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Urban Sprawl and Spatial Population Estimation Using High-Resolution Satellite Imagery in the Mouila Catchment Areas (Ngounié-Gabon)

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Abstract

Since the 1990s, Gabon has faced numerous difficulties in conducting its population censuses due to technical, financial, institutional and political reasons, as well as widespread disputes over the data once these censuses are completed. Indeed, the country is often faced with repeated delays and postponements between censuses, officially attributed to organisational constraints. Furthermore, the country is facing alarming urbanisation, particularly in the management of its catchment areas, which are subject to uncontrolled urban development, thereby exacerbating the risk of flooding. The aim of this study is therefore to assess urban dynamics and to estimate and model the spatial distribution of the population within the Mouila catchment areas in the Ngounié province of Gabon. In light of the challenges posed by urban expansion and traditional Gabonese censuses, we will rely on a 2008 orthophoto and a high-resolution SAS Planet 2023 image to manually digitise built-up areas in QGIS in order to produce our urban sprawl map.

The population was estimated by assigning 5 people per built unit, then spatialised using the ordinary kriging geostatistical method. The results reveal a 31.4% increase in built units and a spatial expansion of population density in the Manvouka, Doufoura, Doussama and Dourougni basins respectively. These extensions have developed from the city centre outwards towards the periphery. These very high densities follow the distribution of basic infrastructure. This satellite-based geostatistical approach offers a robust alternative for spatial planning and catchment management in a context of rapid urbanisation.

Keywords: Urban sprawl, Ordinary Krigeage, Population estimation, Catchment areas, Mouila, Gabon

1. Introduction

Africa is urbanising rapidly. Its urbanisation rate rose from 15% in 1960 to 40% in 2010, and is set to reach 60% by 2050 (BAFD/OECD/UNDP, 2017; UN-Habitat, 2010). Urbanisation is generally regarded as an indicator of development and wealth creation. It promotes investment, infrastructure development and a reduction in unemployment. However, it can lead to the emergence and deepening of inequalities, perpetuating the vicious circle of poverty and insecurity (Lachaud, 2006). Having a precise understanding of the state and dynamics of a population is an essential prerequisite for the effective management of a country's or region's economic and social development. Unfortunately, many developing countries, particularly in Africa, have little information in this area (Hansen et al. 2009).

Very high-resolution satellite imagery offers a new opportunity to observe settlements in detail. Population growth and its spatial distribution are important factors to consider for sustainable development (Digital Earth Africa, 2021). 'The population and housing census is one of the most complex and extensive undertakings a country can undertake in peacetime. In most low- and middle-income countries, the population and housing census is the primary source of data on population size and spatial distribution. Census data are essential for good governance, national development, risk reduction and crisis response, social protection programmes, and business market research. However, a census remains a costly and logistically challenging exercise and is ideally conducted once every ten years" (Juran et al., 2020). Effective, real-time estimates of population density are crucial for monitoring urban systems and disaster response (Yagoub et al., 2024).

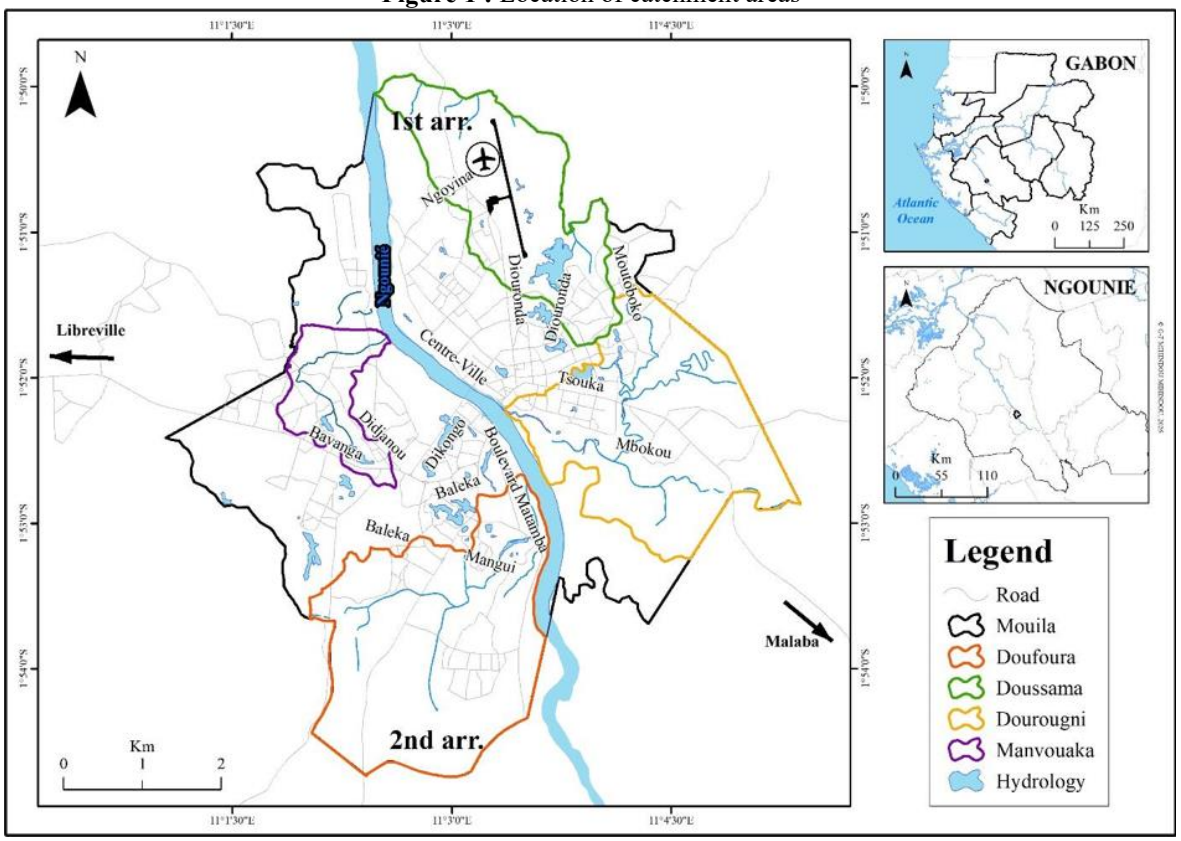
Gabon is no exception to this problem. Since the 1990s, Gabon has faced numerous difficulties in conducting its population census due to

technical, financial, institutional and political reasons. Indeed, the country is often faced with repeated delays and postponements between censuses, with successive postponements officially attributed to organisational constraints. The presence of numerous isolated areas that are difficult to access complicates the completeness of the count despite the deployment of thousands of enumerators. This makes it difficult to cover the entire territory. Unfortunately, when these censuses are finally completed, the reliability of the data is often disputed. Several past censuses have been rejected, namely those of 1970, 1980 and 2003. 'This mistrust is further exacerbated by the significant historical discrepancy between official figures and estimates from statistical services. The population census is also a major political issue. Demographic data lies at the heart of electoral controversies due to the issues surrounding voter registration' (Badji Samba Dialimpa, 2016). Analysis at the catchment level is even more important because it enables the precise identification of areas at risk of flooding, improves spatial planning and protects ecosystem services. In other words, estimating the population by catchment allows us to directly link water, safety and development issues to the actual functioning of the hydrological system. This study therefore aims to assess urban dynamics and to estimate and model the spatial distribution of the population within the Doufoura, Dourougni, Doussama and Manvouaka catchment areas in Mouila, in the Ngounié province of Gabon.

Location of the study area

Gabon is a country in Central Africa, situated within the Gabon River basin. It is divided into nine provinces, including Ngounié, which lies in the south-west of Gabon. This province covers 37,750 km², representing over 14% of the national territory, making it one of the country's largest provinces. Its capital is Mouila, situated right in the centre of the province, which takes its name from the Ngounié River (Figure 1). The town extends on both sides of this river. The Doufoura basin is situated to the south-west of Mouila. It covers an area of 767.11 ha, making it the largest basin in the municipality. The second-largest basin in the commune of Mouila is the Dourougni. This basin covers an area of 653.68 ha. Doussama, the north-eastern watershed of Mouila, covers an area of 461.85 ha. It is drained by the river of the same name and contains one of the largest lakes in Mouila, namely Lake Tombi. The Doussama River, which shares the same name, has tributaries such as the Pango and numerous lakes such as Ivora and Missouma. The Manvouaka catchment is located in the north-west of the municipality; it is drained by the river of the same name and the Moulingui. This catchment covers an area of 163.10 ha, making it the smallest of the four catchments studied.

Figure 1 : Location of catchment areas



Source: Based on the SDAU 2021 and field data from 2023

2. Methodology

This study explores an alternative or complementary method to traditional censuses, based on the integration of high-resolution satellite imagery, statistical models and data from field surveys. Thus, to analyse urban dynamics and estimate the population of the Doufoura, Dourougni, Doussama and Manvouaka catchment areas, we utilised these images and field observations, and applied geostatistical methods to estimate and spatialise the population.

2.1. Data used

To obtain the aerial data, we approached the Ngounié Provincial Directorate of Urban Planning, Surveying and Cadastral Affairs in Mouila, which provided us with an orthophoto from 2008. This image has a spatial resolution of 50 centimetres per pixel. The second image was obtained using the free, open-source software SAS Planet, utilising Maxar imagery with a high spatial resolution of 0.5 metres. We also used a PHANTOM 4 ADVANCED drone during our field observations (figure 2).

Figure 2 : Acquisition of drone imagery for validation of the digitisation

Source: Captured by drone (PHANTOM 4 ADVANCED)

2.2. Data analysis

2.2.1. Digitisation of built-up areas

Using the 2008 orthophoto and the 2023 Sas Planet image, we carried out a manual digitisation of the buildings (Figure 3). Overall, these aerial and satellite images are satisfactory for monitoring individual houses and highlight the forms of clustered housing, including the spatial organisation of the town (Essono Milla, 2022). As the catchment areas are relatively small Manvouaka (163.10 ha), Doussama (461.85 ha), Dourougni (653.68 ha) and Doufoura (767.11 ha) we encountered no difficulties during the digitisation process. The raster from SAS Planet was validated in the field. The figure 3 below illustrates the process of digitising buildings in QGIS 3.34.14.

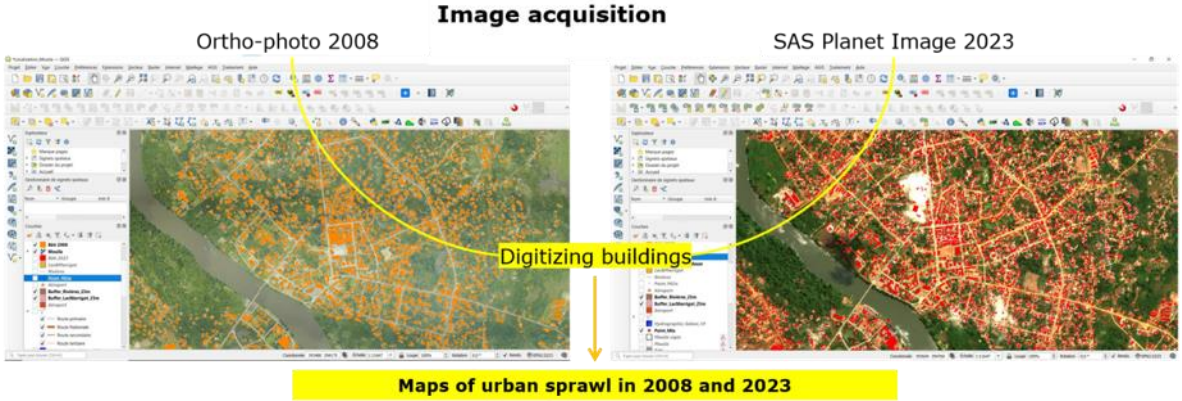


Figure 3 : Digitisation process in QGIS

2.2.2. Estimation of the population of the Mouila catchment areas

The population at the catchment level is estimated based on the number of dwellings identified using a satellite image, multiplied by the average household size. According to the 2013 General Population and Housing Census, the average size of a standard household is 4.1 people per household. However, for our study, we have assumed 5 people per

household, as used by Rapoport (2002), Libongui (2023) and MIHINDOU MIHINDOU (2024). This choice is based on the fact that we treat ordinary and collective households without distinction, and on field surveys that enabled us to validate this approach. Furthermore, the lack of verticality (high-rise construction) in the municipality of Mouila (Mambani 2007) limits bias in the population estimate. From the above, one might be tempted to say, quite rightly, that Mouila is a horizontal town.

This method of population counting using aerial photographs has already been employed by numerous authors to determine population size in developing countries (Abdalla Elsadig 1988; Dureau and Barbary 1990; Darin, Kuépié, Bassinga, Boo, and Tatem 2022; Neal et al. 2022). The lack of high-quality satellite data led us to analyse population growth and population density in the catchment areas from 2008 to 2023. To do this, we used vector data derived from the digitisation of built-up areas from the 2008 Orthophoto and a very high-resolution SAS Planet image from 2023 to determine the population of our catchment areas. A grid with 100-metre squares (Figure 4) was created, from which centroids were generated to count the number of dwellings within each grid cell. This was used to determine the population per grid cell (the number of dwellings in the cell multiplied by 5) and to calculate population density using ordinary kriging.

The results of this analysis enabled us to establish five categories: Very low (0–5), Low (0–15), Medium (15–30), High (30–45) and Very high (45 and above). Thus, to calculate population density, we proceed as follows:

$$\text{Density} = \frac{Population}{Area\ in\ hectares}$$

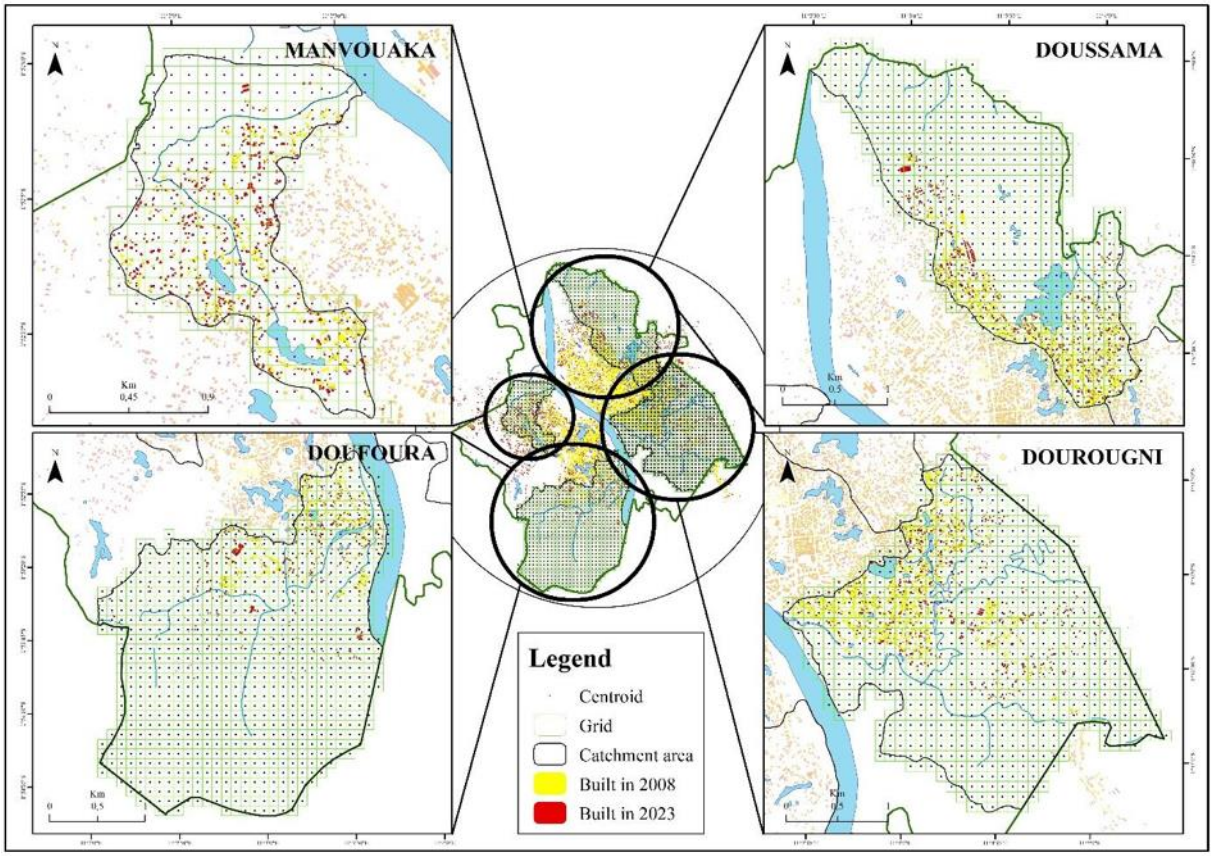
2.2.3. Method for spatialising population density

Kriging is an advanced geostatistical procedure that generates an estimated surface from a scattered set of points with Z-values. The family of interpolation methods includes geostatistical techniques (such as kriging) that are based on statistical models incorporating autocorrelation, i.e. the statistical relationships between the measured points. The Kriging tool applies a mathematical function to all points, or specific points, located within a precise radius. It determines the output value for each location (ESRI, n.d.). The semi-variogram model used is spherical with a variable radius, allowing the range of spatial correlation to be adapted according to the data distribution. We validated our model using a qualitative method based on urban structure. Specifically, we compared built-up corridors with the densities estimated by ordinary kriging, which correspond to urban development axes. As Mouila is a 'horizontal city', urban sprawl was reflected in the interpolation. This spatial concordance between the model results and the urban morphology confirms the validity of our approach. This

analytical method was used to interpolate population density within the catchment areas. Indeed, after determining the population based on centroids spaced 100 m apart (Figure 4). Ordinary kriging, by taking into account the spatial structure of the data, provides continuous and robust estimates of population density in the catchment areas of Mouila. We favoured ordinary kriging over kernel density mapping or dasymetric mapping because it incorporates spatial dependence and allows for the production of continuous surfaces.

Z(si) = value measured at location i
λi = unknown weighting of the value recorded at location i
S0 = prediction location N = number of recorded values

Figure 4 : 10 000 m² grid of built-up areas from 2008 and 2023



Source: Based on the 2008 orthophoto and the 2023 Sas Planet image.

3. Results

3.1. Changes in the built environment

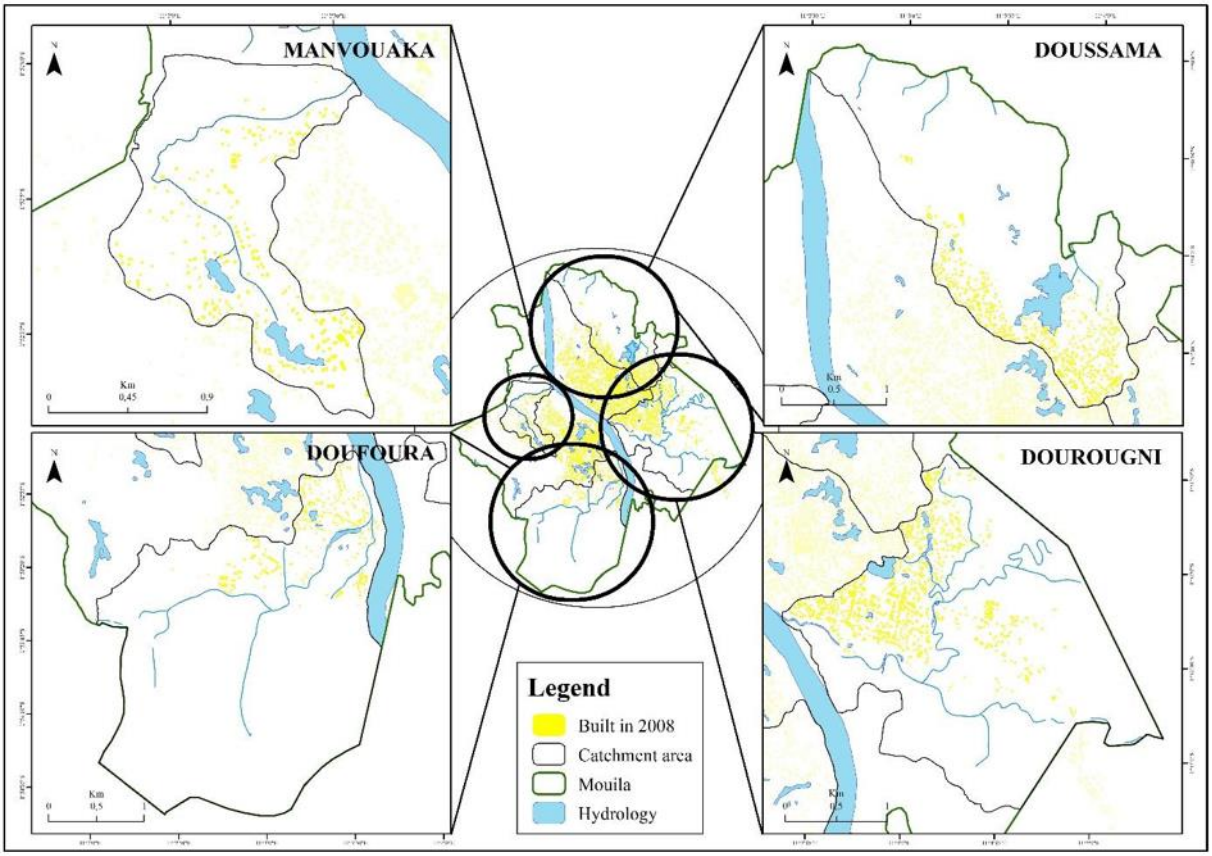
Cities are growing at an average rate of 3.5% per year. By 2050, Africa is expected to have nearly one billion more inhabitants, with its

population rising from 1.5 to 2.5 billion. 80% of this population growth will occur in cities (Centre for Strategic Studies in Africa, 2025).

3.1.1. State of the built environment in 2008

The built environment in 2008 within the Doufoura, Dourougni, Doussama and Manvouaka catchment areas is characterised by a distribution centred on the urban centre of the municipality of Mouila (Figure 5). Thus, concentrations of buildings are located in the north and centre-west of the first catchment, in the north and north-east of the second, in the south and centre-west of the third, and are rather scattered in the last catchment.

Figure 5 : Building constructed in 2008



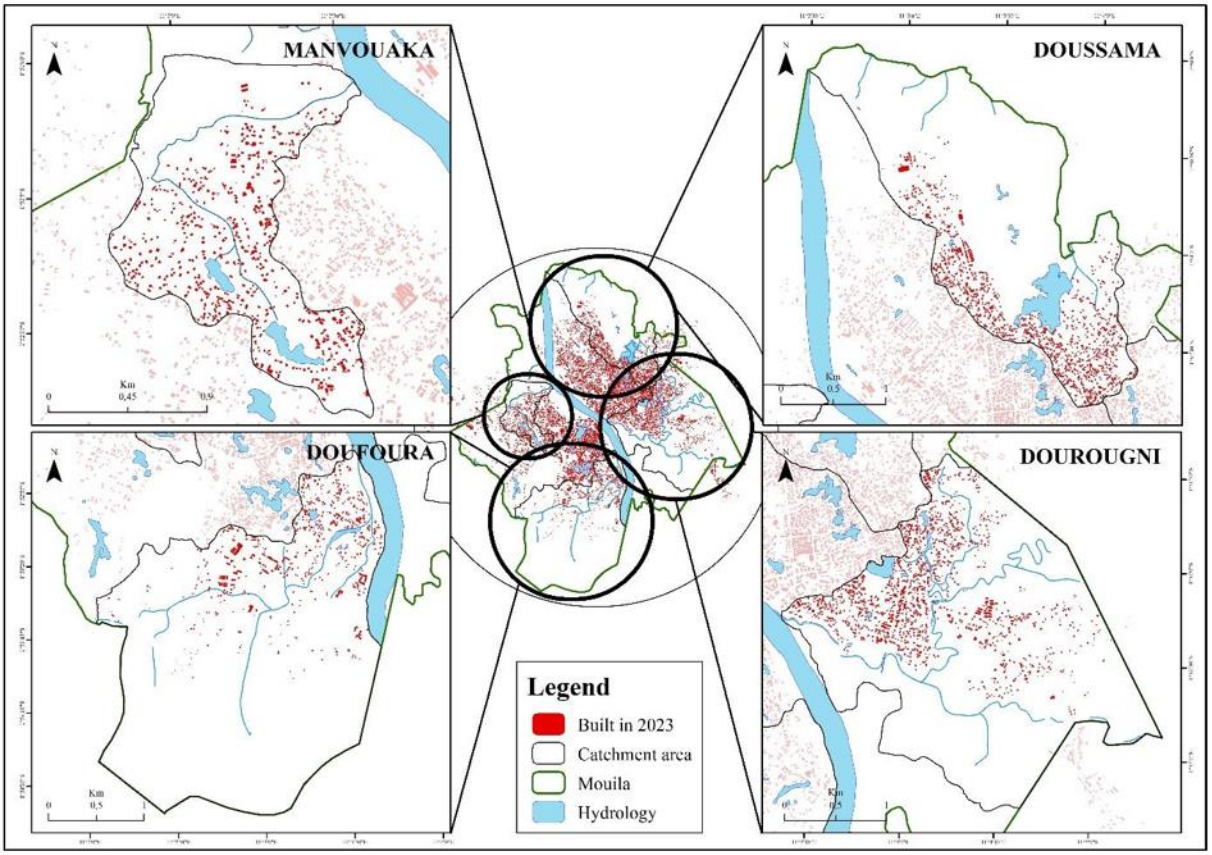
Source: Based on the 2008 orthophoto

3.1.2. Status of the built environment in 2023

The map below shows the distribution of built-up areas in 2023. It reveals a concentration of buildings in the south, in the Doussama and Manvouaka catchment areas, and a high density of built-up areas in the north, in the Doufoura and Dourougni catchment areas. This rather distinctive distribution of built-up areas within these catchment areas follows

the pattern of the distribution of water, electricity and administrative infrastructure. The town centre of Mouila is home to the municipality's main infrastructure. Further expansion is expected to continue to follow this pattern, to the detriment of the wetlands in the municipality of Mouila.

Figure 6 : Building unit constructed in 2023

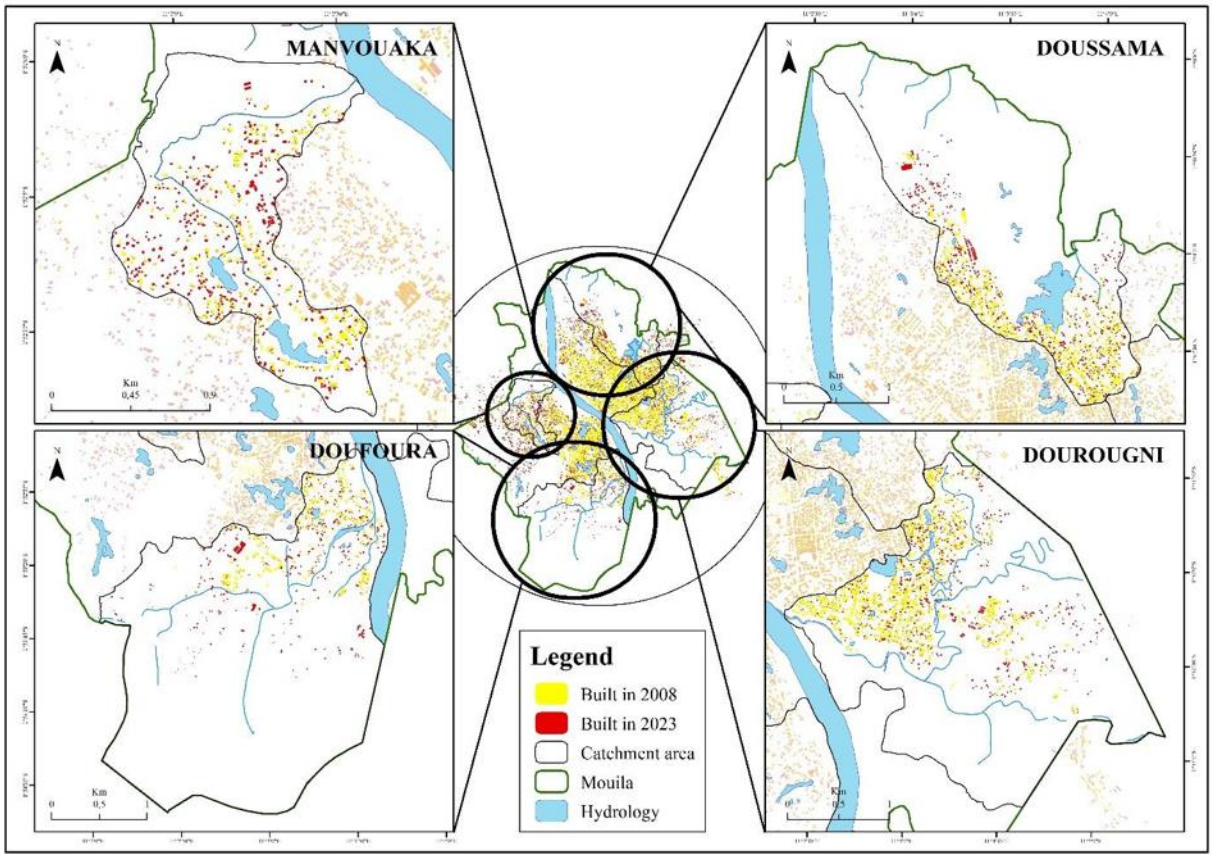


Source: Based on the image by SAS Planet 2023

3.1.3. Urban trends from 2008 to 2023

Urbanisation remains a pressing issue across the whole country, particularly in Mouila. The aim of this section is to analyse urban sprawl between 2008 and 2023 in the Doufoura, Dourougni, Doussama and Manvouaka catchment areas. Figure 7 shows the development trends of built-up areas in these catchment areas within the municipality of Mouila. New construction extensions can be observed in the centre of Doufoura and in the south-west of Dourougni. In Doussama, new developments have taken place in the central-western and south-eastern areas. In contrast, in Manvouaka, built-up areas are spreading in a diffuse manner, mainly in the centre and north-east.

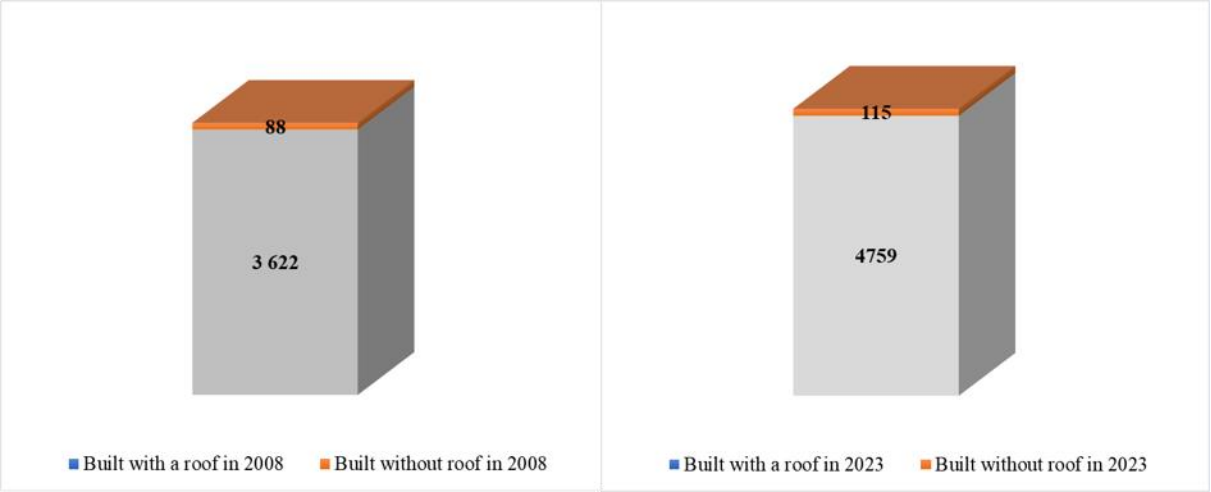
Figure 7 : Changes in built-up areas between 2008 and 2023



Source: Based on the 2008 orthophoto and the 2023 SAS Planet image

The digitisation of the built environment has enabled us to distinguish between buildings with and without roofs (Figure 8). There is a clear predominance of buildings with roofs in all four areas, both in 2008 and in 2023. To estimate our population, we only took into account buildings with roofs. This is because, during our fieldwork, we did not observe anyone living in this type of dwelling, and no one reported living there. We stand by this information as we are from the local area.

Figure 8 : Built with and without a roof in 2008 and 2023



Source: Based on the 2008 orthophoto and the 2023 SAS Planet image

3.2. Estimating population growth

Analysing population trends is essential for estimating the areas that need to be made available for development to accommodate these populations and to build the facilities and infrastructure required to support this growth. The aim is to plan how the urban area will develop to accommodate these additional residents: land area, location, and supporting measures (Mouila SDAU, 2021). Population growth in the Mouila catchment areas has increased significantly (Table 1). Across all the catchments, the population has risen from 18,110 in 2008 to 23,795 in 2023, representing an increase of 5,685 people. More specifically, there has been sustained growth over the last 15 years, in ascending order, in the Manvouaka, Doufoura, Doussama and Dourougni catchments. Indeed, between 2008 and 2023, the population of the Manvouaka catchment area more than doubled, rising from 1,760 inhabitants to 3,785 inhabitants – an increase of 2,025 inhabitants over 15 years. In the Doufoura catchment area, there has been a fairly significant increase in the number of inhabitants. Doufoura's population increased by 1,805 inhabitants between 2005 (2,075 inhabitants) and 2023 (3,880 inhabitants). The Doussama basin has experienced fairly strong growth, with an increase of 1,285 inhabitants observed over the same period. The Dourougni catchment area saw the lowest growth, with 570 inhabitants (Table 1). A number of factors could explain this growth in these areas, particularly access to land.

Table 1: Population estimates and density in 2008 and 2023

Manvouaka					
Built in 2008	**Population**	**Density (inh./ha), 2008**	**Built in 2023**	**Population**	**Density (inh./ha), 2023**
352	1, 760	**10.79**	757	3, 785	**23.21**
Doufoura					
Built in 2008	**Population**	**Density (inh./ha), 2008**	**Built in 2023**	**Population**	**Density (inh./ha) 2023**
415	2, 075	**2.70**	776	3, 880	**5.06**
Doussouma					
Built in 2008	**Population**	**Density (inh./ha), 2008**	**Built in 2023**	**Population**	**Density (inh./ha), 2023**
1 204	6, 020	**13.03**	1, 461	7, 305	**15.82**
Dourougni					
Built in 2008	**Population**	**Density (inh./ha), 2008**	**Built in 2023**	**Population**	**Density (inh./ha), 2023**
1 651	8, 255	**12.63**	1, 765	8, 825	13.50

Source: Glenn-Freddy MIHINDOU MIHINDOU, 2026; based on the 2008 orthophoto and the 2023 SAS Planet image

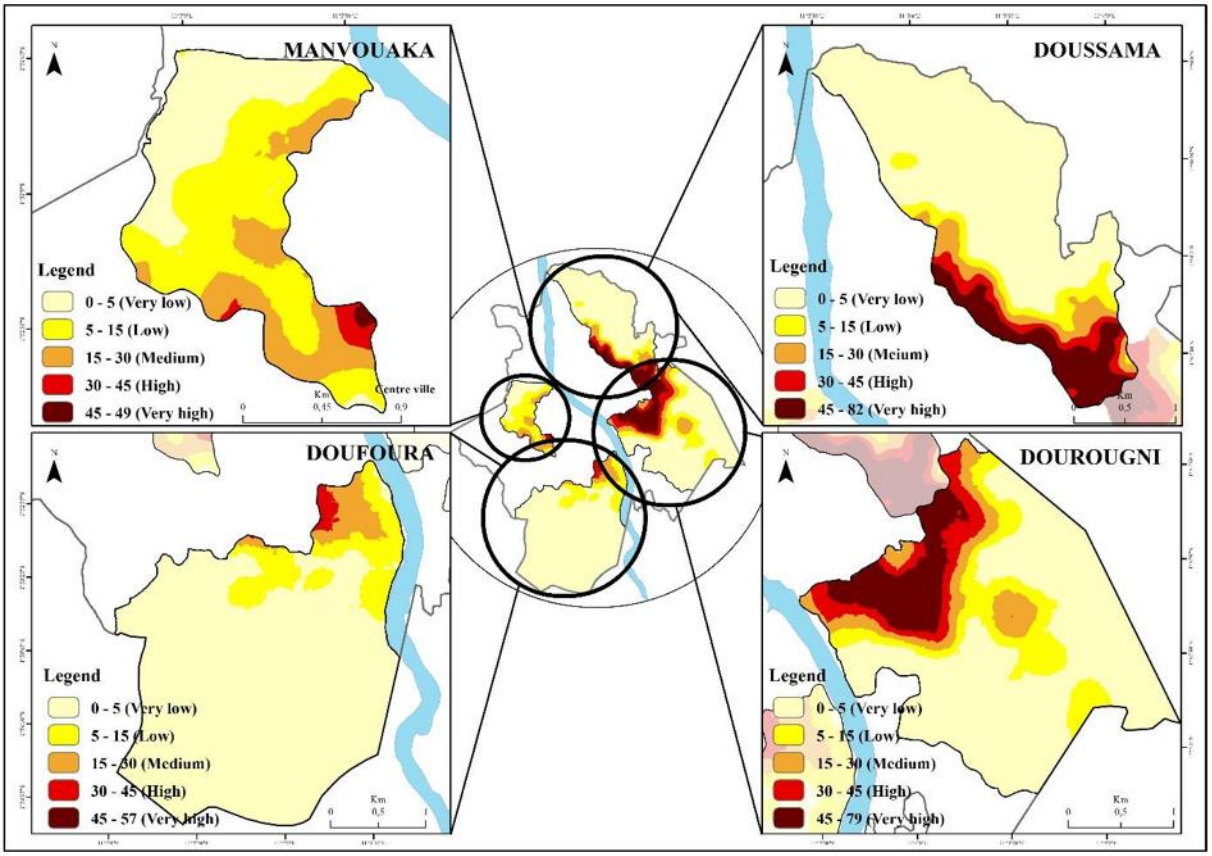
3.3. Spatial modelling of population density

The population density maps show the results obtained using the kriging interpolation method. They present a mapping of population density in the four main catchment areas of Mouila for 2008 and 2023. Generally speaking, very high population density is observed in the north of the Doufoura and Dourougni catchments. In contrast, in the Manvouaka and Doussama catchments, the very high density is mainly located in the south of these catchments.

3.3.1. Modelling of population density in 2008

In 2008, population density in the Manvouaka catchment was predominantly very low, with the few areas of very high concentration located in the south-east. The same applies to the Doufoura basin, which was mainly very sparsely populated but had a fairly high population density in its northern part. The Dourougni basin has a much more pronounced population density, particularly in the north, where high and very high population densities are observed, with an average population density at its centre. Characterised by a very high and conspicuous population density in the south and south-west, the Doussama basin shows a contrast in density between its sparsely populated north and its densely populated south. In 2008, the population density in the Manvouaka catchment area was This is thought to be due to the southern part of the area's proximity to the city centre. The same phenomenon is observed in all the other catchment areas, where very high population densities are found in areas close to the city centre (Figure 9).

Figure 9: Population density in 2008

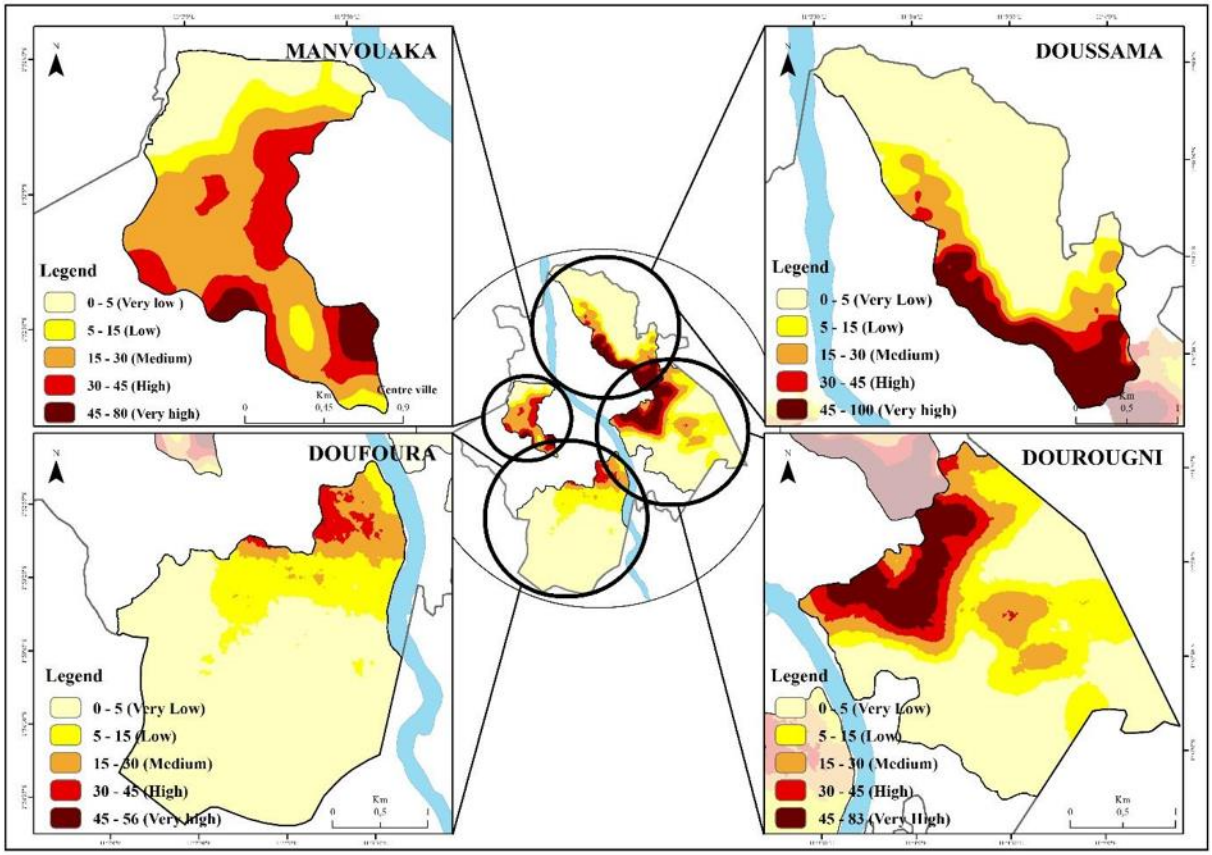


Source: Glenn-Freddy MIHINDOU MIHINDOU, 2026; based on the 2008 orthophoto

3.3.2. Population density in 2023

In 2023, population density across the four catchment areas increased relatively across the board (Figure 10). The Doussama catchment area is the prime example of this. Very high population densities are now observable not only in the south but also in the east and west. The so-called 'medium' density has also gained ground, dominating almost the entire central-western part of the catchment. In the Doufoura catchment, there is instead an increase in the so-called 'medium' and 'low' density categories, with a very high-density concentration in the north, just as in the Dourougni catchment. In Doussama, the density remains relatively very high not only in the south but also in the west and north-east, with an increase in the low-density category in the north-west and north-east. This population growth, marked by these sharply rising population densities, is explained by various factors. Economic prosperity and the pro-natalist policy advocated by the state would explain this population growth.

Figure 10 : Population density in 2023



Source: Glenn-Freddy MIHINDOU MIHINDOU, 2026; based on the image by SAS Planet 2023

Discussion

This section compares the validity of the urban dynamics results and population estimates derived from high-resolution satellite imagery with previous studies.

The analysis of urban dynamics shows a significant increase in built-up areas across the four main catchment areas of the municipality of Mouila. Over a 15-year period, the catchment areas of Doufoura, Dourougni, Doussama and Manvouaka have seen a 31.4% rise in built-up units. This urbanisation follows a concentric pattern, spreading from the city centre towards the periphery, as also identified by Essono Milla (2022), Biboutou (2022), Okanga-Guay (2013) and Bloc-Duraffour (1998). This average annual growth rate of 1.8% corroborates the estimates of the SDAU in Mouila (2021), which reported a similar rate of 2% between 2003 and 2018. The catchment area that has experienced the strongest urban growth is the Manvouka catchment area, due to its proximity to the city centre but also

because of developments carried out over the last decade, such as access to water and electricity. The Dourougni basin has seen the slowest growth, due to the fact that it has been neglected by the relevant authorities, as this basin suffers from a glaring lack of road infrastructure, water supply and waste management systems. This trend is consistent with the work of Mihindou Mihindou et al. (2025), Okanga-Guay (2013), Nguema (2005) and Engo Assoumou (2007), who describe a similar pattern of urbanisation in Gabonese cities, where construction follows existing infrastructure corridors such as the water and electricity networks.

Estimating the population by multiplying the number of dwellings by 5 people per household (Rapoport 2002; Libongui 2023 and MIHINDOU MIHINDOU 2024) provides support and/or a complementary alternative to the RGPL, which takes place every ten years and whose results are consistently contested in Gabon. This method, validated by numerous authors (Darin et al. 2022; Hallot et al. 2020; Neal et al. 2022; Yagoub et al. 2024), who view it as a promising method for providing frequent and reliable demographic estimates at the local level. The disparity in population trends between catchment areas highlights local factors such as access to land and proximity to the city centre.

Knowledge of population distribution is essential for infrastructure development and resource allocation. Although censuses can provide this information, in Gabon they are conducted only once every ten years. The population may change between censuses due to rapid migration, development and natural disasters. Population estimation approaches independent of censuses, which use alternative data sources such as satellite imagery, have shown promise in providing frequent and reliable population estimates at the local level (Neal et al. 2022). This approach, combining manual digitisation of built-up areas, fieldwork and geostatistical modelling, provides decision-support information for policymakers.

Conclusion

At the end of this article, entitled ‘Urban sprawl and spatial population estimation using high-resolution satellite imagery in the Mouila catchment areas (Ngounié, Gabon)’, we have assessed urban dynamics and estimated and modelled the spatial distribution of the population in the Doufoura, Dourougni, Doussama and Manvouaka catchment areas using two high-resolution images, geostatistics and the ordinary kriging spatial model. It is worth noting that population growth in the catchment areas of the municipality of Mouila has intensified remarkably over the last 15 years. Across all catchment areas, the population has risen from 18,110 inhabitants in 2008 to 23,795 inhabitants in 2023, representing an increase of 5,685 inhabitants. Population density has also increased, even doubling in the

Manvouaka and Doufoura catchments. Significant increases are also observable in the Dourougni and Doussama catchments.

Conflict of Interest: The authors reported no conflict of interest.

Data Availability: All data are included in the content of the paper.

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