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Landslide Hazard Mapping in Mbankolo Yaounde Cameroon: Multi-Factor Analysis and Outlook

Seumo Saint-Clair[1], Nouembissi Feukam Emmanuel[2]
[1]PhD Fellow, Department of Geography (physical geography), University of Yaounde1 P.O Box 755 Yaounde Cameroon
[2]PhD Fellow, Department of Geography (physical geography), University of Yaounde1 P.O Box 755 Yaounde Cameroon
Email address: Joakimstrullson@gmail.com

Abstract**—***Demographic growth coupled with the high cost of land in tropical countries, and the city of Yaoundé in particular, reinforce the mechanisms for producing natural hazards through the heavy anthropization of natural environments. The anarchic urbanization of urban environments is reflected in the pressure of land use and the non-conforming occupation of so-called "non aedificandi" zones. This research examines the causality of the Mbankolo disaster, by mapping risk factors using a multi-factor approach. It focuses on geology, morphology, vegetation cover, land use, site texture and rainfall. Data was collected via field observations, geospatial analysis, local surveys and analysis of satellite and geotechnical data. The study identifies risk zones beyond the disaster site, classifying the risk of rockfall from low to very high. The results indicate that steeply sloping areas (including the disaster site), with little vegetation and a clay-sand texture, are particularly vulnerable. The impact of uncontrolled urbanization and deforestation on increasing this risk is also highlighted. By way of mitigation and prevention, slope stabilization, proper drainage and the adoption of sustainable land-use practices are strongly recommended. Raising awareness and educating local communities about the risks and mitigation measures are also recommended.*

Keywords**—** *Hazard, Landslide, Risk mapping, Multi-factor approach, GIS, Remote sensing, Mbankolo.*

I. INTRODUCTION

In an increasingly urbanized world, the issue of natural hazards in urban environments carries high stakes, (Saha et al., 2018). For several years now, the city of Yaoundé, with its steeply sloping mountainous terrain, has been experiencing a serious crisis of instability in its natural environment due to complex natural and anthropogenic factors. The issue of land-use planning and poor management of urban space is at the heart of the debate. With its high population density and high demand for space, the city of Yaoundé is experiencing very high land prices in the urban core. As a result, populations are spreading out to undeveloped peripheral sites, most of which are at risk and ill-prepared to accommodate them, leading to the recurrence of natural disasters such as mass movements and floods. In this way, human action on these newly conquered spaces leads to changes in soil stability conditions, increasing susceptibility to natural disasters (D'Ercole & Thouret, 1994; November, 1994; Metzger & D'Ercole, 2011).

II. STUDY AREA

Mbankolo is located in the central region of Cameroon, in the Mfoundi department, more precisely in the council of Yaoundé 2 (figure 1), with geographic coordinates 3°53'20 "N and 3°55'30 "N for north latitude, and between 11°29'50 "E and 11°31'55 "E for east longitude (figure). The disaster site is located from the southwest (230°SW), with coordinates 3°54'30 "N latitude North and 11°20'20 "E longitude East for the point upstream of the hazard (823.8m altitude); and coordinates 3°54'26 "N latitude North and 11°29'27 "E longitude East for the point downstream of the hazard (780m altitude).

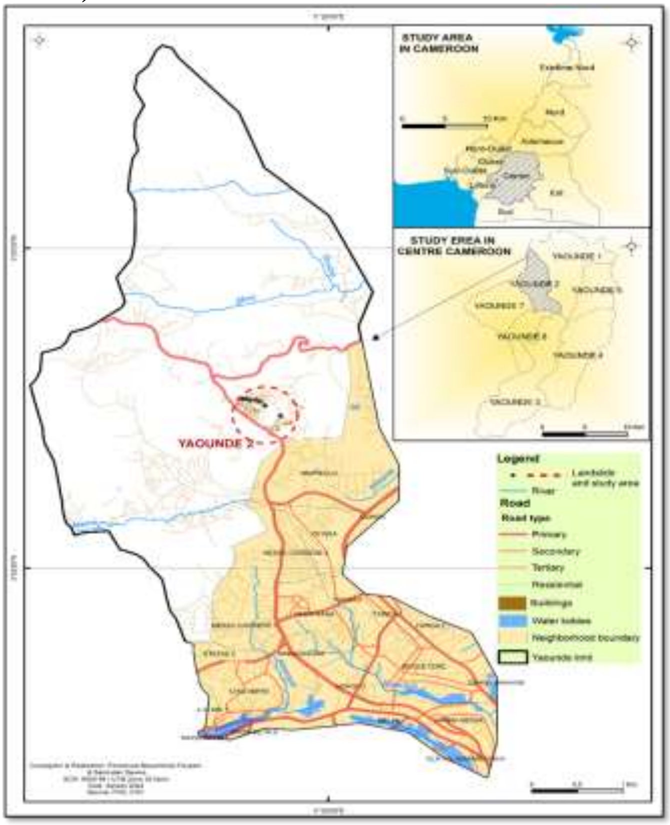

Figure 1: Location of Mbankolo in the council of Yaoundé 2

The Mbankolo district in the Yaoundé 2 council is an under-structured neighborhood with a very uneven topography and steep slopes. On the evening of October 8, 2023, a landslide caused the death of around thirty people, as well as significant material damage. Observations in the field show that the movement was rotational at the trigger point and transrational thereafter, given the slope gradient. This observation is supported by the presence of uprooted trees pointing downslope, with the fallen retaining wall facing

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downslope. What's more, a mini pond that used to be full of water was emptied during heavy rainfall, putting pressure on the wall built on sandy clay soil, which eventually gave way.

III. METHODOLOGY

In order to carry out a complete mapping of the hazard, the methodological approach applied for this research was based on several techniques according to the following stages:

Data collection: Gathering (Table 1) of geo-spatial data (DEM, SRTM, LANDSAST), GPS survey of risk zones with Mobile Topographer pro, geological, meteorological and topographical data relevant to the Mbankolo area.

Multi-factor analysis: Identification and analysis of factors contributing to landslides (slope, slope orientation, relief, pedological aspect, geology, precipitation, land use, flow accumulation, hypsometry, land use etc.) Coupled with terrain surveys, following the classification and prioritization of these by level of influence using GIS software (ArcGIS10.8, Google Earth pro and statistical techniques.

Modelling: Development of rockfall hazard models integrating the various factors identified, enabling the creation of hazard maps (susceptibility, vulnerability and risk).

Field validation: Verification of generated models by comparing results with historical rockfall data and field observations.

Risk zone mapping: Creation of precise maps identifying the areas most at risk from rockfalls, providing crucial information for decision-makers.

Table 1: Data used

IV. RESULTS

Risk factors :

Mapping the landslide hazard in the Yaoundé 2 council, in this case the Mbankolo district, reveals multiple risk factors. These factors include.

1-Complex hypsometry coupled with rugged terrain conducive to hazard development

Mbankolo's hypsometry (figure 2) features a complex topography that has played a crucial role in the occurrence of the hazard. Indeed, variations in altitude influence slope stability, as they determine the force of gravity acting on soil materials. What's more, areas with higher altitudes are generally more susceptible to landslides, as gravity exerts a greater force on unstable materials. Situated in a convex-concave relief zone, Mbankolo has variable altitudes, ranging from lowlands (720m) to higher areas (1093m). Hypsometric analysis reveals that the disaster zone corresponds to that with steep slopes and high altitudes in the range (1046m-953m). The integration of contour lines into hypsometry allows precise visualization of altitude variations. In this way, areas with contour lines forming smaller circles, indicate steep slopes, which are associated with an increased risk of landslides observed on the site.Similarly, given the steep gradient, the removal of vegetation cover coupled with the weight of buildings, these high-altitude areas are subject to increased instability, subject to extreme weather conditions such as heavy rainfall. In fact, this was the mechanism at play during the disaster, when heavy rainfall caused a man-made lake located upstream of the disaster site to break up and wash away the sandy-clay soil. Under the effect of the great mass of rushing water, poorly-built staircase-like structures were destroyed as they passed from upstream to downstream.

TABLE 1

Data	Resolution/ Details	Source
DEM	Raster, 10m	www.nsa.gov.np
Satellite images	Raster 5m/10m/30m	Google Earth pro/ Earth Explorer Live 3D
SRTM	Raster 30m	https://. www.USGS.com

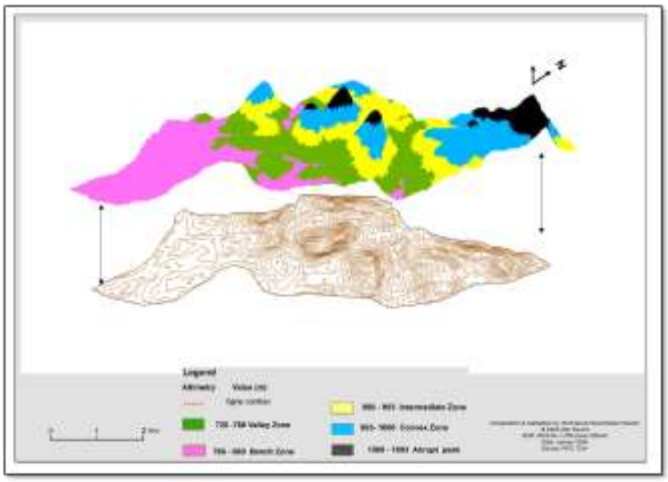

Figure 2: Mbankolo hypsometric map

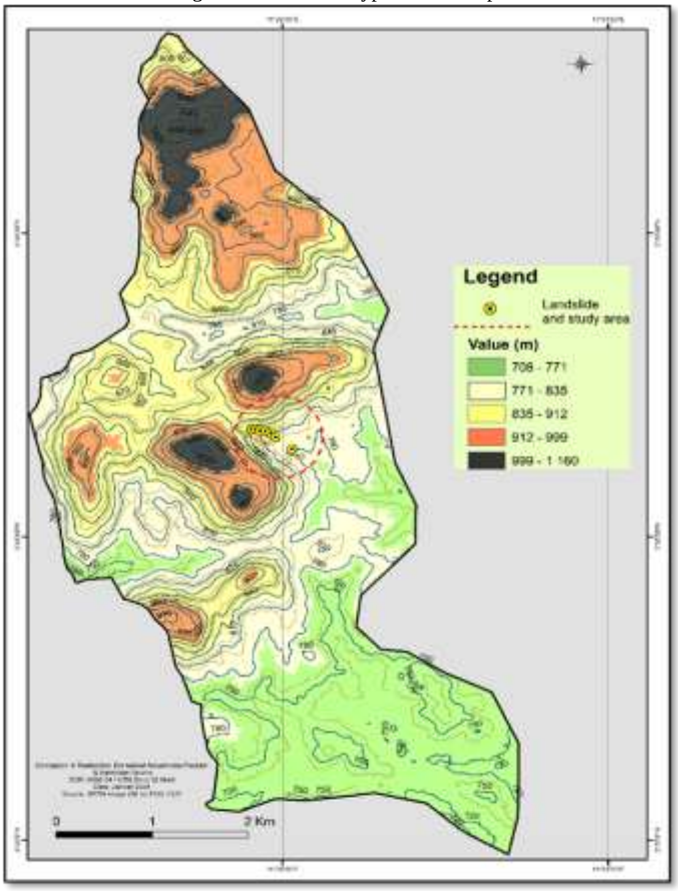

Figure 3 : Mbankolo topography map

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Moreover, the topographical analysis of Mbankolo shows a complex, highly uneven relief. Indeed, the relief varies in altitude from low (708m) to very high (1160m). The disaster area lies in the range from 999m upstream to 771m downstream (figure 3). The role played by relief in the Mbankolo disaster lies in its variation, which created zones of stress concentration, favouring the formation of faults or fractures that contributed considerably to the creation of the hazard. The fault sections created by the relief facilitated water circulation, resulting in soil saturation and reduced material cohesion, thus increasing the risk of landslides.

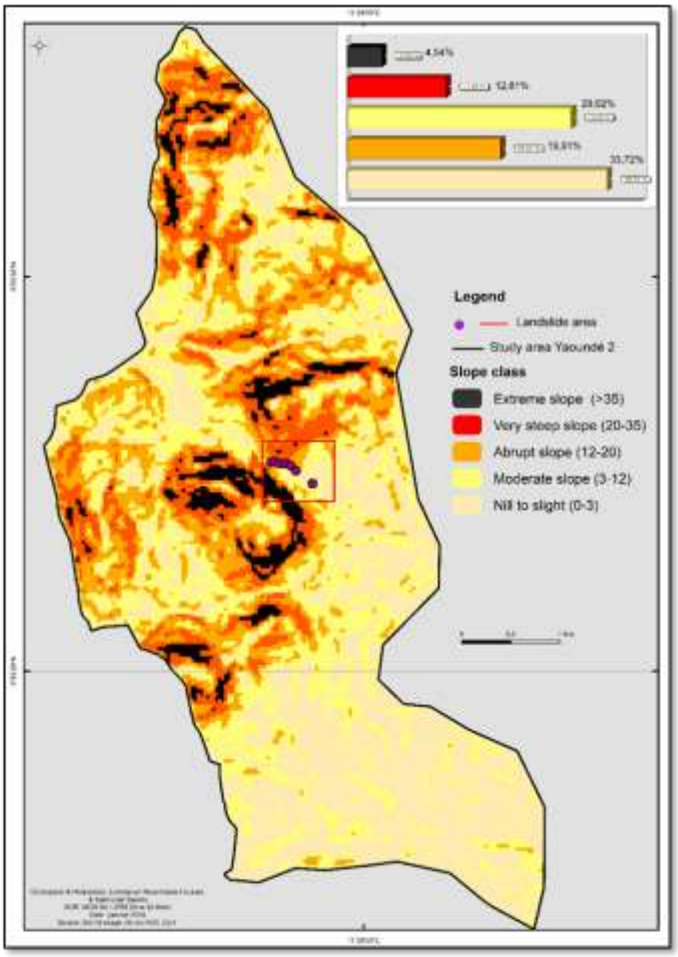

Figure 4 : Mbankolo slope map

2-From steep slopes to steep gradients

Slope plays a crucial role in the development of landslides. The steeper the slope, the more likely it is that the ground will be unstable and susceptible to sliding. Factors such as vegetation, soil moisture, rainfall and human activity can also influence the likelihood of a landslide on a given slope. Evaluation of the Mbankolo slope map (figure 4) shows five slope classes: very slight slopes (0-3) representing 34%, moderate or medium slopes (3-12) representing 20%, steep or steep slopes (12-20) representing 29%, very steep or steep slopes (20-35) representing 12%, and extreme slopes (>35) representing 5%,,. Based on the slope class values observed, it can be deduced that the area is generally steep. However, the disaster site is located in the steep or steep slope class (12-20) and the very steep or very steep slope class (20-35), reflecting the steep gradient observed. Field observations coupled with geospatial analysis of the site reveal that the action of the slope has been coupled with other parameters such as human activity through earthworks for construction purposes, which have led to changes in soil cohesion causing instability. The second factor is the removal of plant cover, whose roots stabilize the slope and slow down water erosion. This removal of vegetation cover is reflected in the occupation of areas formerly occupied by vegetation by built-up areas. The third factor is the site's moisture content, given the presence of a trickling watercourse coupled with the site's sandy clay texture, which influences soil permeability and porosity.

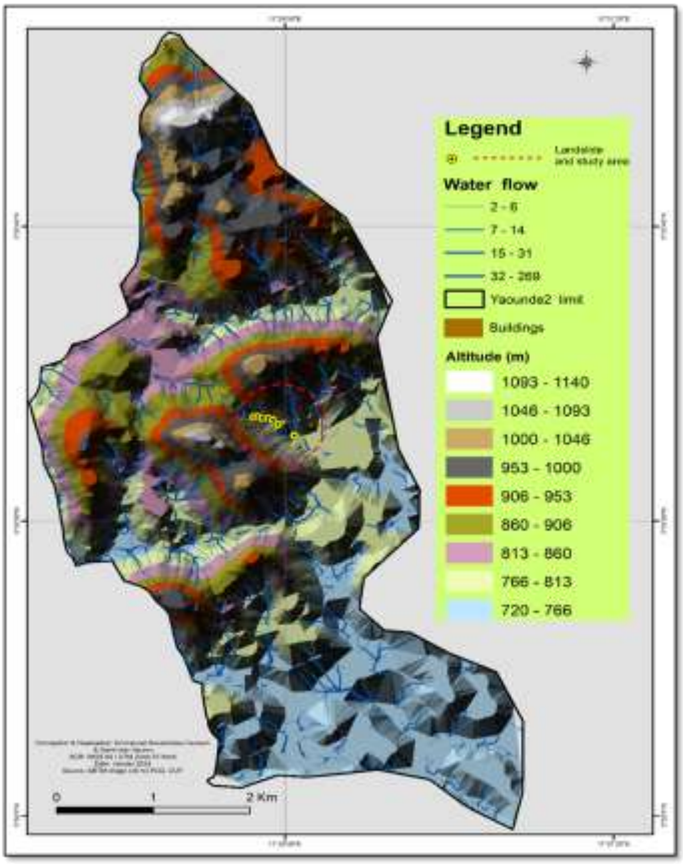

Figure 5 : Mbankolo orohydrographic map

3-Orohydrographic morphology conducive to slope instability

In the study of landslide hazards, the orohydrographic aspect (figure 5) plays a crucial role in establishing the hazard. In the case of Mbankolo, steep slopes, the nature of the soil (sand, clay), the presence of watercourses criss-crossing the basin of the disaster site, rainfall coupled with gravitational action are all factors that interact to influence the stability of the slope subject to the tragedy. Indeed, the steep slopes (20-35) to which the disaster site belongs were combined with other factors that led to the tragedy. These factors included: poorly cohesive soil due to human activity (urbanization, land development), heavy rainfall which increased water saturation in the soil, increased hydrostatic pressure in the soil and

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accelerated surface erosion, all of which led to the instability of the terrain, resulting in the landslide. In addition, erosion caused by run-off along the slopes at the site of the tragedy weakened the slopes by eroding the bases of the slopes.

4-Geology and soil characteristics favorable to the hazard

Landslide hazard mapping revealed a heterogeneity of risk zones in the council of Yaoundé 2 across Mbankolo, with a high concentration of high-risk zones on the steepest slopes and areas of contact between geological formations. Densely populated urban areas located on these unstable terrains have been identified as particularly vulnerable.

5-Intense rainfall

In the context of studies on natural hazards, and in this case landslides, the action of rainfall is a decisive factor. The intensity of heavy rainfall once on the ground saturates surfaces and subsurfaces through infiltration. Infiltration plays a major role in soil pore pressure. These pore pressures exert pressure on the soil wall, causing deformation and leading to site instability. In the case of the Mbankolo disaster, an estimated 28.13mm of precipitation was recorded, which represents a significant rate given that the rain fell in just a few hours. In addition, a monthly rainfall total of 423.47mm was recorded (figure 6). This heavy rainfall played a major role in setting up the Mbankolo disaster as the main catalyst.

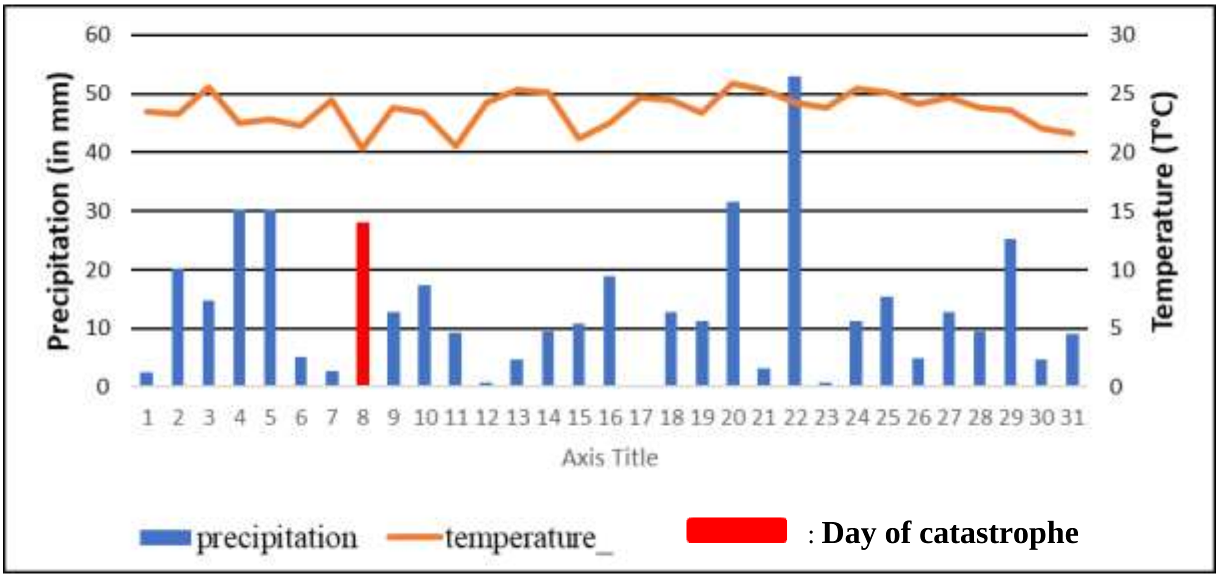

Figure 6: Umbrothermal diagram for October 2023

6-Evaluation of susceptibility at Mbankolo

Assessing susceptibility to landslides involves analyzing the factors that contribute to or predict the hazard. By weighting the parameters of these different factors, a susceptibility map can be drawn up. In modeling susceptibility (figure 7) at Mbankolo, several factors were identified, including: topography, geology (lithology), vegetation, hydrology, pedology and human activities. The analysis of susceptibility to landslide hazard outside the Mbankolo site was carried out on other slopes in the council with similar topographical, geological, vegetation and anthropogenic characteristics. Thus, the assessment of susceptibility shows three classes of hazard susceptibility: the low susceptibility class, corresponding to areas with little urbanization, high vegetation cover and little anthropogenic action. The second category is medium susceptibility, corresponding to areas with a medium rate of instability and medium vegetation cover. The high susceptibility class corresponds to areas with high levels of anthropogenic action, heavy urbanization, steep slopes, high levels of vegetation cover suppression and unstable soils. Overall, the council of Yaoundé 2, to which the Mbankolo district belongs, is home to other areas (slopes) likely to experience landslides in the coming periods if measures are not taken to evacuate populations and minimize damage in the event of a disaster.

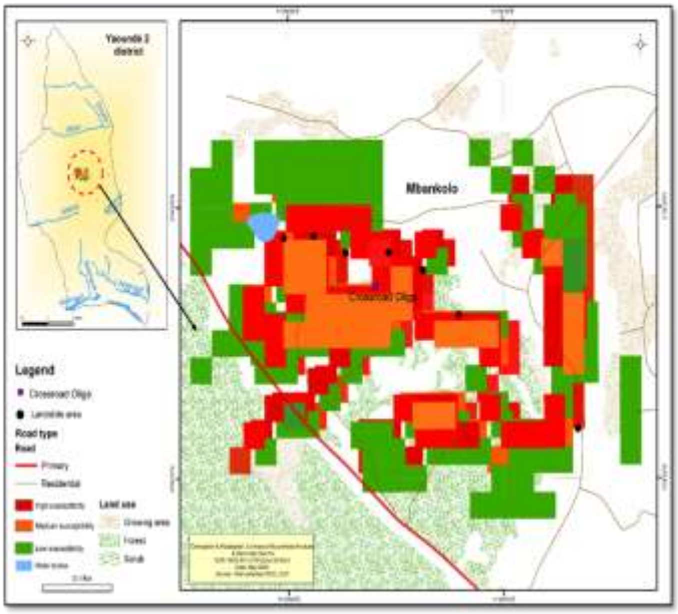

Figure 7: Susceptibility map of the Mbankolo area

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What's more, susceptibility zones are multiplying (figure 8) as urbanization progresses towards hillside areas, with the predominantly poor population settling on steep slopes and destabilizing the building site by shearing the slopes, thus predisposing these sites to mass movements and increasing the level of exposure to the risks of boulders and rockfalls, as specific building standards are not taken into account. This general susceptibility map shows the potential areas of future hazard occurrence (mass movement, rockfall, boulder fall).

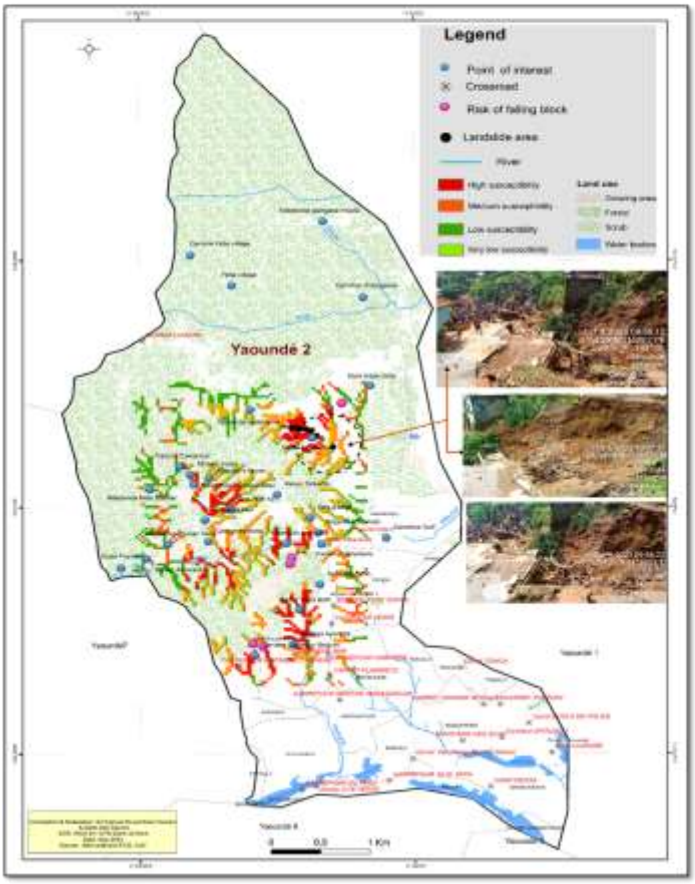

Figure 8: General susceptibility map of Yaoundé 2 council

As can be seen in figure 8, susceptible zones are multiplying in several areas of the Yaoundé 2 council, such as cités de la paix, carrefour beignet carrière, carrefour Tonta Bar, Mbankolo petit paris and collège ayungha. Susceptibility levels are divided into four classes: high-susceptibility zones in red, medium-susceptibility zones in yellow, low-susceptibility zones in orange, and very low-susceptibility zones in green. And these susceptibility levels enable us to directly observe vulnerable areas and entities (figure 9).

This map shows that, in the event of a landslide, blockfall or debris-flow hazard, a number of entities will be vulnerable, such as housing, roads, water supply points and certain areas of urban cultivation. This vulnerability is categorized into several levels, depending on the impact and stakes involved. High vulnerability zones are shown in red, medium vulnerability zones in yellow, low vulnerability zones in orange, and low vulnerability zones in green.

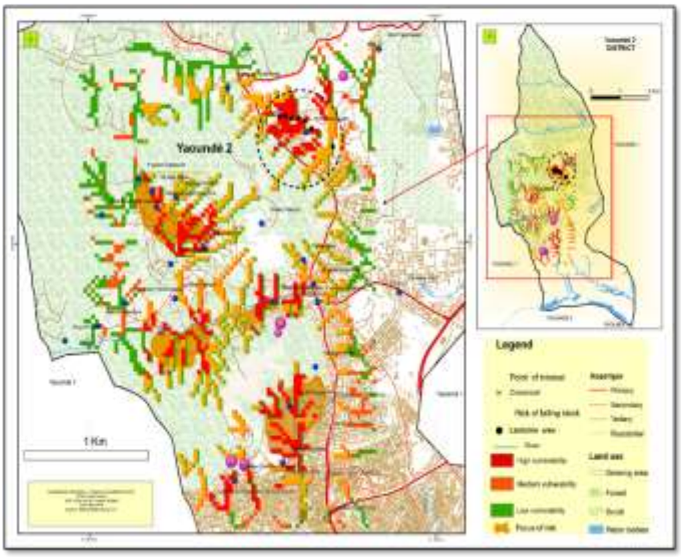

Figure 9: Vulnerability map of Yaoundé 2 council

7-Cartography of risk zones in Yaounde 2 council

The spatial analysis of the risk zones in the yaounde 2 council, which include the Mbankolo area, reveals several risk zones categorized into five classes: very high-risk zones, high-risk zones, medium-risk zones,low-risk zones, and very low-risk zones (figure 10).

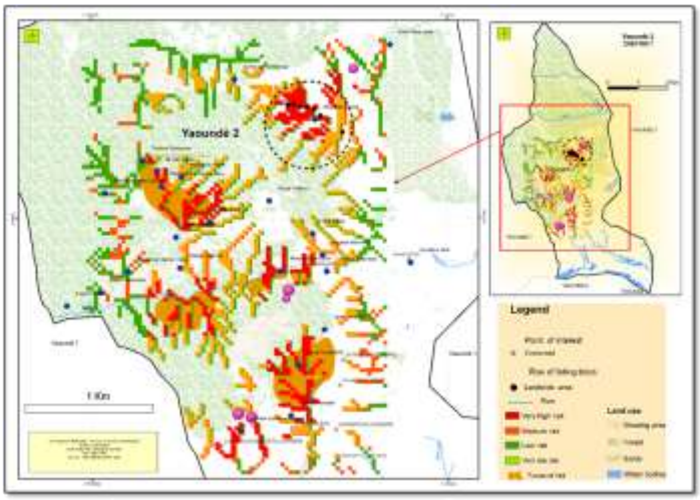

Figure 10: Risk map of Yaounde 2 council

V. Discussion

The study of the Mbankolo disaster in the Yaoundé 2 council is the result of a combination of two predisposing factors: physical and human factors.

There are four groups of causative factors for landslides in built-up areas, most of which are influenced by human action (Desodt et *al*., 2017b). Hygrometry (1): this factor has a direct influence on the mechanical properties of the soil in terms of porosity, and becomes very sensitive during heavy rainfall, increasing the risk factor for landslide-prone areas. Abnormal soil water saturation weakens the mechanical properties of the flow, accelerating its onset; hygrometry can also be influenced by human action on the soil. Mechanical loading of the slope

(2): structural design influences the behavior of slopes by opening cracks. Backfilling and excavation practices also accelerate the potential for landslides. Direct human action (3): slopes can be stabilized by afforestation, through biostasy or phytostasy; on the other hand, deforestation very often leads to slope instability, while tall grasses limit wind action on slopes. Construction and deconstruction activities affect soil stability. Accidental (4): external actions can affect slope stability, such as floods causing soil saturation and erosion, or earthquakes causing soil liquefaction. The location of high-risk zones is reinforced by the presence of human activities on slopes, leading to leaching and erosion of natural surfaces (Enchaw et al, 2023).

In the case of Mbankolo, the factors that led to the disaster are multiple. First and foremost, the highly uneven topography (1), the landslides recorded occurred in an area of uneven topography due to the natural instability of the slopes. The abrupt variations in relief observed have created areas where run-off water is concentrated, promoting erosion and increasing the risk. The second causative factor is rainfall (2): prolonged heavy rainfall of high intensity has a crucial negative impact on unstable slopes.On the day of the disaster, an estimated 28.13mm of precipitation was recorded, with a monthly rainfall of 423.74mm. Given the aspect of the soil (clayey - sandy), the large quantities of precipitated water filled the existing artificial lake, then seeped into the ground, saturating the surface layers and thus reducing the cohesion of the soil and causing the tragedy. The third element is anthropogenic action (3): the strong anthropization of the environment through uncontrolled urbanization and non-conforming construction (simple buildings and structures), the development of roads, non-conforming earthworks on the slopes, the removal of existing plant cover, etc., have disrupted the natural balance of the site. These elements have also altered the natural drainage of the soil in the environment, increasing runoff and erosion. The fourth element is slope (4): the steeper the slope, the greater the force of gravity acting on the soil, coupled with other factors such as rain and erosion. The disaster site belongs to the class of very steep slopes (20°-35°), which account for 29% of the area. Given the disaster site's topographical setting at an altitude of almost 900 m, the gravitational action applied with great force due to the steep gradient and other factors mentioned above. The fifth factor is orohydrography (5). The watercourses that criss-cross the slopes (figure 5) at Mbankolo, as on all other slopes in the council, erode the slopes over time, weakening the soil and increasing the risk of landslides, should they occur. In addition, the presence of water saturates the soil, reducing its cohesion and making it unstable and conducive to the manifestation of the hazard. In addition, there is the action of interstitial pressure, manifested by the large quantity of water present in the soil and exerting pressure on the soil or soil materials, leading to soil deformation. Once subjected to an additional load (weight of structures or buildings), the soil eventually gives way. The action of interstitial pressures on slopes is supported by the action of gravity. The sixth factor in the establishment of the Mbankolo hazard is vegetation (6). Vegetation plays a major role in protecting soil against erosion and stabilizing it. The roots of trees and plants help maintain soil cohesion by binding it together. Removing plant cover from a site or area weakens this stability, exposing the soil to water erosion. The case of the Mbankolo slope is similar and palpable, especially as the natural vegetation that once existed and stabilized the banks has been destroyed in favor of buildings and roads, without any measures being taken to mitigate the threats that could arise in its absence on a steep, uneven slope prone to erosion. The seventh factor taken into consideration is geology (7). The geological element highlighted here is lithology. The lithological structure, composed mainly of migmatic Gneiss and Embréchite, undergoes alteration processes over the years under the effect of climatic parameters (heat and rain). This rock alteration weakens the site's geological structure, causing instability on the slopes and leading to slope movements where appropriate.

Overall, the Mbankolo disaster was the result of a combination of biophysical factors. These physical factors (topography, orohydrography, vegetation, rainfall, geology, etc.) and human factors (anthropogenic activities: anarchic urbanization, earthworks, etc.) interacted to lead to the disaster. By analyzing and understanding these two factors, we can establish causality and draw conclusions.

Furthermore, vulnerability to the Mbankolo landslide hazard was characterized by several parameters, notably: the type of building materials (1) used to construct the destroyed buildings (some of which were made of semi-hard mud bricks, cement or planks). Foundation types (2): after geo-spatial analysis of the site, the foundation types were not consistent for many of the buildings destroyed by the hazard. In fact, most of the buildings were built on rocky structures laid to slow down water erosion, given the water run-off from the lake at the summit. Similarly, the nature of the soil (clayey, sandy) offered a significant margin for water permeability, increasing porosity and thus favoring subsurface runoff. Another factor contributing to the vulnerability of the victims was the absence of an early warning system (3). The presence of such a system would have alerted people to rainfall levels, slope movements and associated risks. Rain radars to assess rainfall amounts, inclinometers to monitor slope movements, geophones and piezometers are all instruments that can be used to predict or prevent a threat and limit damage in areas deemed sensitive or prone to topographical instability. Unfortunately, none of these devices were present on site to prevent the risk, leaving the populations affected vulnerable. It is therefore vital to implement such systems in all sensitive areas that may be subject to any kind of hazard.

While the multi-factor approach used in this research has its advantages in identifying risk factors and the correlations between them, it should be noted that other approaches, such as multi-criteria analysis, enable us to go into greater depth in the analysis and study of the hazard. In addition to risk factors, this approach allows other evaluation criteria to be taken into account, thus providing a broader view of the study.

VI. CONCLUSION

Geographic information systems and cartography are now positioning themselves as excellent tools in territorial diagnosis for effective decision-making, Tsoata (2020). Coupled with multi-factor analysis, GIS can be used to model hazards and assess potential risks in human, social, economic and environmental terms. Landslide hazard mapping in Mbankolo revealed a series of factors contributing to this devastating phenomenon. From the results obtained, it is clear that the landslide hazard is multifactorial, with a complex interaction between human activities, topographical, geological, hydrographic, vegetation and climatic features. Non-compliant human activities such as uncontrolled urbanization and earthworks on slopes have considerably exacerbated the risk of landslides. In addition, the lithological aspect, with the alteration of the main rock, gneiss, contributes to the weakening of slopes and the increased risk of landslides. Orohydrographic features, such as the rugged topography and the pronounced layering of the relief, as well as climatic conditions, notably intense and prolonged heavy rainfall, also play a crucial role in the genesis of the Mbankolo landslide. In addition, the susceptibility assessment revealed other areas at risk on other slopes of the vulnerable council in the area. Similarly, the hazard vulnerability assessment revealed major shortcomings in housing construction, such as the use of inappropriate materials, as well as poorly designed foundations on unstable laid stones. In addition, the lack of an effective warning system and poor evacuation mobility of victims aggravated the situation, increasing the vulnerability of local populations to landslides. The mapping of the Mbankolo landslide hazard highlights once again, following the Ngoache landslide of October 2019 in the West Cameroon region, the urgent need for proactive risk management and sustainable territorial planning. Preventive measures such as regulating urbanization, introducing up-to-date and appropriate building standards that take into account the morphological and topographical aspects of each site, installing early warning systems (inclinometers, piezometers, extensometers, geophones, rain radar, etc.), setting up an agency to manage, plan and prevent risks and natural disasters, reforesting exposed slopes, banning construction on steeply sloping and uneven slopes, and improving evacuation infrastructures are all essential to reducing the vulnerability of populations or communities and mitigating negative impacts, while making them more resilient.

APPENDIX

Monthly precipitation rate: 423.47mm
Rainfall on the day of the disaster:28.13mm
Monthly average: 13.66mm

TABLE 2: Yaounde weather data for October 2023

Time	Temperature	Precipitation
01/10/2023	23,5	2,46
02/10/2023	23,3	20,26
03/10/2023	25,6	14,72
04/10/2023	22,5	30,25
05/10/2023	22,8	30,23
06/10/2023	22,3	5,1
07/10/2023	24,5	2,65
08/10/2023	20,3	28,13
09/10/2023	23,8	12,83
10/10/2023	23,4	17,3
11/10/2023	20,5	9,36
12/10/2023	24,3	0,81
13/10/2023	25,4	4,67
14/10/2023	25,1	9,54
15/10/2023	21,2	10,75
16/10/2023	22,5	18,85
17/10/2023	24,7	0,2
18/10/2023	24,5	12,75
19/10/2023	23,4	11,32
20/10/2023	25,9	31,5
21/10/2023	25,3	3,23
22/10/2023	24,3	53,01
23/10/2023	23,8	0,81
24/10/2023	25,5	11,26
25/10/2023	25,1	15,47
26/10/2023	24,1	4,82
27/10/2023	24,7	12,83
28/10/2023	23,8	9,41
29/10/2023	23,6	25,19
30/10/2023	22,1	4,59
31/10/2023	21,6	9,17
Total		**423,47**

Pictures of Landslide area

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