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URBAN EROSION IN THE CITY OF MATAMÉYE: VULNERABILITY, DAMAGES, AND CONTROL STRATEGIES

Mataméye Şehrinde Kentsel Erozyon: Kırılganlık, Zararlar ve Kontrol Stratejileri

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ABSTRACT

Urban gully erosion represents a growing environmental hazard in rapidly expanding Sahelian cities, where intense rainfall events interact with fragile soil conditions, topography, and unplanned urban development. This study assesses the vulnerability of Mataméye (Niger) to gully erosion resulting from the combined influence of climatic, physical, and anthropogenic factors, and evaluates its environmental and socio-economic impacts while critically examining existing local management strategies. The methodology integrates field observations, morphometric measurements of gullies, spatial analyses, and hydrometeorological data between 1998 and 2021. Field investigations identified seven active gullies concentrated in the most vulnerable urban neighborhoods, with lengths ranging from 17 to 120 m and widths exceeding 10 m. In 2019, four major occurred with an estimated total soil loss of 3,540.7 m³, whereas the number of gullies increased from four to seven, with volumes ranging from 60 to 1,800 m³, indicating rapid expansion driven by repeated extreme rainfall events, which produced simultaneous formation of three distinct gully types within the same area, namely the R5 gully (characterized by aggressive and intense erosion), the R6 channel (representing passive gully erosion), and the R7 gully (defined by aggressive vertical incision). This variability highlights the heterogeneity of soil erodibility within the study area. The geometric properties of the measured gully channels were mathematically estimated based on an idealized parabolic gully geometry. The predictions consistently underestimated the observed values, indicating scale bias. The Standardized Precipitation Index (SPI) indicated that the 12-year period preceding the measurements was characterized by extreme drought conditions, followed by the last five years of excessive rainfalls, being closely associated with gully erosion processes and the lack of vegetation cover. The rainfall events converted the watershed to 5th order stream gully network.The Modified Fournier Index (MFI) ranges from 158.6 to 167, indicating very high to extreme erosivity, while the erosivity factor (R) varies between 8,500 and 9,500 MJ mm ha^{-1} h^{-1} yr^{-1}, promoting runoff concentration and the rapid development of gullies. The results indicate that erosion intensity is strongly amplified by anthropogenic factors, notably unpaved roads, lack of drainage infrastructure, and progressive occupation of natural flow paths. Local mitigation measures (infilling and the use of sandbags) remain temporary and largely ineffective, highlighting the absence of an integrated approach and the urgent need for coordinated watershed-scale strategies.

ÖZET

Şehir gully erozyonu, hızlı bir şekilde büyüyen Sahel şehirlerinde giderek artan bir çevresel tehdit oluşturmaktadır. Bu durum, yoğun yağış olaylarının kırılgan toprak şartları, yerel topoğrafya ve plansız kentsel gelişim ile etkileşimi sonucu ortaya çıkmaktadır. Bu çalışma, Mataméye (Nijer) kentinin iklimsel, fiziksel ve antropojenik faktörlerin birleşik etkisi altında oluşan oyuntu erozyonuna karşı kırılganlığını değerlendirmekte; bunun çevresel ve sosyo-ekonomik etkilerini incelemekte ve mevcut yerel yönetim stratejilerini detaylı bir şekilde analiz etmektedir. Metodolojik çerçeve; arazi gözlemleri, oyuntu morfometrik ölçümleri, CBS tabanlı mekânsal analizler ve 1998–2021 dönemini kapsayan hidro-meteorolojik verilerin entegrasyonuna dayanmaktadır. Arazi çalışmaları, kentsel alanın en hassas mahallelerinde yoğunlaşan yedi aktif oyuntunun varlığını ortaya koymaktadır. Bu oyuntuların uzunlukları 17 m'den 120 m ye kadar değişmekte olup, yer yer genişlikleri 10 m'yi aşmaktadır. 2019 yılında dört büyük oyuntu toplam 3.540,7 m^3 tahmini toprak kaybına neden olurken, 2021 yılına gelindiğinde oyuntu sayısının dörtten yediye yükseldiği ve hacimlerin 60-1.800 m^3' arasında değiştiği belirlenmiştir; bu durum, tekrarlayan aşırı yağış olaylarıyla hızlanan hızlı bir genişlemeyi göstermektedir. Bunlar R5 oyutusu (agresif ve güçlü erozyon), R6 hedeği (pasif oyuntu erozyonu), ve R7 hendeği (agresif dikey yarıntı erozyonu) olup toprak erodibilitesinin heterojenliğini göstermektedir.Yağışlar havzayı 5.inci derece akış şiddetine sahip gali drenaj ağıyla donatmıştır. Ölçülen oyuntu hendeklerinin geometrik değerleri parabolik oyuntu hendekleri esas alınarak matematiksel olarak hesaplanmış ve gözlemler ve tahminler karşılaştırılmıştır. Tahminler her zaman gözlem değerlerini düşük olarak tahmin etmiştir. Standard yağış indeksi (SPI) ölçümlerden önceki 12 yılın aşırı kurak geçtiğini ve son beş yılın aşırı yağışlı geçtiğini göstermiştir. Bu durum oyuntu erozyonu ve bitki örtüsü eksikliğiyle çok yakın ilişkili bulunmuştur. Islak dönem yağışları 2021 yılında üç değişik oyuntu tipini aynı nada oluşturmuştur. Modifiye Fournier İndeksi (MFI) değerleri 158,6 ile 167 arasında değişerek çok yüksek ve aşırı yüksek-erozyon potansiyeline işaret ederken, erozivite faktörü (R) 8.500 ile 9.500 MJ mm ha^{-1} h^{-1} $yıl^{-1}$ arasında değişmekte ve yüzey akışının yoğunlaşması oyuntu gelişimine neden olmuştur. Sonuçlar, erozyon şiddetinin özellikle stabilize edilmemiş yollar, drenaj altyapısının yetersizliği ve doğal akış yollarının giderek işgal edilmesi gibi antropojenik faktörler tarafından önemli ölçüde arttığını göstermektedir. Yerel ölçekte uygulanan dolgu çalışmaları veya kum torbaları gibi azaltım önlemleri geçici ve büyük ölçüde etkisiz kalmakta; bu durum, entegre bir yaklaşımın eksikliğini ve havza ölçeğinde koordineli stratejilere duyulan acil ihtiyacı ortaya koymaktadır.

1. INTRODUCTION

In sub-Saharan Africa, urban centers are increasingly confronted with environmental degradation resulting from their high exposure to climatic hazards and the insufficiency of urban planning mechanisms (UN-Habitat, 2020; World Bank, 2021). Climate change, marked by rising extreme rainfall events, seasonal irregularity, and intensified runoff, exacerbates natural risks such as flooding and water erosion (IPCC, 2022; Niang et al., 2014). In Niger, these dynamics are reflected in the multiplication of urban floods, accelerated soil degradation, and significant challenges in stormwater management and sanitation (I. Mamadou et al., 2016; DGPC, 2023). Several studies show that urban vulnerability is intensified by household poverty, the use of low-resistance construction materials, and weak infrastructure (Wallez, 2010; Yamba et al., 2014), while the concentration of informal settlements in flood-prone or unstable areas highlights the fragility of urban governance (IOM, 2019; Brückmann et al., 2020). Rapid demographic growth, driven by rural exodus and internal migration since the 1990s, has fueled unplanned urbanization that disrupts natural drainage networks and increases soil impermeabilization (A. Bachir et al., 2019; INS, 2023). Urban gully erosion has become a major environmental issue in rapidly expanding Sahelian cities, where the interaction between climate variability, fragile soils, and unplanned urbanization accelerates land degradation processes. Previous studies have shown that the increase in surface runoff caused by urban land transformation significantly enhances the erosive power of concentrated flows, leading to rapid gully initiation and expansion (Valentin et al., 2005; Poesen et al., 2003).

These dynamics contribute to the formation and expansion of deep gullies, particularly in the loamy-sandy zones of Zinder and Maradi (Mahaman, 2018; Abdoul-Aziz et al., 2021; Saadou et al., 2016; Gonda et al., 2019). The city of Mataméye represents a representative case of these processes, having experienced severe gully erosion since 2019, characterized by gully widening, infrastructure degradation, housing destruction, and increasing risks of collapse. This vulnerability is explained by the combined effects of fragmented topography, loose soils sensitive to runoff, increasing extreme rainfall events (CRA Niger, 2022; AGRHYMET, 2021), and rapid, uncontrolled urbanization (Maman et al., 2020). The absence of functional drainage systems, the proliferation of informal settlements in high-risk areas, and the reduction of tree cover further heighten the city's environmental and socio-economic fragility (Haci, 2017; Abdou, 2020). Despite the magnitude of the observed damages, local responses remain fragmented, short-term, and largely ineffective, reflecting the absence of an integrated urban planning and water-risk management strategy. Understanding the spatial dynamics of gully erosion, its climatic drivers, and its socio-environmental impacts is therefore essential to support sustainable urban development and risk reduction policies in Mataméye.

This study aims to evaluate the physical and climatic vulnerability of Mataméye to rainfall-induced gully erosion using geomorphological, topographic, and hydrometeorological indicators. It also seeks to quantify and spatially analyze erosion processes and associated damages through field measurements and GIS-based approaches, while examining the influence of anthropogenic factors such as urban expansion, settlement patterns, and inadequate drainage infrastructure. In addition, the study critically assesses the effectiveness of existing local mitigation practices and institutional responses in order to better understand their role and limitations in managing erosion risks and urban vulnerability to extreme rainfall events. Despite the growing recognition of urban erosion processes in semi-arid environments, medium-sized Sahelian cities remain underrepresented in the scientific literature. This research contributes to filling this gap by providing a detailed hydro-geomorphological assessment of urban gully erosion in Mataméye under conditions of rapid urban expansion and increasing climatic variability. This study provides a rare integrated assessment of urban gully erosion in a medium-sized Sahelian city by combining rainfall erosivity indices (MFI and R factor), field-based morphometric measurements, and GIS-based topographic analysis. It further distinguishes between natural geomorphological controls and urban-induced amplification processes, which remains poorly addressed in similar contexts.

2. MATERIALS AND METHODS

2.1. Study Area

Located in the Kantché Department (Zinder Region), between longitudes 8°27′36″ and 8°29′13″ E and latitudes 13°24′18″ and 13°26′7″ N, the city of Mataméye rests on a geomorphological substrate composed of Sahelian sandy formations that are highly prone to erosion. Apart from the limited structural routes identified as asphalt or clay-stabilized roads, the remainder of the urban network consists entirely of bare sandy tracks (Figure 1). These unpaved thoroughfares, lacking protective surfacing, act as natural drainage pathways during intense rainfall events. The low cohesion of the sandy soils facilitates rapid runoff concentration, promoting the initiation and development of linear erosion processes (gullying), which pose a direct threat to the stability of urban infrastructure located in topographic depressions. Such conditions enhance the speed and intensity of runoff during heavy rainfall, thereby increasing vulnerability to linear erosion, particularly in urban depressions where water accumulation is pronounced (Nyssen et al., 2002). In the absence of an effective stormwater drainage system, rainfall runoff is conveyed through bare streets and unpaved pathways, which act as natural flow channels and frequently intensify surface erosion processes.

The topography of Mataméye is characterized by a relatively low altitudinal amplitude, structured by a succession of interdunal depressions and slightly elevated sandy areas. Topographic profiles (Figure 2 and Figure 3) indicate that several neighborhoods, such as Kanguiwa and Nassarawa I, are located in lower sectors, while areas such as N'Wala, Sabon Gari, and Angoual Dapodou occupy comparatively higher positions. The central part of the city corresponds to a more depressed zone, whereas higher elevations are mainly observed in the southeastern sector.

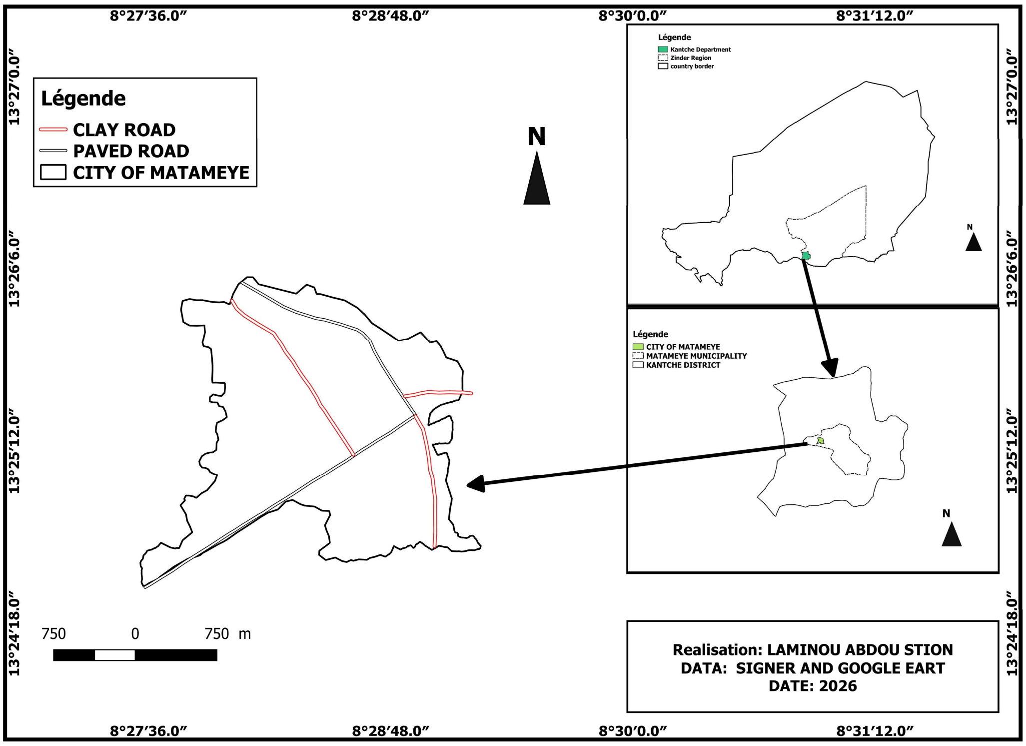

Figure 1: Location of the city of Mataméye.

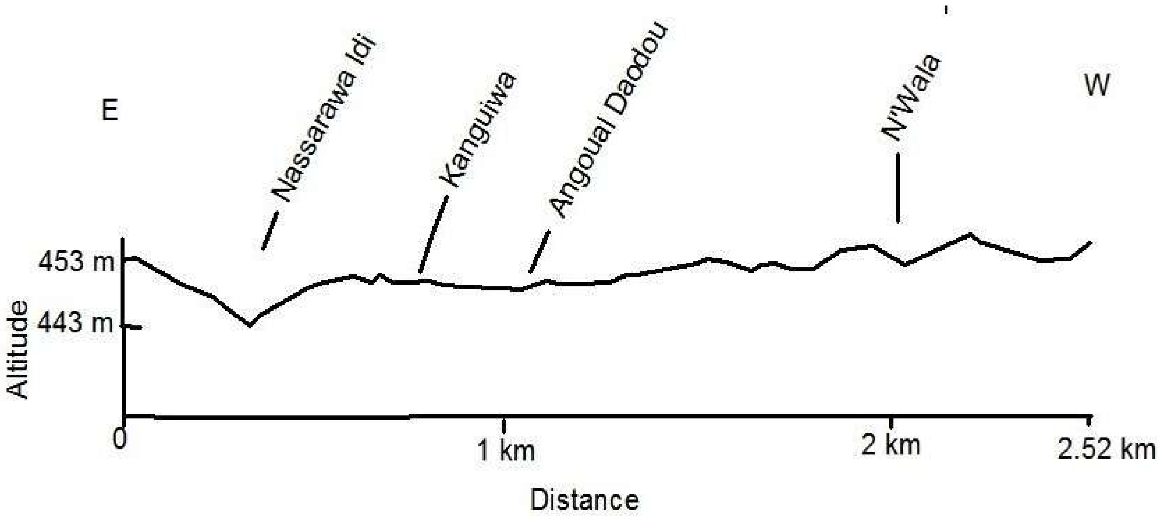

Figure 2: East–West topographic profile of Mataméye city derived from Google Earth imagery (2022).

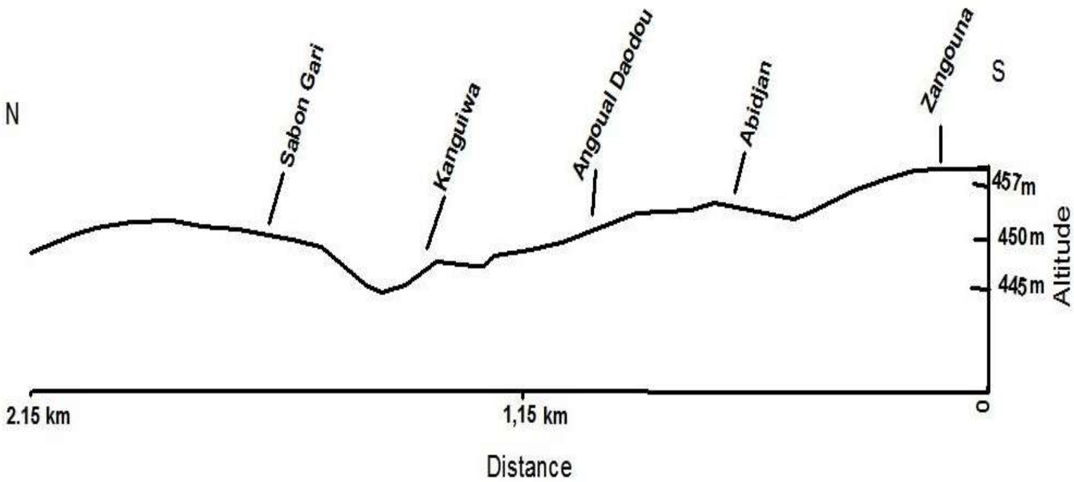

Figure 3: North–South topographic profile of Mataméye city derived from Google Earth imagery (2022).

2.2 Methods

This study adopts an integrated methodological framework combining geomorphological field observations, hydrometeorological analysis, GIS modeling, and socio-environmental surveys. This approach enables a comprehensive characterization of gully erosion dynamics, the identification of its controlling factors, and the assessment of its impacts on the urban environment, while also analyzing the coping and mitigation strategies implemented by local populations in Mataméye in response to guly erosion. Fieldwork involved recording precise coordinates of gullies and affected areas using a GPS, including monitoring surface runoff and identifying the most vulnerable urban sectors. The boundaries of neighborhoods, the city, and sites experiencing erosion-related damage were delineated in the field to ensure an accurate spatial representation. Following data collection, the coordinates were imported into Google Earth to create a georeferenced database, which was subsequently used to generate thematic maps in QGIS.

These maps facilitated the analysis of gully spatial distribution, neighborhood exposure, and identification of high-risk areas. Eroded volumes were estimated from morphometric field measurements, including gully length, average width, and depth. Volumes were calculated by multiplication of gully length(L), width(W), and depth(D). Although gully cross-sections are inherently irregular, this morphometric approximation is widely applied in geomorphological studies to provide a consistent first-order estimation of erosion magnitude, particularly where detailed topographic surveys are not feasible (Poesen et al., 2003; Nyssen et al., 2002). During the monitoring of gully erosion processes, fixed markers were installed along each gully, particularly at the gully heads and at representative cross-sections used for width measurements. A leveling line was also placed at the bottom of the gullies in order to monitor their morphological evolution after each rainfall event. Morphometric measurements were therefore carried out after each significant rainfall event to assess the dynamics and progression of gully development over time.

This method is thus suitable for assessing spatial variability of erosion severity and comparing gully development across different urban sectors. To complement field observations, geospatial analyses were conducted using a Geographic Information System (QGIS 2.16). A Digital Elevation Model (DEM) was derived from the Shuttle Radar Topography Mission (SRTM) and used to characterize topographic variability and drainage conditions. The SRTM DEM, obtained from the USGS Earth Explorer database, has a spatial resolution of approximately 90 m x 90 m and covers an area of roughly 8,350 km². After correction, mosaicking, and reprojection to ensure spatial consistency, the DEM was used to generate elevation, slope, and flow accumulation maps, which are essential for understanding surface hydrological processes and erosion dynamics (Moore et al., 1991; Tarboton, 1997). These topographic derivatives enabled the delineation of the urban watershed, extraction of the drainage network, and hierarchical classification according to Strahler's stream order method (1957). Flow accumulation analysis also facilitated the identification of runoff convergence zones particularly susceptible to gully initiation and development. Integrating these topographic parameters with land-use information and GPS field data provided a robust foundation (Garmin El Etrex 10) for identifying the urban areas most exposed to erosion.

Hydrometeorological analysis was conducted using daily rainfall data covering the period from 1998 to 2021, obtained from the Departmental Directorate of Agriculture of Mataméye, Niger. These data were analyzed to assess interannual rainfall variability, mean annual precipitation, and the occurrence of extreme rainfall events. The Standardized Precipitation Index (SPI) was calculated to identify wet and dry phases over the study period. The Modified Fournier Index (MFI) was used to quantify rainfall erosivity. MFI accounts for both the intensity and concentration of rainfall and is particularly suitable when high-resolution rainfall data are lacking. The formula follows as below:

$$MFI = \sum_{i=1}^{n=12} \frac{{P_i}^2}{P} \qquad Eq.1$$

Pi is the precipitation of month i (mm) and P is total annual precipitation (mm). The index n is the total number of months a year.

MFI was computed for each year using the available monthly rainfall data. MFI values were classified according to standard thresholds to assess rainfall erosivity: Low (<60), moderate (60-90), high (90-120), very high (120-160), and extreme (>160). The estimated R factor was then used to quantify the potential for gully formation and soil loss. The rainfall erosivity factor (R) is a key parameter in soil erosion models, typically calculated from high-resolution rainfall data (30-min or hourly) using the EI30 method. Due to the absence of sub-daily rainfall data, the R factor was empirically estimated from MFI using the following relation.

$$R = 0.7397MFI^{(1.847)} \qquad Eq.2$$

The MFI and R gully erosion indexes are empirical formula and derived from global and regional studies (Arnoldus, 1980; Fournier, 1960), allowing a reliable approximation of rainfall erosivity when only monthly rainfall data are available. It provides a practical and scientifically accepted alternative to calculate R without high-resolution data, making it suitable for data-limited regions such as the Sahel. Although direct soil texture measurements were not available for the study site, regional pedological studies conducted in the Zinder region and comparable Sahelian environments provide a reliable approximation of the dominant soil characteristics. These studies report that soils are predominantly sandy to sandy–loamy, typically composed of 60–75% sand, 10–25% clay, and less than 1% organic matter, resulting in low aggregate stability and weak structural cohesion (Bationo and Buerkert, 2001; Hiernaux et al., 2009). Therefore, these regional findings were used as a comparative framework to interpret the hydrometeorological controls on gully erosion dynamics in the urban environment of Mataméye. Urban surface characteristics were qualitatively assessed during field surveys, including the identification of paved and unpaved roads, drainage conditions, and settlement patterns. Particular attention was given to the role of lateritic and sandy unpaved roads, which act as preferential runoff pathways during rainfall events.

In addition to physical measurements, the socio-environmental survey aimed to assess the perceptions of populations living in neighborhoods affected by erosion, particularly households located in close proximity to gullies. A structured questionnaire survey was conducted using a simple random sampling approach within the selected neighborhoods. A sample of 25 households in four areas was surveyed in each neighborhood, representing approximately 100 individuals in total. Data were collected using a survey guide designed with Sphinx software (version 1.5.1). The collected data were coded, entered into Excel, and analyzed using descriptive statistical methods (frequencies and percentages). The results were then presented in graphical form to highlight the main perceptions and socio-environmental impacts associated with the erosion phenomenon. Multidisciplinary approaches are widely recommended in gully erosion research because they allow a comprehensive understanding of both hydro-geomorphological processes and anthropogenic influences in semi-arid environments (Poesen et al., 2003; Valentin et al., 2005).

3. RESULTS

3.1. Predisposition of the City of Mataméye

Field observations combined with the analysis of DEM images, interviews, and surveys conducted with local populations made it possible to identify the factors behind the intensification of erosion in the city of Mataméye. The results indicate a clear spatial heterogeneity of gully erosion across the urban landscape of Mataméye, with a strong concentration of active gullies in low-lying and densely urbanized neighborhoods, suggesting a direct relationship between topography, runoff concentration, and anthropogenic land use patterns.

3.1.1. Physical Factors

Geomorphology: The city of Mataméye is drained by a tributary of the Korama watershed, the main hydrological system controlling surface runoff within the urban area. Within this watershed, elevations range between 430 and 500 m, reflecting a moderately uneven topography. The lowest altitudes are concentrated in the central and eastern sectors, which act as natural convergence zones for surface flows and are therefore particularly exposed to runoff accumulation during intense rainfall events. According to Strahler's stream order classification, the hydrographic network of the watershed is composed of channels ranging from first (1) to fifth (5))order, indicating a well-developed and hierarchized drainage system. The urban area itself is crossed and drained by a fifth-order stream, which plays a major role in collecting runoff generated both within the city and in upstream catchments.

The spatial and hydrological configuration contributes to the concentration of surface water in low-lying urban sectors and enhances the erosive power of flows during heavy rainfall episodes, thereby favoring gully initiation and rapid channel incision processes observed in Mataméye(Figure 4).

The altitudes vary between 440 and 460 m within the urban area (Figure 5). The highest area is located in the southeast, while the lowest (depressed) zone is in the central part, illustrating a relatively uneven terrain. The sandy nature of the soil and the low elevation exposed severe gully erosion in the neighborhoods of N'Wala, Sabon Gari, Kanguiwa, Zangouna 2, and Nassarawa Idi.

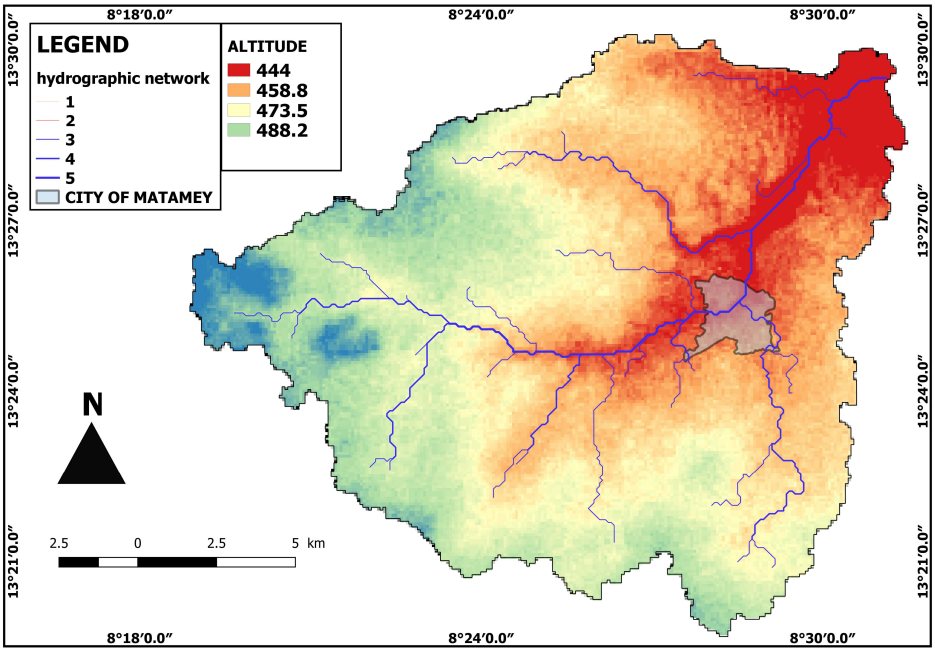

Figure 4: Watershed of Mataméye.

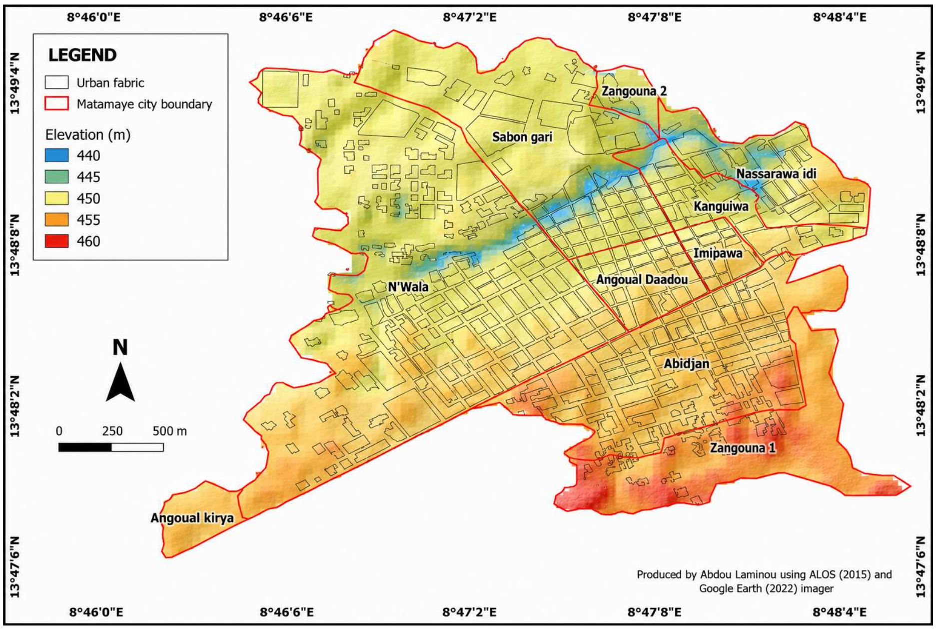

Figure 5: Altitude Variation in the City of Mataméye.

Soil characteristics: Based on the regional pedological characteristics described in the methodology, the soils of the study area can be interpreted as predominantly sandy to sandy–loam with low structural stability. Such conditions favor high infiltration under normal rainfall; however, during intense precipitation events, infiltration capacity is rapidly exceeded, leading to the generation of significant surface runoff. This behavior plays a key role in the initiation and development of gully erosion, particularly in areas where runoff becomes concentrated. In addition, localized variations in soil texture, particularly the presence of clayey or transitional soils with lower permeability, significantly enhance runoff concentration and promote gully initiation. This is consistent with David and Jackson (1997) reporting how urbanization and impeding layers declined infiltration and generated concentrated flows in drainage ways. Consequently, these zones become highly susceptible to gully development, especially during high-intensity rainfall events, as illustrated in Figure 6.

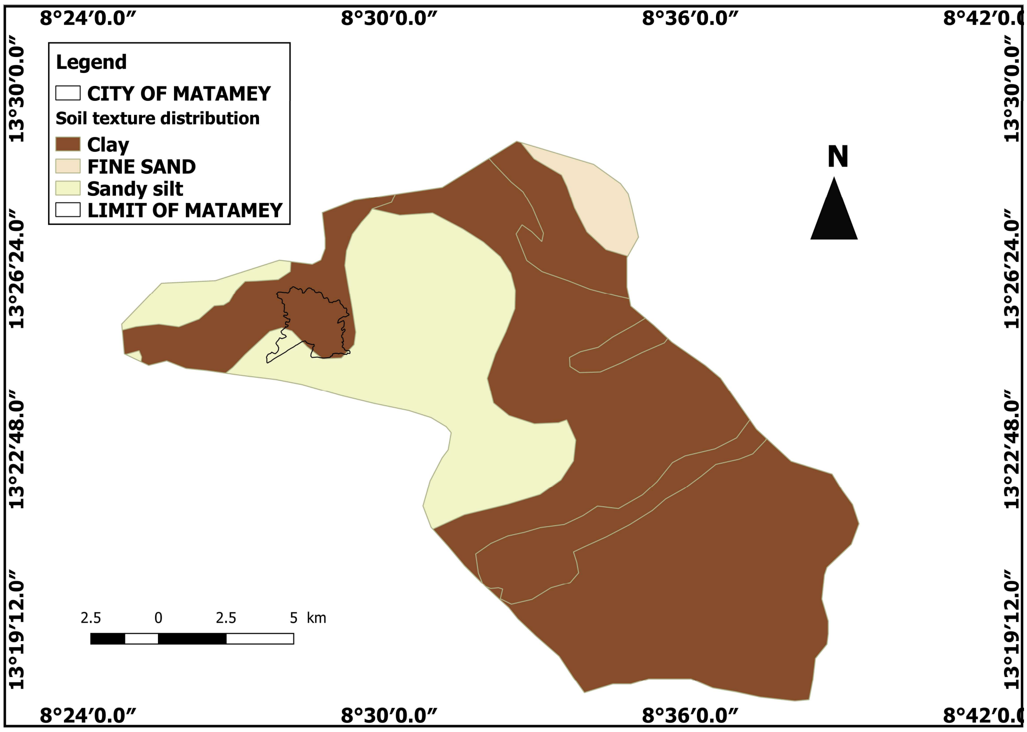

Figure 6: Soil texture distribution in the city of Mataméye Source: Field survey and DEM analysis, 2021.

Rainfall: Rainfall analysis for the period 1998–2020 indicated a mean annual precipitation of approximately 547 mm, characterized by a wet phase (1998–2001), a prolonged dry period (2002–2016), followed by a resumption of rainfall since 2017 marked by a progressive increase in wet event intensity (Figure 7). Prior to 2019, erosion processes in Mataméye were predominantly linear and limited, associated with relatively low and widely spaced rainfall events that constrained runoff concentration along vulnerable topographic pathways. In contrast, daily rainfall data for 2019 (Figure 8) reveal a sequence of closely spaced high-intensity rainfall events, totaling approximately 633 mm within only 40 days. These conditions led to rapid soil saturation and increased hydrological instability. Combined with local topography, they promoted the widespread development of gullies across several urban sectors, particularly during August, when rainfall intensity and frequency reached at their peak levels. The year 2019 thus represents a clear transition from limited linear erosion to more extensive and destructive gully formation, directly linked to rainfall intensity and temporal concentration. This trend is also clear from the intensity-duration=frequency curve of the rainrecords in the region (Figure 9). This shift resulted in the formation of four major gullies, with an estimated total soil loss of approximately 3540.7 m^3 during the 2019 rainy season (Figure 11). The figure 9 clearly shows a gully in the N'Wala neighborhood in 2019 after these ranin events.

The analysis of rainfall erosivity using the Modified Fournier Index (MFI) further supports these observations. For 2019, the MFI is estimated at approximately 158.6, indicating very high erosivity, close to the extreme threshold. This value is consistent with the strong seasonal concentration of rainfall, particularly in August, which enhances surface runoff generation and promotes gully development. The corresponding rainfall erosivity factor (R) is estimated at approximately 8500 MJ mm ha^{-1} h^{-1} yr^{-1}, confirming the high erosive power of rainfall during this year. In 2020, the MFI reaches approximately 167, indicating extreme rainfall erosivity. This increment reflects a higher concentration and intensity of rainfall events compared to the previous year. The estimated R factor of about 9500 MJ mm ha^{-1} h^{-1} yr^{-1} further confirms the exceptional erosive potential of rainfall during this period. Such conditions favor rapid runoff generation, increased flow concentration, and accelerated gully development. Overall, these results highlight strong interannual variability in rainfall erosivity, characteristic of Sahelian environments where precipitation is highly concentrated within a short rainy season, amplifying hydrological responses, particularly in urban areas.

Figure 10 illustrates the statistical distribution of daily rainfall, showing that the probability of occurrence decreases exponentially with increasing return period (T). A combined analysis of this curve and the climatic indices calculated for the area highlights a context of extreme rainfall erosivity. Indeed, short return period events (T < 5 years), although frequent, already exhibit sufficient intensity to saturate urban soils, while rarer events, located on the right-hand side of the curve, can trigger catastrophic gully formation processes.

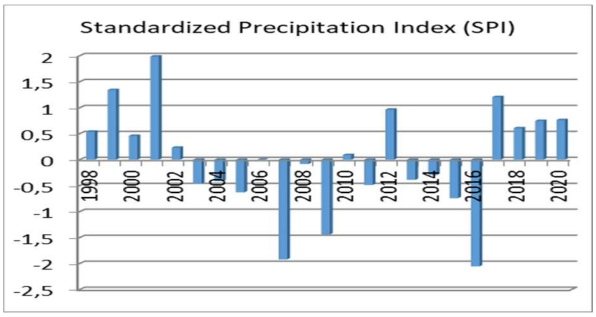

Figure 7: Standardized Precipitation Index (DDA Mataméye).

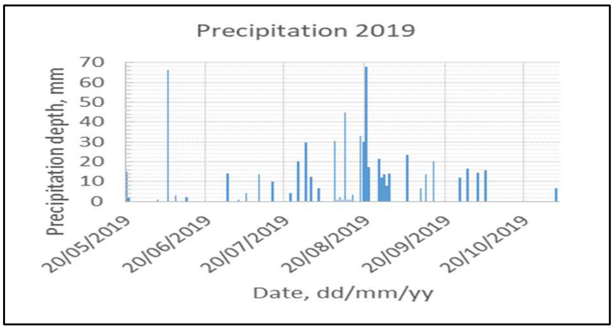

Figure 8: Daily Rainfall Evolution for 2019 (Source: DDA) Mataméye).

Figure 9: Gully erosion in the N'Wala neighborhood (right side of R3, depth 2.07 m). Figure by Abdou Sitou L. (2020).

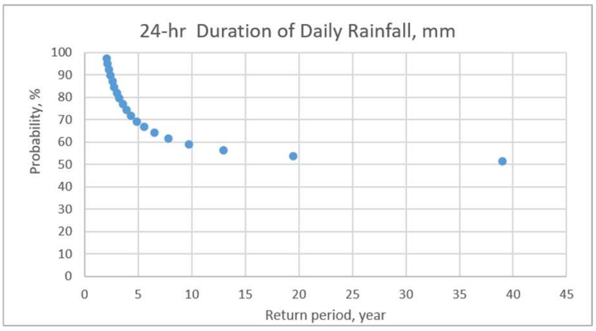

Figure 10: Statistical distribution of daily rainfall.

A similar pattern was observed in 2021, when closely spaced rainfall events, especially during August, further intensified erosion processes. Under these conditions, the number of gullies increased from 4 to 7 across the urban area, with significant soil losses, as illustrated by ravine R5, which reached a volume of approximately 1836 m^3 (Figure 11). This evolution highlights the cumulative impact of successive intense rainfall events on already weakened soils. This process is further exacerbated by the progressive reduction of permeable surfaces in the urban environment, which enhances runoff concentration and accelerates both the expansion of existing gullies and the initiation of new ones. However, these values displayed in the Figure 6 should be interpreted with caution, as seasonal backfilling operations carried out after each rainy season temporarily alter gully morphology. Subsequent rainfall events often reactivate or recreate erosion features, meaning that recorded measurements frequently correspond to newly formed or reactivated gullies rather than the original forms. This shows that, under similar rainfall conditions, erosion intensity is significantly higher within the urban area than in surrounding non-urban zones. This difference is mainly explained by the concentration of runoff along unpaved roads and the occupation of natural drainage pathways, which enhance flow energy and accelerate gully formation.

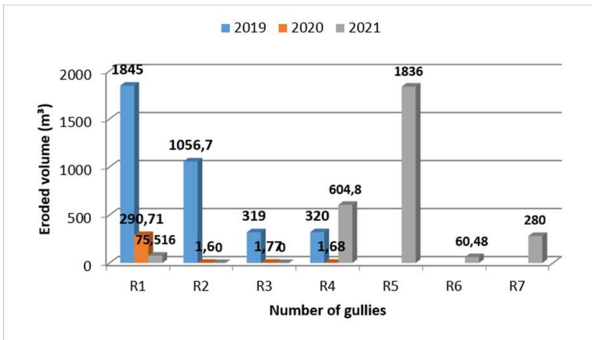

Figure 11: Gully inventory and eroded volume to 2019-2021.

Figure 12: Headcut retreat after a 73 mm rainfall event (42 m^3 of soil removed) source: Abdou Sitou L., 07/09/2021.

Finally, event-based analysis confirms the critical role of extreme rainfall in soil loss processes. For example, in 2021, two consecutive rainfall events occurring on September 6 and 7, totaling 108 mm, resulted in an estimated soil loss of approximately 42 m^3 due to headcut retreat in R4 gully located in the Sabon Gari neighborhood (Figure 12). Overall, these results demonstrate a strong relationship between rainfall intensity, frequency, and erosivity, and the observed dynamics of gully erosion in Mataméye. In the year 2021, three significant gully formed occurred, namely R5 gully (characterized by aggressive and intense erosion), the R6 channel (representing passive gully erosion), and the R7 gully (defined by aggressive vertical incision). The concentration of rainfall within short periods significantly enhances runoff generation and flow concentration, particularly in urban areas where surface conditions favor rapid hydrological response.

3.1.2. Anthropogenic Factors

Beyond natural factors, several human-driven processes significantly contribute to erosion in Mataméye, particularly rapid urbanization occurring in the absence of effective planning and the lack of a comprehensive urban development master plan. Uncontrolled urban expansion, precarious housing conditions, settlement in low-lying depressions, and insufficient drainage infrastructure collectively exacerbate erosion-related damage (Mahaman Dan Ladi, 2015; Abba, 2021; Aboubacar Ousmane, 2019; Meva'a Abomo et al., 2010). Mataméye has experienced rapid spatial growth driven by demographic dynamics such as migration, decentralization, and family dispersion (Zakari, 2014), leading to the progressive occupation of environmentally sensitive areas, including valley bottoms and sloping terrains. As a result, vulnerable populations are increasingly concentrated in high-risk neighborhoods such as Kanguiwa, Sabon Gari, N'Wala, and Nassarawa Idi, where population densities range from approximately 50 inhabitants/ha to nearly 250 inhabitants/ha (Table 1). In addition, urban infrastructure remains poorly developed. With the exception of a limited number of asphalted or stabilized roads, most of the urban network consists of unpaved sandy or lateritic tracks (Figure 1). These surfaces, combined with the absence of structured drainage systems, act as preferential pathways for runoff during high-intensity rainfall events. Consequently, stormwater becomes highly concentrated along these linear features, increasing flow velocity and promoting the initiation and development of gully erosion.

The analysis of urban expansion based on multi-temporal satellite imagery (Google Earth, 2006, 2018, and 2021) reveals a substantial increase in built-up areas over the study period. The urban surface nearly doubled within approximately 12 years, expanding from 201 hectares in 2006 to 400 hectares in 2018, and reaching 489 hectares in 2021. This rapid spatial growth reflects increasing pressure on land resources and contributes to the disruption of natural drainage pathways, thereby intensifying hydro-erosive processes. Overall, these findings highlight the critical role of unlanned urban development in amplifying natural geomorphological dynamics and increasing the vulnerability of the city to gully erosion (Figure 13). In addition, land use was estimated through the spatial overlay of the total urban expansion area of the city in 2021, estimated at 489 ha, and the built-up urban area, estimated at 366 ha. The results indicate that approximately 74% of the urban space is occupied by built-up or developed surfaces, which were considered in this study as predominantly impervious areas. For example, road density for clay and asphalt roads (Figure 1) equals to 1.77 (road length/city boundary polygon area, 8.45/4.79 = 1.77) indicating the gully channels form in the city area rather than rural areas. This indicator provides an assessment of the potential influence of urbanization on the intensification of surface runoff and erosion processes.

Table 1: Density of Matamey.

Neighborhoods	Sabon Gari	In’ wala	Angoual Kirya	Abidjan	Zangouna 2	Nassarawa Idi	Zangouna 1	kanguiwa	Liminawa
Density (inhbts/km^2)	50	48	60	64	100	150	160	250	279

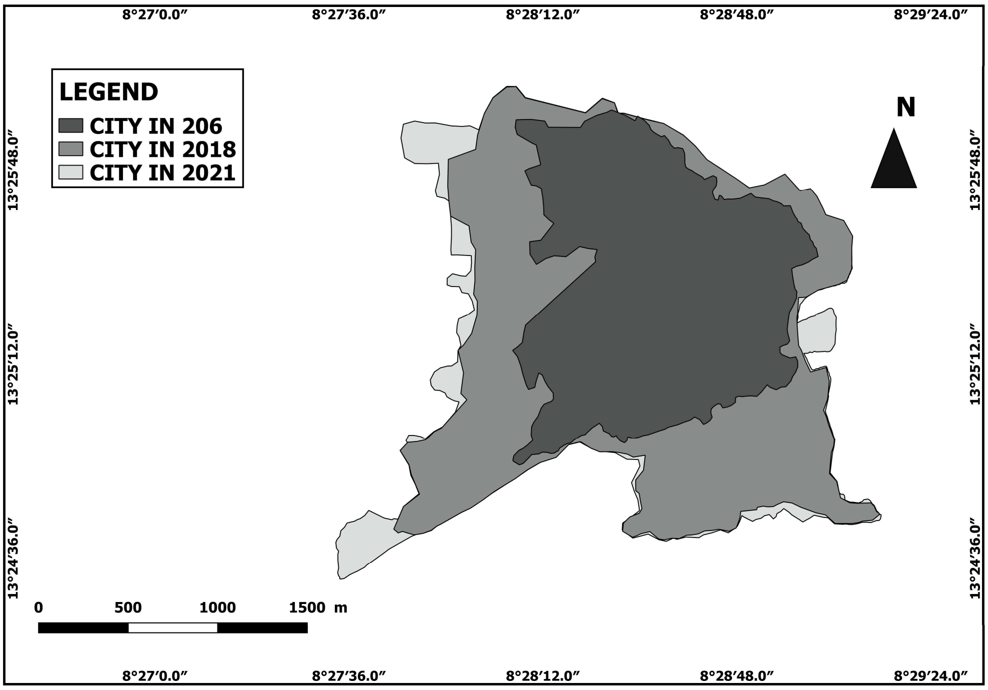

Figure 13: Spatial Expansion of the City of Mataméye (Source: Google Earth, 2021).

3.2. Water Erosion and Associated Damage

In Mataméye, water erosion occurs in two main forms: diffuse erosion and gully erosion. Diffuse erosion develops irregularly on sandy and weakly cohesive surface soils, where it mainly results in superficial stripping and progressive soil degradation. In contrast, gully erosion represents the most severe and geomorphologically significant process, characterized by deep incision, rapid lateral expansion, and substantial soil losses. Over recent years, the city has been increasingly affected by the development and expansion of gullies, particularly in neighborhoods located in erosion-prone areas along the Korama valley, including N'Wala, Kanguiwa, Sabon Gari, and Nassarawa Idi. These sectors combine unfavorable physical conditions (low elevation, soil friability, runoff convergence) with intense urban pressure and limited drainage infrastructure, which together enhance erosion susceptibility.

Table 2: Gully inventory (2019–2021).

	2019		2020		2021	
Neighborhood	Number of gullies	gully length (m)	Number of gullies	Total gully length (m)	Number of gullies	gully length (m)
Kanguiwa	1	120	1	32,6	1	17,4
Sabon gari	1	80	1	76	1	7
N'Wala	2	100	2	3,2	4	82
Nassarawa idi	-	-	-	-	1	20
Total	4	300	4	111,8	7	126,4

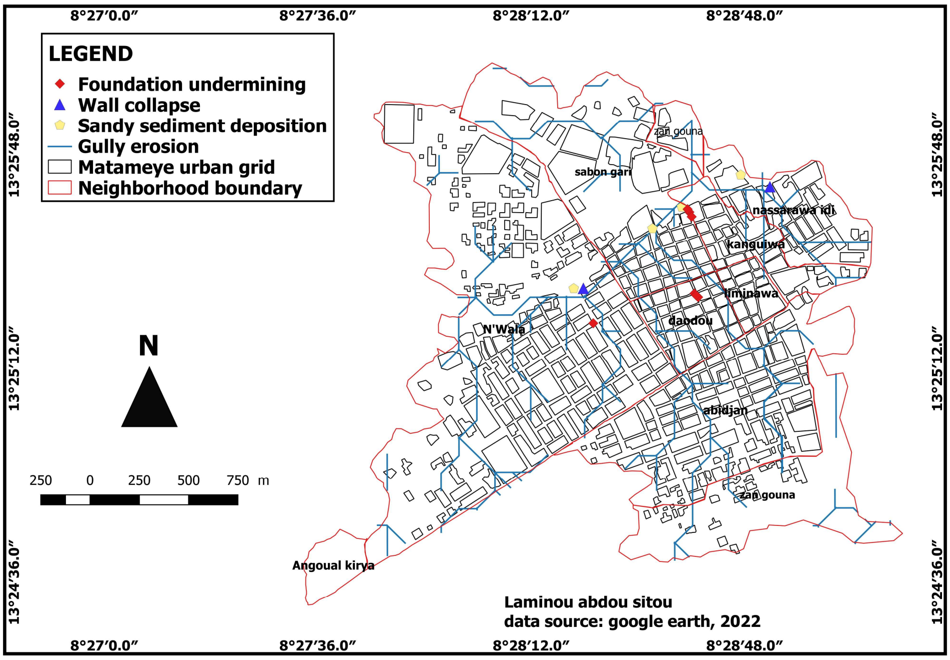

Figure 14: Damage Distribution.

A systematic inventory conducted between 2019 and 2021 highlights the rapid evolution of gully erosion within the urban area (Table 2). In 2019, four gullies were identified, with a cumulative length of 300 m, mainly concentrated in N'Wala and Kanguiwa. In 2020, although the number of gullies remained constant (four), the total recorded length decreased to 111.8 m, reflecting partial infilling of some channels and local stabilization efforts. However, in 2021, a marked increase was observed, with seven gullies reaching a cumulative length of 126.4 m, indicating renewed incision and the initiation of new erosion features, particularly in N'Wala (R5 and R6) and Nassarawa Idi (R7). This temporal evolution demonstrates the highly dynamic nature of gully processes in Mataméye and confirms the strong sensitivity of the urban environment to both climatic forcing and anthropogenic disturbances. The persistence and expansion of gullies pose significant threats to housing, road infrastructure, and public safety, underlining the urgent need for integrated erosion control and urban drainage management strategies (Figure 14).

Spatial and morphometric analyses indicate that N'Wala (harboring the R5 and R6 ravens) is the most severely affected neighborhood, with more than four gullies totaling 183.2 m in length in 2021. In Sabon Gari, N'Wala, and Kanguiwa, gullies reach advanced dimensions, with widths exceeding 10 m, average depths of approximately 1.46 m, and lengths ranging from 80 to 120 m, reflecting an advanced stage of morphodynamic development. The heavy rainfall events recorded in 2019 caused substantial soil losses and rapid channel expansion. In response to this critical situation, municipal authorities implemented mechanical backfilling of a major gully (R1) in the Kanguiwa neighborhood. This gully was approximately 7.1 m wide and nearly 2 m deep and posed a direct threat to nearby residential areas (Figure 15).

However, field observations and post-intervention imagery (Figure 16) reveal that this backfilling operation significantly altered the original gully morphology without ensuring long-term stabilization. Partial infilling resulted in the formation of an artificial and unstable cross-sectional profile, characterized by steep banks composed of loose, poorly compacted materials highly susceptible to concentrated runoff. Following the first intense rainfall events of 2020, these deposits were rapidly remobilized, leading to renewed channel incision, accelerated lateral widening, and reactivation of erosional processes. This evolution highlights the limited effectiveness of backfilling techniques when not combined with adequate drainage control and bank stabilization measures (e.g., riprap, vegetation cover, energy dissipation structures). It also illustrates the difficulty of controlling gully enlargement in urban environments when interventions remain local, short-term, and reactive, without consideration of the broader hydrological functioning of the watershed.

Consequently, the current gully morphology observed in Kanguiwa results from the combined effects of intense natural hydrological processes and inadequate anthropogenic interventions, which tend to enhance geomorphological instability and prolong land degradation dynamics.

Figure 15: Dynamics of Ravine R1 (2019) source: Abdou Sitou L.

Figure 16: Renewed Gully Erosion in Ravine R1 (2020) source: Abdou Sitou L.

In the Nassarawa neighborhood, diffuse erosion dominated during the first two years of observation, mainly due to gentle slopes and the predominance of sandy surface formations, which favored sheet runoff and superficial soil stripping. However, in 2021, the construction of permanent housing substantially modified local soil hydrodynamics by increasing surface impermeabilization, reducing infiltration capacity, and concentrating runoff along preferential flow paths. These changes directly contributed to the initiation of gully erosion, marking a transition from diffuse to linear and more destructive erosion processes (Figure 17). The ravines exhibit deeply incised channels with wide cross-sections, and four gullies show evidence of rapid headcut retreat following intense rainfall events. The year 2019 recorded the largest soil losses due to the high frequency of rainfall events. The filling of some gullies temporarily slowed erosion processes, while some communities also developed local mitigation strategies.

Figure 17: Housing Construction Triggering a Ravine (2021) source: Abdou Sitou L.

Figure 18: Road Degraded by Gully Erosion source: Abdou Sitou L. (2020).

Gully erosion in Mataméye has severely damaged unpaved and lateritic roads, causing frequent impassability and loss of accessibility. This disrupts daily commuting, hinders the transport of goods, slows local economic activities, and forces residents to take long, unsafe detours. The ongoing road degradation also heightens social vulnerability by limiting access to markets, schools, health services, and emergency response (Figure 18).

There is also a major health risk. Buried water pipes are exposed in N'Wala and Angoual Daoudou, making them vulnerable to solar radiation and deterioration.

3.3. Control Strategies

Local residents have implemented various individual protection measures, including sandbag dikes, gully infilling with household waste, sand or stones, the use of discarded tires, small retaining walls, and collective labor initiatives. However, 78% of respondents consider these measures ineffective (Figure 19), as they are small-scale, uncoordinated, and require frequent reconstruction after each rainy season. The mitigation strategies identified in this study are mainly individual and ad hoc responses implemented by households to protect their dwellings from erosion. These include local protective actions such as small-scale earth filling around houses. In addition, some interventions carried out by the municipality, through road maintenance services, consist mainly of simple backfilling of gullies without technical design, hydraulic calculations, or long-term stabilization measures.

These interventions have proven short-lived and ineffective under high runoff energy. For instance, lateritic fill along the Mataméye–Magaria road was rapidly washed away during the first rainfall events of 2020, leading to immediate erosion reactivation (Figures 20 and 21). These observations demonstrate that such reactive approaches fail to address the underlying hydrological drivers of gully formation, particularly runoff concentration. It is important to note that these interventions do not represent structured or scientifically designed erosion control strategies, but rather reactive and localized actions aimed at temporarily reducing immediate exposure. Within this context, the assessment of their effectiveness is based on field observation over time. The persistence and continued expansion of gully erosion after repeated backfilling operations indicate that these measures do not provide durable control of the process. In fact, field observations show that erosion progresses annually despite these interventions, highlighting their limited long-term effectiveness. The ineffectiveness of the protection measures was visually inspected and taken as photographs for each extreme rainfall event in the region. For example, the Figure 15, 16, and 17 depicted the dynamics of the gully channel expansion for each extreme rainfall and the limits of the expansion in the channels were measured and mapped with the GPS machine. In the photographs mentioned, it is obvious no local measures for protection of gullying floods were effective to protect the foundations of wall, roads and dwelling structures in the region. In other words, the floods and eventual gullying processes carved underneath the foundations and bag-walls, resulting in failure of protection measures.

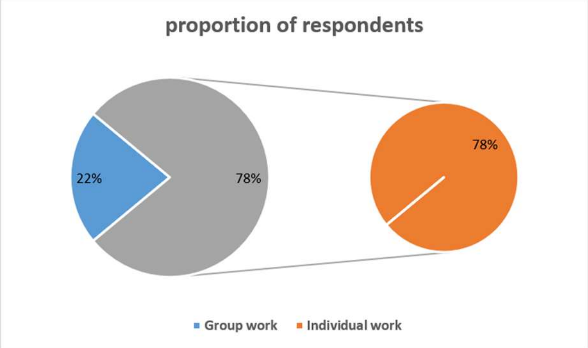

Figure 19: Proportion of respondents.

Compared to structured interventions in similar semi-arid environments, these approaches remain ineffective due to the absence of integrated planning and hydraulic control. These results provide a basis for identifying appropriate erosion control strategies. Effective mitigation therefore requires a shift from localized and reactive practices toward coordinated, process-based management at the watershed scale. In areas affected by concentrated runoff along urban roads, priority should be given to controlled drainage systems such as side ditches, lined channels, and flow diversion structures, which reduce runoff concentration and flow velocity (Morgan, 2005; Nyssen et al., 2004). In zones characterized by diffuse runoff, micro-topographic redistribution measures such as contour bunds, small earth ridges, and surface roughening can enhance infiltration and reduce flow connectivity (Roose et al., 2012). In actively eroding areas, small-scale sediment retention structures including check dams, stone lines, and fascines are essential to reduce flow energy, trap sediments, and stabilize gully heads (Nyssen et al., 2009). In addition, bioengineering techniques such as grass strips, vetiver hedges, and vegetated waterways improve soil cohesion and increase hydraulic roughness, thereby reducing runoff velocity and sediment transport (Stokes et al., 2014; Truong et al., 2008). For highly trafficked unpaved roads, low-cost surface stabilization methods, including gravel cover, lateritic surfacing, or locally available binding materials, can significantly increase resistance to erosion (FAO, 2015). Overall, the effectiveness of these measures depends on their combined and spatially targeted implementation at the catchment scale rather than isolated interventions. Such integrated approaches have proven effective in reducing runoff concentration and limiting gully expansion in comparable semi-arid environments (Poesen et al., 2003; Valentin et al., 2005).

Figure 20: Proportion of respondents.

Figure 21: Proportion of respondents.

5. DISCUSSION

The Digital Elevation Model (DEM) data derived from the SRTM dataset (90 m spatial resolution) were used in this study for the general morphologic analysis and to understand the topographic structure of the urban area of Mataméye. However, this resolution presents certain limitations for the detailed analysis of gully erosion processes at the urban scale. It does not adequately capture microtopography, small drainage channels, or the detailed interactions between the road network and surface runoff pathways. Consequently, some uncertainties may arise in the fine-scale characterization of flow trajectories and runoff concentration zones. Therefore, GPS located fine resolution points in the region to improve consistency between field measured scale and STRM dataset of 90 m spatial scale points used in the analysis. To mitigate these limitations or inconsistencies, the DEM-based analysis was complemented by field observations and in situ measurements, including direct monitoring of gullies and their morphometric characteristics. Therefore, the SRTM data were primarily used to identify general topographic trends and watershed characteristics rather than to analyze fine-scale geomorphic features. This combined approach improves the reliability of the results and provides a sufficiently robust basis for understanding the spatial distribution and environmental impacts of gully erosion in the study area, despite the constraints associated with the spatial resolution of the satellite-derived data.The results demonstrate that Mataméye is experiencing highly active erosive dynamics resulting from a complex interaction between natural and anthropogenic factors, indicating that gully erosion is not a temporary phenomenon but rather a systemic and long-term process. Natural controls, including local geomorphology, sandy soils, and topographic configuration, predispose the area to erosion by facilitating runoff concentration, particularly in low-lying interdunal sectors. These findings are consistent with previous studies emphasizing the role of morphopedological characteristics in controlling gully development in semi-arid environments (Mamadou & Abdou, 2016; Mekonnen et al., 2018; Nyssen et al., 2002).

Rainfall analysis further highlights the decisive role of climatic forcing. The occurrence of high rainfall amounts combined with closely spaced rainfall events since 2017, including approximately 633 mm recorded over a short rainy season in 2019, has significantly enhanced soil saturation and reduced infiltration capacity, thereby increasing runoff coefficients and promoting rapid gully initiation and expansion. The high rainfall erosivity values obtained through MFI and R-factor calculations confirm the strong hydro-erosive potential of these events. These results are consistent with IPCC (2022) and Niang et al. (2014), which underline the intensification of extreme hydrometeorological events in Sub-Saharan Africa under current climate change conditions. However, climatic factors alone cannot fully explain the magnitude and spatial concentration of erosion observed in Mataméye. Anthropogenic influences play a decisive amplifying role. Unplanned urban expansion, settlement in topographically vulnerable areas, inadequate drainage infrastructure, and increasing soil impermeabilization significantly enhance runoff concentration.

In particular, the predominance of unpaved lateritic roads promotes the development of preferential flow pathways, thereby increasing flow velocity and erosive power. These findings support previous studies identifying weak land-use planning and urban pressure as major drivers of intra-urban erosion in West African cities (Tchotsoua, 1994; Wallez, 2010; Wouters & Wolff, 2010). Furthermore, compared to surrounding non-urban areas with similar climatic and geomorphological conditions, erosion intensity in Mataméye is significantly higher, highlighting the critical role of urban surface modifications such as soil sealing, road construction, and the disruption of natural drainage pathways. Similar dynamics have been reported in other Sahelian cities, including Zinder and Maradi, where rapid urban expansion combined with intense rainfall accelerates gully development (Valentin et al., 2005; Poesen et al., 2003). This comparison confirms that the observed erosion patterns result from an amplification of natural processes by human-induced changes in surface and hydrological conditions. The impacts of these processes are clearly reflected in the urban environment, where significant damage has been recorded, including house collapses, road degradation, exposed foundations and pipelines, and broader socio-economic disruptions. These observations confirm previous findings in Niger highlighting the severe consequences of runoff-driven erosion on infrastructure and livelihoods (Aboubacar Ousmane, 2019; Abdou et al., 2016; Mahaman Dan Ladi, 2015).

These results provide a robust basis for identifying priority intervention areas and for developing appropriate erosion control strategies, particularly in zones characterized by high runoff concentration and extreme rainfall erosivity (MFI > 150). Despite the implementation of local mitigation measures, current responses remain largely insufficient. Practices such as filling gullies with laterite or using sandbags provide only temporary protection and lack both durability and hydrological effectiveness. Their limited efficiency is mainly due to the absence of runoff control mechanisms, as these interventions do not address the processes of flow concentration and surface water routing. As a result, erosion processes are rapidly reactivated following intense rainfall events, leading to repeated degradation of the same areas.

In this context, effective mitigation requires integrated and process-based approaches in the region. The implementation of controlled drainage channels along roads and runoff diversion structures is essential to reduce flow concentration in vulnerable areas. In active gullies, small check dams and sediment retention structures can help dissipate flow energy and limit headcut retreat. In addition, vegetation-based bioengineering techniques may improve soil cohesion and contribute to slope stabilization. Such measures, when implemented at the scale of the urban watershed, can significantly reduce hydro-erosive risks. Overall, the results indicate that erosion dynamics in Mataméye should be interpreted as a coupled human–environment system rather than a purely natural geomorphological process. Although gully erosion is inherently linked to climatic variability and soil characteristics in semi-arid environments, its current intensity and spatial distribution are largely controlled by anthropogenic factors that modify hydrological pathways and amplify runoff processes. Consequently, the results indicate that runoff concentration constitutes the primary driver of gully erosion in Mataméye, and therefore represents the key leverage point for reducing hydro-erosive risks in rapidly expanding Sahelian urban environments.

5. CONCLUSION

In this study, it is demonstrated that Mataméye constitutes a highly vulnerable urban system exposed to intense hydro-erosive dynamics driven by the interaction between morpho-pedological constraints, increasing rainfall erosivity, and rapid land-use transformations. The humid climatic phase observed since 2017, characterized by frequent high-intensity rainfall events, has significantly enhanced surface runoff, sediment mobilization, and channel incision, thereby accelerating gully expansion across vulnerable sectors of the city. The high rainfall erosivity, reflected by MFI values ranging from approximately 158.6 to 167 and R factors between 8500 and 9500 MJ mm ha^{-1} h^{-1} yr^{-1}, confirms the dominant role of climatic forcing in intensifying erosion processes. These dynamics are further amplified by anthropogenic pressures, including unplanned urban expansion, increasing population density, progressive surface impermeabilization, and insufficient drainage infrastructure. Compared to surrounding non-urban areas with similar environmental conditions, erosion intensity within the city is significantly higher due to these urban surface modifications, highlighting the critical role of human-induced land transformation in accelerating runoff concentration and gully development.

Current mitigation practices remain limited in effectiveness due to their fragmented and short-term nature. Therefore, integrated and cost-effective strategies are required, including the development of runoff diversion structures, small-scale check dams, and bioengineering stabilization techniques. These measures, combined with improved land-use planning and the protection of natural drainage pathways, are essential to reduce runoff concentration and limit gully expansion in vulnerable urban sectors. Without the implementation of integrated drainage and land-use planning strategies, gully erosion will continue to threaten the long-term sustainability of rapidly expanding Sahelian cities. To conclude, gully initiation and development in the long-run in the region needs scientifically sound protection measures such as gully erosion and open channel flow modeling that couples with bioengineering techniques for vegetation restoration in the region and soil conservation structures to store and divert floods to enhance socio-environmental resilience in the region.

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