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Urbanization and Floods in Sub-Saharan Africa: Spatiotemporal Study and Analysis of Vulnerability Factors—Case of Antananarivo Agglomeration (Madagascar)

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Abstract: Flooding is currently one of the major threats to cities in Sub-Saharan Africa (SSA). The demographic change caused by the high rate of natural increase, combined with the migration toward cities, leads to a strong demand for housing and promotes urbanization. Given the insufficiency or absence of adequate planning, many constructions are installed in flood-prone zones, often without adequate infrastructure, especially drainage systems. This makes them very vulnerable. Our research consists of carrying out a spatiotemporal analysis of the agglomeration of Antananarivo (Madagascar). It shows that urbanization leads to increased exposure of populations and constructions to floods. There is a pressure on land in flood-prone zones due to the exponential growth of the population at the agglomeration level. Some 32% of the population of the Antananarivo agglomeration lived in flood-prone zones in 2018. An analysis of the evolution of built spaces from 1953 to 2017 highlights that urban expansion was intense over those years (6.1% yearly increase of built areas). This expansion triggered the construction of built areas in flood-prone zones, which evolved from 399 ha in 1953 to 3675 ha in 2017. In 2017, 23% of the buildings in the agglomeration, i.e., almost one out of every four buildings, were in flood-prone zones. A share of the urban expansion in flood-prone zones is related to informal developments that gather highly vulnerable groups with very little in terms of economic resources. Better integration of flood risk management in spatial planning policies thus appears to be an essential step to guide decisions so as to coordinate the development of urban areas and drainage networks in a sustainable way, considering the vulnerability of the population living in the most exposed areas.

Keywords: demographic change; urbanization; flooding; drainage system; vulnerability; Sub-Saharan Africa; Antananarivo

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1. Introduction

Floods have become more recurrent and usual events in several countries [1]. Compared to the figures of the 1990s, the number of floods has almost doubled in the world since the 2000s [2]. They represent a threat with a major impact in terms of victims. In 2018, floods accounted for 50% of people affected by natural hazards [3]. Floods also have severe consequences in terms of economic loss and material damage [4].

The upsurge in floods can be explained by various factors, including climate change [5], which generates changes in precipitation regimes and intensity [6], and often manifests in torrential rains. Intense precipitation can cause flooding in small river basins and in rivers [4]. Extreme events in Africa [7], Europe [8], and Asia [9] are examples of the significance of climate change in increasing flooding. However, floods are not exclusively linked to climate change, but also to urbanization dynamics [10]. Jha, Bloch, and Lamond argue that regardless of climate change, urbanization can increase the risk of flooding [11]. With an emphasis on exposure and vulnerability, we would like to highlight this aspect in this paper.

Urbanization generally leads to an increase in impervious surfaces, which limits the possibility of water infiltration in the soil and increases the volume of water runoff on the surface [12]. Additionally, urbanization is often accompanied by an artificialization of urban rivers, which further increases the risk of water overflows [13,14]. This modifies existing land use not only inside cities but also in the outskirts [15].

In 1900, 15% of the world's population lived in urban areas [16]. Currently the proportion is more than 50% [17]. The numbers are increasing by 200,000 people a day, or 70 million people a year, and the proportion is estimated to reach 70% in 2050 [17]. This urban growth increases the demand for housing and land to build [16]. Given the competition for urban land, some people are tempted to build on areas exposed to risks [18,19].

Controlling exposure to floods implies a combination of urban planning and management of drainage systems. It requires follow-up of spatial planning policies [11], because risks are partly related to governance [1]. A lack of planning or poor planning can lead to an increase of informal installations and constructions, often exposing vulnerable residents to risks [10,20]. Lower-income residents usually do not have access to services and infrastructures that could mitigate the problems [21]. On the other hand, extending the drainage system should go hand-in-hand with any increase in built spaces, and it should be resilient [22] by having the capacity to evacuate water in the face of flooding. Without an adequate, sufficient, and well-maintained drainage system [23], urbanization cannot be sustainable.

Africa is one of the two continents in the world most affected by floods [24]. Floods are the most frequent disaster and remain a threat, especially in Sub-Saharan Africa (SSA)'s cities [25,26]. At the same time, the continent contains a population that is growing twice as fast other regions in the world [27]. Beyond this high growth, management and planning remains a problem throughout the continent and particularly in the region south of the Sahara [23,28]. The absence or ineffectiveness of disaster management plans and the inadequacy of basic systems, infrastructures, and services contribute to increasing vulnerability of urban areas [11]. The inability to accommodate a fast-growing population in decent conditions explains why constructions are located on unsuitable and dangerous sites, exposing cities to natural disasters [18], including floods. The deficiency of the drainage systems means a part of the population is affected by floods [14].

In this study, we show that urbanization leads to increased exposure of populations and constructions to floods and tends to add to their vulnerability. In order to reduce exposure and vulnerability to floods, it is important to recognize all aspects related to flooding, including socioeconomic factors that explain why flood-prone zones keep attracting a part of the population. We thus adopt a co-evolutionary perspective in order to better understand the long-term bi-directional relations between flood exposure, urban expansion, and vulnerability [29,30].

This paper is centered on the agglomeration of Antananarivo, the capital of Madagascar. Apart from the extreme climatic hazards the country is exposed to every year [31], it has most of the characteristics of SSA's cities mentioned above, in particular growing urbanization. According to the Institut National de la Statistique de Madagascar (INSTAT), nearly 5 million Malagasy people lived in urban areas in 2018 [32]. Rapid urban expansion is a problem due to the lack of planning [33]. It is associated with drainage problems plaguing the country. Insufficient capacity and poor functioning of the drainage network due to clogging with solid waste and deterioration are among the causes of floods [34]. The growing urban population is settling more and more in flood-prone areas [35], with the majority in informal spaces with limited services [36]. All of these factors contribute to the vulnerability of low-income groups.

The study starts from the birth of the agglomeration and proceeds with an analysis of its demographic growth, and then the evolution of the built-up areas. Two case studies on a finer scale are presented in order to better understand the socioeconomic conditions of urban areas located in lower areas of the city. These sites were selected based on the identification of sensitive areas affected by flooding during the 2018 rainy season by Service Autonome de Maintenance de la Ville d'Antananarivo (SAMVA). They are among the black spots of the city, since they are flooded every year. They have a similar urban dynamic and socioeconomic situation but differ in terms of the motivation of the people living there. This makes the comparison relevant. The case study analysis is followed by a discussion of results, conclusions, and limitations of the research.

2. Study Area: Agglomeration of Antananarivo

The agglomeration of Antananarivo, also called Greater Antananarivo, is located on the central Malagasy highlands (Figure 1). It covers an area of 76,800 ha and in 2018 had about 2.9 million inhabitants according to INSTAT. On the administrative and institutional level, it brings together the Urban Community of Antananarivo (CUA) composed of six boroughs forming the city of Antananarivo and 37 peripheral municipalities. The whole is located in the Regions of Analamanga and Itasy and is subdivided into 571 neighborhoods called Fokontany.

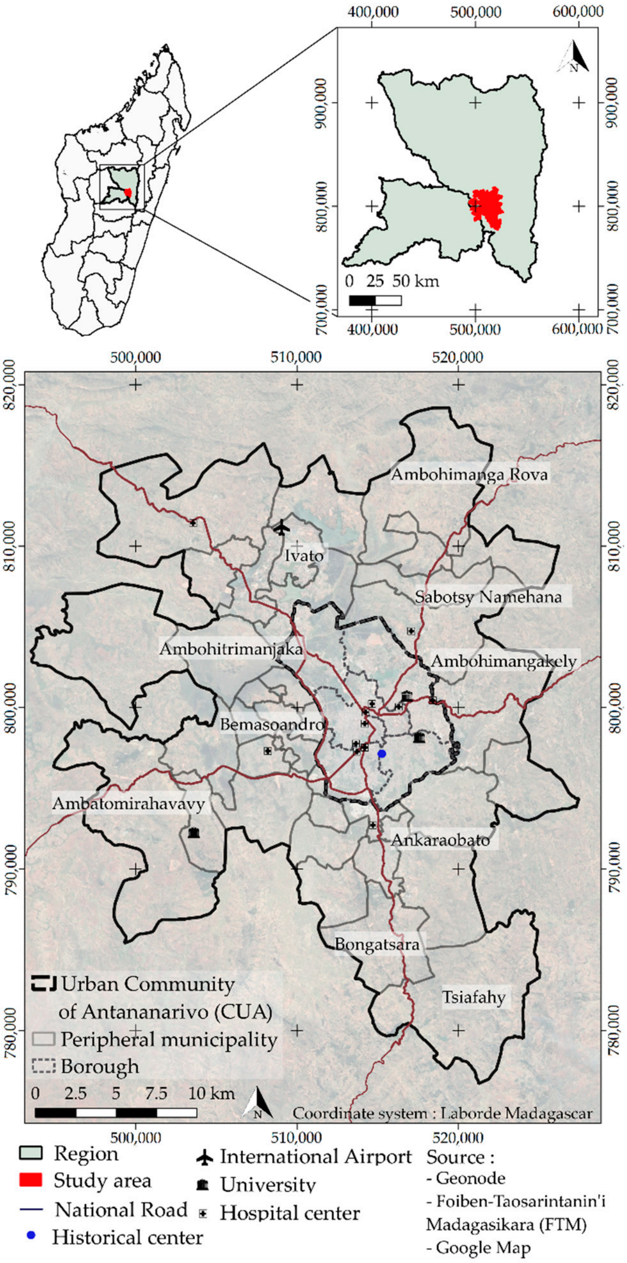


Figure 1. Location of agglomeration of Antananarivo.

Located at an altitude between 1200 and 1500 m above sea level, Antananarivo is characterized by a wide variety of landforms. It is made up of a set of elevated areas with steep slopes to the south, lower areas to the east and center, and a vast alluvial plain in the north and west (Figures 2 and 3).

The plain is drained by the Ikopa and its tributaries (Figures 2 and 3), flowing mainly from the south, southeast, and east to the northwest [37]. Upstream, the flow is more fluid, because the rivers face areas with steep slopes. The river slows down and generates water retention in the lower parts upon its arrival in the plain. This is due to the slight slope of about 0.25% [38] as well as the confluence of the rivers. The topography of the site and its hydrographic network make it very vulnerable to flooding. Almost a third of the urban area is occupied by flood-prone areas (Figure 3).

These flood-prone zones (Figure 3) were produced from a combination of the topographic wetness index (TWI), a soil moisture index, and the stream power index (SPI), an index characterizing the intensity of surface runoff. They are extracted from calculations carried out based on a digital Shuttle Radar Topography Mission (SRTM) model with geographic information system (GIS) software. These two indices are important parameters in flood sensitivity analysis [39].

After the last confluence in the northwest, the Ikopa flows to a single point [34], characterized by a succession of rock outcrops that reduces the water evacuation capacity and generates the formation of alluvial deposits at the level of the plain [40]. In the CUA, the plain forms a polder surrounded by dikes that protect it from overflowing rivers. However, as the river levels are often higher than its level during the rainy season, it is very sensitive to flooding [41].

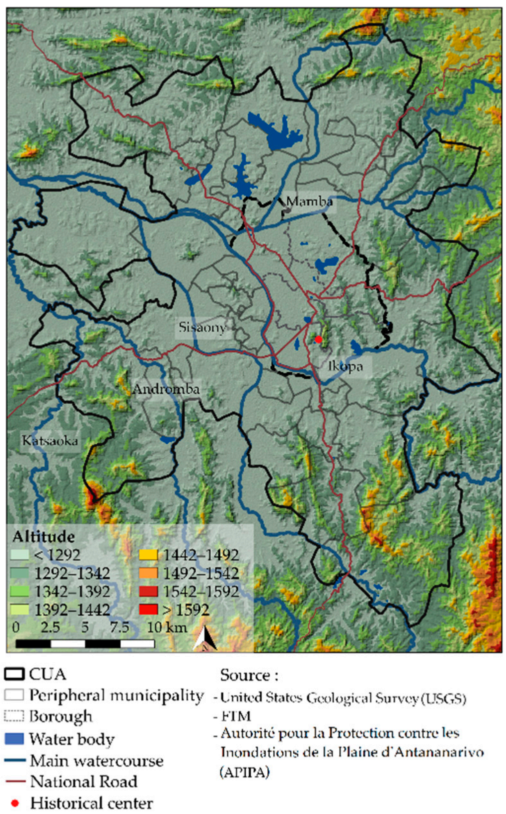


Figure 2. Relief of study area.

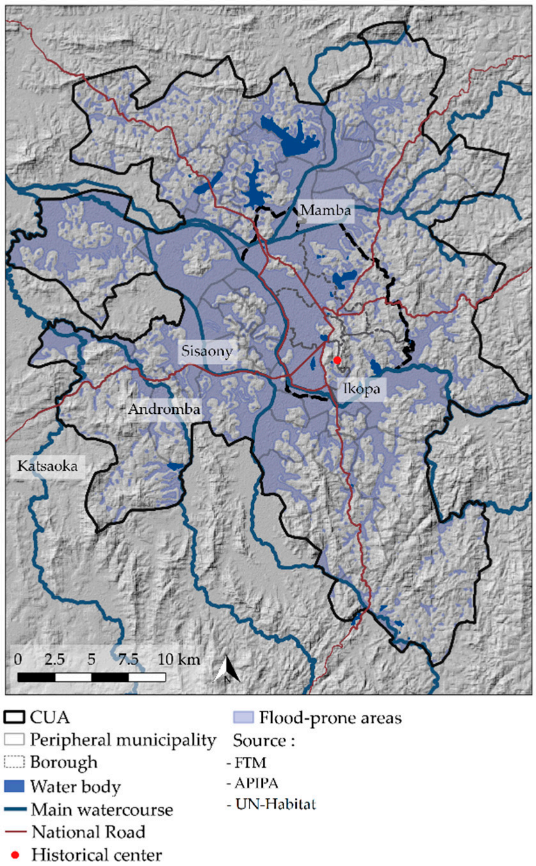


Figure 3. Flood-prone areas.

The first hydraulic infrastructures date from the royal period in the 17th and 18th centuries, consisting of river embankments and canals constructed to protect the plain and ensure the evacuation of irrigation water [42]. Currently, the drainage system is denser and more complex. It is structured along three main channels with multiple functions: drainage of rainwater, wastewater, and sewage, as well as irrigation of the agricultural plain. These are the Andriantany, C3, and GR (Génie Rural) channels (Figures 4 and 5). Primary canals, open drains, and buried pipes of various dimensions are connected to these three main channels. Pumping stations and retention basins have been added to this to ensure operation.

At the CUA level, the Andriantany and C3 channels are the main drainage channels. The upstream Andriantany runs through the western part of the city to the pumping station to the northwest and collects water from the hills and eastern plain. It collects rainwater, but also wastewater, from some Fokontany [37]. Downstream, it takes up water from the pumping station and drains to its point of confluence with the Ikopa [43]. As for channel C3, it collects water from the southern plain and agricultural drainage flows as well as excess flows from Andriantany [41]. The GR channel irrigates the plain [44] and acts as a drain during the rainy season [45].

Despite the existence of this drainage system, water tends to accumulate in the plain. At the pumping station, the flow remains paltry compared to the total flow to be drained [46]. Moreover, the increased intensity and volume of runoff due to soil sealing accelerates the degradation of the drainage system [47]. These problems cause flooding during the rainy season.

The peripheral municipalities are not connected to the main drainage network. In these municipalities, water is channeled through sanitation devices along the road network that evacuate rainwater, concrete or earth canals, and drainage ditches leading into the natural environment. In some communes, a collective sanitation system does not even exist [34].

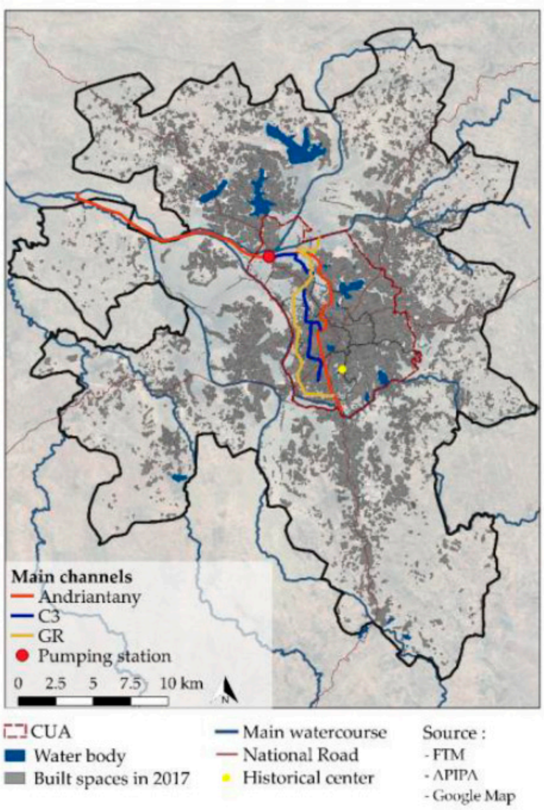


Figure 4. Agglomeration's main drainage system.

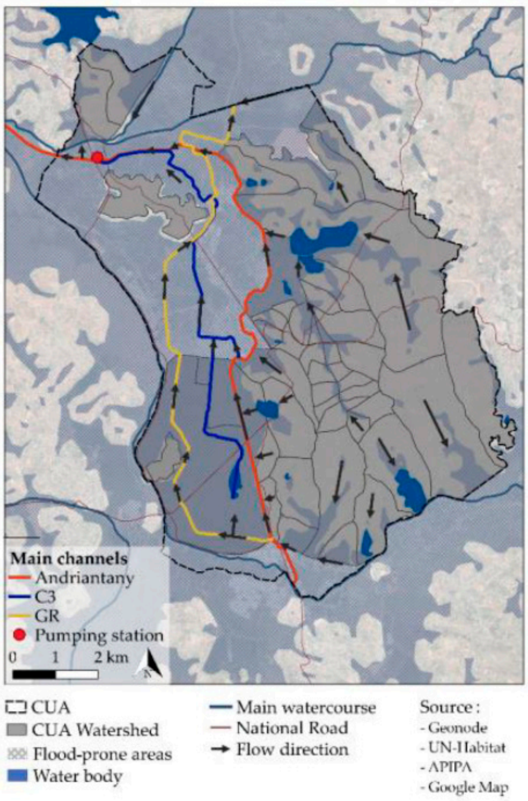


Figure 5. Urban Community of Antananarivo (CUA) watershed.

3. Materials and Methods

3.1. Collected Data

The demographic data used for this work were collected from a general population census based on administrative divisions provided by INSTAT conducted in 1993. For 2018, the figures are based on estimates, since the current general census is not yet official.

Built spaces correspond to structures that host housing, service, industrial, and economic activities. Those represented in this study were digitized based on historical maps and aerial photos. The first base map are maps of Antananarivo from 1953 and 1975. They were provided by Foiben-Taosarintanin'i Madagasikara (FTM), a public establishment in charge of cartography and geographic information in Madagascar. It covers the Greater Antananarivo area except for a few communes to the north and west of the agglomeration. The map representing the areas built in 2006 and 2017 was developed through vectorization of aerial images provided by Google Earth.

The flood-prone zones used in this study are those described in Figure 3 and explained in Section 2. These data were provided by UN-Habitat Madagascar.

Data related to the drainage system came from two organizations that specialize in sanitation and flooding in Madagascar, Autorité pour la Protection contre les Inondations de la Plaine d'Antananarivo (APIPA) and SAMVA.

Table 1 shows the details of these data.

Table 1. Data used in the analysis. INSTAT, Institut National de la Statistique de Madagascar; FTM, Foiben-Taosarintanin'i Madagasikara; APIPA, Autorité pour la Protection contre les Inondations de la Plaine d'Antananarivo; SAMVA, Service Autonome de Maintenance de la Ville d'Antananarivo.

Name of the Data	Spatial Extent	Scale	Date	Source
Demographic data	Agglomeration	-	1993 and 2018	INSTAT
Topographic map	CUA and 32 peripheral municipalities	1/100,000 1/50,000	1953 1975	FTM
Aerial images	Agglomeration	-	2006 and 2017	Google Earth
Flood-prone areas	Agglomeration	-	2012	UN-Habitat Madagascar
Drainage network: main channels	Agglomeration	-	2017	APIPA
Drainage network: secondary channels	CUA	-	2017	SAMVA

In order to cross-check all of the data, cartographic work was carried out. Analysis, modeling, and display of results was done using QGIS geographic information system software.

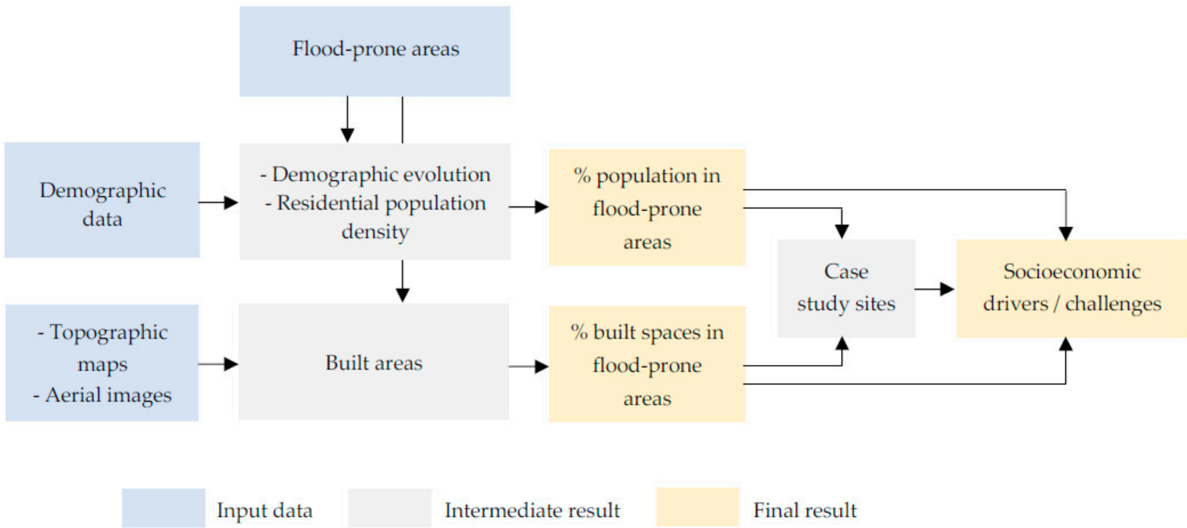
3.2. Method

The number of inhabitants is a first measure of the degree of exposure to flooding. Demographic data were first mapped at the level of the peripheral municipalities and boroughs of the CUA. This map was used to identify the annual demographic evolution between 1993 and 2018 and the population in 2018. Demographic data were then mapped at the level of the Fokontany in order to obtain the residential population density in 2018 (Scheme 1). Residential population density is defined here as the ratio between the number of inhabitants and the area of built spaces.

Considering that in 2018 the average residential population density of the Fokontany of the agglomeration was estimated at 250 inhab/built ha, the following thresholds were established:

- Fewer than 25 inhab/built ha: very low density
- 25 to 150 inhab/built ha: low density
- 150 to 350 inhab/built ha: moderate density
- 350 to 600 inhab/built ha: densely populated
- 600 to 1200 inhab/built ha: very densely populated
- More than 1200 inhab/built ha: very high density

The density map highlights the overall geographic distribution of the population throughout the agglomeration. Crossed with the area of flood-prone zones of each Fokontany in 2018, it allows estimation of percentage of the population living in flood-prone areas (Scheme 1).



Scheme 1. Overview of method adopted in the study.

Historic topographic maps and recent aerial data were used to map the extent of urbanization in 1953, 1975, 2006, and 2017. This makes it possible to understand the actual structuring of urbanization and the evaluation of the rate of waterproofing of the soil. The urbanization maps were used to determine the progress of construction in flood-prone zones (Scheme 1).

Two groups of Fokontany from the south plain of the CUA were studied in order to understand the factors underlying urbanization in these areas. These Fokontany, Ampefiloha Ambodirano and Ampandrana-Besarety and Besarety, which were selected based on previous analyses, are located in flood-prone areas and witnessed strong demographic growth over the last years. Site visits were made in order to map current land uses and study the local drainage systems. These site visits further allowed us to observe the living conditions in these areas so as to better understand the interplay between flooding, urbanization, and socioeconomic drivers/challenges (Scheme 1).

4. Results

4.1. Demographic Change and Residential Population Density in 2018

Antananarivo experienced considerable demographic growth over the last decades. It was home to more than half of the urban population of the country and around 11.3% of the total population in 2018. Between 1993 and 2018 (25 years), annual growth was estimated at 3.8%.

In 2018, the CUA had approximately 50% of the total population of the agglomeration. However, population growth in the CUA between 1993 and 2018 was rather modest compared to the growth observed in peripheral municipalities (Figure 6). Population growth in peripheral municipalities was mainly driven by migratory flows from the CUA, defined as proximity migration [48], but also from other regions of the country [37].

The demographic density was much higher in the CUA than in the peripheral municipalities in 2018 (Figure 7). It can be observed, however, that the distribution of the population within each commune varies from one Fokontany to another, with some denser nodes outside the CUA.

The highest density values in 2018 are seen in the Fokontany in the center of the CUA and within a radius of 2.5 km (Figure 7). The density peak reached up 2000 inhabitants/built ha, four times the average density of the Fokontany of the CUA and eight times that of the agglomeration. Most of the denser Fokontany were in the western floodplain.

In the peripheral municipalities, densification was led by national roads toward five main axes and grew with an area of expansion around a 10 km radius of downtown CUA (Figure 7). In these communes, the Fokontany were less dense than those of the CUA. However, some of them were in flood-prone areas.

Based on the residential population density and the size of the built-up areas in flood-prone areas in each Fokontany, it is estimated that about 32% of the population of the agglomeration and 43% of the population of the CUA lived in flood-prone areas in 2018.

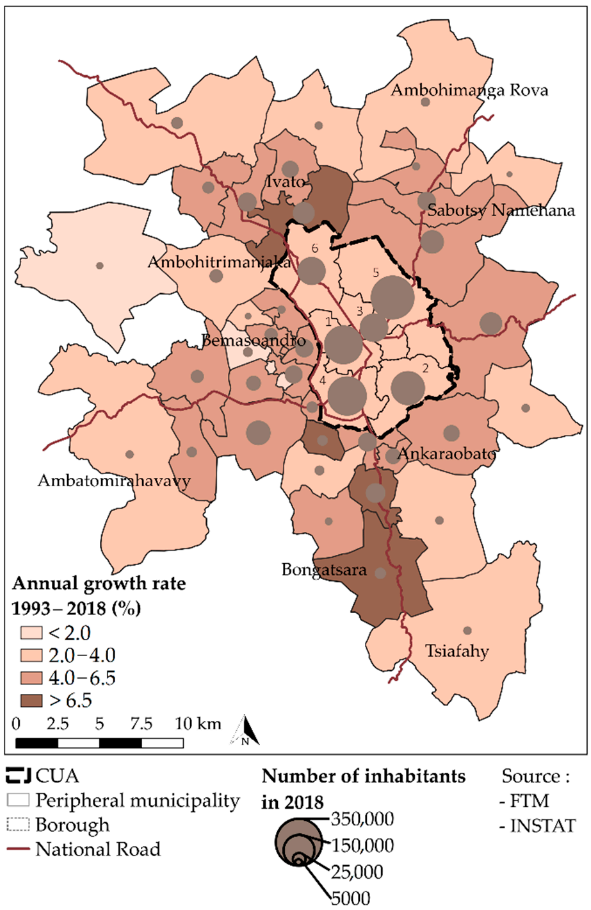


Figure 6. Annual growth rate between 1993 and 2018 and population in 2018 by borough in the CUA and by commune in the outskirts.

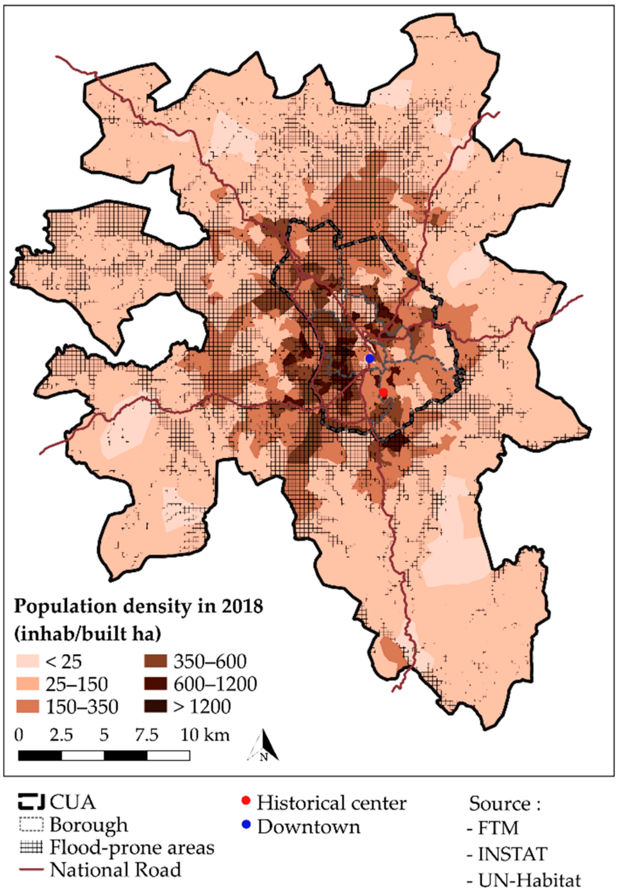


Figure 7. Residential population density in 2018.

4.2. Evolution of Built Spaces

Antananarivo developed in the center of the historic region of Imerina (Figure 8), an ethnic group in the central highlands of Madagascar. The first settlement was the Rova, a royal palace established during the 17th century, on the highest hill in the city [49]. Other constructions were progressively erected around the palace [50]. Some time later, the 30,000 inhabitants of city [51] settled on this first urbanized terrace of the city, called the "upper city" [52]. The extension continued beyond the limit of the hill and spread on the flanks and ridges of neighboring hills, in the north and west, toward the second half of the 19th century and formed the "medium city" [50]. It then gradually developed into the plain, with the installation of small settlement cores in the middle of rice fields [53].

Under the French regime, the extent of this encroachment became more important, and Antananarivo underwent its first major urban transformations. Some 20 hectares were backfilled in order to form the first Fokontany in the "lower town", and other new neighborhoods were created [54,55]. Between 1896 and 1903, 35 km of paved roadways were opened, tunnels were dug, places were created [56], and work on railway lines started [57]. This was only the beginning of the urbanization that would occupy the entire lower area a few years later.

In 1953, the built space mainly occupied elevated areas and covered around 1806 ha, i.e., 2.4% of the area of the present agglomeration (Table 2). In the CUA, urbanization was mainly oriented toward the east, around the historic center (Figure 8). On the other hand, the development of buildings in the lower town of the west continued. 10% of the CUA area was urbanized, and some 2.6% of the area was then covered by built areas located in flood-prone zones (Table 2). Outside the CUA, the development line progressed gradually to the east and northwest. Throughout the agglomeration, spatial development operated through the densification of spaces that were already built and through "fingerprint" urbanization, where most constructions were arranged along the main national axes (Figures 8 and 9). Among all built areas, 22% were in flood-prone zones, covering an area of 399 ha (Table 2).

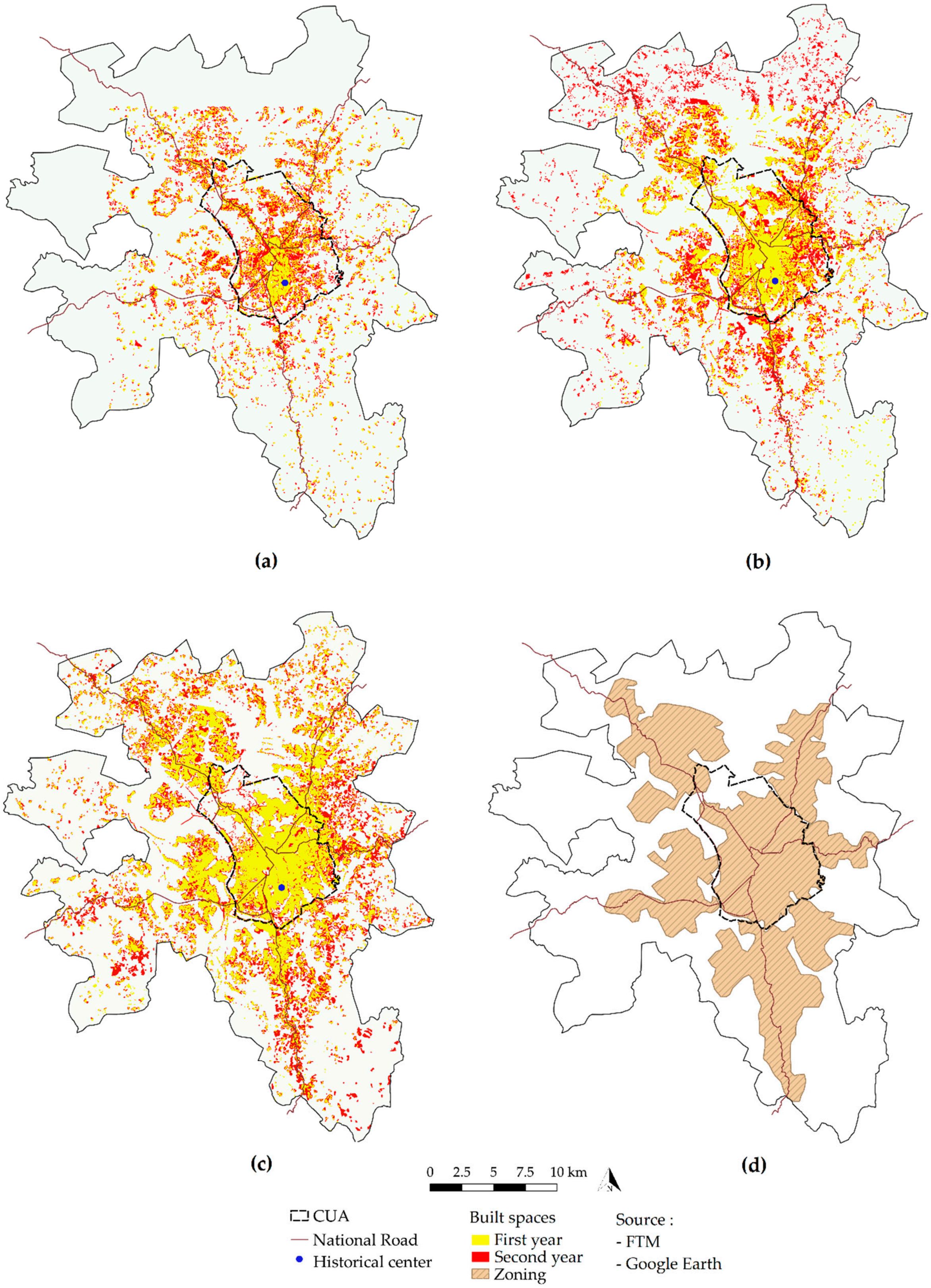


Figure 8. Urbanized cells: (**a**) 1953–1975; (**b**) 1975–2006; (**c**) 2006–2017; (**d**) 2017.

Table 2. Extent and increase of urbanized cells and built areas in flood-prone zones.

Date	Built Areas					Built Areas in Flood-Prone Zones					
	CUA	Agglomeration		Total Increase	Yearly Increase	CUA	Agglomeration		Total Increase	Yearly Increase	Compared to Built Spaces
	(%)	(%)	(ha)	(%)	(%)	(%)	(%)	(ha)	(%)	(%)	(%)
1953	10	2.4	1806			2.6	0.5	399			22
1975	25.5	5.4	4143	129	5.9	8.3	1.4	1101	176	8	26.5
2006	48.2	10.5	8048	94	3	13.9	2.7	2038	85	2.7	25
2017	55.3	21.2	16,250	102	9.3	19.8	4.8	3675	80	7.3	23
1953–2017					6.1					6	

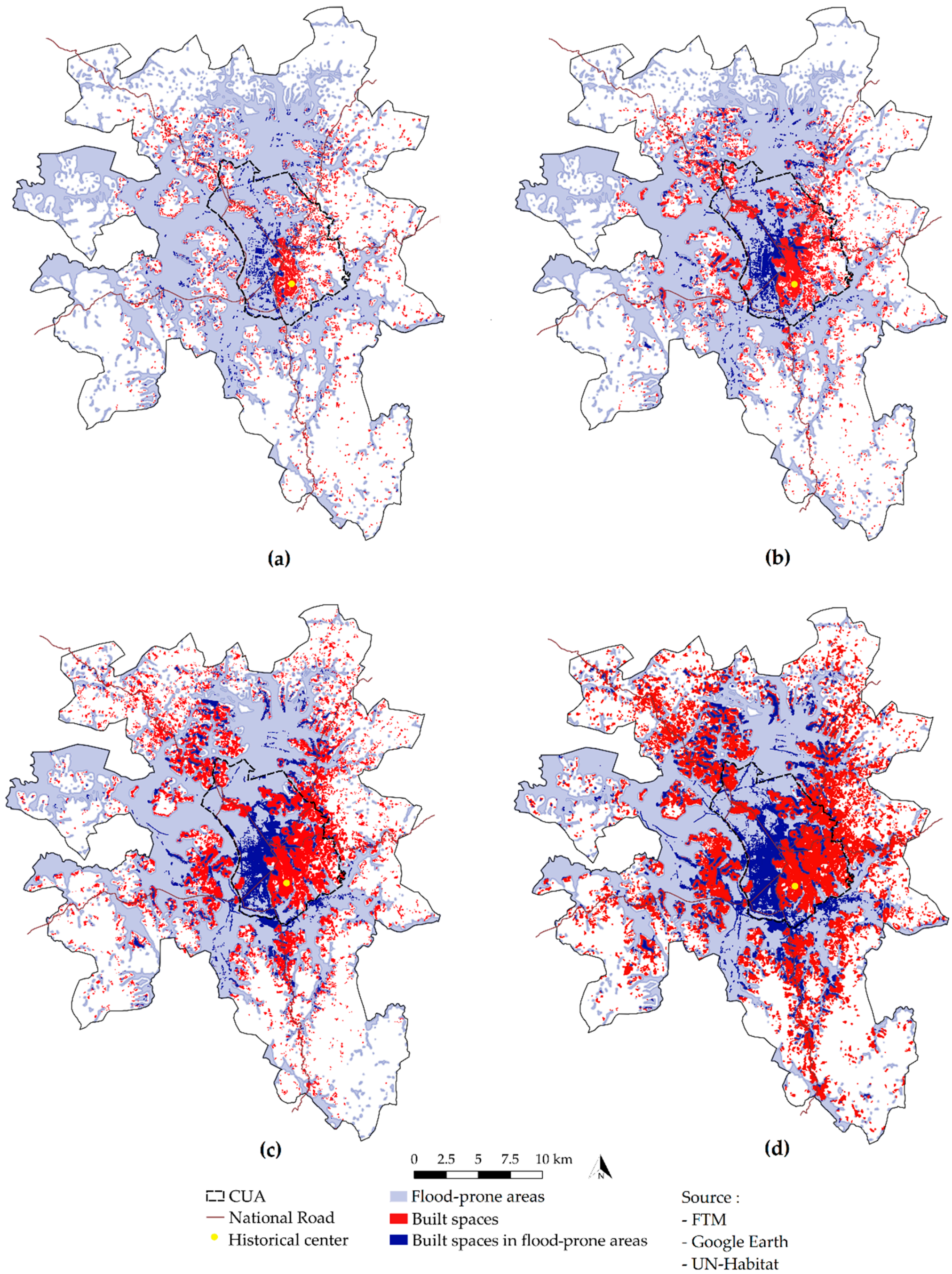


Figure 9. Urbanized cells in flood-prone zones: (**a**) 1953; (**b**) 1975; (**c**) 2006; (**d**) 2017.

From the 1960s, the period of independence, backfilling continued in the flood plain (Figures 8 and 9). Several new urban areas were built, and this did not protect the city from flooding. Urbanization continued until 1975, with approximately 2330 ha more of built areas than in 1953, and built areas then covered 5.4% of the agglomeration. The increase compared to 1953 is estimated at 129%, an annual increase of 5.9% (Table 2). Inside the CUA, built areas grew considerably and covered 25.5%. These are divided into two distinct parts: to the east toward the elevated areas and to the west in the flood plain (Figure 9). Built areas in flood-prone zones then represented 8.3% of the CUA, a sharp increase compared to the situation in 1953. In peripheral municipalities, urbanization mainly occurred through the filling of voids and the densification of existing areas. In addition to this urban expansion at the agglomeration level, the share of built areas located in flood-prone zones increased very rapidly. Compared to 1953, built areas located in flood-prone zones increased by 176%, an annual increase of 8%, covering 26.5% of the entire built area at the agglomeration level (Table 2).

From 1975 to 2006, urban expansion progressively shifted toward peripheral municipalities, especially in the neighboring municipalities of the CUA (Figure 8). It was guided by national roads and showed five centers of urban growth. In the CUA, urban consolidation continued and densified the area to the east and northwest. Built areas then occupied 48.2% of the CUA. In the whole agglomeration, between 1975 and 2006, the built areas increased by 94%, corresponding to an annual increase rate of 3%. The built areas then occupied 10.5% of the agglomeration, i.e., 8048 ha. It can be seen from Table 2 that 25% of built areas were then located in flood-prone zones. This is equivalent to an 85% increase compared to the situation of 1975, i.e., a 2.7% yearly increase over the period 1975–2006 (Table 2).

Between 2006 and 2017, urban expansion further intensified, especially in peripheral areas. Constructions was dispersed in areas far from the CUA. Approaching the CUA, the urban fabric became denser, especially in the northwest and the south (Figure 8). In the CUA, despite high density, urbanization continued to progress, to a large extent at the expense of rice fields in the lower town (Figure 8), by filling interstices to the west and rising slightly toward empty spaces to the north (Figures 8 and 9). A total of 55.3% of the CUA was occupied by built areas and 19.8% was occupied by built areas located in flood-prone zones. At the agglomeration level, built areas covered 16,250 ha, or 21.2% of the territory. It doubled over the years 2006–2017. The increase of built areas since 2006 was estimated at 102%, i.e., an annual increase of 9.3%. Constructions kept settling in the flood plain, and 23% of the total built areas was located in flood-prone zones in 2017. With an increase rate of 80%, or 7.3% yearly, built areas located in flood-prone zones occupied 4.8% of the agglomeration (Table 2).

Between 1953 and 2017, the annual rate of increase of built areas in the agglomeration was 6.1%. In flood-prone zones, it was estimated at 6% (Table 2). Urban expansion in flood-prone areas developed in parallel with that in other areas of the agglomeration. Practically, it means that building in flood-prone zones in Antananarivo was driven by the general expansion of the city, which was intense.

4.3. Case Studies

4.3.1. Case Study 1: Fokontany of Ambodirano Ampefiloha

The lower neighborhoods of the west, including the Fokontany of Ambodirano Ampefiloha, are the Fokontany located in the lower town on the left bank of the Andriantany canal (Figure 10). They constitute the extension of backfilled spaces in the plain of Antananarivo during the colonial period. Urbanization in these places accelerated following major subdivision operations in the 1970s. Apart from these constructions and a few service buildings, most houses are made of recycled materials such as wood, plastic, or brick and are in very poor condition [43] and underserved. The area gathers populations with low income, which prevents them from accessing other housing [54]. Homes are cramped and overcrowding prevails. They are exposed to flooding due to river floods and even overflows of drainage canals, and to health risks. These are not negligible due to the almost permanent accumulation of water during the rainy season.

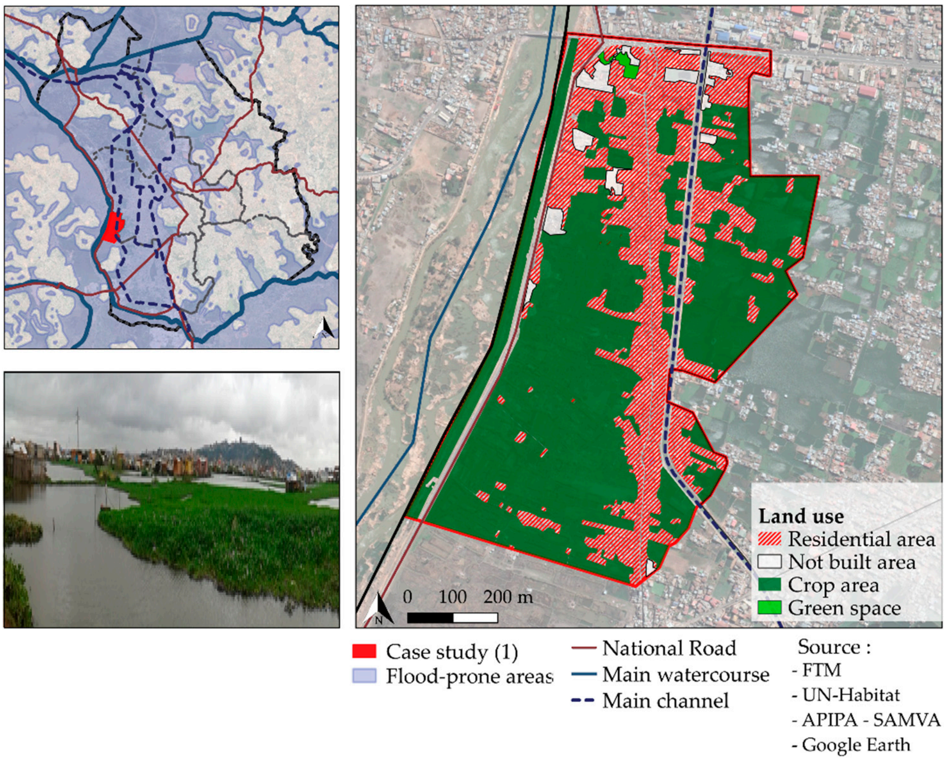


Figure 10. Map of Fokontany of Ambodirano Ampefiloha in CUA.

Ambodirano Ampefiloha covers an area of 63 ha. It is crossed in the east by the GR channel, the irrigation channel of the agricultural plain, and bordered by the Ikopa in the west. It has a flat topography with areas that form basins accumulating large volumes of water.

Between 1993 and 2018, the population almost tripled. With the growing population, this Fokontany is densely populated, with a residential density estimated at 484 inhabitants/built ha. The dynamics of family migration based on family support to overcome the difficulties encountered in the rural world is a main source of this considerable densification [43]. The residential area occupies 30% of the total area and rice fields 60%. The Fokontany does not have a specific drainage network (SAMVA).

This large urban space should contribute to the storage of water during rainy periods [58]. Nevertheless, it is increasingly invaded by constructions.

4.3.2. Case Study 2: Fokontany of Ampandrana-Besarety and Besarety

The Fokontany of Ampandrana-Besarety and Besarety are classified among the working-class neighborhoods at the foot of the upper town (Figure 11). They are located at altitudes between 1251 and 1252 m and extend over 22 ha. As in most of the Fokontany in the lower areas, backfilling allowed a progressive urbanization of the zone [59]. Floods are mainly linked to the overflow of drainage channels.

With a residential population density of 548 inhab/built ha, well above the CUA average, these Fokontany are categorized as densely populated. Population growth was 2.9% per year between 1993 and 2018. This upsurge was due to the high birth rate and the arrival of new migrants. The proximity to the city center and industrial zones explains why new inhabitants have come to settle there.

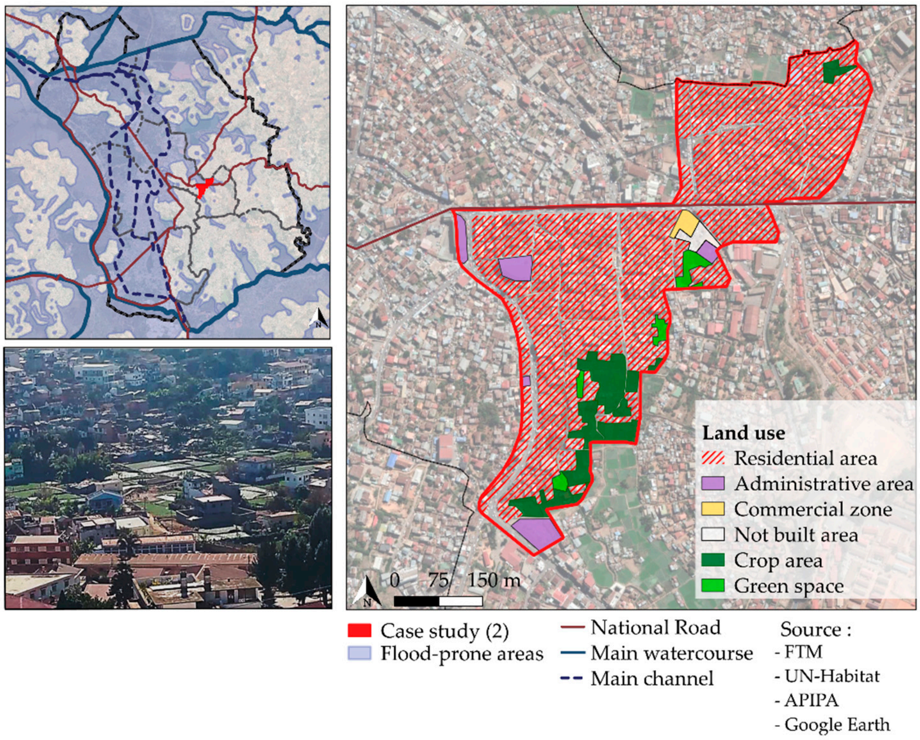


Figure 11. Map of Fokontany of Ampandrana-Besarety and Besarety in CUA.

Mainly residential activities and constructions are developing, to the detriment of rice fields. Two categories of settlements can be identified here: traditional or modern concrete constructions and small constructions made of sheet metal or wood. Currently, dwellings cover 75% of the total area, and 7% is occupied by cultivated areas. However, the whole area has a waterproofing rate of more than 80%, which generates large runoff.

The drainage system works differently on both sides of the area (SAMVA). It is operated through underground networks to the west and provided by gutters in the east. The whole system is subsequently taken up by primary channels. Despite the existence of this system, the primary network remains constrained by the accumulation of water with an important flow upstream of the site and by the weak slopes of the plain. Furthermore, the sections of these channels are heterogeneous. In certain sections, the load is much greater. In addition, the flow of water is hampered by the congestion of gutters and the obstruction of manholes by deposits of sand or waste [43]. Some installed structures also make it more difficult for water to flow during rainy events [60]. All of this, together with the proximity of the constructions to the drainage network and even their encroachment on the network, makes these Fokontany areas with recurrent floods.

5. Discussion

In SSA, several urban areas have experienced high population growth in recent decades. Gardi has shown that 12 of the top 30 fastest-growing urban agglomerations in the world are in SSA [17]. Antananarivo ranks 20th in the world and 9th in SSA in this ranking, right next to the major cities of Nairobi, with an annual rate of 3.87%, and Kinshasa, with 3.89% [17]. This growth is due to the high rate of natural increase and the rural exodus to and near urban areas [36]. In SSA, internal growth has been a determining factor for many years [16,61,62]. Nevertheless, migration is also part of the driving force behind population growth and urban sprawl [63–65]. For sociocultural, economic, political, and environmental reasons, whether it is a choice or a necessity, this migration seems to be a way to allow better living conditions for rural migrants [63,66]. In South Africa, due to inadequate social services and the lack of employment in rural areas, people migrate to urban areas [66,67]. In the Democratic Republic of Congo, it is because of conflicts and insecurity [65,68]. In Burkina Faso and Kenya, it is due to climatic disturbances [69]. The expansion of informal activities [66] and the concentration of services and facilities in cities also easily attract the rural population [65,70]. In Madagascar, social and land insecurity in the countryside [45] as well as economic difficulties [71] due to declining agricultural productivity [34] are pushing rural populations to migrate to Antananarivo. Due to the accessibility of services and infrastructure, students, civil servants, and people involved in small trade migrate and increase the size of the city's population [53].

This demographic growth creates unease for urban centers, since the supply of housing and spaces to be built does not meet the growing demand [63,72–74]. The fragility of urban governance, manifested in the lack of support and prioritization of urban infrastructure and land-use management initiatives by governments, is one of the reasons for this [75]. Parnell, Pieterse, and Watson also refer to a lack of good planning [20] due to poorly conceived planning laws and standards for construction as well as insufficient funding [16]. As a result, many informal settlements are developed [18]. The proliferation of these informal settlements is also related to increasing urban poverty and leads to the involvement of many poor people in the informal economy [65,76]. On the other hand, it is produced by the proximity of informal employment, which pushes migrants and poor households to settle nearby [77,78]. It is also accompanied by the development of new housing areas in flood-prone areas [18,19,79]. These settlements are generally precarious, with poor infrastructure, and are heavily impacted by flooding [18,70,80]. For Antananarivo, given the weakness of urban planning and the absence of housing policies, the demand greatly exceeds the supply that the city can offer [81]. This has led to illegal installations and constructions in the west of the city, in the flood plain [82]. In order to overcome this deficit, public authorities indirectly approved and anticipated the extension of urbanization in the plain [83].

In SSA, most of the urban population live in informal settlements in areas at risk [23], such as floodplains, swamps, and riverbanks [84,85]. This population group mainly consists of the urban poor [84]. They are often excluded from the land market due to unaffordable prices and imposed standards and regulations that they are unable to follow, and that force them to occupy these dangerous lands [11,21,86]. In addition to this group are refugees and persons who are displaced due to forced displacement in cities who settle in these areas for various reasons [87–90]. These situations and the increased population density in these areas make them more vulnerable to flooding [84,89,91].

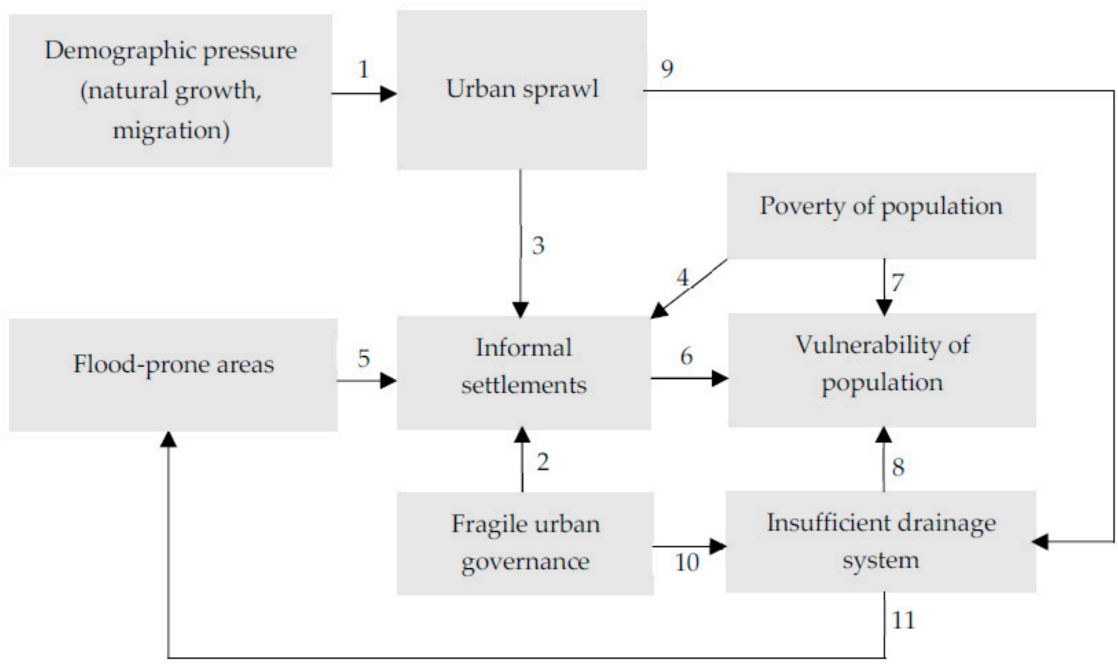
This set of processes is linked to the history of urbanization in SSA. In the region, the pre-colonial period is characterized by a low level of urban development [76] that intensified during the period of colonization [16,65,76]. The occupation of colonial cities by settlers [76,79] favored the development of informal settlements formed by the indigenous population, who were excluded from planning [92]. In Nairobi, this led to the construction of several illegal settlements by homeless Africans who were only allowed to be in the city for work [92]. It also promoted the development of habitats in flood-prone areas, as in the case of Antananarivo. In the 1930s and 1960s, development of the colonial city led to the displacement of several population groups, who took refuge in low areas [93]. In addition, the overcrowded hills of the middle city and the conveniences of the plain attracted inhabitants of the upper city to the lower city [53]. In the 1950s and 1960s, urbanization was mainly fueled by the development of industrial facilities [43], part of the orientation of the 1954 colonial-era urban plan [83]. These works changed the hydraulic regime of the plain and led to densification of the flood plains [59]. Flood-prone zones also became more favorable for speculators and real estate developers. Actually, building is less onerous and investments more profitable in low lands, given the more suitable topography [83]. By contrast, the extension of existing habitats and the widening of service roads were more expensive in the eastern part, given the steep slopes (up to 20%) [40,94]. There are also landslide risks in this part of the city [95].

In the years following independence, around 1960 and 1970, many cities in SSA experienced rapid population growth [65,79,96]. This growth can be linked to policies adopted after independence, which were related to the deployment of jobs, the establishment of several industries in city centers [65,97], and investment in public works [98]. The average annual population growth rate in urban areas was approximately 5% [99]. However, the cities inherited from the colonial era were not designed to accommodate such a massive population [20,76]. This reinforced the proliferation of informal settlements [76] that are more exposed to flooding [74]. In Accra, Ghana, the informal development of some communities in watersheds around rivers and lagoons increased their exposure to flooding [100]. In addition, the economic crisis that hit Africa in the 1970s fueled such difficulties throughout the region [101]. There has been a decline in investment in urban infrastructure and housing [76]. For Antananarivo, the 1970s were characterized by the completion of development and subdivision work to replace the thousands of homes destroyed following the devastating 1959 floods [83,102]. Other districts were then created in the lower town to accommodate the affected populations [94]. As these social housing units were not affordable for vulnerable populations, the construction of precarious housing proliferated. Antananarivo was also plunged into a lasting multifaceted crisis [56]. The construction sector was strongly affected. Materials were more expensive and scarcer. This led to the proliferation of informal habitats in flood-prone zones [43]. This was favored by the absence or inadequacy of urban land management tools [103]. It is difficult to access land due to expensive administrative procedures and a lack of updated information about the legal status of the land [45].

From the 1990s, urban development accelerated, especially in the peripheral areas around cities [62]. This is partly due to the decline in land values in these areas [104]. However, these habitats are often built outside of planning and regulations [65,104,105], and are places where various risks, including flooding, are prevalent [23]. For Antananarivo, the emergence of several peri-urban cores outside the CUA was supported by the establishment of the city's 2004 urban plan, which proposed unclogging the city center [37]. The migratory flow consequently became more important toward peripheral municipalities. This is further related to the limited accommodation capacity of CUA houses linked to their architecture [106] and the lack of available land for development in residential areas [107]. Peripheral areas were more attractive for residential installations in terms of both availability of building land and cost of living [108]. The establishment of industrial buildings [46] and the proliferation of infrastructure projects led to the acceleration of urbanization, which is increasingly taking place in flood-prone areas where land is cheaper and rents moderate [82,106]. The proximity of these settlements to industrial areas attracts the population, as shown in the case studies. These factors were favored by the absence of urban planning for a long period (from 1968 to 2004) [83].

This growing urbanization in SSA is also accompanied by a lack of infrastructure, including drainage systems, which makes cities vulnerable [19,79,91]. In Antananarivo, the case studies reveal this. The proximity of constructions to drainage canals and informal encroachments on these canals progressively reduce their capacity [60]. As the load on the existing network increases, this leads to greater susceptibility to the effects of further flooding [74].

Scheme 2 synthetizes the co-evolution of urbanization and vulnerability of poorly managed urban environments. The demographic pressure leads to urban sprawl around major cities (1). Due to the lack of housing and appropriate urban management (2), the expansion of the city occurs through informal settlements (3). It is more the case that incoming populations, especially from rural areas, are usually associated with low economic resources (4). Flood-prone areas are associated with the development of informal settlements (5): land is cheaper, and constructions are not authorized by planning documents. Furthermore, flood-prone areas located near canals and rivers are well adapted to maintaining subsidence urban agriculture, especially for inhabitants coming from rural areas. The construction of precarious settlements in flood-prone areas (6) by low-income groups (7) obviously exacerbates the vulnerability of these groups and their habitat; even more as the drainage system in these areas is often insufficient (8), which can partly be explained by the fast urban growth witnessed by SSA cities (9) and the lack of adequate integration of drainage in urban planning policies (10). The lack of drainage combined with urban sprawl and soil-sealing further contribute to increasing floods at the agglomeration level (11).



Scheme 2. Flood vulnerability factors, a co-evolutionary perspective.

6. Conclusions

Flooding is an occurrence that plagues most countries in the world, particularly in urban centers in SSA. Over time, poorly planned urbanization, combined with several other factors, expose people and buildings to flooding and increase their vulnerability. The agglomeration of Antananarivo is a clear example. Like many African urban agglomerations, it faces strong demographic pressure due to the high rate of natural growth and population migration toward urban areas. The city progressively expanded in the lower zone without much control. Our analysis shows that around 32% of the population of the agglomeration lived in flood-prone zones in 2018. The annual growth of built-up areas in flood-prone zones between 1953 and 2017 is estimated at 6%. In 2017, 23% of the buildings of the agglomeration, i.e., almost one out of four buildings, were in flood-prone zones.

The dynamics of urbanization inherited from the colonial era led over time to the proliferation of informal settlements, which are more exposed to flooding. This led to a modification of the hydraulic system of the city and a high degree of vulnerability in the flood plain. Given the inadequacy of the drainage infrastructure, the agglomeration is suffering from increasingly harsh flood events, especially during the rainy period. This is a trend known and present in the literature on urban agglomerations in SSA.

Faced with the rapid growth of the population, which leads to high demand in terms of constructions, urban planning and management are essential to avoid installations in flood-prone areas. This concerns dwellings as well as other structures that may attract inhabitants. The inadequacy or even the absence of planning, most of the time accompanied by a lack of provision of adequate services and equipment, leads to concentrated precariousness in flood-prone zones, where land is obviously cheaper. Integrating flood risk management in spatial planning policies is essential to curb this phenomenon. It should be combined with proper implementation of these policies, targeting both newly developed and existing urban areas. Since many people live in flood-prone areas, it would be more relevant to work on resilience to reduce vulnerability than to relocate this large volume of people.

7. Limitations of the Research

In the study of flooding in urban areas, it is advisable to consider the different parameters mentioned above to understand the issue and be able to propose solutions to reduce vulnerability. In the framework of our research, we focused on the product of urbanization and its combination with other parameters that promote vulnerability. We did not consider here some factors that may contribute to increase urban flooding, such as climate change. The flood-prone areas considered in our study remain constant over time, because they are based on the calculation of topographic indices (TWI and SPI) relative to the topography. The study does not consider either the amount of precipitation or the flood history. Finally, in our paper, we considered urbanization relative to the whole of the built spaces. It would be relevant to consider built spaces that are only residential areas and integrate land use and land use change.

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