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**Dynamics of the Banks of the Tsiémé River in Brazzaville
(Congo): Urbanization, Vulnerability to Flooding, and
Sustainable Management Strategies**



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Dynamics of the Banks of the Tsiémé River in Brazzaville (Congo): Urbanization, Vulnerability to Flooding, and Sustainable Management Strategies

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Abstract

Purpose: This study analyzes the dynamics of the banks of the Tsiémé River in Brazzaville (Republic of Congo) in order to assess the influence of unplanned urbanization on vulnerability to urban flooding. It examines the interactions between hydro-geomorphological transformations of the channel, occupation of the riparian corridor, social exposure, and land governance, with a view to guiding the sustainable management of urban river spaces.

Methodology: A descriptive and analytical approach based on a mixed methodology was adopted. The study focused on a 4,013-meter urban section located between the districts of Ouenzé and Talangaï. Primary data were collected through household surveys, institutional interviews, field observations, and GPS surveys. Multi-date satellite images, topographic and rainfall data, and planning documents were used to supplement the analysis. Hydrogeomorphological, spatial, social, and institutional indicators were processed using statistical tools and geographic information systems.

Findings: The results reveal a marked contraction of the channel and increased bank erosion, reducing hydraulic capacity and promoting flooding. Significant occupation of the regulatory strip and loss of riparian vegetation weaken natural hydrological regulation functions. Flooding appears to be recurrent and socially impactful, with high exposure of riverside households. Despite the existence of a regulatory framework, its application remains partial.

Unique Contribution to theory, Policy, and Practice: The study demonstrates that flood vulnerability along the Tsiémé River is the result of interactions between physical dynamics, urban pressure, and institutional weaknesses. It highlights the need for integrated flood risk management and nature-based solutions to strengthen the resilience of urban river corridors.

Keywords: *Urban flood vulnerability; Bank dynamics; Informal urbanization; Integrated flood risk management; Urban resilience.*

1.0 INTRODUCTION

Floods are now one of the most frequent and devastating natural hazards worldwide, accounting for approximately 40% of recorded natural disasters (UN, 2020). Between 1990 and 2020, more than 2.3 billion people were affected by flooding events worldwide, while cumulative economic losses exceeded US\$650 billion over the last two decades, making flooding the natural phenomenon that generates the highest economic losses, ahead of earthquakes and storms (UN, 2020). This dynamic is part of a context of accelerated global urban growth. In 2008, for the first time in history, 50% of the world's population lived in urban areas, a proportion that now exceeds 56% and could reach 70% by 2050 (Jha et al., 2012). This rapid urbanization greatly increases exposure to hydrological risks, particularly in cities located along rivers and floodplains, where a growing proportion of the population and infrastructure is concentrated, to the extent that, globally, 75 cities with more than five million inhabitants could be exposed to flooding by 2030 (Jha et al., 2012).

Vulnerability to flooding is particularly pronounced in low- and middle-income countries, which account for nearly 89% of those affected worldwide (World Risk, 2025). This increased exposure also translates into high mortality rates linked to hydrometeorological disasters. In 2021, 6,493 people lost their lives in 373 water-related disasters, including floods, storms, and droughts, accounting for 62% of all deaths due to natural disasters, with floods alone causing 4,143 deaths (HELP, 2022). This situation is closely linked to unplanned urbanization, which encourages the occupation of floodplains, soil sealing, and increased urban runoff. These dynamics are exacerbated by climate change, which has led to a 134% increase in flood-related disasters since the 2000s (UNDRR, 2025). This trend is confirmed by the 142 flood events recorded in 2024 alone (World Risk, 2025).

In Africa, the situation appears particularly critical. The continent accounts for around 25% of people affected by flooding worldwide, while only accounting for around 17% of the global population (UN, 2020). Sub-Saharan Africa has the fastest urban growth in the world, with an estimated average annual rate of 3.5%, while more than 60% of African city dwellers live in informal settlements, often located along rivers and in flood-prone areas (UN, 2020). Floods affect an average of 25 to 30 million people per year and generate annual economic losses estimated at between US\$3 and US\$5 billion (UN, 2020).

The Republic of Congo is highly vulnerable to hydrological and urban risks. Located in an equatorial zone with high rainfall, the country is exposed to a variety of natural hazards, primarily flooding, erosion, and landslides (UNFCCC, 2009). Over the last 100 years, floods have affected 173,114 people, or 85% of the total population affected by natural disasters in the country (SNPRRC, 2017), while in 2015, torrential rains caused more than 10,154 casualties in the departments of Brazzaville and Pointe-Noire (SNPRRC, 2017). This situation is exacerbated by national population growth estimated at 3% per year, with a projection of 83% of the population living in urban areas by 2035 (SNPRRC, 2017). As the political capital and main urban area of the country, Brazzaville has a population of approximately 2.15 million, representing nearly 35% of the national population (RGPH-5, 2023). The acceleration of

urbanization in recent decades has complicated the organization of urban space and the management of exposed areas, particularly riverside areas, and has resulted in the increasing occupation of non aedificandi zones, linked to housing shortages, weak land control, and inadequate sanitation infrastructure.

Among Brazzaville's urban waterways, the Tsiémé River is a major hydrological axis in the city's drainage system. It flows through densely urbanized areas and plays a key role in storm water drainage, in a context marked by rapid urbanization, strong anthropogenic pressure, and increased exposure to hydrological hazards. These characteristics make the Tsiémé a particularly sensitive urban river area, at the crossroads of urbanization, flood risk management, and aquatic environment preservation issues.

1.1 ISSUES

In Brazzaville, the Tsiémé River is now a highly vulnerable urban river area, where the combined effects of unplanned urbanization and hydrological hazards are concentrated. Approximately 20 km long and draining a watershed of 6,370 hectares, it flows through densely populated urban areas, particularly in the Ouenzé and Talangaï districts, before emptying into the Congo River (DGGT, 2024). The central problem lies in the gradual and uncontrolled degradation of the banks, combined with the uncontrolled occupation of the floodplain and riparian areas, which are recognized as non-building zones, compromising the hydromorphological functioning of the watercourse and structurally increasing vulnerability to urban flooding. This degradation is closely linked to rapid and poorly controlled urbanization, marked by the establishment of spontaneous settlements, agricultural activities, and precarious infrastructure along the banks. Increasing soil sealing, the disappearance of riparian vegetation, and the obstruction of the riverbed by solid waste reduce the natural flow and flood expansion capacities. With annual household waste production in Brazzaville estimated at around 400,000 tons (SDU, 2016), urban waterways, including the Tsiémé, are frequently used as informal outlets, contributing to worsening flooding during heavy rainfall.

The populations living along the Tsiémé are among the main groups affected by this situation. Recurrent flooding causes material losses, damage to homes, persistent residential insecurity, and forced displacement of households. Data from development operations indicate that more than 350 plots of land are directly affected by the works, impacting more than 2,600 people, a significant proportion of whom suffer both physical and economic impacts (DGGT, 2024). These effects also affect urban infrastructure, drainage networks, and local public services, while riparian ecosystems are experiencing a continuous degradation of their hydrological regulation and erosion protection functions.

Beyond the material and social impacts, the degradation of the banks of the Tsiémé River generates significant health risks related to water stagnation, contamination of wells and latrines, and increased exposure to waterborne diseases. These risks are exacerbated by the precariousness of individual sanitation systems and the immediate proximity of homes to the river, contributing to the deterioration of the living environment of riverside populations.

In this context, despite the existence of a structured regulatory and institutional framework, including the Urban Planning Code, the Local Urban Development Plan, the Urban Development Master Plan, and Environmental Framework Law No. 33-2023, which prohibits construction in river protection zones and classifies flood zones as unbuildable, the management of the banks of the Tsiémé River remains fragmented, sectorized, and insufficiently operationally. Public interventions remain mainly ad hoc and reactive, with no coherent link between urbanization dynamics, flood risk management, and the preservation of river ecosystems, while local scientific knowledge on urban riverbank dynamics, the mechanisms of vulnerability, and the interactions between urbanization and flooding remains limited and scattered. The central question guiding this research is therefore: to what extent do the dynamics of the banks of the Tsiémé River, under the effect of unplanned urbanization, contribute to urban flood vulnerability in Brazzaville?

In order to provide answers to this question, this study aims to analyze the dynamics of the banks of the Tsiémé River in a context of unplanned urbanization, in order to understand the mechanisms that produce vulnerability to urban flooding in Brazzaville and to guide the sustainable management of urban river spaces.

More specifically, the aim is to:

1. Characterize the spatial and morphological evolution of the banks of the Tsiémé River under the effect of urbanization dynamics;
2. Analyze the physical, anthropogenic, and institutional factors contributing to the vulnerability of riparian areas to flooding;
3. Assess the social, environmental, and health impacts of riverbank degradation;
4. Examining the limitations of current management and regulatory mechanisms with a view to proposing improvements for the sustainable management of urban river areas.

2.0 LITERATURE REVIEW

Urban flooding is now one of the main risks affecting African cities, particularly in contexts marked by rapid urban growth, largely unplanned urbanization, and limited institutional capacities. Numerous studies emphasize that flooding cannot be understood solely as a natural or climatic phenomenon, but rather as the product of complex socio-spatial processes resulting from the interaction between hydrological dynamics, land use patterns, and urban governance systems (UN-Habitat, 2017). In African cities, the establishment of informal settlements in flood-prone areas, particularly along riverbanks, combined with inadequate drainage infrastructure and poor urban planning, significantly increases the exposure and vulnerability of populations to recurrent flooding.

Recent literature also highlights that these vulnerability dynamics are part of urban development trajectories marked by structural poverty, informality, and unequal access to urban services, which contribute to transforming hydrological hazards into recurrent disasters. In this

context, urban flooding appears to reveal the limitations of urban development models and sectoral approaches to risk management in African cities.

2.1 Theoretical review

The analysis of urban flooding is based primarily on disaster risk theory, developed within international disaster risk reduction frameworks, widely disseminated by the United Nations through UNDRR (2015), and then formalized at the regional level by ECCAS (2021). This theory posits that risk results from the interaction between a hazard and the vulnerability of exposed assets, according to the relationship $Risk = Hazard \times Vulnerability$. It conceives of vulnerability as a socio-spatial construct influenced by unplanned urbanization, ecosystem degradation, poverty, and institutional weaknesses. In Central African cities, this approach highlights the central role of urban waterways as major risk vectors when their banks are occupied informally. In the context of this study, this theory allows us to understand the floods affecting the Tsiémé River as the result of interactions between hydrological hazards, the vulnerability of riverside populations, and the limitations of existing management systems in Brazzaville.

From a complementary perspective, the literature increasingly draws on the theory of resilience applied to development and global change, developed in particular by Katrina Brown (2016). This approach goes beyond a strictly technical conception of risk management by considering resilience as a systemic process linking socio-ecological dynamics, development trajectories, and power relations. It highlights that climate and environmental crises, such as urban flooding, cannot be entirely avoided but must be managed in a context of uncertainty and constant transformation. Resilience is not limited to the ability to bounce back or adapt, but involves a structural transformation of urban systems, including modes of governance, planning, and land use. Applied to urban flooding, this theory highlights the limitations of responses focused exclusively on infrastructure and justifies a territorialized and transformative approach to risk management.

In line with this thinking, the theory of integrated climate risk adaptation management, developed by O'Brien and O'Keefe (2014), provides additional insight. This approach views climate change as a permanent risk, characterized by uncertainty and multiple scales of impact, and criticizes fragmented responses that separate climate adaptation, disaster management, and development. It advocates for integrated, people-centered adaptation that combines risk reduction, local capacity building, and social learning. In African urban contexts, this theory makes it possible to analyze how recurrent flooding results not only from climatic hazards, but also from institutional fragmentation and the limitations of sectoral urban policies. It thus justifies the need for multi-stakeholder governance and long-term preparedness for hydrological risks.

In addition, recent literature draws on the framework of nature-based solutions (NbS), a concept formalized by the World Bank and theorized by the IUCN (International Union for Conservation of Nature), to analyze the climate resilience of African cities (Kiribou et al., 2024). NbS are defined as actions that rely on natural ecosystems to simultaneously address

environmental, social, and climate challenges. They are based on the restoration of ecological functions, hydrological regulation, and the multifunctionality of natural infrastructure. According to these authors, NbS offer significant potential for reducing urban flooding and restoring waterways, but remain poorly integrated into the climate adaptation strategies of African cities due to governance, funding, and localized scientific knowledge constraints. In this research, this theoretical framework is used to analyze the role of the Tsiémé riverbank natural infrastructure as natural infrastructure that can contribute to flood risk reduction.

The theoretical analysis is also based on the theory of integrated flood risk management, formalized by the World Bank through the work of Jha, Bloch, and Lamond (2012). These authors view urban flooding as a systemic phenomenon resulting from the interaction between hydrological dynamics, rapid urbanization, and modes of territorial governance. This theory is based on the principle that flood risk cannot be completely eliminated, but only reduced and managed over time through a coherent combination of structural and non-structural measures. It criticizes exclusively technical strategies, which are considered costly and ineffective in the long term. Applied to the Tsiémé River, this approach makes it possible to move beyond ad hoc responses and justify integrated management of urban riverbanks.

Finally, this thinking is reinforced by the Integrated Flood Risk Management (IFRM) framework, as formalized by the Asian Development Bank (ADB, 2022). IFRM conceives of risk as a combined function of hazard, exposure, and vulnerability, and adopts a systemic and multi-scale approach that explicitly integrates the watershed scale. It emphasizes that unplanned urbanization is a major driver of risk and highlights the limitations of strategies focused solely on hazard reduction. In the context of this study, IFRM provides a relevant framework for analyzing the dynamics of the banks of the Tsiémé River as a complex socio-hydrological system and guiding the identification of sustainable flood risk management strategies in Brazzaville.

2.2 Conceptual framework

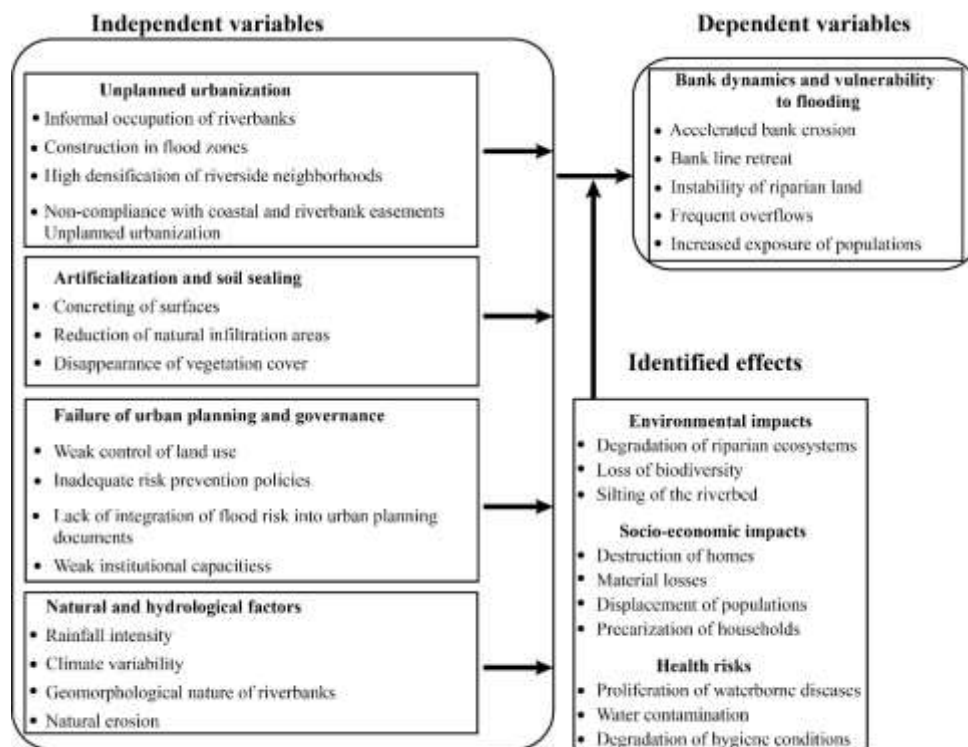


Figure 1: Conceptual framework

Source: Researcher (2026)

2.3 Research gaps

Previous work on the development of the Tsiémé River, carried out in particular as part of the Brazzaville Stormwater Drainage Program, has focused on technical and land issues (route, sizing, parcel inventory, compensation, regulatory framework), but has several limitations. On the one hand, the analysis remains descriptive and focused on land management and resettlement, without any real link between hydro-geomorphological dynamics, spatial occupation, and flood vulnerability, thus neglecting morphological factors such as bed narrowing and silting. On the other hand, no integrated approach has been able to quantitatively link riparian urbanization, riparian forest loss, and flood frequency, which reduces the systemic understanding of risk. Finally, river governance has been addressed from a legal perspective, without a concrete assessment of the level of enforcement of regulations. This study aims to fill these gaps by using an integrated approach that combines hydro-geomorphological analysis, spatial assessment of riverbanks, quantitative vulnerability indicators, and objective measurement of governance, in order to go beyond a strictly technical or land-based interpretation and propose a systemic view of flood risk in the Tsiémé river corridor.

3.0 METHODS AND MATERIALS

Study design: This research takes a descriptive and analytical approach with an explanatory focus. It uses a mixed methodology combining quantitative and qualitative tools to analyze the interactions between urbanization, morphological dynamics of riverbanks, and flood vulnerability in the Tsiémé river corridor. The study includes a spatio-temporal analysis of channel transformations and a socio-environmental assessment of riparian populations. This integrated approach aims to produce a systemic reading of the physical and anthropogenic processes influencing the stability of the riverine corridor.

Study location: The study was conducted along the urban section of the Tsiémé River, located in the northern part of Brazzaville, capital of the Republic of Congo. The riverine corridor studied extends between the fifth district of Ouenzé and the sixth district of Talangaï within the city of Brazzaville. It specifically encompasses districts 58 and 58 bis (Ouenzé), as well as districts 601, 602, 603, 604, and 606 (Talangaï).

Target population: The study was conducted over a period of four (4) months, from October 2025 to January 2026. The target population includes households located in the immediate vicinity of the riverbanks, municipal authorities, technical services in charge of urban planning and the environment, as well as institutional actors involved in risk management and land use planning. This diversity of actors allows the analysis to integrate the social, institutional, and operational dimensions of river corridor management.

Sampling: Stratified and reasoned sampling was used to select households located in the areas most exposed to erosion and flooding. Key informants were identified on the basis of their institutional responsibility and technical expertise. This method aims to ensure the representativeness of exposure situations while ensuring the relevance of the information collected.

Data collection: Primary data was collected through questionnaire surveys of riverside households, semi-structured interviews with institutional actors, direct field observations, and GPS surveys enabling the geolocation of affected areas. Secondary data included multi-date satellite images (Landsat, and Sentinel), topographic maps, rainfall data, and administrative documents relating to urban planning and land regulations. All of these sources were used to articulate morphological analysis, spatial occupation, and vulnerability assessment.

Statistical analysis: Data analysis is based on a set of indicators structured around four dimensions: hydro-geomorphological, spatial, socio-environmental, and institutional. Statistical processing was carried out using software adapted to descriptive analysis, while spatial analysis and thematic mapping were performed using GIS tools.

- Hydrogeomorphological analysis

The lateral dynamics of the banks are assessed on the basis of the average rate of retreat (Rb), determined by:

$$Rb = \frac{D}{\Delta t}$$

where D ($D_{t_2}-D_{t_1}$) represents the observed retreat distance and Δt (t_2-t_1) the time period considered.

The morphological variation of the riverbed is also assessed using the rate of variation in riverbed width (TVI), calculated as follows:

$$TVI = \frac{Lt_1 - Lt_2}{Lt_1} \times 100$$

where L_{t_1} corresponds to the initial width and L_{t_2} to the width measured on the following date.

The peak flow (Q_{flood}) is estimated in order to assess the hydrological responsiveness of the watershed, according to:

$$Q_{\text{crue}} = k \times Q_{\text{moyen}}$$

and compared to the hydraulic capacity of the channel obtained using Manning's formula:

$$Q = \frac{1}{n} AR^{2/3} S^{1/2}$$

where n is Manning's roughness coefficient (≈ 0.035), A corresponds to the wet area (m^2), R to the hydraulic radius (m) and S to the slope of the bed.

These indicators make it possible to assess the morphological stability of the river system and its capacity to contain flows during periods of flooding.

- **Analysis of land use along the banks of the Tsiémé River**

The anthropogenic pressure exerted on the riparian zone is assessed using the linear occupation rate of the banks (Tol):

$$Tol = \frac{S_u}{S_{\text{total}}} \times 100$$

where S_u represents the urbanized area and S_{total} represents the total area of the regulatory corridor.

Ecological degradation is measured by the rate of riparian forest loss (Trip):

$$Trip = \frac{Sr_1 - Sr_2}{Sr_1} \times 100$$

where Sr_1 and Sr_2 correspond respectively to the initial and final vegetated areas.

These indicators make it possible to assess the reduction in the natural mobility margins of the channel.

- **Assessment of flood vulnerability**

The frequency of flooding is estimated by:

$$Fi = \sum(pi \times ni)$$

where pi represents the proportion of households reporting a certain number of annual events and ni the number of corresponding floods.

Human exposure is assessed by:

$$Eh = \frac{P_{exposed}}{P_{total}} \times 100$$

where $P_{exposed}$ represents the number of people physically displaced and P_{total} corresponds to the total number of people affected.

These indicators make it possible to assess the recurrence of the risk and the intensity of its social impact.

- Analysis of governance and land management

The rate of compliance with river regulations (TC_f) is determined by:

$$TC_f = \frac{S_{compliant}}{S_{total}} \times 100$$

Where $S_{compliant}$ represents the area that complies with regulatory requirements and S_{total} corresponds to the total area of the river corridor.

Land regularity is assessed by:

$$TR_f = \frac{N_{regular}}{N_{total}} \times 100$$

Where $N_{regular}$ represents the number of plots with a recognized administrative document and N_{total} corresponds to the total number of plots surveyed.

Finally, the strong land security index is calculated as follows:

$$IS_f = \frac{N_{TF}}{N_{total}} \times 100$$

Where N_{TF} represents the number of plots with a formal land title.

These indicators make it possible to assess the effective degree of application of land use standards and the legal soundness of occupations in the riparian corridor.

4.0 Analysis results

4.1 Hydrogeomorphological analysis of the Tsiémé River

The Tsiémé River is part of the Brazzaville hydrographic system, within the Congo River watershed. Approximately 20 km long and draining a watershed of 6,370 hectares (63.7 km²), it originates in a hilly area northeast of the city before crossing densely urbanized areas and flow into the river. Its morphostructural environment is dominated by loose sedimentary formations (sand, sandy silt, and polymorphic sandstone) that are particularly susceptible to water erosion. In a humid tropical climate characterized by a long rainy season (October–May), the Tsiémé has high hydrological reactivity: despite a moderate average flow of around 0.5

m³/s, it experiences rapid flooding during periods of intense rainfall due to a short concentration time and rapid soil saturation.

The study area specifically covers the downstream section of the river, located between the fifth district (Ouenzé) and the sixth district (Talangaï) of Brazzaville. It encompasses districts 58 and 58 bis (Ouenzé) as well as districts 601, 602, 603, 604, and 606 (Talangaï), covering a length of 4,013 meters from the Tsiémé bridge to its outlet into the Congo River. This section of the river is characterized by intense urban pressure, gradual and sometimes uncontrolled occupation of the banks, and a reduction in the morphology of the minor bed. These changes accentuate the processes of lateral erosion, gully erosion, and sediment accumulation, reduce the hydraulic capacity of the channel, and increase vulnerability to flooding. The choice of this section is therefore justified by the concentration of human and material issues, the recurrence of observed overflows, and the intensity of urbanization dynamics that profoundly alter the hydro-geomorphological balance.



Photo 1: Erosion processes observed on the banks of the Tsiémé River

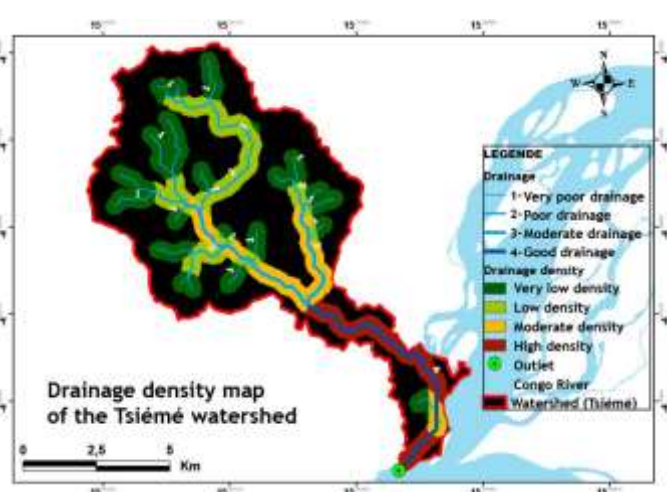
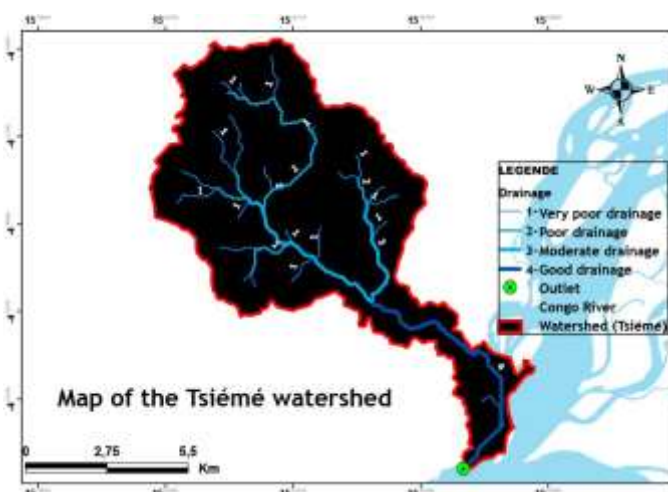
Source : Researcher (2026)

4.2 Order of flow in the Tsiémé watershed

The Tsiémé watershed has four levels of drainage intensity. The first two classes correspond to very low and low drainage, representing small tributaries and drainage heads located upstream. The third class reflects moderate drainage, including secondary watercourses such as the Mikalou River and an intermediate part of the Tsiémé. The fourth class corresponds to strong drainage, concentrated along the main course of the Tsiémé, where flows are greatest before joining the Congo River. Thus, the higher the drainage intensity, the greater the density of the hydrographic network, reflecting a gradual concentration of water downstream.

Map 2: Tsiémé watershed

Map 3: Drainage density of the watershed



Source: Researcher (2026)

Table 1: Bank retreat rate (Rb) of the Tsiémé River

Section	Observed retreat 2014–2024 (m)	Observed rate (m/year)	Projection for 2024–2026 (m)	Rate 2024–2026 (m/year)	Projection 2026–2035 (m)	Rate 2026–2035 (m/year)	Percentage
Upstream	6	0.6–1.2	1.2–2.4	0.6–1.2	5.4–10.8	0.6–1.2	4.6%
Urban areas	25–45	2.5–4.5	5	2.5–4.5	22.5–40.5	2.5–4.5	26.7%
Downstream	60–120	6	12–24	6–12	54–108	6–12	68.7%
Total	-	-	-	-	-	-	100%

Source : Researcher (2026)

The average rate of bank retreat was calculated using the equation $R_b = \frac{D}{\Delta t}$. Over the period 2014–2024, the observed retreats vary from 6 to 12 m upstream, 25 to 45 m in the densely urban section, and 60 to 120 m downstream, corresponding to average rates of 0.6–1.2 m/year, 2.5–4.5 m/year, and 6–12 m/year, respectively.

By updating these dynamics to 2026 and then projecting them to 2035 in accordance with the deadline of the Urban Development Plan ($\Delta t = 9$ years), the potential cumulative retreats over the period 2026–2035 are estimated at between 5.4 and 10.8 m upstream, between 22.5 and 40.5 m in the densely urban section, and between 54 and 108 m downstream.

These results confirm a highly differentiated erosion dynamic depending on the section. The intensity of the retreat increases gradually from upstream to downstream, reflecting the combined effect of urban pressure, degradation of riparian vegetation, and concentration of flows. The densely urbanized section and, above all, the downstream sector appear to be critical areas requiring priority measures for stabilization and management of the river banks.

Table 2: Rate of change in channel width by sector (2014–2026)

Sector	Period	Initial width (m)	Final width (m)	Percentage
Upstream	2014–2024	14	12	–14.3%
	2024–2026	12	5	–58.3%
	2014–2026	14	5	–64.3%
Urban	2014–2024	16	13	–18.8%
	2024–2026	13	4	–69.2%
	2014–2026	16	4	–75%
Downstream	2014–2024	18	15	–16.7%
	2024–2026	15	3	–80%
	2014–2026	18	3	–83.3%

Source : Researcher (2026)

The rate of change in channel width was calculated using the following equation: $T\% = \frac{L_{t1} - L_{t2}}{L_{t1}} \times 100$ Where L_{t1} represents the initial channel width and L_{t2} represents the width measured on the following date. Over the period 2014–2026, the results show a significant contraction of the channel in the three sectors studied. Upstream, the width decreases from 14 m in 2014 to 5 m in 2026, a cumulative reduction of –64.3%. In the urban area, the decrease is even more pronounced, with the width decreasing from 16 m to 4 m, corresponding to a variation of –75%. The downstream sector appears to be the most critical, with a reduction from 18 m to 3 m, representing a cumulative contraction of –83.3%.

These results reveal a major morphological transformation of the channel, characterized by a gradual but rapidly accelerating narrowing in recent years. The intensity of the contraction increases spatially from upstream to downstream, probably reflecting the cumulative effect of sediment inputs, anthropogenic pressure, and the degradation of riparian vegetation. The substantial reduction in the active width of the riverbed implies a decrease in hydraulic capacity and increased vulnerability to flooding, particularly in the densely urbanized and downstream areas, which appear to be priority areas for river management and restoration interventions.

1.1.1. Estimation of the peak flow of the Tsiémé River

The hydrological functioning of the Tsiémé River is based on a relatively low average flow: $Q_{moyen} = 0,5 \text{ m}^3/\text{s}$.

However, during periods of intense rainfall, the flood flow can be estimated as a multiple of the average flow according to the relationship: $Q = Q_{crue} = k \times Q_{moyen}$

where k represents a multiplier coefficient between 20 and 60 for small, highly reactive urban basins. Applying this relationship gives:

$$Q_{crue} = 20 \times 0,5 = 10 \text{ m}^3/\text{s}$$

$$Q_{crue} = 60 \times 0,5 = 30 \text{ m}^3/\text{s}$$

The potential flood flow is therefore between 10 and 30 m³/s.

In addition, the hydraulic capacity of the channel was estimated using the Manning formula:

$$Q = \frac{1}{n} AR^{2/3} S^{1/2}$$

The wet section is determined by: $A = \text{width} \times \text{depth}$

$$A = 4 \times 2 = 8 \text{ m}^2$$

The hydraulic radius is given by: $R = \frac{A}{P}$ with:

$$P = \text{width} + 2 \times \text{depth} = 4 + 2(2) = 8$$

$$R = \frac{8}{8} = 1. \text{ Applying Manning's formula gives: } Q = \approx 10 \text{ m}^3/\text{s}$$

The current hydraulic capacity of the channel therefore appears to be limited to approximately 10 m³/s. This comparison shows that, although the average flow rate is low (0.5 m³/s), potential flood flows (10 to 30 m³/s) can significantly exceed the flow capacity of the riverbed. When $Q_{\text{flood}} > Q_{\text{capacity}}$, the channel becomes insufficient to contain the flows, resulting in lateral overflows and flooding of riparian areas.

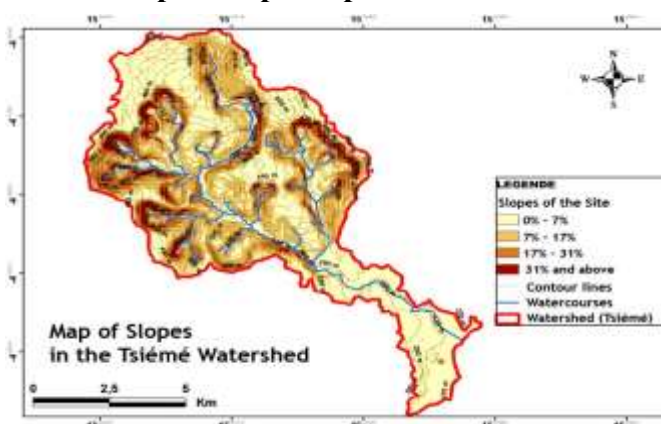
The risk therefore lies not in a permanently high flow rate, but in the high hydrological variability of the system: $\text{Variability: } \frac{Q_{crue}}{Q_{moyen}} = 20 \text{ à } 60$.

This high hydrological amplitude, combined with the morphological narrowing of the riverbed and the occupation of the banks, reduces the hydraulic safety margin and explains the recurrence of overflows observed in the riparian corridor studied.

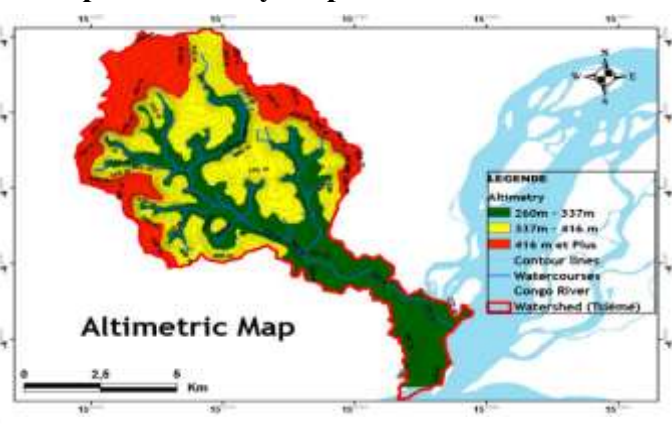
4.3 Morphological and physical characteristics of the watershed

Topography of the watershed

Map 4: Slope map



Map 5: Altimetry map



Source: Researcher (2026)

Topographic analysis of the Tsiémé watershed reveals a morphological structure divided into four slope classes: 0–7%, 7–17%, 17–31%, and over 31%. Low slopes (0–7%) correspond to relatively flat areas where runoff is slow. Moderate slopes (7–17%) are transition zones between plateaus and valleys. Steep to very steep slopes ($\geq 17\%$) are mainly located in lowlands and steep-sided valleys, which form the main natural drainage axes, particularly along the Tsiémé River. This configuration promotes the rapid concentration of rainwater towards the valley floors. During periods of heavy rainfall, the steep slopes accelerate runoff, leading to a rapid increase in flow rates and an increased risk of overflow. Urbanization of lowlands and inadequate storm drainage reduce the basin's natural regulation capacity, thereby exacerbating bank erosion and flooding in downstream areas.

4.4 Potential vulnerability to erosion Risk

Table 3: Classification of slopes and surface vulnerability classes

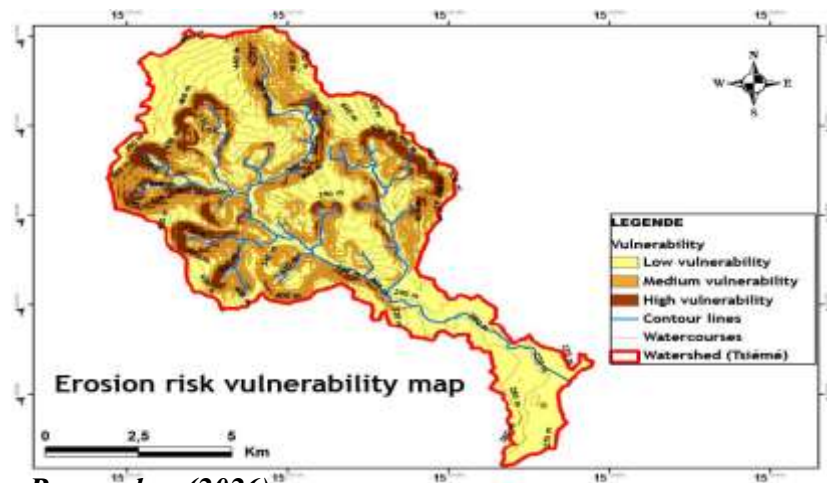
Vulnerability class	Slope class (%)	Area covered (km ²)	Percentage
Low vulnerability	0	40	58.0%
Moderate vulnerability	9	23	33.3%
High vulnerability	≥ 25	6	8.7%
Total	—	69	100%

Source : Researcher (2026)

The analysis of erosion risk vulnerability in the Tsiémé watershed highlights three main classes determined on the basis of slopes. Low vulnerability (0–9%) covers the largest area, i.e., 40 km². These low-slope areas have low and diffuse runoff, limiting the intensity of erosion processes. Medium vulnerability (9–25%) covers 23 km² and corresponds to transition zones where increased slopes promote more concentrated runoff, moderately exposing land and buildings to gully erosion.

High vulnerability ($\geq 25\%$), although spatially limited to 6 km², represents the most sensitive areas of the watershed. These steeply sloping areas promote rapid and energetic runoff, accentuating slope erosion and sediment transport to the riverbed. This dynamic contributes to soil destabilization and increases the risk of flooding downstream. Thus, even though areas of high vulnerability are limited, they constitute critical areas that require special attention in any strategy for the sustainable development and management of the Tsiémé watershed.

Map: Vulnerability to erosion risk



Source: Researcher (2026)

4.5 Analysis of spatial occupation of the studied linear area

Linear occupation rate of riverbanks

Spatial analysis of the study section reveals significant occupation of the Tsiémé river corridor. Over a linear distance of 4,013 m, the cumulative area of the plots surveyed covers 6.77 ha within a 50 m wide strip (25 m on either side of the riverbed). The linear occupancy rate of the banks, calculated according to the relationship $Tol = \frac{S_u}{S_{total}} \times 100$, reaches 33.7%. This means that approximately one-third of the riparian strip studied along the analyzed section is occupied by urbanized plots.

This level of occupation reflects significant local land pressure concentrated in the most sensitive area of the river system. Although this area remains marginal in terms of the total watershed (6,370 ha), its impact is spatially strategic. Urbanization in the riparian zone reduces the natural margins of mobility of the channel, limits flood expansion areas, and can accentuate the erosion and sedimentation processes observed.

Thus, the main issue is not the overall proportion of urbanization at the watershed scale, but its direct location within the riparian corridor. Occupancy of nearly 34% of the protection strip is a major local factor in morphological instability and increased vulnerability to flooding, particularly in a context of rapid and insufficiently regulated urbanization.

Loss of riparian forest on riverbanks (2014–2026)

Table 4: Changes in Vegetation Cover (2014–2026)

Classes	Area in 2014 (km ²)	Area in 2026 (km ²)	Difference (km ²)	Change
Dense vegetation	27.93	26.73	-1.19	-4.3%
Herbaceous vegetation	69.74	49.47	-20.27	-29.1%
Sparse vegetation	34.98	29.34	-5.64	-16.1%
Total riparian forest	132.65	105.54	-27.11	-20.4%

Source: Calculations performed by the authors using the Molusce 5.0 plugin on Qgis, 2026.

The rate of riparian forest loss was calculated using the following formula: $Trip = \frac{Sr_1 - Sr_2}{Sr_1} \times 100$ where S_{r1} represents the initial riparian forest area and S_{r2} represents the area measured on the following date. Over the period 2014–2026, the results show a significant decrease in riparian vegetation cover. The total area of plant formations (dense, herbaceous, and sparse vegetation) decreased from 132.65 km² in 2014 to 105.54 km² in 2026, representing an absolute loss of 27.11 km² and a cumulative reduction of -20.4%. The most significant decrease concerns herbaceous vegetation, which has declined significantly, reflecting a gradual conversion of natural areas to artificial or degraded surfaces.

These results reveal substantial ecological degradation of the riparian corridor during the period studied. The gradual disappearance of riparian forest weakens the mechanical stability of riverbanks through the loss of root anchoring, reduces soil infiltration capacity, and promotes accelerated runoff. This dynamic contributes to intensifying erosion processes, increasing sediment transport, and increasing vulnerability to flooding. Thus, the loss of 20.4% of riparian forest is a major aggravating factor in the morphological instability observed along the Tsiémé River, interacting directly with increased urbanization and reduced riverbed width.

4.5 Assessment of vulnerability to flood risk

Table 5: Classification of flood exposures by elevation and area occupied

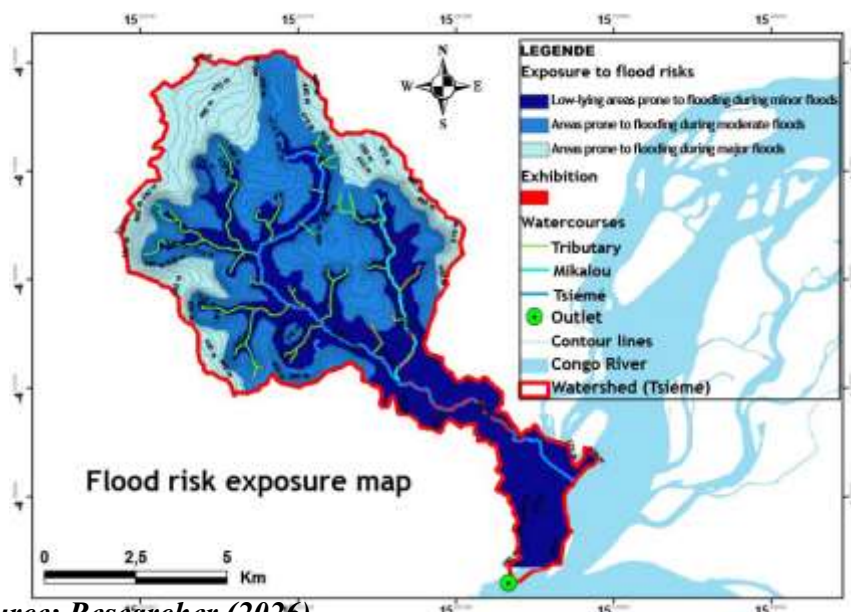
Class	Elevation class (m)	Area covered (km ²)	Percentage
Low-lying areas prone to flooding during minor floods	260–337	27	39.1%
Floodplains during moderate floods	337–416	25	36.2%
Land subject to flooding during high floods	≥ 416	17	24.6%
Total	—	69	100%

Source : Researcher (2026)

Flood risk exposure mapping, based on elevation thresholds ranging from 260 m to over 416 m, distinguishes three levels of vulnerability. The first class (260–337 m), covering approximately 27 km², corresponds to low-lying areas that are frequently flooded during low to medium floods. These areas, often located in the immediate vicinity of the riverbed, are the most vulnerable due to their low topographical position and the recurrence of flooding. The second class (337–416 m), covering approximately 25 km², includes areas mainly affected during medium floods; vulnerability is intermediate, with impacts depending on rainfall intensity and drainage conditions. Finally, the third class (> 416 m), covering nearly 17 km², corresponds to areas exposed only during exceptional floods; buildings there have low to very low vulnerability.

Overall, the analysis shows that low-lying areas have the highest levels of exposure and vulnerability, which justifies the priority implementation of prevention measures, urbanization control, and appropriate hydraulic developments in these critical areas of the watershed.

Map 6: Exposure to flood risk



Source: Researcher (2026)

Table 6: Estimated Flood Frequency Index (2014–2026)

Report category	Proportion of households (%)	Number of floods/year (ni)	Weighted product (pi × ni)
1 flood/year	60% (0.60)	1	0.60
2 floods/year	25% (0.25)	2	0.50
3 floods/year	15% (0.15)	3	0.45
Total / Annual average (Fi)	—	—	1.55

Source : Researcher (2026)

The flood frequency index was estimated using the following formula: $Fi = \sum(pi \times ni)$ where pi represents the proportion of households reporting a certain number of annual floods and ni the number of corresponding events. Based on the proportions observed (60% reporting 1 flood/year, 25% reporting 2/year, and 15% reporting 3/year), applying the formula yields an average annual frequency of 1.55 events/year. For the period 2014–2026 (12 years), this value corresponds to approximately 19 cumulative floods.

These results highlight a significant recurrence of floods during the period studied. A frequency of more than one flood per year indicates that the phenomenon is not an isolated or exceptional event, but part of a regular pattern. This almost annual recurrence reflects the continuous exposure of riverside populations to hydrological risk.

The value obtained thus suggests a persistent vulnerability of households located in the riverine corridor, with potentially repeated impacts on housing, economic activities, and living conditions. The frequency index is therefore a relevant indicator for assessing the recurrence of risk and supporting the analysis of flood vulnerability over the period 2014–2026.

3.1. Human exposure to flooding index (Eh)

The indicator was calculated using the following formula $Eh = \frac{P_{exposed}}{P_{total}} \times 100$, where $P_{exposée}$ corresponds to the number of people physically displaced and P_{total} to the total number of people affected by flooding. Applying this formula gives a value of 55.1%. This value means that more than half of the people affected by the floods were physically displaced from their homes. It is therefore not an exposure index for the entire population of the sector, but an indicator of the severity of the impact among the individuals affected.

Surveys reveal that 1,455 people were physically displaced and 2,639 individuals were affected to varying degrees by the floods. These figures demonstrate the social scale of the phenomenon in the corridor studied. The fact that 55.1% of those affected had to leave their homes or saw them directly impacted reflects the high intensity of the damage suffered.

This proportion highlights a marked social vulnerability in the area studied. It underscores the fact that flooding is not limited to occasional disruptions, but has significant material and human consequences for the majority of the populations affected.



Photo 2: Flooding observed in the study area

Source: Photo taken by researchers (2026)

4.7 Analysis of governance and land management

River regulation compliance rate (TCf)

The analysis of land governance along the Tsiémé River aims to assess the level of compliance with regulatory provisions governing the occupation of riparian areas and river easements. The river regulation compliance rate (TCf) is an indicator used to assess the proportion of plots established in compliance with the requirements relating to minimum distances from the riverbed and urbanization standards in flood zones.

This indicator provides a quantitative reading of the degree of application of development rules and highlights any discrepancies between the regulations in force and the land use practices observed in the field. The table below shows the calculation of the river regulation compliance rate (TCf).

Table 7: Calculation of the river regulation compliance rate (TCf)

Element	Value	Unit	Remarks
Length of the studied stretch (L)	4,013	m	Analyzed section
Regulatory lane width (W)	50	m	25 m on either side
Total corridor area (Stotal = L × W)	200,650	m ²	Gross area under consideration
Total corridor area (Stotal)	20.07	ha	Conversion to hectares
Urbanized area (Su)	6.77	ha	Recorded land use
Compliant area (Compliant = Total – Su)	13.30	ha	Area compliant with regulations
Compliance rate (TCf)	66.3%	%	Level of regulatory enforcement

Source : Researcher (2026)

The river regulation compliance rate (CFR) was calculated using the following formula: $TC_f = \frac{S_{compliant}}{S_{total}} \times 100$ where $S_{compliant}$ represents the area that complies with regulatory requirements (river easements, no-build zones, mandatory setbacks) and $S_{(total)}$ represents the total area of the river corridor studied. Over a length of 4,013 m and a regulatory strip of 50 m (25 m on either side of the riverbed), the total area analyzed is 20.07 ha. After deducting the 6.77 ha occupied by non-compliant buildings or uses, the area complying with regulations amounts to 13.30 ha, or a TC_f of 66.3%.

These results highlight the partial application of river regulations in the area studied. While nearly two-thirds of the corridor formally complies with the regulations in force, approximately one-third of the regulatory strip (33.7%) is occupied in a non-compliant manner. This proportion is not marginal and reflects significant land pressure on riparian areas.

The value obtained thus suggests a gap between development standards and actual land use practices. Compliance limited to 66.3% indicates that control, planning, and regulatory enforcement mechanisms are only partially operational. This situation encourages urbanization in sensitive areas, reduces natural hydraulic safety margins, and potentially increases vulnerability to flooding.

The TC_f is therefore a relevant indicator for assessing the effective level of governance of the river corridor. It makes it possible to objectively assess the degree of enforcement of land use regulations and identify areas for improvement in land management and hydrological risk prevention.

Land regularity rate (LRR)

The land regularity rate was determined according to the following relationship: $TR_f = \frac{N_{regular}}{N_{total}} \times 100$

Field surveys were used to identify and classify plots according to their land tenure status, as shown in the table below.

Table 8: Land tenure status of surveyed parcels

Land tenure status	Number of plots	Percentage
Plots with land title	14	4.2%
Plots with occupancy permits	62	18.7%
Lots with a certificate of sale	244	73.5%
Lots without documentation	12	3.6%
Total	332	100%

Source : *Chercheur (2026)*

Applying the formula gives: $TR_f = \frac{320}{332} \times 100 = 96,4\%$. This result suggests that a large majority of parcels have some form of administrative recognition. However, this apparent regularity must be qualified by the nature of the documents held.

Strong land security index (IS_f)

In order to assess the actual level of legal security, a strong land security index was calculated:

$IS_f = \frac{N_{TF}}{N_{total}} \times 100$ where N_{TF} corresponds to plots with formal land titles. With 14 titled plots out of 332 surveyed: $IS_f = \frac{14}{332} \times 100 = 4,2\%$

This result reveals that only a very small proportion of plots benefit from strong legal security. The majority of occupations are based on intermediate forms of recognition (permits or certificates), which are legally more fragile.

The combined analysis of TC_f (66.3%) and IS_f (4.2%) highlights contrasting land governance. While a significant part of the corridor still formally complies with spatial requirements, the effective legal security of plots remains very limited.

This situation reflects a gap between the regulatory framework, land practices, and control mechanisms. Land use along the riverbanks is mainly based on intermediate administrative forms, which are likely to encourage the gradual urbanization of sensitive areas.

Thus, the vulnerability observed in the riverine corridor is not only the result of hydrological dynamics, but also of institutional fragility characterized by partial enforcement of standards and limited land security.

5.0 DISCUSSION

The results confirm that the current dynamics of the banks of the Tsiémé River are part of a process of profound socio-hydrological imbalance, where morphological changes to the channel, riverside urbanization, and institutional fragilities interact to produce structural vulnerability to urban flooding in Brazzaville. This situation concretely illustrates the theoretical relationship formulated by UNDRR (2015) and reiterated by ECCAS (2021), according to which risk results from the dynamic interaction between hazard and vulnerability.

In the case of the Tsiémé, the hydrological hazard characterized by high flow variability and rapid flooding in a humid tropical context only becomes problematic because of the socially and spatially constructed vulnerability along the river corridor.

The spectacular morphological contraction of the channel (−83.3% downstream between 2014 and 2026) is a major indicator of the disruption of the river's equilibrium. This drastic reduction in the active width of the riverbed mechanically leads to a decrease in hydraulic capacity, estimated at around 10 m³/s, while potential flood flows can reach 30 m³/s. This situation corresponds precisely to the pattern described by Jha, Bloch, and Lamond (2012), according to which rapid urbanization alters flow conditions, increases flood peaks, and reduces the absorption capacity of urban river systems. The Asian Development Bank (2022), in the context of Integrated Flood Risk Management (IFRM), also emphasizes that the reduction of the hydraulic section is one of the most determining factors in the intensification of urban flooding. At Tsiémé, the gradual increase in bank retreat rates, particularly downstream (6–12 m/year), reflects not only geomorphological instability, but also the cumulative effect of anthropogenic pressure and the concentration of runoff from urbanized slopes.

Furthermore, the loss of 20.4% of riparian forest between 2014 and 2026 confirms the central role of ecological functions in hydrological regulation. The literature on nature-based solutions (Kiribou et al., 2024) emphasizes the role of vegetated corridors as natural infrastructure capable of mitigating floods, stabilizing banks, and promoting infiltration. The degradation of riparian forest observed at Tsiémé leads to a loss of root anchoring, a decrease in natural hydraulic roughness, and an increase in sediment transport, contributing to silting and narrowing of the riverbed. These results are consistent with the analyses of UN-Habitat (2017), which show that the destruction of urban river ecosystems amplifies the frequency and intensity of flooding in African cities.

The occupation of 33.7% of the 50-meter regulatory strip highlights localized land pressure precisely in the functional space of the watercourse. This spatial configuration confirms that vulnerability does not depend solely on the overall volume of urbanization, but on its strategic location in flood expansion areas. As highlighted by the theory of integrated flood risk management (Jha et al., 2012), the urbanization of floodplains reduces the natural capacity to dissipate floods and transforms ordinary hydrological events into recurring crises. The situation observed in Brazzaville fits perfectly into this pattern.

Social analysis reinforces this interpretation. The flood frequency index (1.55 events/year) indicates that flooding is a quasi-structural phenomenon. This recurrence is consistent with trends observed in low- and middle-income countries, where 89% of people affected by hydrological disasters are concentrated (World Risk, 2025). The human exposure index (55.1%) reveals that more than half of those affected experience physical displacement, reflecting a high intensity of residential impacts. This situation illustrates the socially constructed vulnerability described by Brown (2016), for whom environmental crises reveal structural inequalities in access to secure land and urban infrastructure. In Tsiémé, households

living in low-lying areas (260–337 m) are exposed to both hydrological risks and socio-economic fragility, confirming that the risk is as much institutional and social as it is physical.

Land governance is a key factor in this vulnerability. While the spatial compliance rate is 66.3%, the strong land security index remains extremely low (4.2%). This disconnect reveals a paradox: apparent administrative regularity coexists with structural legal fragility. O'Brien and O'Keefe (2014) emphasize that institutional fragmentation and insufficient coordination between urban planning, climate adaptation, and risk management are invisible drivers of risk. In Brazzaville, despite the existence of the Urban Planning Code, the PLU, and Environmental Law No. 33-2023, the partial application of river easements reflects insufficiently operational governance. This institutional weakness encourages the gradual urbanization of non aedificandi zones and reduces the scope for preventive action.

Overall, the results confirm the central hypothesis of the research: the dynamics of the banks of the Tsiémé River, under the effect of unplanned urbanization, directly contribute to the production and intensification of vulnerability to urban flooding in Brazzaville. The riverine corridor appears to be a socio-hydrological system in a state of imbalance, as defined by the IFRM (ADB, 2022), where the morphological contraction of the channel, the loss of ecological functions, and land pressure combine to reduce territorial resilience.

These findings highlight the need for an integrated and transformative approach to riverine corridor management. In accordance with the principles of integrated flood risk management (Jha et al., 2012) and integrated climate change adaptation frameworks (O'Brien & O'Keefe, 2014), sustainable vulnerability reduction in Brazzaville cannot be achieved through ad hoc or exclusively technical interventions. It requires active restoration of riparian vegetation, ecological stabilization of riverbanks based on bioengineering, effective control of river easement occupation, and strengthening of land tenure security. More broadly, it requires a structural transformation of urban river planning and development modes, explicitly integrating socio-ecological dynamics into urban policies.

6.0 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This study shows that the dynamics of the Tsiémé River's banks are part of a socio-hydrological imbalance closely linked to the unplanned urbanization of the riverine corridor. Morphological changes in the river channel, marked by increasing bank instability and reduced hydraulic capacity, interact with intense land-use pressure and ecological degradation, leading to increased vulnerability to urban flooding. The occupation of riparian zones and the gradual loss of vegetation have weakened natural hydrological regulation functions and reduced floodplain areas, resulting in recurrent flooding and significant social impacts on local populations. Furthermore, the institutional analysis highlights a disconnect between the existence of regulatory frameworks and their effective implementation on the ground, contributing to continued exposure to flood risks. Overall, the results show that flood risk along the Tsiémé River stems from the interaction between physical dynamics, anthropogenic pressures, and

governance weaknesses, indicating that vulnerability is not solely linked to hydrological hazards but also constitutes a socio-spatial construct shaped by rapid urbanization.

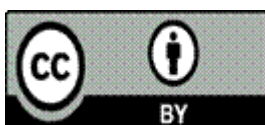
6.2 Recommendations

It is recommended that an ecological restoration program for riverbanks be implemented, including the restoration of riparian vegetation and the application of stabilization techniques based on phytotechnology, in order to strengthen the hydraulic resilience of the riparian corridor. Urban authorities should also strengthen the effective enforcement of watercourse easements, as well as the provisions of the Urban Planning Code and the Local Urban Development Plan, notably through strict monitoring of new developments in regulated zones. It is also necessary to implement gradual relocation or redevelopment of households located in areas highly exposed to flooding, while establishing appropriate social support mechanisms. Institutional capacities for integrated flood risk management should be strengthened to improve coordination among urban planning, environmental, and risk management departments. Finally, additional longitudinal studies should be conducted to monitor the morphological evolution of the river channel and assess the effectiveness of the stabilization and management measures implemented.

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