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Vulnerability to Land Slides in Bafoussam I Council (West Region-Cameroun): Multi-Factor, Cartographic and Geographic Information System Analytical Approach

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Abstract— *Populations and their property are becoming increasingly vulnerable to landslide hazards. High demographic and land use pressure in tropical countries increase the chances of natural hazards such as landslides. With increasing vulnerability to landslides, populations and their property are exposed to hazards. The population of Bafoussam I doubled within a period of 15 years increasing household numbers and anthropogenic activities. These rapid increases coupled with anarchical land occupation even in risk zones aggravate vulnerability to landslides in Bafoussam I Council area. This study seeks to assess the level of vulnerability of Bafoussam I to landslides using multi-factor analysis from GIS processed data, oral histories and field observation. Response scores of 80-100% indicate that the level of susceptibility of sites exposed to landslides in Bafoussam I is in relation to predisposing factors such as texture, structure and geology that increase soil water retention capacity, accentuated relief, and population pressure, land use (farming, houses/roads construction), climate (heavy rainfall) and hydrology. By modeling these predisposing factors, we were able to generate a map with five levels of landslide susceptibility (very low, low, moderate, high and very high) to which the population is vulnerable. In addition, a criticality grid enabled us distinguished three categories of landslide risk zones, to wit: high vulnerability, moderate vulnerability and low vulnerability in Bafoussam I. Based on a critical assessment of these three categories of landslide risk zones, the paper suggests management strategies for a reduction of population's vulnerability to landslide risk in Bafoussam I.*

Keywords— *Bafoussam 1, GIS, Hazard, Mapping, Multi-factor analysis, Landslide, Risk, Vulnerability.*

I. INTRODUCTION

Despite scientific and technological advances that give scientists some control over the planet earth, a number of natural phenomena continue to occur and cause damage and casualties every year. In 2019, 463 fatal non-seismic landslides were recorded worldwide (Petley, 2020). The striking issue here is that they are the result of rapid population growth, land and social imbalances in urban areas (Diagana et al., 2016). In countries of the South, the cost of land in urban centres is very high, causing city dwellers to occupy risky marginal sites, most of which are ill adapted to human habitation. Thus, the recurrence of natural disasters such as landslides, mudslides and floods (Eliccel, 2002; Zogning et al., 2008; Diagana et al., 2016). Human activities in these newly colonised sites lead to changes in the condition of a land mass from stable to unstable state, thereby, increasing susceptibility to natural disasters (D'Ercole & Thouret, 1994; November, 1994; Metzger & D'Ercole, 2011).

Landslides are rapid discontinuous downward displacement of earth mass along a slope under the influence of gravity (Taleb, 2019). They are geological and geophysical phenomena that occur in various environments characterized by steep or gentle slopes such as mountain ranges, coastal cliffs or even underwater, in which case they are called submarine landslides (Haflidason, 2004 and Payne et al., 2009). The consequences of landslides on human life and property vary widely making it difficult for accurate estimation (Schuster & Fleming, 1986; Gokceoglu et al. 2005; Highland & Bobrowsky, 2008 and Desodt et al. 2017b). The extent to which a land mass is exposed to landslide hazard is generally determined by a joint effect of topography, lithology and physical occupation of the land in question (Desodt et al., 2017a). Currently, some methods that integrate GIS have been developed to ease the process of determining vulnerability to landslide as employed in Bafoussam I Council area. The first of the methods focuses on the use of GIS to identify all predisposing factors that contribute to landslides in a site under study. A second is to elaborate a susceptibility map of landslide risk using mapping tools, and a third is to propose resilient management techniques.

Study area

Bafoussam I Council is an integral part of the Mifi Division, in the West Region of Cameroon. It is located between longitudes 10°29'20" and 5°33' 0" East and between latitudes 10°24'0" and 5°28' 40" North. The surface area of Bafoussam I Council is 91 km², segmented into 18 km² for the urban section and 73 km² for the rural, with a road network of over 225 km. The Bafoussam I Council has 22 villages, which correspond to the different urban neighbourhoods with 19 found in the rural area of the municipality (Bafoussam I Council and PNDP, 2013). The council is bordered in the north by Bafoussam II Council, in the south by Koung-Khi Division, in the east by Noun Division and in the west by Bafoussam III Council (Figure 1).

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The geological history of Bafoussam I Council has been quite eventful. The current landforms in the municipality were shaped by erosive activities that were preceded by widespread fissural volcanism. The products of this volcanism have masked the morphology of the landscape set up by an earlier orogeny event called brittle tectonics, which is explained by brittle deformation. Brittle deformation is the primary mode of deformation of Earth's crust and at a long timescale, it manifests through faulting, while at a short times horizon, it is through earthquakes. It is one of the best-known examples of a system exhibiting self-organized criticality. The soil structure in the study area reveals a substratum made up of unweathered granite, overhung by aphyric olivine basalts and a layer of alterites with varying thickness depending on slope and the action of erosion.

Bafoussam I Council has few streams that criss-cross certain neighbourhoods and their flow vary with season. The volumes of these streams shrink steadily with urban pressure, the quantity of solid waste they transport and the influence of climatic variability. This presence of numerous small watersheds in the municipality justifies the ability of soil moisture content to create underground cracks during hypodermic flow. Leaching and percolating water enhance dislocation of cavities leading to subsidence and then, landslides. Water is a key element in the landslide process.

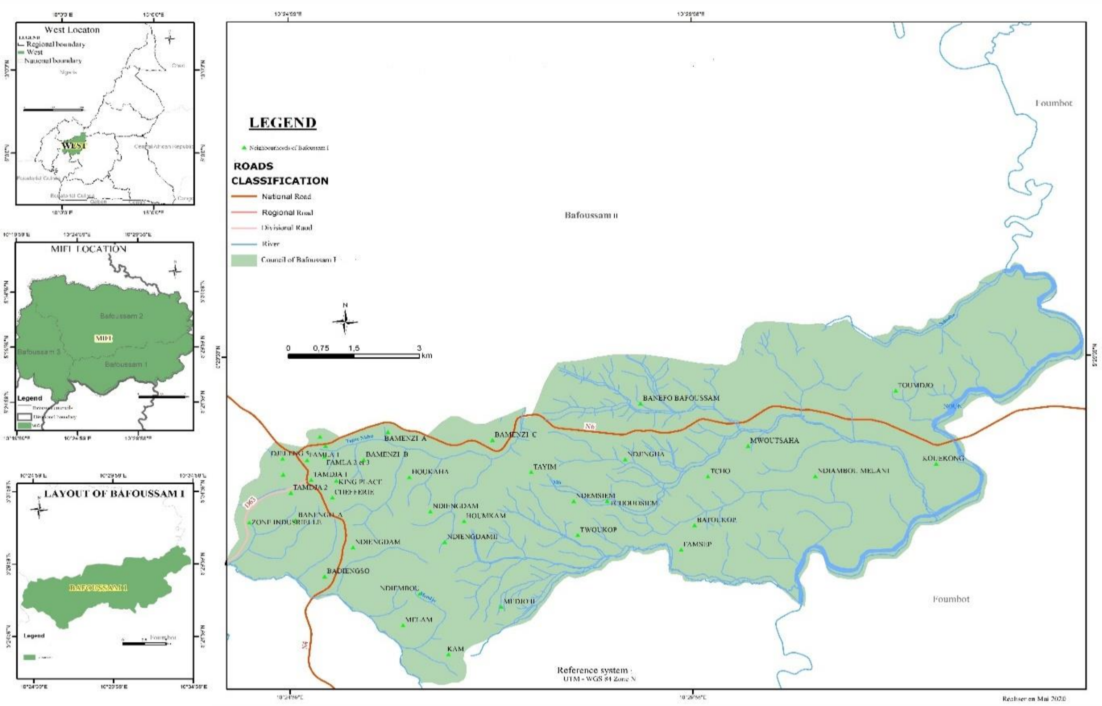

Figure 1: Location map of Bafoussam I Council

The municipality is affected by the seasonal cycle in Cameroon, governed essentially by the annual movements of the intertropical front (ITF) between the convergence zones of the Southern Trade Winds (wet monsoon from the Saint Helena anticyclone) and the Northern Trade Winds (dry harmattan from the Saharan anticyclone). The town of Bafoussam, which hosts Bafoussam I Council, is located in the sub-equatorial zone with a subtropical climate. This climate, which under normal circumstances is characterized by two dry seasons and two wet seasons (Tsalefac, 1999) is under the influence of a mountainous zone. The combined influence of the relief (1450m altitude) and the monsoon coming from the Gulf of Guinea and SW-NE Trade Winds has transformed this climate into a pseudo-tropical type with just two seasons, a dry season from 15 November to 15 March and a long rainy season from 15 March to 15 November. The rains are relatively abundant and extend from the end of March to the beginning of October.

II. Methodology

A survey methodological approach was used for this study for the collection of secondary, primary and spatial analysis data. Secondary data were collected from documents such as the Bafoussam I Council Development Plan (CDP), the PDU, articles, dissertations, theses and websites such as that of SEDAC, grounded in vulnerability to landslides hazards. For the primary data, a sample of 138 households was selected and surveyed for the vulnerability of the populations of Bafoussam I to landslides and for an in-depth understanding of landslides causalities in the council area. Primary qualitative data were collected from 5 interviewees of whom 2 were representatives of Bafoussam I Council and the other 3 coming each from Bafoussam I Divisional Office, traditional authorities and female victims of landslides. Informant discussions and field observation also served for data sourcing. The data were complemented with those collected using a GPS and those extracted from the land use plan (POS) of Bafoussam I,

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Landsat8 images and Google Earth satellite images downloaded from https:// www.earthexplorer.usgs.gov. The GPS was used to take waypoints at landslide prone sites and to track round the sites. Spatial data on the sprawl of Bafoussam I urban space was extracted from the Google Earth satellite images. Land cover data were extracted from the POS and the Landsat8 images downloaded free of charge from https://www:remotepixel.ca/).

The Landsat8 image was processed with ArcGis 10.8 software for Geographic Information Systems (GIS) data. Altitudinal (relief) data extracted from the Landsat8 images enabled us generate a digital elevation model (DEM) of the municipality, which was subsequently used to calculate a topographic wetness index (TWI) in ArcGis 10.8, produce a slope gradient map as well as graphics that illustrated the corresponding convexo-concave shapes of the slopes. In addition, data extracted from the Landsat8 image provided geologic information on the composition of the different rock type in the area as well as the spatial distribution of the rocks. The processed GIS data enabled us to identify the physico-human factors that trigger landslide hazards to which Bafoussam I Council is vulnerable. GPS waypoints and tracking data in landslide prone sites were downloaded and superimposed on the map of Bafoussam I Council in ArcGis software where algebraic mathematical operations were carried out for the generation of a susceptibility map of the Council area. The susceptibility map was beefed-up with spatial data on the sprawl of Bafoussam I urban space extract from Google Earth satellite images. In order to quantify the risk and delimit the areas following their degree and frequency of risk, we used the criticality grid.

III. Results and Discussion

The processed GIS results of this study, which is based on the non-exhaustive predisposing factors of landslides in Bafoussam I Council show that the vulnerability of the council area to landslides is determined by 7 main factors. Slope gradient, Land use, Lithology, shapes of slopes, topographic moisture index, distance from hydrological network, and quantity and intensity of rainfall. These predisposing factors, which contribute to the development of landslide hazards in Bafoussam I Council area, can be classified into natural and human as confirmed by response scores of 80 to 100% (table 1), the five interviewees and other informants.

TABLE 1: Respondents views on predisposing factors to landslide vulnerability in Bafoussam I Council area

Neighbourhood	Resps	Drivers of landslide vulnerability in Bafoussam I Council area						
		Human activities				Physical factors		
		Population pressure	Construction of houses/roads	Unplanned settlement	Farming	Heavy rains	Accentuated relief	Soils retain much water
Bamendzi	67	61	67	56	56	67	67	67
Banengo	62	59	62	48	48	62	62	62
Famla	9	7	9	6	6	9	9	9
TOTAL	**138**	**127**	**138**	**110**	**110**	**138**	**138**	**138**
%	**100**	**92**	**100**	**80**	**80**	**100**	**100**	**100**

Source: Fieldwork 2019

3.1 Natural factors contributing to the development of landslide hazards

All the 138 respondents acknowledged that Bafoussam I Council accommodates many of the landslides predisposing natural (physical) factors, which have rendered the municipality vulnerable. These factors include the rugged relief nature of the area with numerous convex and steep slopes, a favourable hydrographic network, a geological formation that consists of a substratum of unweathered granite, overhung by aphyric olivine basalts and recent formation of alterites, which constitute residual rock resulting from weathering. The thickness of the alterites is greater in the western part of Bafoussam I Council than the east, predisposing the western portion to landslides. The climate is dominated by relatively abundant rainfall per year, and a mainly sandy-clay soils lithology, which is less stable.

The relief of Bafoussam I Council is made up of a succession of highly undulating plateaus, classified into four main relief features with varying spatial extent. They include a 9.6% plain area, which is an extension of the Noun Plain, moderately steep-slope plateaus that occupy 33.4% of the area, highly steep-slope plateaus that occupy 49.14% and a 7.9% thalweg (figure 2). From the relief map, it is estimated that just 33.4% of Bafoussam I Council area has favourable relief conditions for human occupation, mainly towards the southeastern part of the municipality.

This uneven relief shows a gradual decrease in altitude as one moves away from the central parts of the town in the west towards the banks of the Noun in the east. In the west of the municipality, average altitude ranges from 1,600 to 1,400m and drops steadily to a range of 950 to 1,150m in the east. Between these extremes, there are intermediate altitudes that range between 1200 and 1350m in a north-south direction. If 33.4% of Bafoussam I Council area is potentially landslide free, the implication is that 66.6% of the municipally is landslide prone or vulnerable to landslides. This is quite feasible particularly as the area shows a predominance of highly contrasted and uneven relief with a superposition of hills, plateaus and valleys that form a convexo-concave slope shape assembly (figure 3).

Slope shape was also found to be a predisposing factor to landslide vulnerability in the municipality. Convex slopes favour the development of landslides, subsidence and many other mass movements. Steep convex slopes are quite conspicuous in areas away from the southeast of Bafoussam I Council. Most of the convex slopes, particularly in the entire west and parts of northeast, were computed to be at gradients

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above 20% (figure 4). This category of slopes is common in the neighbourhoods of Ndiembou, Medjo II in the south and Banefo in the north, passing through Houkaha and Tayim, and to a lesser extent towards the northeast.

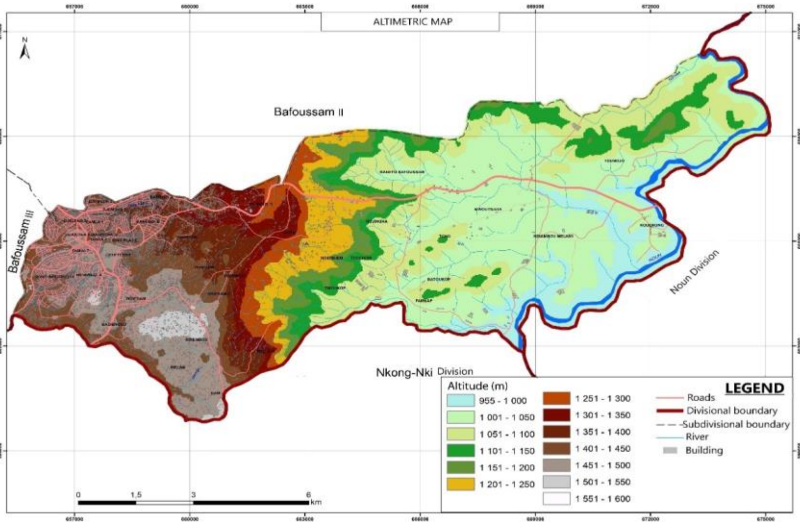

Figure 2: Relief map of Bafoussam I Council

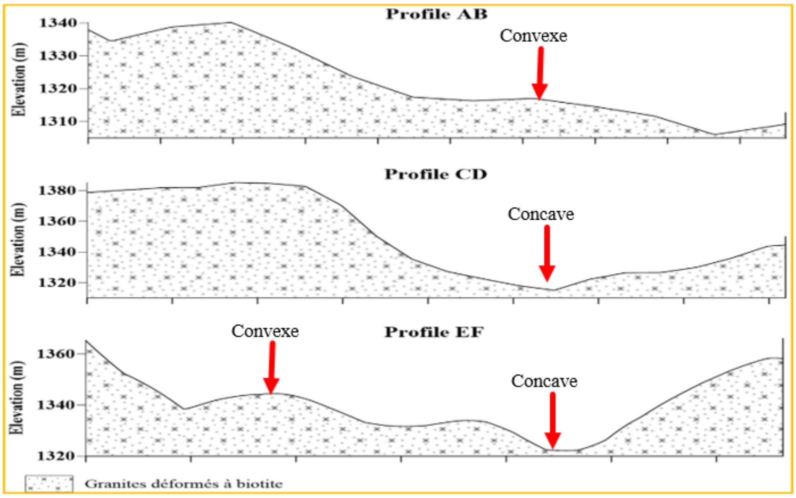

Figure 3: Topographic profile of Bafoussam I Council area

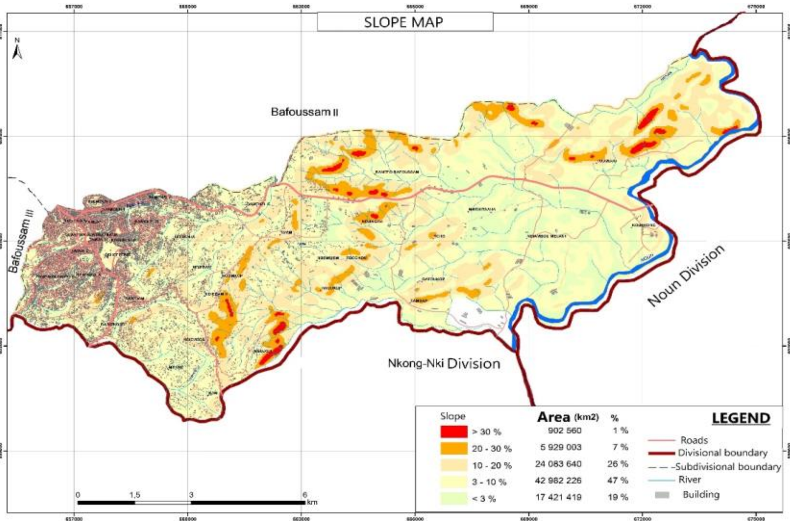

Figure 4: Slope gradient map of Bafoussam I Council

Through field observation and as confirmed by slope gradient data extracted from the Landsat8 image, all the landslide sites in the municipality were in areas where the slopes were convex in shape. The rate of material sliding is high on convex slopes, and it is probably the reason for which the western parts of Bafoussam I Council area are quite vulnerable to landslides. Literature confirms these findings as according to Wischmeier (1974), a concave slope decreases material transport while a convex slope increases it (Qiu et al., 2017; Leumbe et al., 2018). Elsewhere, they occur sporadically. Towards the Noun Plain in the southeast, the slopes are less steep and drop below 9% in the areas of Mvoutsa'a, Ndiembou Melan I and Kouékong. The high slope areas are under greater vulnerability to landslides due to the action of gravity. Between 2000 and 2022, the western part of Bafoussam I Council area registered 20 landslide events as against just 9 on the eastern portion (Mifi MINEPDED, 2022).

Some of the landslides in the council area are provoked by a combination of triggering factors such as slope gradient, lubricating agent (moisture content) and gravity. Bafoussam I Council area is drained by few rivers, which however, crisscross many of the neighbourhoods and some flowing in very deep valleys. The erosive activities of some of these rivers on valley slopes has also influenced landslide occurrence in some of the neighbourhoods they drain. These erosive activities have engendered lots of under cuttings that predispose the municipality to landslides, particularly as the vulnerability is facilitated by the geology and lithology of the area. The lithology of Bafoussam I Council is characterised by crustal rocks of type magmatic gneiss, which through partial disintegration give rise to sandy-clay soils that are very prone to sliding when their moisture content increases.

3.1a GIS modelling of susceptibility factors

GIS approach was used to model the physical components of the environment that constitute the elements likely to cause landslides. These components include topography, geology and geomorphology. Through modelling, areas susceptible to landslides in Bafoussam I Council were identified and modelled (Figure 5).

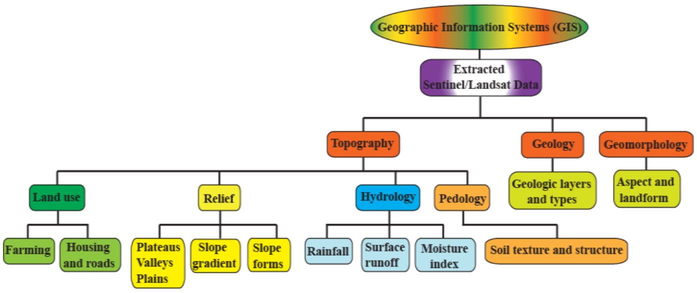

Figure 5: GIS susceptibility modelling matrix

3.1b Spatializing Landslide hazard susceptibility in Bafoussam I

Geographic Information Systems (GIS) data extracted from Landsat8 image after processing with ArcGIS 10.8 software served for a landslide prediction mapping of Bafoussam I Council. A susceptibility map was generated from the GIS data and it shows 5 categories of vulnerability and their spatial extent (Figure 6). The 5 categories of vulnerability range from very low, low, moderate, high to very high. According to the quantified spatial extent of areas susceptible to landslides in Bafoussam I Council, 15.4km² of the entire surface area is threatened by high and very high vulnerability, corresponding to 15.4% of this area (Table 2). The 15.4% area is concentrated in the western and southwestern parts of the map, which is highly accentuated and densely settled.

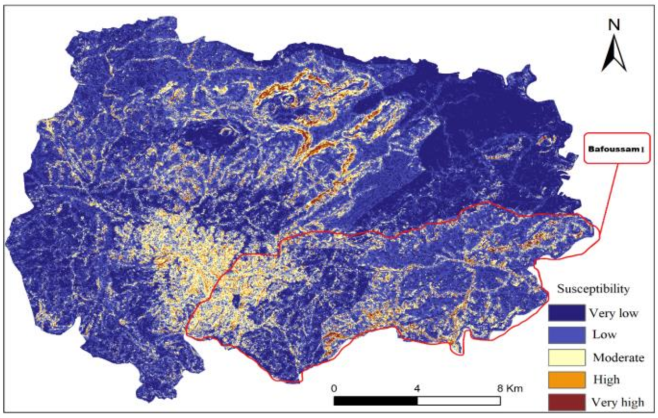

Figure 6: Susceptibility map of Bafoussam I Council

TABLE 2: Percentages of areas threatened by landslides in Bafoussam I Council

Name	Extent of vulnerability					Combined
Category	Very low	Low	Moderate	High	Very high	**High +Very high**
Area (km^2) and (%)	47.8	28.0	8.8	9.7	5.7	**15.4**

Source: Extracted from landsat8 image.

The areas with very low and low vulnerability are mostly in the eastern parts of the map. In the field it was observed that common types of landslides in Bafoussam I Council include fall by undercutting, fall by toppling and the earthflow (Plate 1). These images show the exposed stakes, i.e. the houses built on slopes and threatened with destruction by landslides. These images thus testify to the presence of the landslide hazard and its manifestation on the site.

It was observed that the sites of these landslides in Bafoussam I Council were characterised by waterlogging in the soil during rainfall and were close to water bodies as confirmed by extant literature (Tsalefac, 1999; Bollot et al., 2015 and Dehni, 2015). During heavy rainfall in the municipality, water infiltrates in large quantities into the soil and through hypodermic flow, it leaches and accumulate in underground cavities enhancing blocks dislocation and landslides. The rivers in Bafoussam I Council are at the peak of their erosive activities during the rainy season. On the average, Bafoussam I Council area and its environs receive 1800mm to 2000mm of rainfall per year with an average of 110 to 130 days of rain (Bamougoum Airstrip). Heavy rainfall occurs in July, August and September, which are not only the

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coldest months, but are the months with the highest occurrence of landslides during the year. It is worth noting that in 2019, Bafoussam I Council received rains up to November with the heaviest amount received in October. During this year, monthly mean rainfall was 526.4mm and provoked many landslides, with their sites corresponding to areas where soil moisture was high as explained through the use of topographic wetness index and the criticality grid that was produced using ArcGIS software (figure 7).

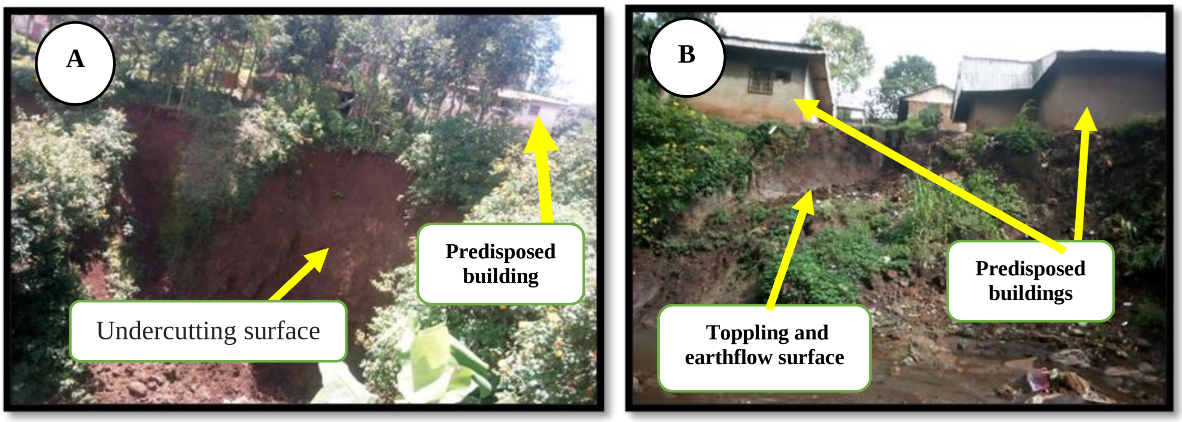
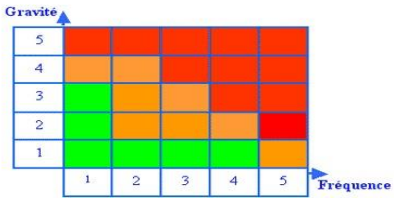


Plate 1: Images of landslides
Photo A: Fall by undercutting and Photo B: Fall by toppling and the earthflow. Both photos show vulnerability of trees and houses to landslide in Bafoussam I Council.



Niveau de Fréquence	Valeur de Probabilité / unité
5	$10^{-3} < P < 10^{-2}$
4	$10^{-4} < P < 10^{-3}$
3	$10^{-6} < P < 10^{-4}$
2	$P < 10^{-6}$
1	$P < 10^{-8}$

Figure 7: Criticality grid

Analysis of this criticality grid shows three main categories of risk areas, to wit, red zones, orange zones and green zones (Figure 8). On this grid, areas with high probability of landslides are indicated in red and their probability to accumulate soil moisture is high $(10^{-3} < P < 10^{-2})$ and correspond to high topographic wetness index of between 2.6-9.3.

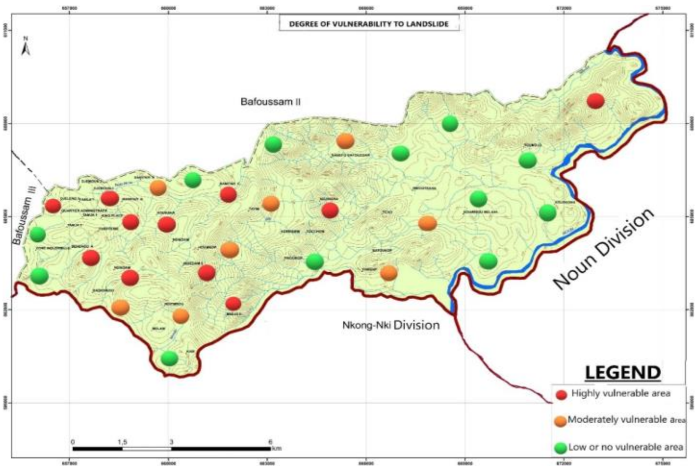


Figure 8: Map of landslide prone zones in Bafoussam I Council.

High vulnerable neighbourhoods in Bafoussam I Council include Quartier Bamendzi (Hôtel Sekem area), Bamendzi Quatier General, Famla (Thereza mother base), Houkaha (boulevard évêché), Bamendzi 2 (rue contre bas carrefour Eneo Djemoun), Quartier Djemoun; Banengo (lower entrance to the villa series), Banengo Ville (lower entrance to the brewery going towards Djuinang), Banengo Ville (lower entrance to the bus station), Banengo (lower entrance to the voltaire college-Kilombo bridge), Medjo Ii, Banefo, Quartier Groupe 3 and Banengo (Tama college area). These are neighbourhoods in the red zones, which are areas of high vulnerability to landslides. The risk here is not only frequent but of high severity since the area is densely populated and human activities are intense. The severity is linked to the attendant damage, which ranges from material losses to loss of human and animal life.

The orange zones correspond to areas of the municipality where the severity of the risk is moderate and the probability of landslides as indicated by the grid is between $(10^{-4} < P < 10^{-3})$ and $(10^{-6} < P < 10^{-4})$. The topographic wetness index of between 1.6 and 2.3, is indicative of moderate soil moisture accumulation. Here the impact is limited to minor material losses as observed in the neighbourhoods of Bamendzi A (bishop's bridge area) and Bamendzi (the area along the municipal stadium going towards the Meka laboratory), and Banengo (Coleduc College area). Neighbourhoods found within the green zones are least vulnerable to landslides. The topographic wetness index here

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is below 1.6 and on the criticality grid the probability is between $P<10^{-6}$ and $P<10^{-8}$ indicating low soil moisture accumulation. Landslide catastrophes are rare in these zones and when they occur, damage is minimal. Neighbourhoods in these zones include Tamdja, Djeleng (I, II, III, IV, V), Madelon and Toket. The influence of these physical factors on vulnerability to landslides is amplified by human drivers.

3.2 Human factors

A number of human factors such as population pressure and human activities were observed to enhance the development of landslides in various parts of Bafoussam I Council, particularly in the west. The demographic growth in the council area is leading to a constant increase of the population over the years. As the population increases, the pressure on land through human activities facilitates soil fragility and disintegration, all of which render the council area vulnerable to landslides. The population of Bafoussam I Council practically doubled in the space of 15 years, increasing from 239,287 in 2005 to 410,630 inhabitants in 2020 (PDU, 2020). Similarly, projections made by PDU put the population at 530 000 habitants in 2025. This alarming trend in the entire council area was even severe within the urban parts as the population skyrocketed from 81 611 inhabitants in 2005 to 164 795 in 2020 with a projected figure of 191 972 in 2025 (PDU, 2020). This geometric increase in population has led to an unprecedented increase in the number of households, which rose from 19519 in 2005 (BUCREP, 2005) to more than 30000 in 2020 following projections.

As the number of households and household sizes increase, land use evolves rapidly. The various household members tend to occupy the land for various reasons such as for the construction of houses leading to accelerated urbanisation, exploiting any available lots for agriculture and creating quarries for the exploitation of stones, sands, ores and minerals. Intensification of these human activities was observed to contribute to landscape modification leading to environmental degradation and often provoke soil instabilities. It was observed in the field that the concentration of settlements on steep slopes in the western part of Bafoussam I Council exposes the population to landslides since undercutting of slopes for the construction of houses and roads is a common practice. The undercutting produces cracks through which water infiltrates easily during rainfall lubricating the contact zones between the overlying sandy-clay soils and the unweathered granite below thereby facilitating the development of mass movements in the form of landslides.

IV. CONCLUSION

This study on vulnerability to landslides in Bafoussam I Council indicates that natural (physical) factors such as climate, vegetation, soil, relief, hydrography, and human factors such as the growing population and human activities contribute to the development and manifestation of landslides. Geographic Information Systems are nowadays excellent tools in territorial diagnosis for effective landslide prediction and mapping for decision-making. Coupled with multi-criteria analysis, GIS allows modelling of hazards and assessment of potential human, social, economic and environmental risks. High and very high risk sites were predicted on slopes underlain by clay soils and where human activities, such as agriculture and the construction of houses and road infrastructure were intense. Ecological imprint through human activities on slopes disturbs the stability of soils formerly covered by forests and therefore, reinforces susceptibility to landslides, particularly when triggered by rain.

Urban growth thus constitutes an important risk-producing factor to which studies of natural disasters should pay particular attention. For better risk management, landslide prediction mapping is an indispensable technical phase. It is also important to develop land-use patterns and rainfall threshold monitoring systems in high and very high hazard-prone areas. In addition, phytostasis should also be applied to revegetate slopes using vetiver plants, which are deep-rooted plants that stabilise slopes and reduce mass movement. Technical monitoring of landslides should make use of devices such as: 1) extensometers, which allow for the monitoring of underground wave variations and information on landslide displacements; 2) Geophones, which allow for a real-time vision of landslide geometry; 3) Piezometers, which allow for monitoring information on the water level and pressure to which each crustal stratum is subjected. Water and pressure constitute important landslide triggering drivers. These measurements can be used to extrapolate landslide movements by recording the profile of a wave emitted on the surface so as to extract information on the subsurface of the landslide. It is also possible to set up a system of countermeasures known as parrying systems or fencing blade work (Fig. 9) in civil engineering techniques to stabilise slopes through embankments.

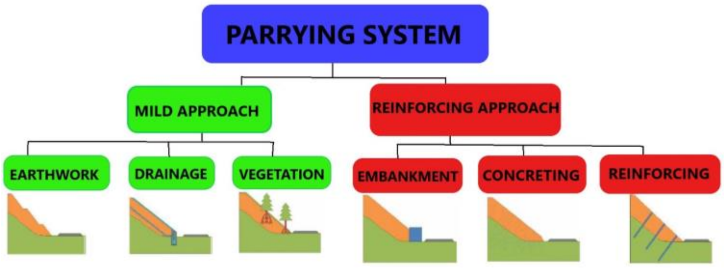

Figure 9: Parrying system

In the build-up of urban planning documents such as the Urban Development Plan (PDU), Land use Plan (LUP) and the Sectorial Plan (SP), policy makers and policy executors need to take hazard maps into account. In this respect, our study holds that checking vulnerability to landslides or resilience to landslides vulnerability is a function of reducing the driving forces or increasing resistant forces, and monitoring.

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