

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

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Abstract

Gabon has experienced many difficulties since the 1990s in conducting its population census due to technical, financial, institutional, and political reasons, as well as numerous disputes over the data when these censuses are completed. Indeed, the country is often confronted with delays and repeated postponements between two censuses, officially linked to organizational constraints. In addition, the country faces alarming urbanization, particularly in the management and planning of its watersheds, which are subject to uncontrolled urbanization, thereby increasing the risk of flooding. Thus, this study aims to evaluate urban dynamics, estimate, and model the spatial distribution of the population in the watersheds of Mouila in the Ngounié province of Gabon. Faced with the challenges of expanding urbanization and traditional Gabonese censuses, we rely on a 2008 orthophoto and a 2023 high-resolution SAS Planet image to manually digitize the built-up areas in QGIS to obtain our map of urban sprawl. The population was estimated by assigning

5 persons per built unit, then spatialized using the geostatistical method of ordinary kriging. The results reveal an increase of 31.4% in built units and a spatial extension of population density in the Manvouaka, Doufoura, Doussama, and Dourougni basins. These extensions occurred from the city core towards the periphery. These very high densities follow the presence of basic infrastructure. This satellite-geostatistical approach offers an alternative for territorial planning and watershed management in a context of strong urban growth.

Keywords: Urban sprawl, Geostatistics, Population estimation, Watershed, Mouila–Gabon

1. Introduction

Africa is rapidly urbanizing. Its urbanization rate increased from 15% in 1960 to 40% in 2010, and will reach 60% by 2050 (BAFD/OCDE/PNUD, 2017, p. 242; ONU-Habitat, 2010, p. 41). Urbanization is generally considered an indicator of development and wealth creation. It promotes investment, infrastructure construction, and unemployment reduction. However, it can lead to the emergence and deepening of inequalities, maintaining the vicious circle of poverty and insecurity (Lachaud, 2006, p. 478). Knowing precisely the state and dynamics of a population is an essential condition for the proper management of the economic and social development of a country or region. Unfortunately, many developing countries, particularly in Africa, have little information in this area (Hansen et al., 2009, p. 16). Very high-resolution satellite images are a new opportunity to observe habitats in detail.

Demographic growth and its spatial distribution are important factors to consider for sustainable development (Digital Earth Africa, 2021). “The population and housing census is among the most complex and extensive exercises undertaken by a country in peacetime. In most low- and middle-income countries, the population and housing census is the main source of data on the number of inhabitants and their spatial distribution. Census data are essential to ensure good governance, national development, risk reduction and crisis response, social protection programs, and business market studies. However, a census remains a costly and logistically difficult exercise and is ideally conducted once every ten years” (Juran et al., 2020, p. 1). Effective and real-time estimates of population density are crucial for monitoring urban systems and disaster response (Yagoub et al., 2024, p. 1).

Gabon is not exempt from this issue. Since the 1990s, Gabon has faced numerous difficulties in conducting its population census due to technical, financial, institutional, and political reasons. The country is often confronted with delays and repeated postponements between two censuses, officially linked to organizational constraints. The presence of many remote areas that

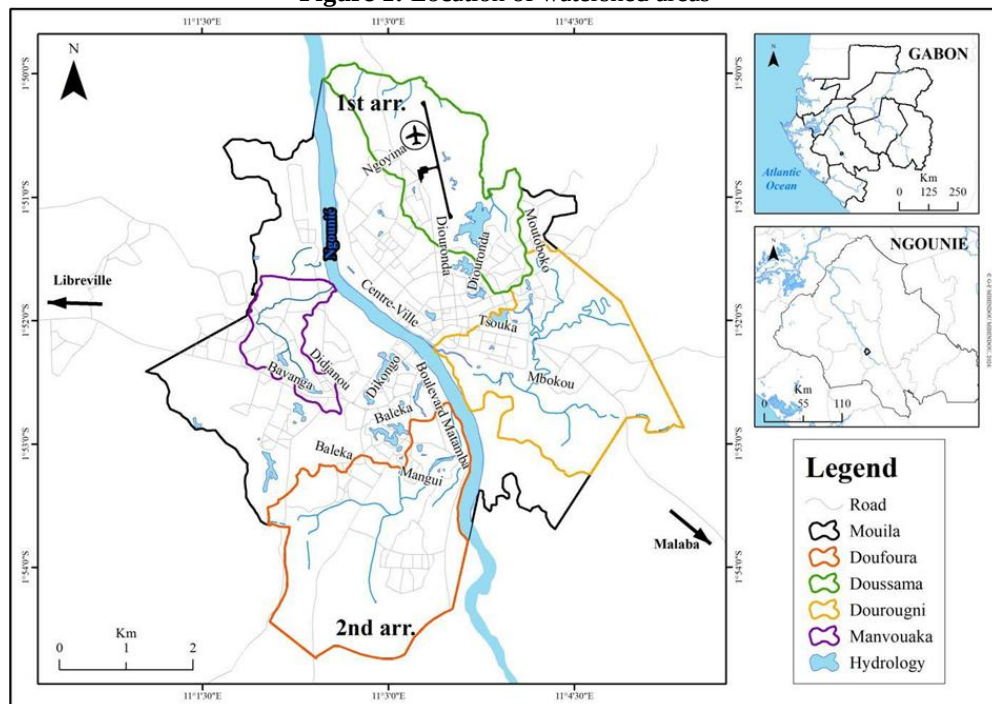
are difficult to access complicates the exhaustiveness of the enumeration despite the deployment of thousands of agents, making it difficult to cover the entire territory. Unfortunately, when these censuses are completed, they are often contested regarding the reliability of the data. Several past censuses were rejected, namely those of 1970, 1980, and 2003. “This mistrust is further accentuated by the significant historical gap between official figures and estimates from statistical services. The population census is also an important political issue. Demographic data are at the heart of electoral controversies due to issues related to voter registration” (Badji Samba Dialimpa, 2016).

Analysis at the watershed scale is even more important because it allows precise localization of areas exposed to flood risks, improvement of territorial planning, and protection of ecosystem services. In other words, estimating the population by watershed makes it possible to directly link water, security, and planning issues to the actual functioning of the hydrological system. Thus, this study aims to evaluate urban dynamics, estimate, and model the spatial distribution of the population in the watersheds of Doufoura, Dourougni, Doussama, and Manvouaka in Mouila, Ngounié Province, Gabon.

1.1. Study area location

Gabon is a Central African country, dependent on the Gabon basin. It is divided into nine provinces, including Ngounié, located in the southwest of Gabon. This province covers 37,750 km², representing more than 14% of the national territory, making it one of the largest provinces in the country. Its capital is Mouila, located in the center of the province, which takes its name from the Ngounié River (Figure 1). The city develops on both sides of this river. The Doufoura watershed is located southwest of Mouila. It has an area of 767.11 ha, making it the largest watershed of the commune. The second largest watershed of Mouila is Dourougni, with an area of 653.68 ha. Doussama, a watershed in the northeast of Mouila, has an area of 461.85 ha. It is drained by the river of the same name and contains one of the largest lakes of Mouila, namely Lake Tombi. With the same name, the Doussama River has tributaries such as Pango and several lakes such as Ivora and Missouma. The Manvouaka watershed is located northwest of the commune, drained by the river of the same name and Moulingui. This watershed has an area of 163.10 ha, making it the smallest of the four studied watersheds.

Figure 1: Location of watershed areas



Source: Based on the SDAU of Mouila (2021) and field data from 2023, by the authors

2. Methodology

This study explores an alternative or complementary method to the traditional census, based on the integration of high-resolution satellite images, statistical models, and data from field surveys. Thus, to analyze urban dynamics and estimate the population of the Doufoura, Dourougni, Doussama, and Manvouaka basins, we used these images and field observations and applied geostatistical methods to estimate and spatialize the population.

2.1. Data used

To acquire aerial data, we requested the provincial directorate of urban planning, topographic works, and cadastre of Ngounié in Mouila, which provided us with an orthophoto from 2008. This image has a spatial resolution of 50 centimeters per pixel. The second image was obtained via the free and open-source software Sas Planet, using the Maxar imagery background with a spatial resolution of 0.5 m. We also used a Phantom 4 Advanced drone during our field observations (Figure 2). All these images are in the World Geodetic System 1984 (WGS 84).

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



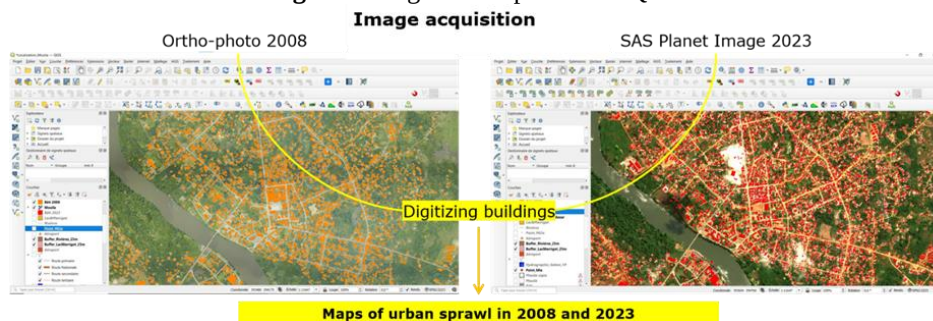
Source: Captured by drone (Phantom 4 Advanced) in 2024, by the authors

2.2. Data analysis

2.2.1. Digitization of built-up areas

From the orthophoto of 2008 and the Sas Planet image of 2023, we carried out the manual digitization of constructions (Figure 3). Overall, these aerial and satellite supports are satisfactory for monitoring individual houses and highlight the forms of grouped housing, including the spatial organization of the city (Essonno Milla, 2022, p. 24). Since the basins are relatively small in size Manvouaka (163.10 ha), Doussama (461.85 ha), Dourougni (653.68 ha), and Doufoura (767.11 ha) — we encountered no difficulty in the digitization process. The raster from Sas Planet was validated in the field. The figure below illustrates the process of building digitization in QGIS 3.34.14.

Figure 3: Digitization process in QGIS



Source: Orthophoto of 2008 and the Sas Planet image of 2023, by the authors

2.2.2. Estimation of the population of the Mouila watershed 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.

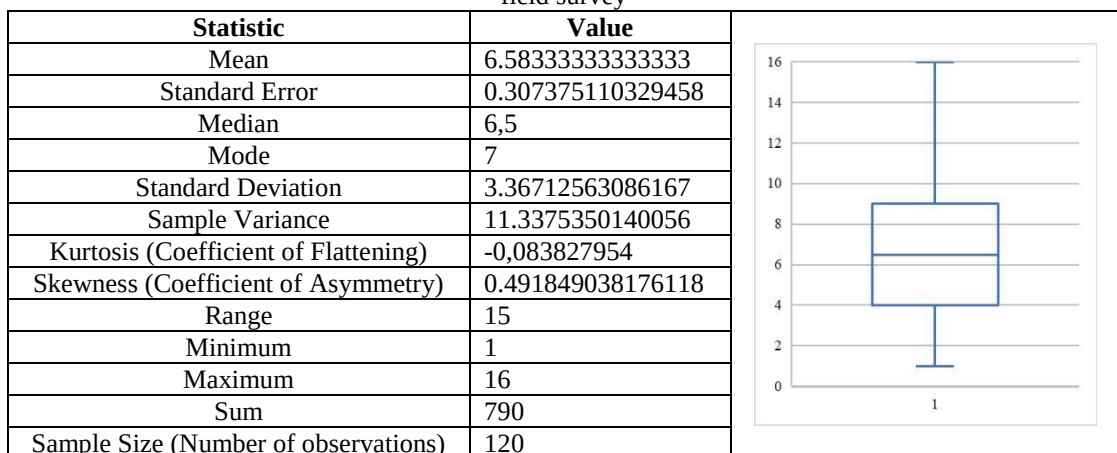
However, for our study, we have assumed 5 people per household, as used by Rapoport (2002, p. 154), Libongui (2023, p. 268), and Mihindou Mihindou (2024, p. 88). This choice is based on the fact that we treat ordinary

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, p. 114) limits bias in the population estimate. From the above, one might be tempted to say, quite rightly, that Mouila is a horizontal town.

We also conducted a household field survey to validate our choice of the average household size in our watersheds. During our field visits, 120 households, 30 per watershed, were interviewed using random sampling. Since the baseline population was unknown for each watershed, we relied on the “rule of 30” $n \geq 30$, an empirical rule rooted in the Central Limit Theorem. Kwak and Kim (2017: 148) state that, as the degrees of freedom increase, the Student’s t-distribution tends toward the normal distribution. With 30 degrees of freedom, the Student’s t-distribution is considered equivalent to the normal distribution (Kim, 2015, p. 543). Therefore, when the sample size is 30, the studentized sampling distribution approaches the standard normal distribution, and assumptions regarding the population distribution become less important because the sampling distribution is considered normal, in accordance with the Central Limit Theorem (Kwak and Kim, 2017, p. 148). However, it should be emphasized that time and financial resource constraints did not allow us to extend our sampling as we had wished in the field. The 30 samples were randomly distributed within each basin according to accessibility and age (we prioritized adults over 21 years old).

Field observations show that the median household size is 6.5, with most households consisting of 6 to 7 people (Figure 4). This means that the value of 4.1 underestimates local specificities. The surveyed households are larger than the national average. Using 5 as the reference value is more representative of local conditions and reduces the bias by 0.9 persons.

Figure 4: Descriptive statistics of the number of people per household obtained from the field survey



Source: Field data collected in 2024 by the authors

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, p. 132; Dureau and Barbary, 1990, p. 64; Darin et al., 2022, p. 467; Neal et al., 2022, p. 2). 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 digitization 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 5) 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 (5,01-15), Medium (15,01-30), High (30,01-45), and Very high (45,01 and above). Thus, to calculate population density, we proceed as follows:
$$\text{Density} = \frac{\text{Population}}{\text{Area in hectares}}$$

2.2.3. Method for spatializing population density

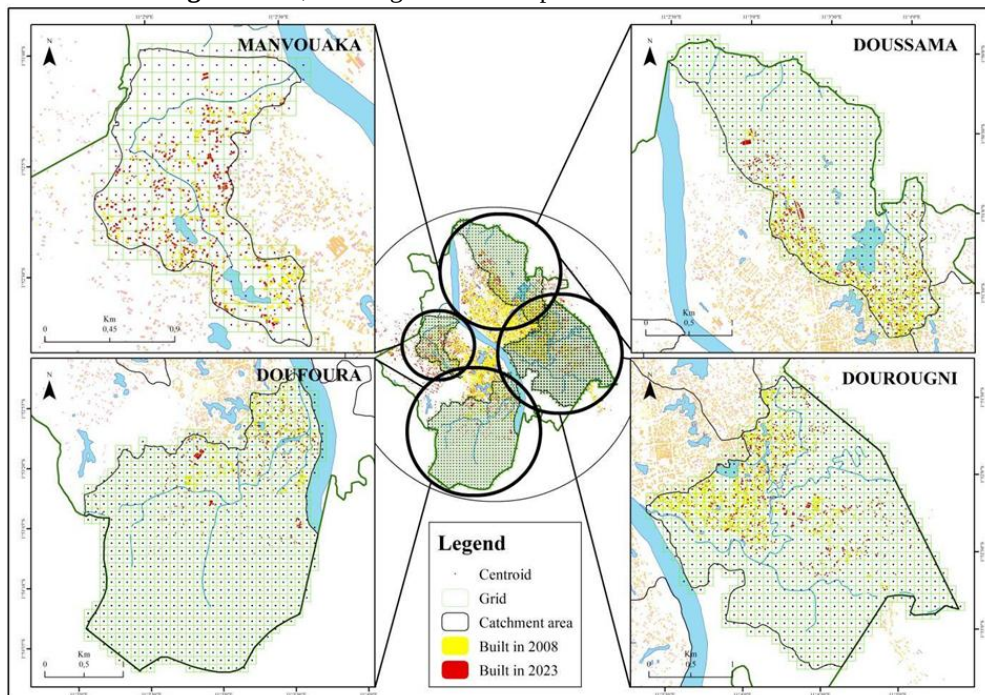
Kriging is an advanced geostatistical procedure that generates an estimated surface from a dispersed set of points with Z values. The family of interpolation methods includes geostatistical techniques (such as kriging) that are based on statistical models, including autocorrelation, that is, the statistical relationships between the measured points. The kriging tool applies a mathematical function to all points, or certain determined points, located within a specific radius. It determines the output value of each location (ESRI, n.d.). The selected semivariogram model is of the spherical type with a variable radius, allowing the adaptation of the range of spatial correlation according to the distribution of the data. We compared our model using the qualitative method based on urban structure. Indeed, we verified the built corridors with the densities estimated by ordinary kriging corresponding to the axes of urban development. As Mouila is a “horizontal city,” urban sprawl was reflected in the interpolation. This spatial concordance between the results of the model and the urban morphology confirms the relevance of our approach. This method of analysis was used to interpolate the population density in the watersheds. Indeed, after having determined the population from the centroids spaced 100 m apart (Figure 5), ordinary kriging, taking into account the spatial structure of the data, provides continuous estimates of population density in the watersheds of Mouila. We favored ordinary kriging, unlike kernel density mapping or dasymetric mapping, because it integrates spatial dependence and makes it possible to produce continuous surfaces.

The general formula used for kriging consists of a weighted sum of the data : $Z^*(S_0) = \sum_{i=1}^N \lambda_i Z(S_i)$

Where :

- $Z(S_i)$ = measured value at location i
- λ_i = unknown weight of the value recorded at location i
- S_0 = prediction location
- N = number of recorded values

Figure 5: 10,000 m² grid of built-up areas from 2008 and 2023



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

3. Results

3.1. Changes in the built environment

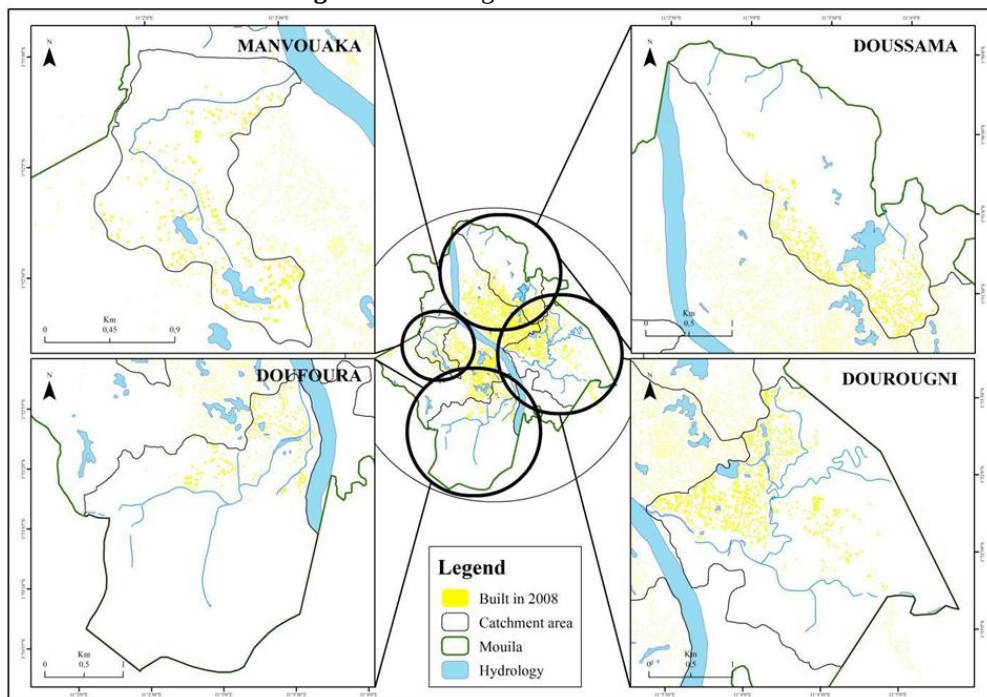
Cities are developing at an average rate of 3.5% per year. By 2050, Africa should have nearly one billion additional inhabitants, its population increasing from 1.5 to 2.5 billion. Eighty percent of this demographic growth will occur in cities (Centre d'études stratégiques de l'Afrique, 2025, p. 2).

3.1.1. State of the built environment in 2008

The built environment in 2008 in the watersheds of Doufoura, Dourougni, Doussama, and Manvouaka is characterized by a location following the urban center of the commune of Mouila (figure 6). Thus, the concentrations of constructions are located in the north and center-west in the

first basin, in the north and northeast in the second, in the south and center-west in the third, and a rather diffuse occupation in the last basin.

Figure 6: Building constructed in 2008

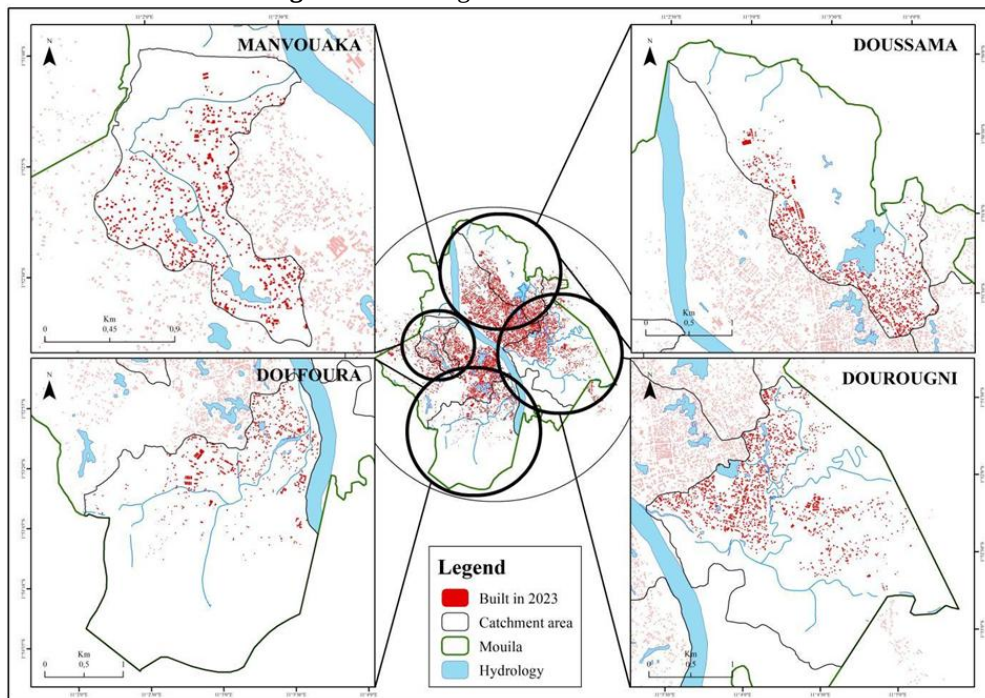


Source: Based on the 2008 orthophoto

3.1.2. Status of the built environment in 2023

The map below shows the distribution of built units in 2023. It indicates a concentration of construction in the south for the basins of Doussama and Manvouaka, and a density of built-up areas in the north of the basins of Doufoura and Dourougni (figure 7). This rather particular distribution of the built environment in these watersheds follows the logic of the distribution of water, electricity, and administrative infrastructures. The city center of Mouila has the main infrastructures of the commune. The new expansions should continue to follow this logic to the detriment of the wetlands of the commune of Mouila.

Figure 7: Building unit constructed in 2023

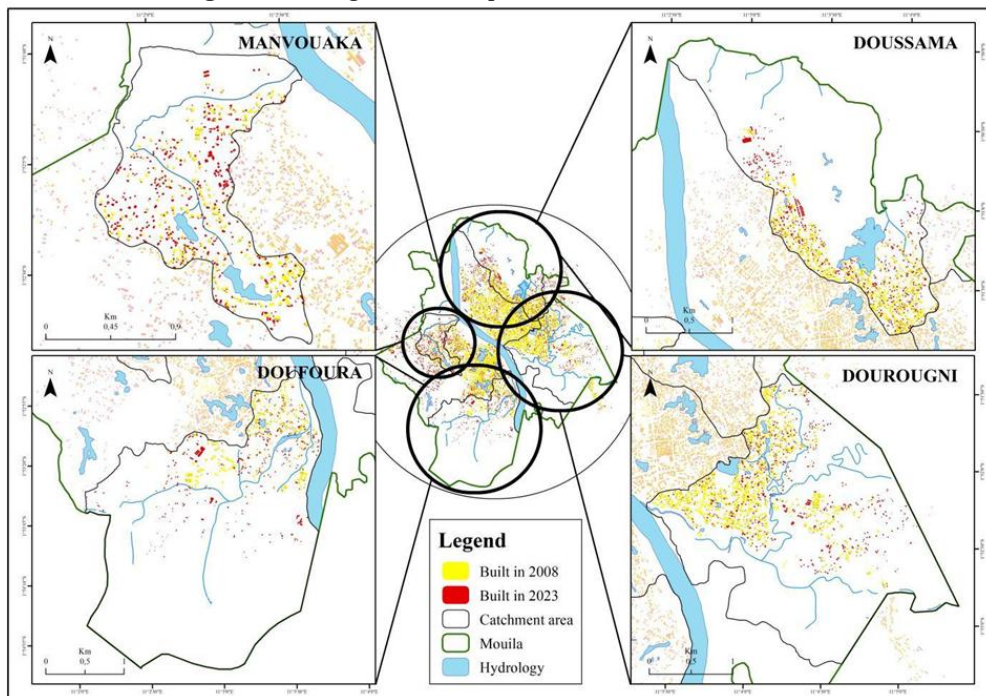


Source: Based on the image SAS Planet 2023

3.1.3. Urban trends from 2008 to 2023

Urbanization remains a current issue throughout the national territory, particularly in Mouila. This section consists of carrying out the diagnosis of urban sprawl between 2008 and 2023 in the basins of Doufouira, Dourougni, Doussama, and Manvouaka. Figure 8 shows the dynamics of the evolution of the built environment in these watersheds of the commune of Mouila. New construction extensions are observed in the center of Doufouira and in the southwest of Dourougni. In Doussama, the new extensions were carried out in the center-west and southeast. On the other hand, in Manvouaka, the built environment extends in a diffuse way mainly in its center and in the northeast.

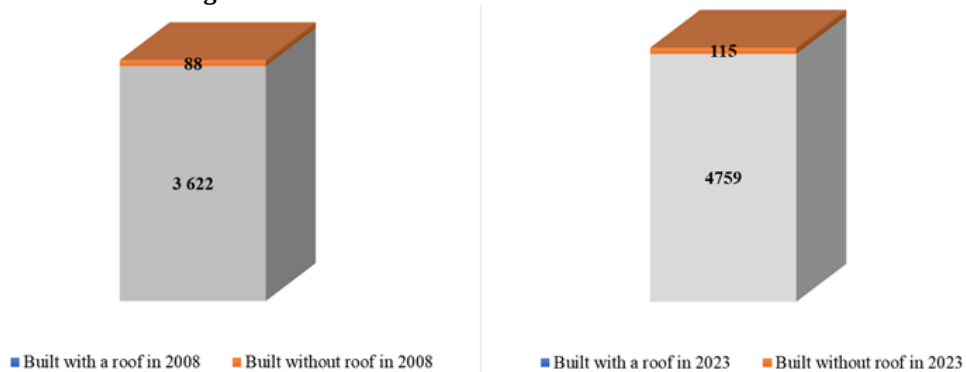
Figure 8: Changes in built-up areas between 2008 and 2023



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

The digitization of the built environment has enabled us to distinguish between buildings with and without roofs (Figure 9). 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 9: 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

The analysis of population evolution is essential to estimate the areas to be opened to urbanization in order to house these populations and build the equipment and infrastructure necessary to accompany this growth. The objective is to plan how the site of the city will evolve to absorb these additional inhabitants: areas, location, accompanying measures (SDAU of Mouila, 2021, p. 22). The evolution of the population in the watersheds of Mouila has intensified remarkably (Table 1). In all the basins, the population increased from 18,110 inhabitants in 2008 to 23,795 inhabitants in 2023, that is, a growth of 5,685 inhabitants. More specifically, sustained progression has been observed over the last 15 years in increasing order in the basins of Manvouaka, Doufoura, Doussama, and Dourougni. Indeed, from 2008 to 2023, the population of the Manvouaka basin more than doubled, increasing from 1,760 inhabitants to 3,785 inhabitants, that is, an increase of 2,025 inhabitants in 15 years. In the Doufoura basin, a significant increase in the number of inhabitants is observed: 1,805 inhabitants is the increase that Doufoura experienced from 2008 (2,075 inhabitants) to 2023 (3,880 inhabitants). The Doussama basin experienced strong growth, with an increase of 1,285 inhabitants observed during the same period. The Dourougni basin is the one that experienced the weakest growth, with 570 inhabitants. Many 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
Doussama					
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: Based on the 2008 orthophoto and the 2023 SAS Planet image

The initial population estimates were obtained by multiplying the number of mapped dwellings by a fixed value of five persons per dwelling. However, the household survey conducted in the study area indicates a median

household size of 6.5 persons and a mean household size of 6.58 persons. In order to assess the uncertainty associated with the use of a fixed occupancy rate, a sensitivity analysis was carried out according to three scenarios: the initial reference scenario of 5 persons per dwelling; a scenario based on the empirical median of 6.5 persons per dwelling; and a scenario based on the empirical mean of 6.58 persons per dwelling.

Table 2 indicates that, under the initial assumption of five persons per dwelling, the total population of the four watersheds is estimated at 18,110 inhabitants in 2008 and 23,795 inhabitants in 2023. When the median obtained from the survey, i.e., 6.5 persons per dwelling, is used, these estimates reach 23,543 inhabitants in 2008 and 30,934 inhabitants in 2023, respectively. The use of the empirical mean of 6.58 persons produces slightly higher values, namely 23,833 inhabitants in 2008 and 31,314 inhabitants in 2023 (Table 2).

Compared with the reference scenario of five persons per dwelling, adopting the median of 6.5 persons increases the population estimates by 30%, while using the mean of 6.58 persons increases them by 31.6%. This relationship is expected since the estimated population is directly proportional to the assumed household size. In contrast, the difference between the two scenarios based on the survey data is small, on the order of 1.2%. The choice between the mean and the median therefore has a marginal influence on the results.

Table 2: Sensitivity of population estimates to household-size assumptions

Watershed	Population in 2008 with 5 persons	With 6.5 persons	With 6.58 persons	Population in 2023 with 5 persons	With 6.5 persons	With 6.58 persons
Manvouaka	1,760	2,288	2,316	3,785	4,921	4,981
Doufoura	2,075	2,698	2,731	3,880	5,044	5,106
Doussama	6,020	7,826	7,922	7,305	9,497	9,613
Dourougni	8,255	10,732	10,864	8,825	11,473	11,614
Total	18,110	23,543	23,833	23,795	30,934	31,314

Source: Based on the 2008 orthophoto, the 2023 SAS Planet image and field data collected in 2024

The density table confirms the same trend. Overall density varies from 8.85 inh./ha in 2008 and 11.63 inh./ha in 2023 under the assumption of 5 persons per dwelling, to 11.51-11.65 inh./ha in 2008 and 15.12-15.31 inh./ha in 2023 when the empirical values of 6.5 and 6.58 persons are used (Table 3). Thus, the survey-based scenarios lead to an increase in estimated density of approximately 30 to 32%.

Despite these significant differences in absolute values, the main results remain stable across the three scenarios. All watersheds experienced population growth between 2008 and 2023. Dourougni and Doussama remain the most populated watersheds, whereas Manvouaka remains the most densely

populated watershed because of its small area and higher concentration of dwellings. Doufoura remains the watershed with the lowest densities, which is notably explained by its large area.

Consequently, the assumption regarding household size significantly affects the absolute level of population and density estimates, but it does not change either the direction of the demographic change observed between 2008 and 2023 or the spatial hierarchy of the watersheds according to their population or density.

Table 3: Sensitivity of population-density estimates to household-size assumptions

Watershed	Density in 2023 with 5 persons (inh./ha)	With 6.5 persons (inh./ha)	With 6.58 persons (inh./ha)	Density in 2023 with 5 persons (inh./ha)	With 6.5 persons (inh./ha)	With 6.58 persons (inh./ha)
Manvouaka	10.79	14.03	14.20	23.21	30.17	30.54
Doufoura	2.70	3.51	3.56	5.06	6.58	6.66
Doussama	13.03	16.94	17.15	15.82	20.57	20.82
Dourougni	12.63	16.42	16.62	13.50	17.55	17.77
Total	8,85	11.51	11.65	11.63	15.12	15.31

Source: Based on the 2023 SAS Planet image and field data collected in 2024

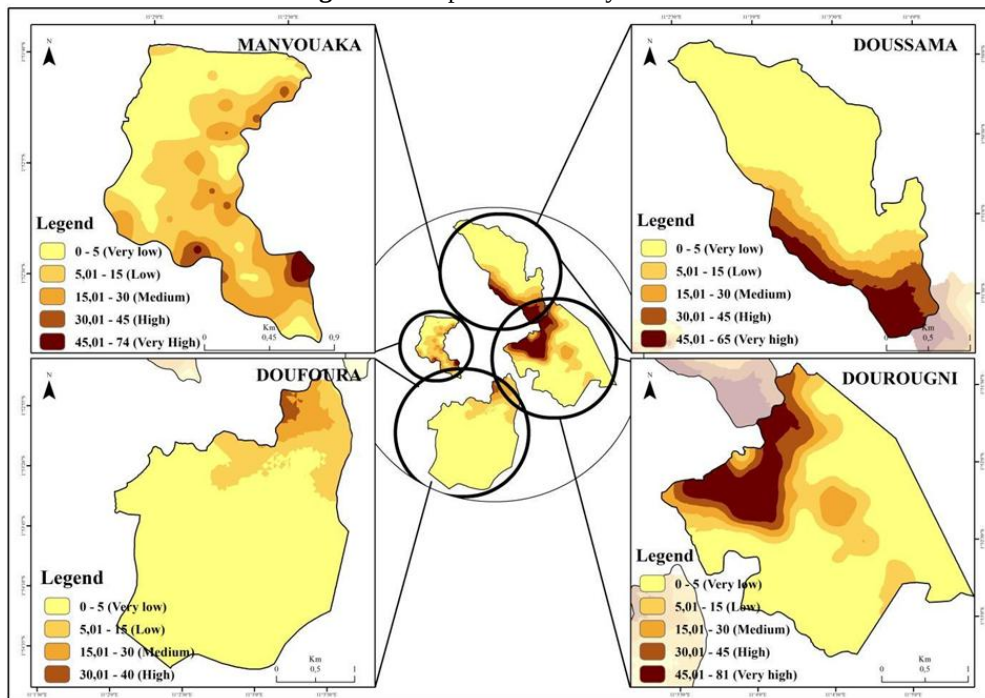
3.3. Spatial modelling of population density

The method used is ordinary kriging. It made it possible to obtain prediction maps without taking into account any possible general trend in the data. A mapping of population density is observed in the four main watersheds of Mouila in 2008 and 2023. From a general point of view, a very high population density is observed in the north of the Doufoura and Dourougni basins, while in the basins of Manvouaka and Doussama, the very high density is located mainly in the south of these basins.

3.3.1. Modelling of population density in 2008

In 2008, the population density in the Manvouaka basin was mostly very low; the rare very high concentration rates were located in the southeast. The same applies to the Doufoura basin, which was mainly very sparsely populated, but in its northern part had a fairly high population density. The Dourougni basin presented a much more marked population density, particularly in its northern part, where a high and very high population density was observed, with a medium population density in its center. Marked by a very high and very remarkable population density in the south and southwest, the Doussama basin presented a contrast in density between its very sparsely populated north and its densely occupied south. This would be the result of the proximity of the southern area to the city center. The same phenomenon is observed in all the other basins, where a very high density is observed in places close to the city center (Figure 10).

Figure 10: Population density in 2008

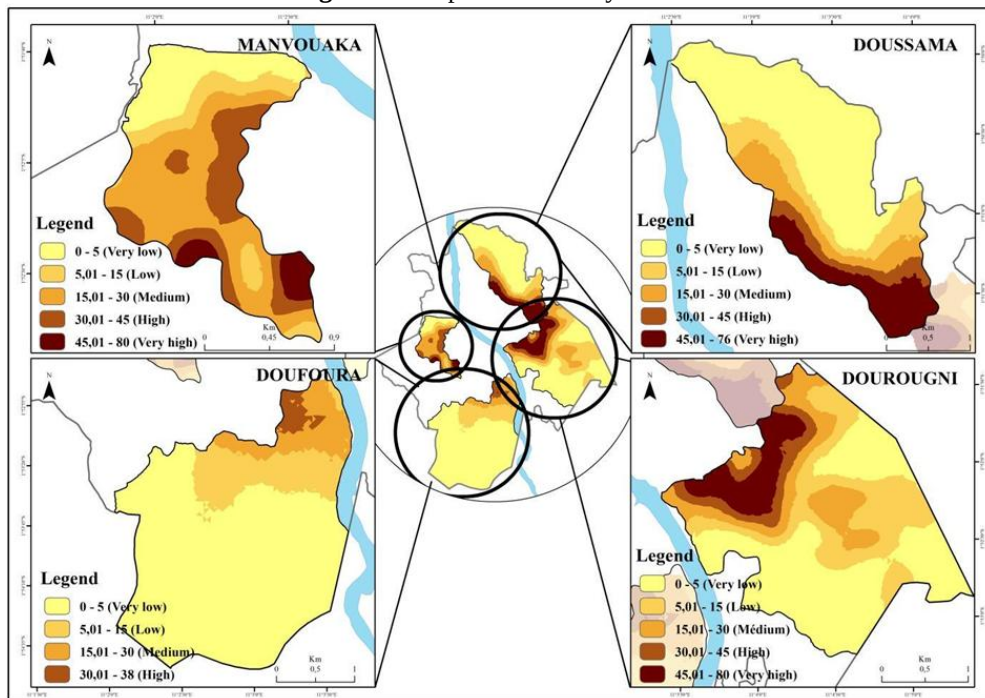


Source: Based on the 2008 orthophoto

3.3.2. Population density in 2023

In 2023, the population density in the four basins relatively increased spatially (figure 11). The Manvouaka basin is the main evidence of this. Very high population densities are observable not only in the south but also in the east and west. The so-called medium density also gained ground to dominate almost the entire center-west of the watershed. In the Doufoura basin, there is rather an increase in the so-called medium and low classes, with a center of very high density in the north, as in the Dourougni basin. In Doussama, the density remains relatively very high not only in the south but also in the west and northeast, with a gain of the low class in the northwest and northeast. This demographic growth, marked by these population densities in clear increase, is explained by different causes. Economic prosperity and the natalist policy advocated by the State would explain this demographic growth.

Figure 11: Population density in 2023



Source: Based on the image SAS Planet 2023

The analysed areas were derived from the 2008 and 2023 population density maps produced using kriging across the four watersheds. For each watershed and each date, the area occupied by each density class was measured, and the classes were then harmonised.

Figure 12 (a, b and c) highlights the area composition by density class, the variation in each class, and the share of the area with a density exceeding 15 inhabitants/ha. Thus, in the Manvouaka watershed and, to a lesser extent, in Doussama, there is a pattern of the lower classes. In Dourougni and Doufouara, an expansion pattern is instead observed. That is, the least densely populated areas are declining in favour of the low and intermediate density classes, corresponding to a more dispersed occupation of space. Across the four watersheds (20.42 ha), the area with a density greater than 15 inhabitants/ha increased from 3.64 to 5.50 ha, that is, from 17.8% to 26.9% of the total area (Figure 12).

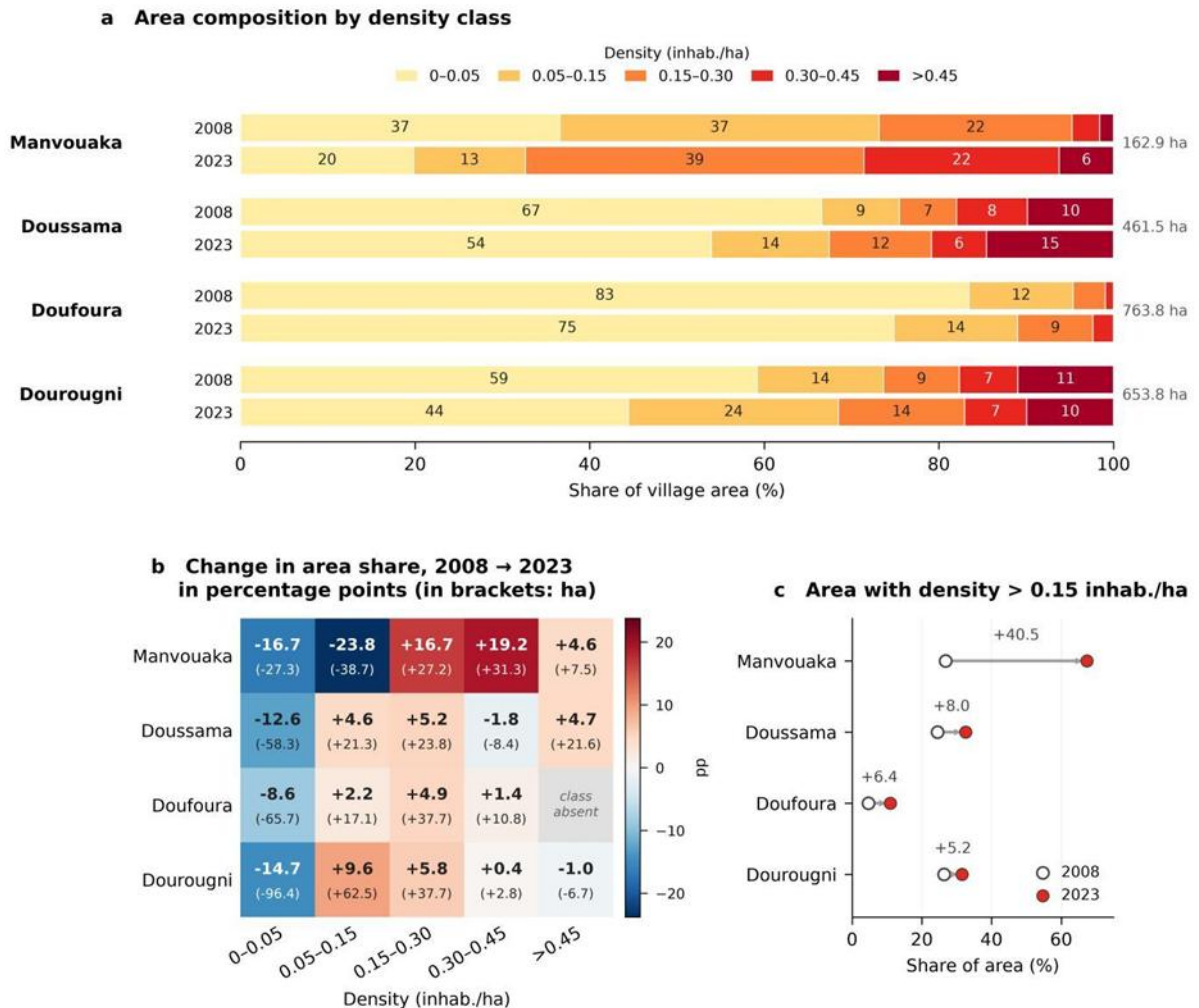


Figure 12: Change in areas by population density class between 2008 and 2023

3.3.3. Cross-validation results of kriging

The kriging cross-validation results for 2008 and 2023 in the Manvouaka, Doufoura, Doussama, and Dourougni watersheds show generally satisfactory calibration of the predictive uncertainties. The mean errors are close to zero and remain below 0.2 units, which represents a negligible bias considering the range of the observed values. The standardized RMS values range from 0.89 to 1.02, indicating that the predictive variances are, on average, correctly estimated. However, the absolute accuracy measured by the RMSE deteriorates between 2008 and 2023 for all watersheds (Tables 4 and 5). The comparison of the RMSE and the Average Standard Error reveals different patterns among the watersheds. In Manvouaka, the RMSE is slightly higher than the ASE, indicating a moderate underestimation of uncertainty. In

Doussama and Dourougni, the RMSE is lower than the ASE and the standardized RMS values are below 1, indicating slightly conservative predictive standard errors.

Table 4: Cross-validation results of kriging for the four Mouila watersheds in 2008

Prediction Errors	Manvouaka	Doufoura	Doussama	Dourougni
Samples	159 of 159	518 of 518	450 of 450	579 of 579
Mean	-0,1876626	-0,05487585	0,1465386	0,07540136
Root-Mean-Square	10,30789	6,107383	12,3553	14,34212
Mean Standardized	-0,013110468	-0,008582416	0,01072873	0,002125205
Root-Mean-Square Standardized	1,021728	0,9758573	0,8906543	1,007042
Average Standar Error	9,965423	6,252494	13,83984	14,29168

Table 5: Cross-validation results of kriging for the four Mouila watersheds in 2023

Prediction Errors	Manvouaka	Doufoura	Doussama	Dourougni
Samples	159 of 159	518 of 518	450 of 450	579 of 579
Mean	-0,01264516	-0,07300688	0,1561738	0,0005403455
Root-Mean-Square	16,74403	8,996369	15,21972	15,41154
Mean Standardized	0,0007015584	-0,008446466	0,009319221	-0,00131836
Root-Mean-Square Standardized	1,019189	1,022656	0,9289312	0,9220982
Average Standar Error	16,37981	8,812065	16,34592	16,6988

Discussion

This section compares the relevance of the results related to urban dynamics and population estimation, obtained from high-resolution satellite images. It also provides an interpretation of the results based on the literature from previous studies. The analysis of urban dynamics shows a notable increase in built-up areas in the four main watersheds of the commune of Mouila. In 15 years, the watersheds of Doufoura, Dourougni, Doussama and Manvouaka experienced a 31.4% increase in built units. This urbanization follows a concentric model starting from the core of the city towards the periphery, as also identified by Essono Milla (2022, p. 337), Biboutou (2022, p. 130), Okanga-Guay (2013) and Bloc-Duraffour (1998, p. 13). This average annual growth rate of 1.8% corroborates the estimates of the SDAU of Mouila (2021, p. 22), which reported a similar rate of 2% between 2003 and 2018. The watershed that experienced the strongest urban dynamics is that of Manvouaka, due to its proximity to the city centre and potentially to developments such as access to water and electricity during the last decade. The Dourougni watershed experienced the weakest progression, due to its abandonment by the competent authorities, since it suffers from a lack of road infrastructure, water supply, and waste management systems, as we were able to observe in the field. This dynamic aligns with the works of Mihindou Mihindou et al. (2025, p. 57), Okanga-Guay (2013, p. 10), Nguema (2005, p.

11) and Engo Assoumou (2007, p. 154), who describe a similar urbanization model in Gabonese cities, where constructions follow the axes of existing infrastructures such as water and electricity networks.

The literature, our knowledge of the field and the surveys carried out with the population of the 4 main watersheds of the commune of Mouila allowed us to estimate the size of a household at 5, just above the 4.1 of the RGPL estimated in 2013. Based on this estimate, a growth of 5,685 inhabitants was observed in 15 years across all the watersheds. However, we wished to compare the population obtained with the population estimate by the mean and the median from the field survey.

This sensitivity analysis allowed us to understand that the adoption of the median (6.5 persons) increases the population estimates by 30%, just as the use of the mean (6.58 persons) increases them by 31.6%. This relationship is expected since the estimated population is directly proportional to the assumed household size. On the other hand, the gap between the two scenarios based on the survey data is small because it is only of the order of 1.2%. The choice between the mean and the median therefore has a marginal influence on the results.

Despite the important differences in the absolute values of the base estimate, the mean and the median, the main results remain stable in the three scenarios. All the watersheds experience a population increase between 2008 and 2023. Dourougni and Doussama remain the most populated watersheds, while Manvouaka remains the most densely populated watershed, due to its small area and its higher concentration of dwellings. Due to its area, Doufoura remains the watershed presenting the lowest densities.

Consequently, the hypothesis relating to household size significantly affects the absolute level of the population estimates. But it changes neither the direction of the demographic evolution observed between 2008 and 2023, nor the spatial hierarchy of the watersheds according to their population or their density. A larger sampling of the surveyed population could have given more strength to the use of these population estimates.

Conclusion

At the end of this article, we evaluated urban dynamics, estimated and modelled the spatial distribution of the population in the Doufoura, Dourougni, Doussama, and Manvouaka watersheds using two high-resolution images, geostatistics, and the ordinary kriging spatial model. It can be concluded that population growth in the watersheds of the municipality of Mouila has intensified remarkably over the past 15 years. Across all the watersheds, the population increased from 18,110 inhabitants in 2008 to 23,795 inhabitants in 2023, representing an increase of 5,685 inhabitants. This

increase in built-up units is characterised by urban sprawl towards the outskirts of the municipality of Mouila and by buildings without roofs.

The literature and field surveys supported our choice to estimate the population of these watersheds using an average household size of five people. Thus, the population experienced an overall growth rate of 31.39% over 15 years, corresponding to an estimated average annual growth rate of 1.84%. This demographic increase concerns all the watersheds and follows an increasing order from Manvouaka to Doufoura, then Doussama and Dourougni.

Following the same trend, population density also increased, even doubling in the Manvouaka and Doufoura watersheds. Significant increases were also observed in the Dourougni and Doussama watersheds. Although the cross-validation results of the 2008 and 2023 kriging show a generally satisfactory calibration of the predictive uncertainties, some variations were observed.

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