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RESEARCH ARTICLE

Analysis of the Impacts of Irregular Development of Hillside Areas and Water Erosion in Brazzaville, Republic of Congo: The Case of Quartier Don Bosco in Arrondissement 9 Djiri

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ABSTRACT

Water erosion constitutes one of the major environmental problems in hilly areas such as district 9 Djiri in Brazzaville, Republic of Congo. Its territory is dotted with ravines of various sizes. Among the most active ravines is that of Don Bosco in the Itatolo district. The objective of this study is to analyze the impact of land development on the erosion dynamics which manifests itself in this district of the city. The study methodology is based on documentary research, analysis of the urban fabric and its superposition on the relief, interviews with populations, field observations and three-dimensional measurement of this ravine. The results show that the ravine, the destruction of homes of which dates back to 2012, progressed by 234 m between 2022 and 2024, to reach a total length of 660 m. It caused a loss of land of 211,200 m3, for 1.8 ha of land, or 117.33 m3ha-1 and the 37 plot. The urban analysis of the site shows that the housing unit is made up of 92% plots and 8% roads, blocks with an average land area ratio (FAR) of 75.4% and plots of 84.85%. This density of housing forces residents to drain rainwater into streets without pipes. The main roads are laid out in the direction of slopes, between 5% and 16%, on sandy soil. Under heavy rainfall (on average 1400 mm/year), this led to gullying. Thus, water erosion is the result of the interaction between development and the physical constraints of the site. This study demonstrates the causal links between irregular land development and water erosion which is developing in this district. It suggests the implementation of responsible spatial planning policies, for better preservation of the land.

INTRODUCTION

Like other African cities, such as Kinshasa, Abidjan or Lagos, Brazzaville in the Republic of Congo has been experiencing exponential demographic expansion for several decades. This continuous increase in population and the consequent extension of the urban area have pushed people to settle in high-altitude areas. Our field research has shown that 72.81% of Brazzaville's territory is located in the upper part of the city, at altitudes ranging from 300 to 650 m, including 60.91% between 300 and

400 m and 11.9% between 400 and 650 m, on very steep slopes (over 15%). This appropriation of natural space and its transformation into habitat is achieved by destroying vegetation (Yang, 2024; Nganmo and Priso, 2022; Addae and Oppelt, 2019; Amontha et al, 2015). It leads to a reduction in vegetation cover in favor of housing, market gardening and equipment (Sène, 2018). Analysis of diachronic maps for the period from 2002 showed that the area of vegetation cover fell from 17,523 ha in 2002 to 8,355.5 ha in 2022, a regression of 52.32%. This phenomenon, which disregards the rules governing land use and development and is a consequence of the city's galloping and uncontrolled urbanization, is at the root of the degradation of the urban environment (Mayima et al, 2022; Mambou and Elenga, 2023).

Urbanization, whether controlled or uncontrolled, always takes place at the expense of natural areas. As a result, the soil is exposed to the hazards of natural phenomena such as climate. Indeed, bare, unprotected soils are subjected to the aggressiveness of rainfall, resulting in water erosion (Nzila et al., 2020). This erosion is also the consequence of a topography marked by slopes that hover around 15%, which are considered by soil physicists to be erosive slopes (Ngatsé et al., 2017). It is at the origin of the formation and development of the phenomenon of soil gullying, leading to significant environmental damage.

Arrondissement 9 Djiri, dominated by Mount Boukiero, is characterized by a relief varying in altitude between 350 and 650 m. Its territory is dotted with regressive gullies that affect many neighborhoods, such as Don Bosco in Itatolo, causing huge losses of land and washing away homes and public infrastructure under the helpless gaze of the local populations and communal authorities (Kombo-Kissangou et al., 2018). Several works have been devoted to the study of erosion in Brazzaville (Loembé and Tchicaya , 1993 ; Ngazzi, 2007 ; Louembé and Nzila, 2007 ; Sitou, 2008 ; Sitou et *al*, 2013 ; Ngatsé et *al*, 2017 Kémpéna et al., 2012; Kombo-Kissambou et al., 2018; Mayima et al., 2018; M'Bouka Milandou, 2022), but very few have affected arrondissement 9 Djiri in general and, by ricochet, the Itatolo district. This district is cut by the phenomenon of gullying, with large gullies resulting in the loss of huge quantities of soil, torn away by runoff water during rainy periods. Among these ravines is the Don Bosco ravine, one of the most active.

The aim of this article is to analyze the erosive dynamics associated with urban development in the Itatolo district, focusing on the Don Bosco ravine in terms of its evolution. It is structured around a presentation of the characteristics of the physical environment, the methodological approach to the study, the results obtained and a discussion of the findings.

1. MATERIALS AND METHODS

2.1. Characteristics of the physical environment

The Itatolo district is part of arrondissement 9 Djiri of the city of Brazzaville. It is located in the northern part of the city, with geographical coordinates of 4°8'53'' south latitude and 15°16'24'' east longitude (Figure 1). It belongs to the sub-watershed of the tributary river of the Congo River, which bears the same name as the district. The climate of the study area, which is the same as that of Brazzaville, is equatorial, characterized by an 8-month rainy season (October to May) and a dry season from June to September (Samba Kimbata, 1978). Annual rainfall is around 1,400 mm, and the average annual temperature is around 25°C, with thermal amplitudes barely exceeding 5°C. Soils are 97.48% sand, 1.89% silt and 0.64% clay (Ngatsé et al., 2018). This high sand content gives them a pedological sensitivity that is accentuated by rainfall erosivity, whose index lies between the range of 0.35 to 0.45 t. ha. h/ha.MJ.mm., i.e. that of soils fairly sensitive to water erosion, according to the classification of Bollinne and Rosseau (1978).

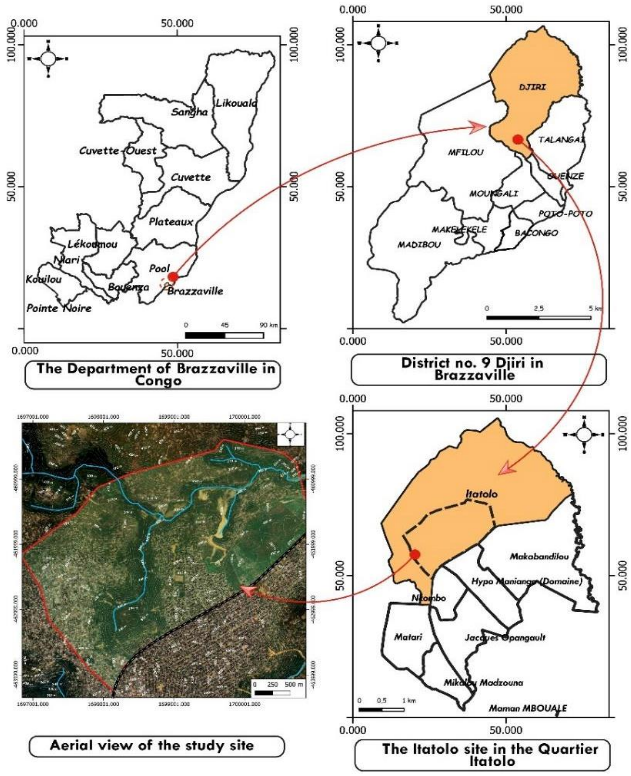


Figure 1: Location of the Itatolo district in Brazzaville

The site chosen for this study is the Don Bosco housing unit, located between Route Nationale n°2 (RN2) and the talweg of one of the branches of the Itatolo River, with geographical coordinates of 4°9'6'' south latitude and 15°15'47'' south longitude. Its relief is characterized by an altitude of between 350 and 450 m, with an average slope of 13.5% (Figure n°2).

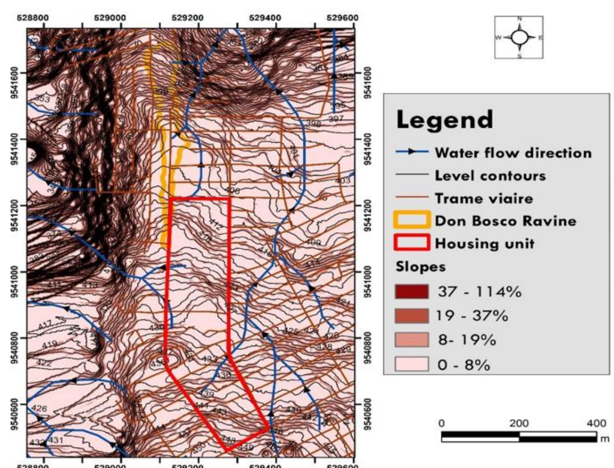


Figure 2: Relief of the study area

Source: Emvoulou, November 2024

The methodology adopted for this study is based on documentary research, surveys and interviews with local residents, and the collection and processing of data from field observations.

Documentary research consisted of using documents relating to general impact studies and documents relating to work carried out in the study area (articles, dissertations, study reports).

2.2 Surveys and interviews

Interviews with neighborhood committees and surveys of local residents were carried out in order to gain a better understanding of the origins of the hazards, their perception of the phenomena and the work carried out to control gullies and ravines, and their responses to these phenomena.

A sample of 143 households was selected by reasoned choice, in a single cluster, and enabled data to be collected from 43 plots located in the neighborhoods where the gullies had been developed. In the course of this study, we combined a quantitative approach using questionnaires (Mettrick, 1994), field measurements (dimensions of structures, quantification of the number of reclaimed and un-reclaimed plots, the number of plots saved from erosion, the area of land lost to erosion) and a qualitative approach (informal and semi-structured interviews). Quantifying the surface area lost involved measuring the length and width of the floor, as well as the height of the gully walls. All these measurements were taken on sections of up to 40 m in length.

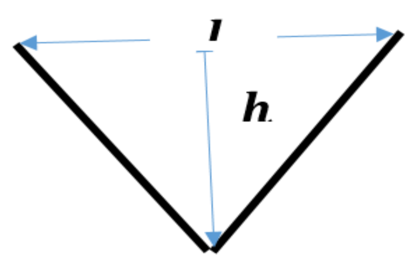
2.3 Field data collection

The fieldwork focused on various parameters, including (1) monitoring the evolution of the Don Bosco gully; (2) three-dimensional measurement of the gully in order to quantify the soil losses caused by this gully and (3) analysis of the urban fabric and its superposition on the relief in the study area.

Ground surveys were carried out between December 2022 and October 2024. They enabled us to calculate the volume of soil lost during this period and to understand the evolutionary dynamics of the ravine. Interviews with local residents enabled us to date and mark the start of the loss of the first homes, which dates back to 2012.

Measuring the gully volume enabled us to estimate the volume of land eroded and assess the extent of the phenomenon. This operation was carried out *in situ* using a topometer, a stringline and a double decameter. The data obtained, comprising values for gully lengths, widths and depths, were used to calculate the areas of the evolved shapes, taking into account their triangular cross-sectional shape (Kombo-Kissangou, 2018) (figure 6). These are the two most common cross-sectional shapes in these neighborhoods. The empirical formulas used to calculate gully cross-sectional areas are as follows:

Figure 3: Calculation of gully cross-sectional area for triangular gullies



$$\mathbf{A} = \frac{lxh}{2}$$

A: gully cross-section; l : cross-section width; h : gully depth.

The maximum assessment of overall gully volumes, consisted in incorporating the coefficient (β) as a function of overall gully morphology. According to the model of Katz & *al. (*2013), **β = 0.5** for triangular sections. Thus, the empirical formula is the following equation:

V = β * ΣA* L or V = β * (A1+A2+A3+...An) * L

V: volume of each shape (m^3); **β**: gully morphological coefficient;

A1; **A2**; **An**: cross-sectional area of each shape; L: total length of each shape.

Before assessing the soil loss, a rough estimate was made of the period of its genesis. This dating is based on the chronological analysis of the genesis and its evolution. The study was based on surveys of local residents. Thanks to their testimonies, the period of the gully's genesis and, above all, the start of the destruction of dwellings were determined. This enabled us to assess the volume of soil lost in m^3. $year^{-1}$. The formulas used to evaluate soil volumes are those used by Nzila et al. (2020):

The average age of the gully is calculated using the empirical formula:

AR = AGR – AP_M

AR: age of gully; **AGR:** year of gully genesis; **APM:** year of measurement.

The volume of gullies in m^3. $year^{-1}$ was obtained using the following empirical formula:

: gully volume in m^3. $year^{-1}$; **V:** gully volume in m^3 **AR:** gully age

3. ANALYSIS AND RESULTS

3.1 Evolution of the Don Bosco gully

Between 2012 and 2022, the head of the Don Bosco gully evolved by regressive erosion of 426 m. Between 2022 and 2023, the head of the ravine continued to retreat by 50 m, then by 184 m between 2023 and 2024. In total, this gully has evolved over a linear distance of 660 m in 12 years from 2012 to 2024 (Figure n°5 & 6), i.e. an average progression by recession of its head of 55 m per year, liquidating 2.5 plots per year.

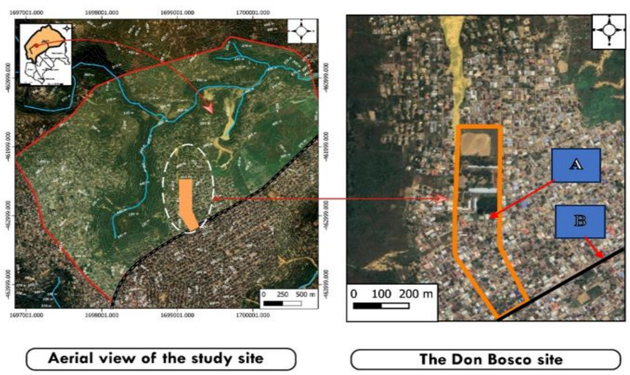


Figure n°2: location map of the Don Bosco site

Source: Emvoulou, November 2024

Legend: **A-** Don Bosco housing unit, used for building density studies; **B-** Main Road n°2, starting point of the main road, constituting the highest point of the site (450 m altitude).

The data obtained from the three-dimensional measurements of the ravine have enabled us to identify three periods of its evolution: 2012-2022, 2022-2023, and 2023-2024 (Table 1). The main measurements are the width and depth of the section and length of the gully for each period analyzed (Photo 1).

Table 1: Main gully measurements for the analyzed periods.

N°	Periods	Width (m)	Depth (m)	Section (m^2)
1	**2023-2024**	10	8	**40**
2	**2022-2023**	20	15	**150**
3	**2012-2022**	45	20	**450**

Source: Emvoulou, November 2024

The total gully length for all periods is 660 m (Figure 5). Applying the formula used by Katz, we obtain a soil loss volume of 211,200 m^3.

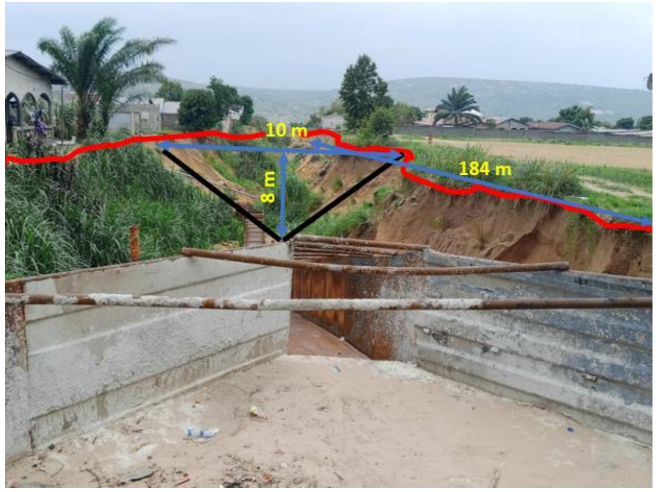


Photo 1: Measurements of gully section 1 (2023-2024)

Source: Photo, Emvoulou, October 2024

This photo illustrates the exercise of taking different measurements of the ravine, for example in section n°1, corresponding to the period 2023-2024. This is how we obtained the quantification data for this gully.

Figure 5: Evolution of the Don Bosco ravine

Source: Field data, 2024

The evolution of the head of the Don Bosco ravine by recession was remarkable and exponential over the period from 2023 to 2024 (Figure n°6), due to the exceptional rainfall recorded in 2023.

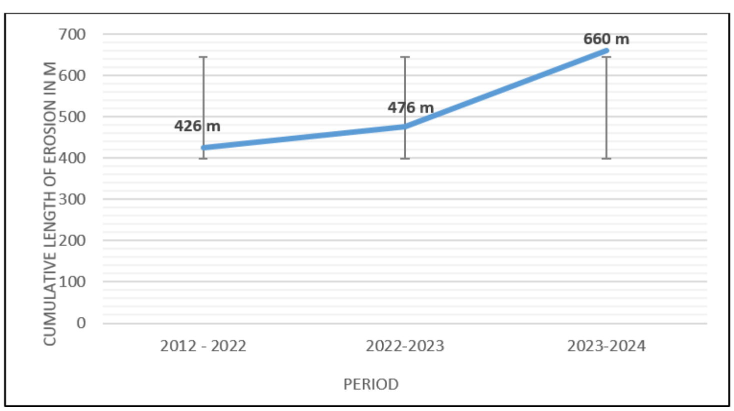


Figure 6: Evolution curve of the gully between 2012 and 2024

This evolution, which reflects the intensity of erosion in the study area, results in a considerable cumulative soil loss of 211,200 m^3, for a surface area of 1.8 ha, i.e. 117.33 t. ha^{-1}.

3.2 Impact of irregular soil management on gully erosion trends

Erosion by gullying is closely linked to the nature of the road layout and the density of housing in the area. In fact, run-off is encouraged by this densification of housing, whose roads are characterized by a lack of drainage channels for rainwater. These roads, with or without pavement, are laid out in the direction of the slope, and become collectors for surface water coming from the plots. In the absence of a sewage system, this water is discharged directly into the roads. The densification of housing in the Don Bosco area is such that 42 plots have been built on either side of the main avenue, over a distance of 750 m, with a floor area ratio of over 80%.

3.2.1. The role of building density

The density of buildings on a plot is defined by its floor area ratio (FAR), or the ratio between the floor area of the buildings and that of the plot. It plays a major role in triggering forms of soil degradation linked to rainwater management. The ratio is expressed as a percentage, ranging from 0 to 100, and expresses the level of occupation of the plot by buildings. Plots with low FAR offer the possibility of managing surface water internally, through infiltration or the construction of structures. On the other hand, plots with high FAR force residents to evacuate all or most of the water into the street (Figure 6).

Caption: 1- 100 m^2 building on a 400 m^2 plot, FAR 25%; 2- 200 m^2 building on a 400 m^2 plot, FAR 50%; 3- 400 m^2 building on a 400 m^2 plot, FAR 100%.

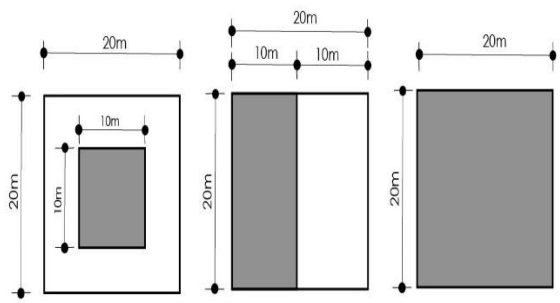


Fig. 6: Example of three types of rights-of-way on a plot of land

These figures illustrate three types of plot occupancy with different FAR. In the first two cases, more than half of the plot is left undeveloped, allowing roof water to be managed internally through infiltration. On the other hand, in the last case (FAR 100%), rainwater is systematically evacuated into the street, increasing the force of runoff (Plate 1).

Plate 1: Gutters draining rainwater into the street

Source: Photo, Emvoulou, January 2023

E- Rainwater drainage pipes.

The photos above show rainwater drainage pipes oriented towards the street.

Urban analysis of the housing unit on the Don Bosco site yields the following results: 92% plots and 8% roads, blocks with an average ESC of 75.4% and plots with an average ESC of 84.85%. This confirms the dense nature of housing in the neighborhood. This density has an impact on runoff. The roofs of the houses concentrate rainwater and discharge it directly onto the ground, with a volume of around 700^{m3} and high runoff intensities. According to Maziezoula and Moukolo (1993), a roof can concentrate up to 8.3$^{m3\ of}$ water, corresponding to 8,300 liters, or the equivalent of 42 drums per plot. On plots with no internal rainwater management facilities, rainwater is collected by roofs and discharged onto roads, increasing the volume of runoff and causing significant damage in terms of soil gullying.

3.2.2. Road layout

The main avenue of the Don Bosco housing estate is in its undestroyed part, 1,100 metres long, starting from national road no. 2 (RN2), where erosion by gullying is triggered by the concentration of runoff water. It is paved with cement cobblestones for 750 metres and is built on a 13.5% slope leading directly into the ravine (Photo no. 2).

Plate 2: Landscaped street ending in the Don Bosco ravine (Itatolo neighborhood, Djiri)

Source: Photo, Emvoulou, October 2024

Legend: 1- Avenue of the Don Bosco Institute (1,100 m), leading to the ravine; 2- Ravine de Don Bosco; 3- Water channeling structure.

The Don Bosco ravine develops along this avenue in a regressive dynamic, starting from the talweg of one of the branches of the Itatolo river, towards the main road n°2. It is one of Brazzaville's active ravines. In its upper reaches, it progressed over a length of 234 m, with a width of 10 m and an average depth of 8 m between 2022 and 2024. As it progressed, it swept away the 194 m-long boundary walls of the Don Bosco complex. All in all, the gully developed, as outlined above, over a length of 660 m between 2012 and 2024, washing away 14,910 m^2 of built-up area, i.e. 37 plots.

4. DISCUSSION

Water erosion in Brazzaville in general and in Djiri in particular represents one of the most recurrent forms of environmental degradation of the urban site. It is the result of the interaction of several factors, grouped into two categories: natural factors **(**climate, relief, soil and hydrography) and anthropogenic factors (land use and development). Over the last twenty years, the city's urban territory, like that of Djiri, has been punctuated by the appearance and development of ravines. They are the cause of huge quantities of land being lost, and of the destruction of buildings and public works. The Don Bosco ravine, the subject of this study, has developed considerably through regressive erosion, liquidating large quantities of soil and dragging plots of land and buildings in its wake. The results obtained in this study are almost identical to those of Nzila et al. (2020) in their study of water erosion dynamics in the Kingouari, Mfilou and Djoué watersheds in Kissoundi, south-west of the city of Brazzaville. The authors point out that between 2007 and 2010, the area of land destroyed was around 4.7 ha, or 2% of the Kinsoundi territory. Similarly, Nzuzi Lelo (2008), Makanzu Imwangana (2008) and Wouthers & Wolff (2010) report significant losses of land due to water erosion in Kinshasa, which has a similar morpho-pedological and bioclimatic context.

These morphogenetic crises are exacerbated not only by the densification of housing, which encourages significant runoff, but also by the lack of stormwater collectors on roadways. The densification of housing in the study area, with a FAR of over 80%, leads to increased surface impermeability, which is responsible for the current erosive runoff. The absence of gutters to channel and control runoff has led to the transformation of roadways into stormwater collectors. This was the conclusion reached by Attipo et al (2023) in their analysis of the main urban technical networks during floods in Brazzaville. These results were confirmed in the work of Emvoulou et al. (2024) on climate change and the vulnerability of the city of Brazzaville to flooding in 2023. These authors point out that the consequence of the lack or inadequacy of drainage structures is an increase in the volume of runoff and significant damage in terms of soil gullying. This responsibility of spatial planning in erosive dynamics in the areas studied is in line with the work of Ngatsé et al. (2017) in the Djiri River watershed, Kombo-Kissambou et al. (2018) in the Mansimou and Mayanga districts, Nzila et al. (2020) in Kissoundi, M'bouka Milandou (2022) in Brazzaville and Mayima et al. (2019) in Kintélé. These same lessons are drawn from the work of Bawa et al. (2019) on water erosion in the Adidogomé-Avatamé district in Lomé and Kaleka Nkole (2021) in Kinshasa.

CONCLUSION

The Itatolo district in arrondissement 9 Djiri is subject to a gully erosion system, like many other districts located on the heights of the city of Brazzaville. With fairly steep slopes, erosive phenomena are favored on the roads, which are often long and oriented in the direction of the slope. This dynamic is closely linked to the densification of housing and the lack of drainage structures. Data collected on the Don Bosco ravine show a cumulative soil loss of 211,200^{m3} over the period studied, for a surface area of 1.8 ha, i.e. 117.33 t. ha^{-1} and a linear progression of 55 m. yr^{-1}. This situation is simply the result of a combination of natural factors predisposing the environment, notably the sandy soils (over 90%), which are cohesionless and fragile on a steep relief, and the triggering factors of highly erosive rainfall, as well as anthropogenic factors aggravating the erosive phenomenon represented by the densification of the habitat and the lack of adequate development.

The Don Bosco ravine is located below the main avenue, 750 m of which is paved, without gutters and bordered by more than 42 densely built plots (over 80% FAR). This high concentration of buildings makes it impossible to manage rainwater internally. This leads to the systematic evacuation of rainwater into the street, which becomes a collector, increasing the volume of runoff and the development of gully erosion. The gully that has formed has already washed away 1.8 ha of land and houses, and is threatening the Don Bosco technical education complex. It is therefore imperative that, in addition to a few attempts to control the gully, which have not been very effective to date, a risk prevention policy be put in place. This must take into account all the hilly areas on which the gullied districts are located, which must be treated as risk zones. Analysis of the urban fabric of the study area must be geared towards urban restructuring, reconciling spatial planning with urban planning standards and the physical constraints of the environment. This analysis of the impact of spatial planning on the development of water erosion in Don Bosco deserves to be extended to the entire urban space of the city of Brazzaville.

AUTHOR CONTRIBUTIONS: Conceptualization, IJE; methodology, IJE, JDDN; software, RVA; validation, JDDN, TYN; formal analysis, BTD, TYN; surveys and data collection, IJE; data processing, IJE, RVA; writing the original draft, IJE; final drafting, review and editing, IJE; visualization, RVA, BTD;

supervision, TYN and JDDN; acquisition of financing, IJE. All authors have read and accepted the published version of the manuscript.

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