6% to 8.2% of total settlement area also raises concerns about drainage capacity and recreational space availability.

Classification accuracy of 87.3% falls within the range typically reported for object-based analysis of informal settlement imagery, though it's somewhat lower than the 90%+ achieved in single-settlement analyses^[18]. The multi-site approach introduced greater land cover variability that may have reduced classifier performance, particularly in distinguishing commercial mixed-use from residential structures.

Conclusion

This research documented the spatial expansion and densification trajectories of six informal settlements in Nairobi over a 15-year period using sub-metre satellite imagery and object-based classification. The combined settlement footprint grew by 34.8%, with Mukuru and Kawangware expanding fastest, while Kibera and Korogocho shifted toward vertical densification as lateral expansion became constrained. Open space within settlements declined from 14.6% to 8.2% of the total area, and mean building heights rose by 22.7% on average.

These spatial patterns carry real implications for urban governance. Service delivery planning water, sanitation, electricity needs to account not just for footprint expansion but for population densification within existing boundaries. The building height data, while approximate, provides an early warning indicator for structural risk that could be incorporated into vulnerability mapping. Future work should integrate very high-resolution drone imagery to improve height estimates and explore machine learning classifiers to push accuracy above 90% across diverse settlement types. Ground-truthing frequency could also be increased to capture seasonal variations in settlement activity patterns, particularly around construction cycles during dry months.

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