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Rainfall Dynamics and Landslides in Urban Areas of Gabon: The Case of Libreville-Est (Gabon)

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Abstract

Due to its abundant rainfall, the city of Libreville, which concentrates more than half of Gabon's population, is frequently confronted with the impacts of natural disasters such as floods and landslides. This study attempts to identify the complex relationships between the dynamics of land use and the role of rainfall in the occurrence of landslides. On the one hand, it uses statistics on landslides compiled from information taken from general news bulletins and, on the other, daily rainfall data obtained from the National Meteorological Department. The study revealed that the Libreville East sector, dominated by Mount Nkol Ogoum, one of Libreville's most prominent landforms, is affected by a land-use dynamic in which human settlement has been progressing for some thirty years, to the detriment of the original vegetation which, among other things, helped to stabilise the soil on the hillsides and the marshy areas at the foot of the slopes. The result is not only an uncontrolled occupation of the land, but also a major landslide every two years in this part of the city, causing significant loss of life and property. However, an analysis of the time series shows little rainfall variability, marked in particular by a predominance of negative anomalies, and the occurrence of a few exceptional daily rainfall peaks. Similarly, the period from 20 October to 20 November, which receives the most rainfall, also appears to be the most conducive to landslides.

Keywords

Libreville, Land Use, Rainfall, Natural Hazards, Landslide

1. Introduction

The issue of environmental degradation and protection is one of the debates that is currently preoccupying politicians and civil society around the world, as well as the scientific world: in this case universities and research centres such as the Laboratory of Spatial Analysis and Tropical Environments (LANASPET) at the Omar Bongo University in Libreville (Maloba Makanga & Mbadinga, 2022). Thus Loungou (2014) argues that talking about geography as a professional practice and its contribution to Gabon's development is equivalent to talking about spatial planning and sustainable development. This means establishing sectoral strategies and policies for the sustainable management of territories and the development of resources. In the early 2000s, Maloba Makanga and Diop (2003) pointed out that on the western edge of equatorial Africa, the major climatic risk is abundant rainfall, which can lead to natural disasters such as flooding. Menié Ovono and Pottier (2019) note that the recent floods affecting the most vulnerable people in Libreville have rekindled the debate on climate change and its possible consequences, highlighting the responsibilities of decision-makers and residents of small urban coastal catchment areas. According to Ndong Mba and Beka Beka (2019), the combination of uncontrolled urbanisation and heavy rainfall poses a real threat to the physical environment and urban populations in outlying districts. As a result, landslides have been observed in Libreville during the rainy season. Beyond the Gabonese capital, landslides generally occur in Western Equatorial Africa (Cameroon, Congo, Gabon, etc.) during the rainy season, when water pressure in the soil is high and therefore detrimental to slope stability (Backita Moussounda, 2019). Moreover, Qianho Tang et al. (2023) consider that intensity has a strong influence on landslide triggering. It should be noted, however, that while the occurrence of landslide risk is difficult to determine, the regions that are prone to landslides are easily identifiable (https://www.climats.com/catastrophe/glissement-terrain). In the case of Gabon's capital, it is in the eastern sector that most of the landslides recorded in Libreville occur, such as those in 2019 and 2023, which resulted in loss of life and the burial of numerous human settlements. This sector, which is the scene of uncontrolled urbanisation, forms a series of collinear hills, including Mount Nkol-Ogoum, which is the highest point (126 m) in the area (Backita Moussounda, 2019).

Based on the principle that heavy rainfall can lead to the occurrence of extreme natural phenomena such as floods and landslides, resulting in changes to the landscape, damage to property and loss of human life, this study seeks to highlight the dynamics of land use and its impact on the bedrock (soil and vegetation), as well as the rainfall characteristics of the season associated with most of the landslides affecting the city of Libreville. This approach should, on an intra-seasonal scale, provide a better understanding of the characteristics of the most intense rainfall sequences. The results of this study could help to strengthen the strategy aimed at reducing the occurrence of landslides in Libreville.

2. Data and Methods

Rainfall and satellite data

The data used are rainfall data from the Libreville airport station supplied by the Direction Générale de la Météorologie Nationale (DGMN), which on the whole have missing values of less than 25% as recommended by the World Meteorological Organisation (2010). Daily data were extracted from this file. It should be noted that a rainy day was considered as such when it recorded a water depth greater than or equal to 0.1 mm. This is the minimum daily rainfall recorded by the weather stations in Gabon. This is an interesting descriptor to take into account because a comparative study carried out on five tropical regions, including Kenya, showed that the interannual variability of NJP tends to be slightly more spatially consistent than the seasonal accumulation (Moron et al., 2007). This variable is directly dependent on the length of the rainy season, such that the probability of having rainy days increases as the season lengthens, and vice versa. The longer the rainy season, the greater the likelihood of landslides.

Moreover, when analysing natural hazards, Belizal et al. (2017) point out that the temporal scale needs to be mobilised because the risk is not the same over time; it varies over the course of history and can change depending on the season or time of day. With regard to landslides, Borgatti and Soldati (2010) found that climatic factors controlling the quantity of water present in the voids in the material determine variations in hydrostatic pressure and, therefore, the state of saturation along the slope. In this way, the duration and intensity of rainfall allow the thresholds to be crossed at which the cohesion of the material becomes zero (Fort et al., 2015). Overall, in the analysis of natural phenomena, intensity, duration and frequency are tools commonly used to describe the probability of various extreme events (He et al., 2019).

It is important to remember that the use of boxplots to visualise the distribution and dispersion of rainfall (Silva et al., 2022) is one of the most frequently used methods for identifying extreme values (Zhao & Yang, 2019). In this graphic illustration, the median line corresponds to the 50th percentile (Banacos, 2011) and the edges of the cigar box indicate the first and third quartile (Adilah et al., 2020). Consequently, values outside the cigar boxes are considered atypical or outliers, which may correspond to extreme values or measurement errors. An observation is thus considered abnormal when the value does not belong to the interval calculated as follows (Zhao & Yang, 2019):

$$Lim\_inf = q_1 - 1.5 * IQR; Lim\_sup = q_3 + 1.5 * IQR$$

Note that q_1 and q_3 are the first and third quartiles respectively, and IQR ($q_3 - q_1$) is the interquartile range.

It should be note that the standard box plot is suitable for normal or symmetrical distributions in particular. For Gaussian data, the probability of this analysis makes it possible to highlight the months with a high occurrence of maximum rainfall or the months with a more variable occurrence. A short cigar box indicates values grouped around the median and a long cigar box indicates high variability. Values outside the box are therefore considered as outliers and therefore represent extreme values.

In addition, rainfall variability has been analysed here using the index method or reduced centred anomalies already used in our previous work (Maloba Makanga, 2002, 2000, 2015; Maloba Makanga & Mbadinga, 2022). It is used to identify surplus and deficit years according to the formula:

$$As = \frac{\left(X_i - \bar{X}\right)}{\sigma}$$

Note that: As = centred reduced anomaly; X_i = observation value; $\bar{X}$ and σ represent the mean and standard deviation, respectively, of the series under consideration. Similarly, the trend in the Libreville time series can be seen on the curve representing the evolution of the five-year moving averages calculated on the annual rainfall totals. Indeed, the moving average makes it possible to smooth the series and give an average idea of the trend (Hlaoui & Henia, 2015). While on the average annual scale, the period common to the data for the variables studied (landslides and rainfall) makes it possible to detect co-occurrences (evolution in phase) between positive rainfall anomalies and the occurrence of landslides, analysis of the decadal patterns highlights the most abundant rainfall periods. This is, in fact, the period most likely to see landslides.

Moreover, geographers and ecologists study changes in land cover and land use based on direct observations using remote sensing techniques and geographic information systems (Lambin et al., 1999). According to Djagnikpo Kpedenou et al. (2016), these techniques, which make it possible to obtain digitised, regular and relatively detailed information on all phenomena related to land occupation and use, are increasingly used, particularly as a means of inventorying natural resources (water, forests, agricultural land, quarries, etc.).

The images used are Landsat 4 (1990), Landsat 7 (2000 & 2010) and Landsat 8 OLI (2020). Although they initially had a spatial resolution of 30 m (**Table 1**), processing using ENVI 5.3 improved the resolution of all the images to 15 m. These data were obtained from the United States Geological Survey (USGS) open source database. Also, because of the age of the images, Landsat data is the most widely used and is a better asset for diachronic studies over long periods. In fact, Landsat remains the only medium-resolution optical satellite capable of providing images over more than 40 years for a given area (Mboumbou Makanga & Maloba Makanga, 2022).

Table 1. List of images used.

Names	Acquisition date	Sensor
LT04_L1TP_186060_19900207_20170131_01_T1	07-02-1990	Landsat 4 TM
LE07_L1TP_186060_20000407_20170212_01_T1	07-04-2000	Landsat 7 ETM
LE07_L1TP_186060_20100302_20200911_02_T1	02-03-2010	Landsat 7 ETM
LC08_L1TP_186060_20200321_20200822_02_T1	21-03-2020	Landsat 8 OLI

It should be noted that the analysis of land use dynamics follows a process, the main steps of which are presented below.

Corrections

Landsat images appear to be an appropriate and indispensable tool for monitoring phenomena over a long period. Landsat is the only medium-resolution optical satellite capable of providing images of a given area for more than 40 years. However, the almost constant presence of clouds in the study area limits the quality of the images available (Mboumbou Makanga & Maloba Makanga, 2022). A number of corrections were made to improve the quality (legibility) of the images used, as this is a prerequisite for reliable interpretations. The various operations carried out were as follows:

1) Radiometric correction: using the Radiometric calibration algorithm;

2) Atmospheric correction: using the Quick Atmospheric Correction tool;

3) Correction of scratches on Landsat 7 images (2000 & 2010): Landsat images have been defective since 2003, due to the extinction of the SLC (Scan line Corrector) system, which results in the presence of scratches at the ends of the scene. Landsat 7 scenes have been corrected using the Landsat Gapfill tool.

Calculating indices

To highlight the transformation of ecosystems (Vitousek et al., 1997), the calculation of two indices, NDVI (Normal Differenciated Vegetation Index) and NDWI (Normal Differenciated Water Index) were implemented according to the formulae presented below:

- Determination of the NDVI (Normal Differentiated Vegetation Index) is used to generate an image highlighting the vegetation cover. Negative or extremely low values represent areas devoid of vegetation, while high or positive values represent areas of forest and lush vegetation (Razagui & Bachari, 2023). The range of values between "−1" and "1" is the result of the following combination:

$$NDVI = \frac{PIR - RED}{PIR + RED}$$

- NDWI (Normal Differentiated Water Index) determination is used to detect or monitor moisture levels (Mboumbou Makanga, 2022). It is calculated according to the following relationship:

$$NDWI = \frac{GREEN - PIR}{GREEN + PIR}$$

Improved resolution and classification

Firstly, a single image was created with all the indices calculated. The Quick Atmospheric Correction images and the NDVI and NDWI indices were combined to form a multispectral image using the "Layer stacking" tool. The spatial resolution was also improved using the Gramm Smidt Pansharpening tool.

Ultimately, the analysis of the four satellite images is based on five types of land use unit:

1) Built-up area: encompassing all the different types of built-up area;

2) Open water: representing all water visible from space, in this case the lake;

3) Herbaceous: including all types of secondary vegetation, urban lawns, herbaceous plants, secondary forests;

4) Forest: representing residual forests;

5) Bare soil: includes all bare soil.

The image was then subjected to supervised classification using the Support Vector Machine algorithm. The result was then vectorised for manual enhancement, area calculation and class statistics.

Class changes

To assess class change, the "global change" calculation for 1990 and 2020 was used, along with the equation proposed by the FAO (1996), which is widely used in studies of land cover change (Noyola-Medrano, Mering, & Rojas Beltran, 2009; Mabika Maganga & Maloba Makanga, 2022). Overall change is deduced using the following formula:

$$Cg = T_2 - T_1$$

where T_2 is the final value and T_1 is the initial value.

Positive values represent an increase in the surface area of the class over the period studied and negative values indicate the loss of surface area of a class between the two dates. Values close to zero indicate that the class remains relatively stable between the two dates.

3. Results

Libreville-Est, an orographic configuration conducive to mass movements

Libreville is Gabon's main city, located between 9˚27'16 South and 0˚23'24 North on the right bank of the Komo River, with a population of around 800,000 (Direction Générale de la Statistique, 2015). Covering an area of around 160 km^2, Libreville is located on a site where a third of its surface area is made up of flood-prone areas. Resting on part of the coastal plain of Gabon's coastal sedimentary basin, Libreville is also built on low hills (Menié Ovono & Pottier, 2019). While the eastern part of the city has the highest elevations (Mont Bouët, 126 m; Nkol-Ogoum, 126 m), these drop inland towards the coastal zone, where elevations are mostly below 10 m (**Figure 1**).

In addition, the city of Libreville has 21 catchment areas of very different sizes, and the relief configuration is partly the result of intense hydrographic dissection. Moreover, Mombo et al. (2007) points out that the topography of Libreville guides the direction of runoff through a gradient of slopes estimated at between 2% and 10%. In fact, the Libreville site is an ancient peneplain that has been reclaimed by erosion, resulting in a succession of low hills with steep slopes, leading to fairly severe soil erosion (Delhumeau, 1969).

In addition, the eastern sector of Libreville, which is the subject of this study, is the water tower (the source) of many small drains that feed various catchment areas. Similarly, the numerous human settlements and the morpho-climatic conditions of this sector of the city make it a favourable site for the movement of materials. In fact, the expansion of the city beyond its initial sites as a result of demographic pressure and, above all, the proliferation of neighbourhoods in hydromorphic zones (watercourses, marshes, swamps, etc.) is one of the factors

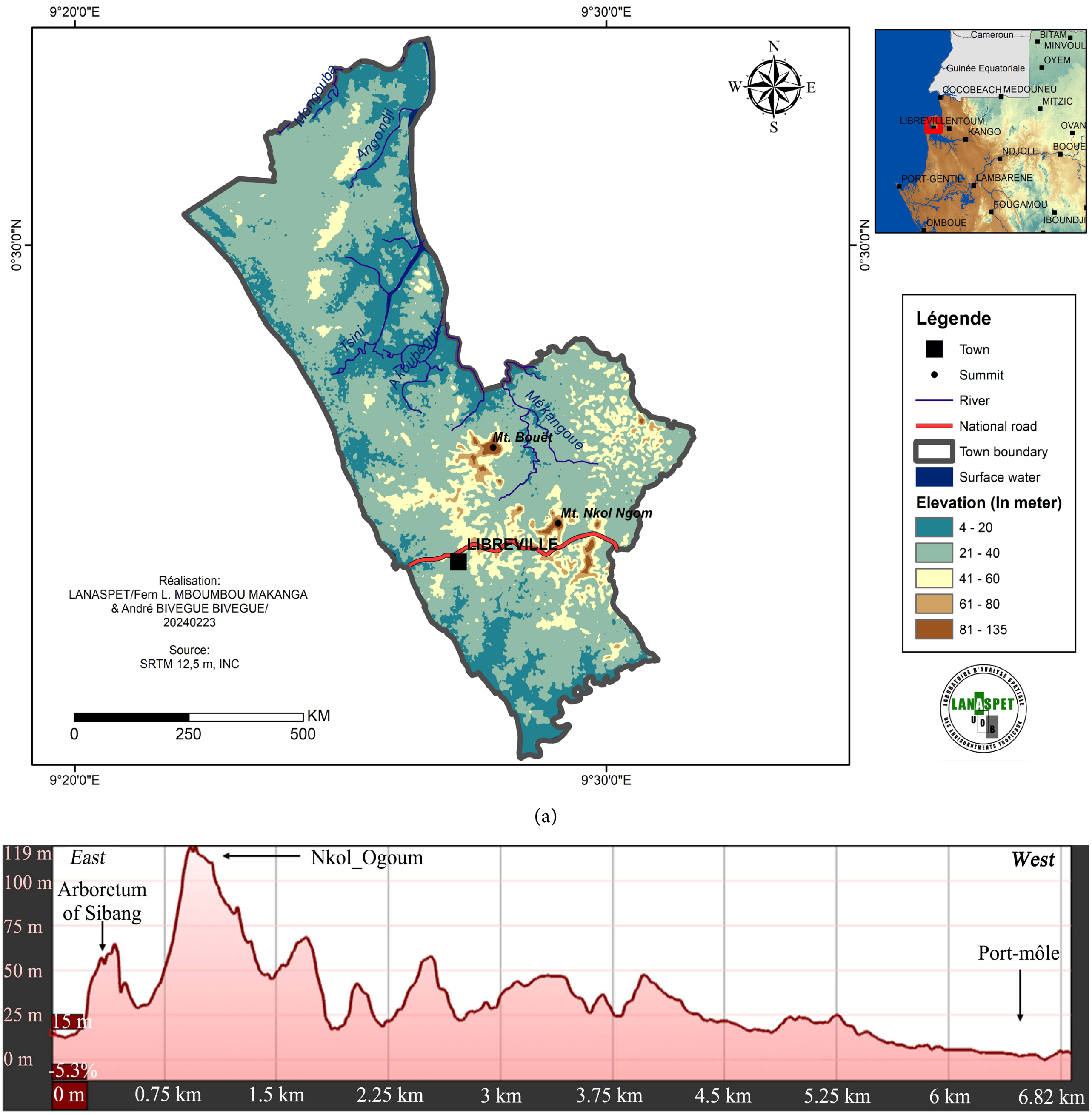


Figure 1. Some characteristics of the physical environment in the study area (Mount Nkol_Ogoum must be positioned in the figure on the right). (a) Oro-hydrographie de la commune de Libreville; (b) Configuration du relief de la plaine côtière au Mont Nkolngoum.

behind landslides. Moreover, although mass movements are natural phenomena, many are linked to human interventions that have the effect of weakening areas already conducive to this phenomenon (Gouvernement du Québec, Ministère des Affaires municipales et de l'Occupation du territoire, 2017). Overall, what does an analysis of the dynamics of land use in the eastern sector of Gabon's capital reveal?

Land use dynamics likely to contribute to mass movements

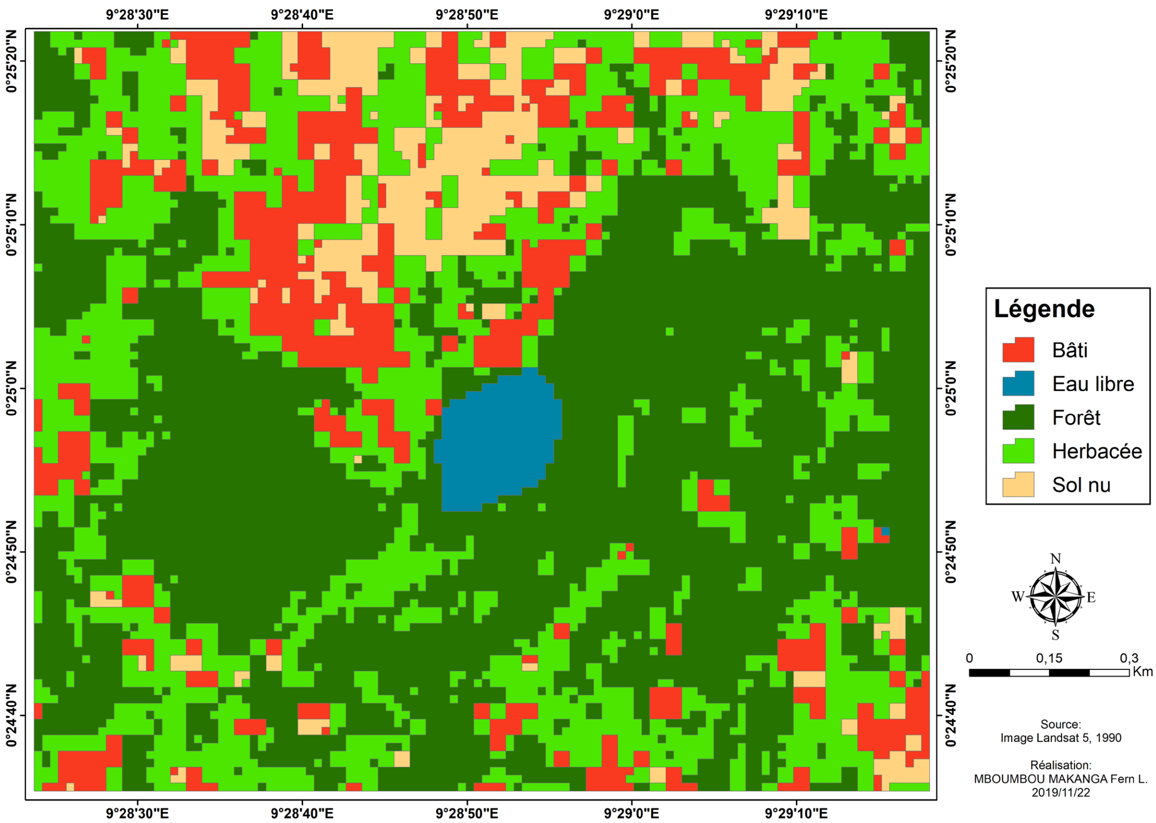
The city of Libreville is known as the political capital, concentrating all the urban functions of a centralising state. The city is home to the majority of administrative, service and commercial centres. But it also has the fastest-growing population, due in no small part to historical, political and economic factors. According to Ndong Mba and Beka Beka (2019), Libreville's population rose from 31,000 in 1960 to 175,000 between 1970 and 1975, and to almost 420,000 in 1993. The latest census (Direction Générale de la Statistique, 2015) shows that Libreville now has more than 800,000 inhabitants, or nearly 45% of the national population estimated at 1,802,728.

Faced with this strong demographic growth, Libreville is experiencing a housing crisis, partly linked to the unavailability of building plots. For several years now, land speculation has resulted in the city expanding beyond its original sites, and the anarchic occupation of space, with a densification of built-up areas in non aedificandi zones. This has led to the proliferation of neighbourhoods in hydromorphic zones (such as the Belle peinture neighbourhoods), all of which is likely to encourage the occurrence of natural disasters such as floods and landslides. In fact, "inappropriate human intervention can act as a trigger for a landslide or, more commonly, as an aggravating factor by reducing the stability of the slope. In the latter case, they have the effect of reducing the safety coefficient of the slope without directly causing a landslide. Subsequently, the failure may be caused by another trigger of natural origin, such as rain or erosion, which would not have been sufficient without these anthropogenic interventions" (Gouvernement du Québec, Ministère des Affaires municipales et de l'Occupation du territoire, 2017).

In the early 2000s, Mihai et al. (2006) showed that human pressures on the environment were being accurately and regularly observed through diachronic landscape analyses, which are one of the most important methods for studying environmental change. As in the study conducted by Okanga-Guay et al. (2018) on changes in the peri-urban landscapes of Libreville, it is considered that analysis of the various satellite images provides an account of changes in the configuration of land use in the study area.

Generally speaking, in the absence of human intervention, the landforms are masked by the abundant vegetation in the study area. Thus, the dynamics of land use concern an area of 260 hectares around Lake Nzeng-Ayong (which is easier to spot on the images) located near Mount Nkol-Ogoum, which is the highest promontory in the eastern sector of the city of Libreville (**Table 2**).

Processing of the Landsat images shows that, in 1990, the areas occupied by the different classes were as follows: forest 134.35 ha (52% of the total area), herbaceous vegetation 71.62 ha (28%), built-up area 31.86 ha (12%), 17.51 ha occupied by bare soil (7%) and open water accounted for around 1.7% (4.66 ha) of the area studied (**Figure 2**).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0°24'50"N
0°24'40"N
Légende
Bâti
Eau libre
Forêt
Herbacée
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Réalisation:
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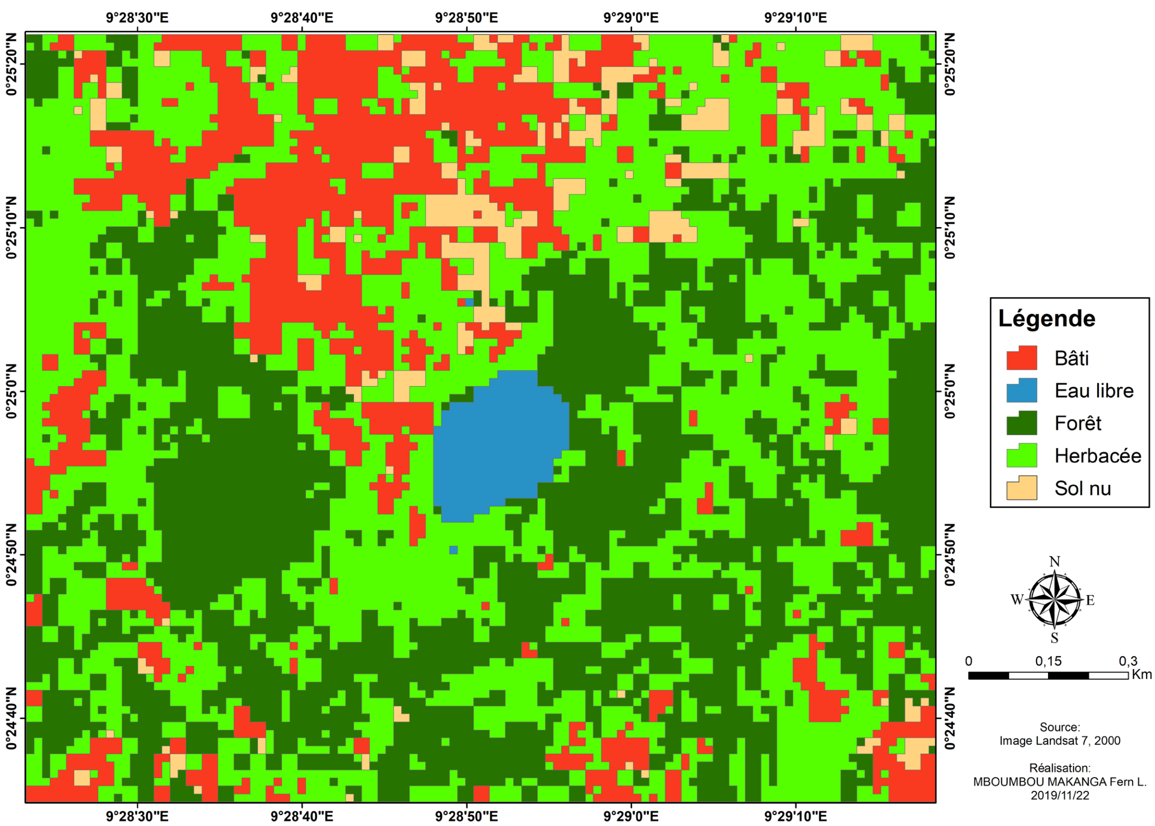
(a)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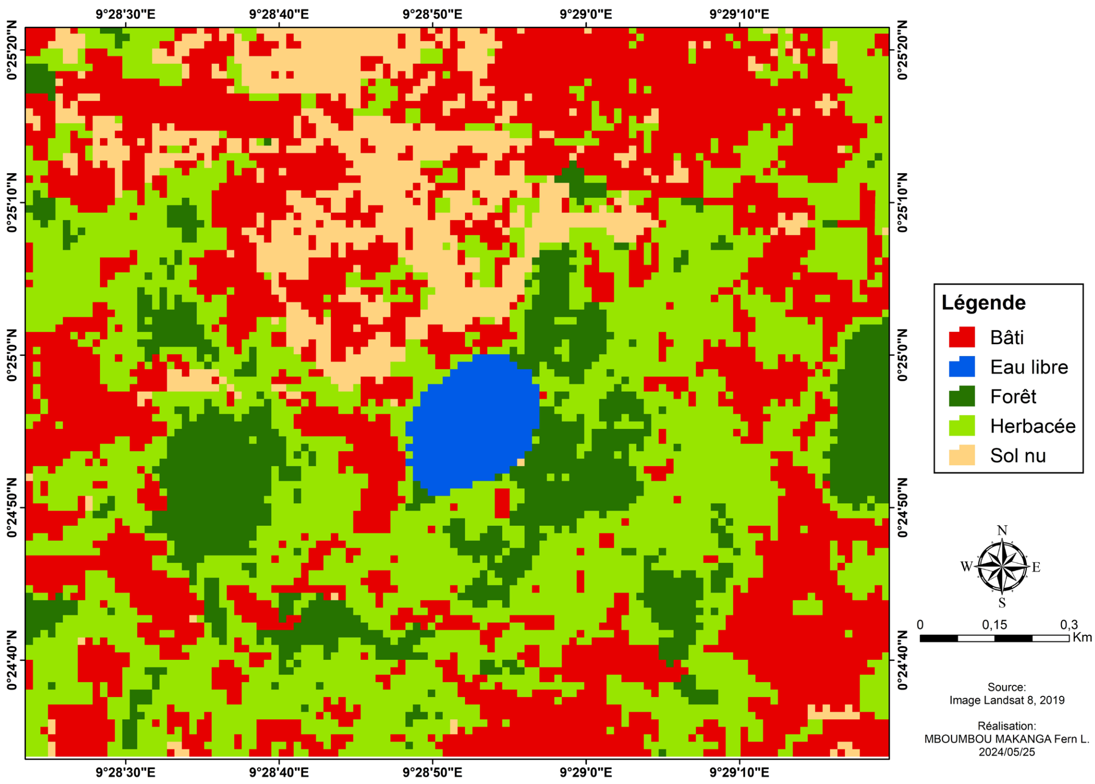
(b)



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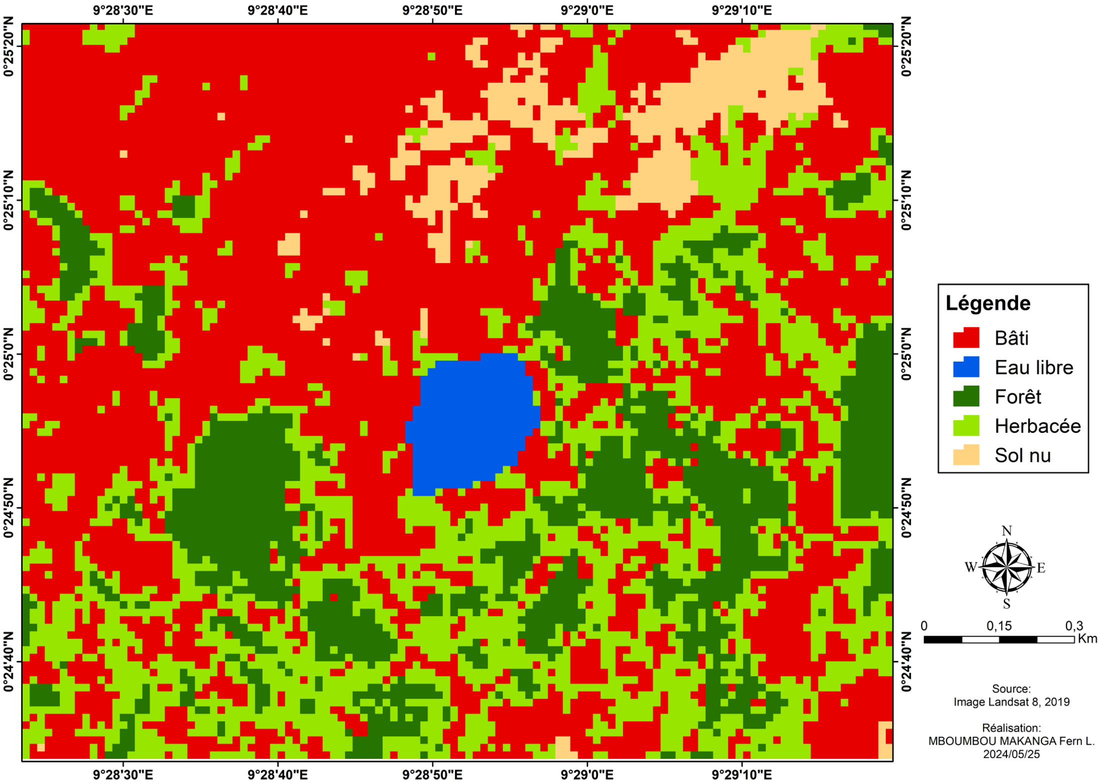


(d)

Figure 2. Land use in 1990, 2000, 2010 and 2020 around Lake Nzeng-Ayong in the eastern sector of Libreville. (a) 1990, (b) 2000, (c) 2010, (d) 2020.

Table 2. Area in hectares and percentage of land use classes.

Classes	1990		2000		2010		2020	
	Sup (ha)	Proportion	Sup (ha)	Proportion	Sup (ha)	Proportion	Sup (ha)	Proportion
Bâti	31.86	12%	41.33	16%	107.95	42%	134.32	52%
Eau	4.66	2%	5.31	2%	5.6	2%	5.67	2%
Forêt	134.35	52%	100.1	39%	42.82	16%	39.8	15%
Herbacée	71.62	28%	103.25	40%	77.1	30%	67.12	26%
Sol nu	17.51	7%	10.01	4%	26.53	10%	13.09	5%
Total	260	100%	260	100%	260	100%	260	100%

The various land use units obtained from the 2000 image are distributed as follows: 100.1 ha of forest (38% of the total area), 103.25 ha of herbaceous vegetation (40%), 41.33 ha of built-up area (16% of the area studied), while bare ground (10.1 ha) and open water (5.31 ha) account for 4% and 2% of the area studied respectively.

Interpretation of the 2010 Landsat image shows that forest covers 16% of the total area, or 42.82 ha, compared with 30% for herbaceous vegetation (77.1 ha), 42% for built-up areas (107.95 ha), 10% for bare ground (26.53 ha) and 2% for open water (5.6 ha).

Descriptive statistics derived from the Landsat 2020 image show that forest covers 39.8 ha, or 15% of the total area, herbaceous vegetation covers 67.12 ha (26%), built-up area covers 134.32 ha (52%), bare soil covers 13.09 ha (5%) and open water covers 5.67 ha, or 2% of the study area.

Figure 3 summarises the changes in the various land use units. Over the period 1990-2020, the "Built-up" class increased by a staggering 102.46 hectares, while the space occupied by the "Forest" class decreased by 94.55 hectares. The other land-use units underwent minor positive (open water) or negative (herbaceous vegetation, bare soil) changes.

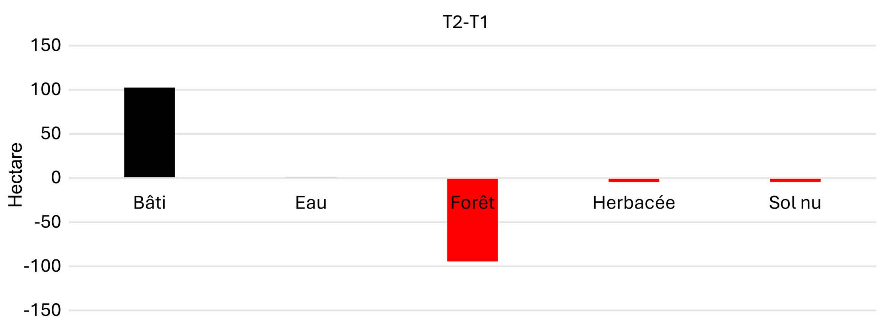


Figure 3. Summary of changes in the various land use units between 1990 and 2020.

Overall, in the eastern sector of Libreville, a study of the evolution of the human footprint based on a diachronic approach to land use between 1990 and

2020 shows not only the extent of the advance of human settlements, but also that this has been to the detriment of the plant cover whose presence on the slopes helps to stabilise the slopes. The fact that grassland areas have changed little is partly due to the fact that they are mainly marshy areas that are difficult to access and costly to develop. Similarly, the 1% increase in open water between 1990 and 2020 is partly linked to human settlements on former river beds. Google Earth satellite images (Figure 4) confirm the results presented earlier.

(a)

(b)

Figure 4. Google Earth satellite image of the Libreville East sector in 1993 and 2024. (a) 1993; (b) 2024.

There has been a considerable increase in built-up areas to the detriment of green spaces. In the eastern sector of Libreville, land use has been anarchic, depending on the conditions offered by the environment. In fact, the chronology of land use follows the following logic. In the absence of a cadastral map, the first settlers settled on the hilltops. This explains the overlap between the various human settlements on these prominences. The lack of "viable" land at higher altitudes meant that the last settlers were forced to settle along the slopes and then gradually colonise the talwegs of the valleys, even though most of these are flood-prone. However, the occupation of the slopes in terms of their gradient (slopes in excess of 20˚) exposes people to various dangers, including the risk of landslides. The latest General Census of Population and Housing in Gabon (Direction Générale de la Statistique, 2015) also shows that while population density at national level is low (6.8 inhabitants per km^2), it is at record levels in some places, exceeding 3700 inhabitants per km^2 in Libreville alone, where the eastern sector is one of the main centres of population concentration. What's more, the people who live near Mont Nkol Ogoum have developed a number of ordinary tertiary activities such as grocery shops, bars and drinks outlets, vehicle repair and furniture workshops, as well as family livestock rearing and gardening. All these activities are exposed to the risk of landslides (**Photo 1**).

Human settlements along a trickle of water (likely to become a larger watercourse in the rainy season) feeding a marshy area (example of the PK6 district).

(a)

Stacked human settlements along the slopes and valley bottoms, characteristic of Libreville's under-integrated neighbourhoods (e.g. PK7)

(b)

Photo 1. Anarchic occupation of space in the eastern sector of Libreville.

Landslides, a complex phenomenon that is strongly influenced by rainfall

It should be remembered that the movement of materials, resulting from morphogenesis, is a set of natural or artificial processes that contribute to the formation of the landscape. They are the result of elementary erosion processes. These processes fall into two groups: weathering and modes of transport. Weathering conditions depend on atmospheric and lithological factors, while modes of transport are subject to relief and runoff patterns in order to evacuate the products of ablation. The movement of materials can constitute a risk when people are exposed to it, and can be divided into two categories: slow movement and rapid movement. These movements also involve several types of movement, such as rockfalls, landslides and subsidence. In the absence of official statistics on the occurrence of the different types of material movement and their manifestations in Libreville, the expression ground or mass movements or landslides for all types of material movement was chosen for this study. The aim was to emphasise the likely conditions (particularly rainfall) for the movement of materials in a region where areas affected by slow movements (creep, subsidence) can, following heavy rainfall, be affected by rapid movements (landslides, collapses, landslides or falling blocks).

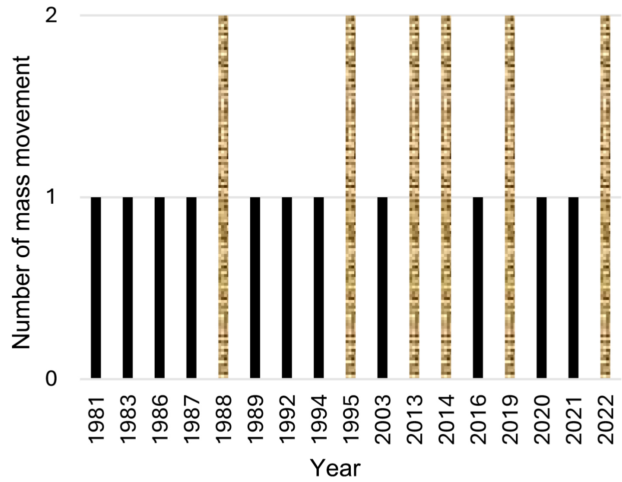
Similarly, when it comes to the occurrence of mass movements in Libreville, we note that they can have devastating consequences: this is the case of the landslide that occurred in October 2019 in a neighbourhood to the east of Libreville (Okinda-Bangos). Following torrential rain on the night of Tuesday 15 to Wednesday 16 October 2019, two people lost their lives when a retaining wall collided with a landslide. Photo 2 shows some of the material damage caused by the landslide. The wall used to demarcate adjoining plots of land caused a house made of vulnerable material (wood) located at the foot of the slope to "disintegrate" as it fell. But how often do landslides occur in Libreville?

Example of a rotational landslide along a main road in the PK7 district	Damage caused by a falling retaining wall in the Okinda-Bangos district

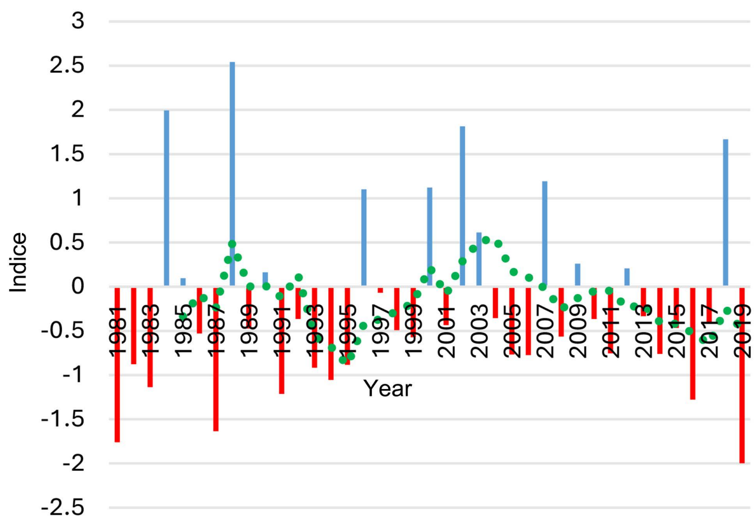
(a) (b)

Photo 2. Unauthorised occupation of non aedificandi zones and destruction of a dwelling as a result of a landslide.

Due to the lack of official statistics on mass movements in general and landslides in particular, in an attempt to assess the frequency of occurrence of mass movements, all events reported by the written press from 1981 to 2022 were listed (Figure 5).



(a)



(b)

Figure 5. Libreville: occurrence of mass movements (a) and multi-year rainfall variability (b).

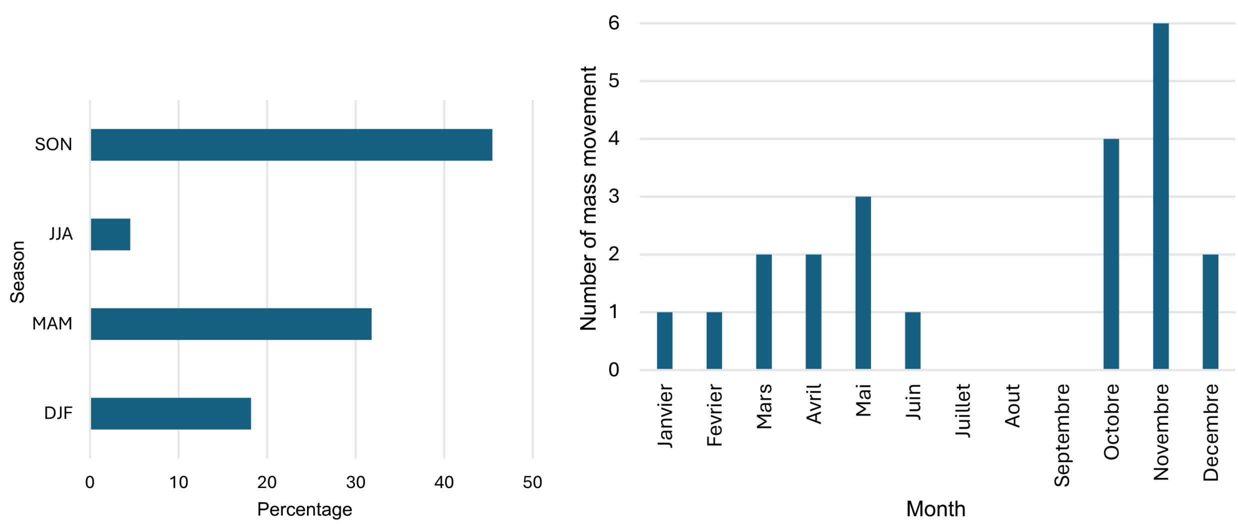
It can be seen from **Figure 5** shows that over some forty years (1981-2022), Libreville has experienced twenty-three mass movements, an average of one every two years. It should be pointed out that, generally speaking, the press does not report all the events occurring in Libreville; only phenomena with a relatively high destructive capacity are taken into account. In fact, we can deduce that mass movements are phenomena that occur regularly in Libreville. But how often do landslides occur on a seasonal and monthly scale in Libreville?

Mathlouthi et al. (2011) point out that meteorological criteria are factors that trigger slope instability, particularly in terms of cumulative rainfall or the intensity-duration of rainy episodes. In Gabon, according to Maloba Makanga (2010), seasonal rainfall analysis highlights the significant phases of the annual cycle. Generally speaking, an analysis of average seasonal rainfall patterns shows that the long dry season (June-August) precedes the long rainy season (September-November), which is followed by the short dry season (December-February), with the short rainy season occurring between March and May. This seasonal rainfall pattern also applies to Libreville over the period 1981-2019.

While the average annual rainfall in Libreville between 1981 and 2019 was 2800 mm, the analysis of variability shows alternating positive and negative anomalies. Moreover, the moving average shows that periods of deficit (1981-1987; 1989-1999; 2008-2019) are more important than periods of surplus (2002-2003, for example) in terms of rainfall.

A detailed analysis reveals a covariation between the landslides of 1988 and the strong positive rainfall anomalies recorded that year, whereas the other years (1995, 2013, 2014, 2019), despite each being affected by two landslides, were marked by negative rainfall anomalies. Even if the annual scale is not the most appropriate for researching significant covariations or correlations between rainfall and landslides, this approach nevertheless gives an idea of the overall rainfall context (favourable or unfavourable to landslides).

Figure 6 provides further details on the occurrence of landslides. It shows that most of these natural disasters occurred during the September-November season (more than 40% of landslides reported in the newspapers), and that October and November accounted for more than half of the events recorded over the period 1981-2022. Similarly, the March-May period accounts for just over 30% of landslides, compared with less than 10% during the long dry season, which can be disrupted in some years by sequences of intense rainfall that are limited in space and time. As for the December-February season, the most significant landslides (almost 20% of occurrences) take place mainly in December, and these are probably conditioned by the (large) volume of water collected at the end of the main rainy season, i.e. in November.



(a) (b)

Figure 6. Occurrences of ground movements on average seasonal (a) (expressed as a percentage) and monthly (b) (expressed as a number of occurrences) scales recorded in Libreville between 1981 and 2022.

These results justify further analysis of rainfall during the September-November season on a finer scale in order to better identify the phases most conducive to landslides.

In a book devoted to rainfall in Gabon, Maloba Makanga (2010) states that a month is ecologically dry in Gabon when it receives less than 50 mm of rain. Any dekad (average of 10 days of rainfall) that receives at least 15 mm of rainfall can therefore be considered wet. On the basis of this principle, **Figure 7** shows that, whatever the dekad, June-July-August is the driest period.

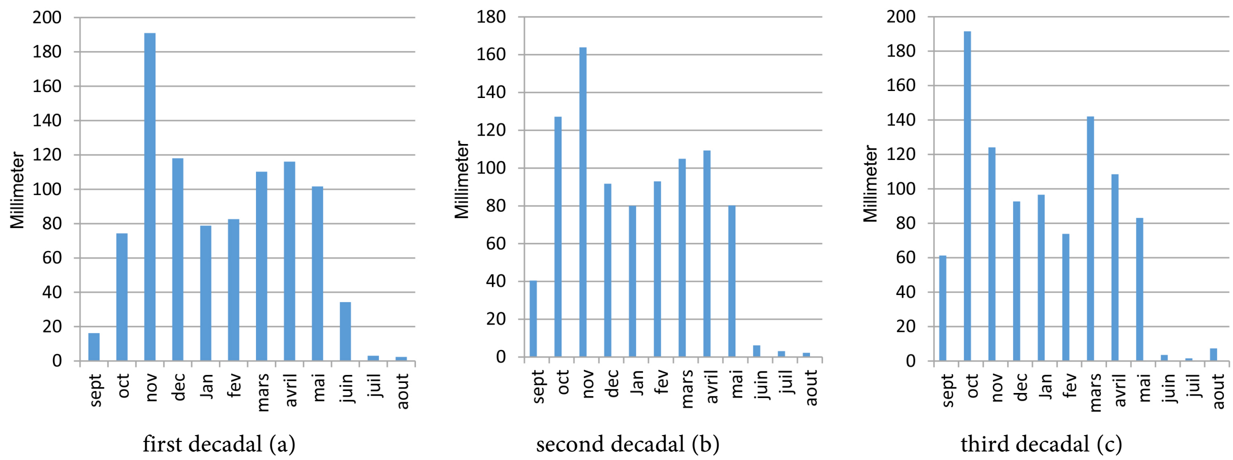


Figure 7. Decadal rainfall patterns in Libreville.

Other findings from this ten-day analysis are that rainfall in the second and third dekads of October varies between 120 and over 180 mm. Similarly, rainfall in the first and second dekads of November varies between 160 and 200 mm. From this we can deduce that the period from 20 October to 20 November is the one with the most rainfall and therefore, a priori, the most conducive to landslides.

Following this decadal analysis, the study of rainfall on a daily time step was implemented. The average rainfall totals obtained on a ten-day scale were sometimes exceeded on a daily scale (24 hours). Generally speaking, the threshold of 50 mm in 24 hours is used to recognise daily rainfall that is considered exceptional (Maloba Makanga & Mbadinga, 2022). It would seem judicious to analyse the occurrence of these daily rainfall failures insofar as they are likely to cause natural disasters. An analysis of the average distribution of the number of rainy days and exceptional rainfall (>50 mm) shows that October and November have 25 and 24 rainy days respectively, while during the March-May and December-February seasons, it rains approximately one day in two (between 16 and 17 rainy days per month). But in the dry season (June-August), there are only 2 to 4 days of rain. This means that the likelihood of landslides occurring during this period is very low. It should also be noted that the months of October and November record an average of more than 2 rainy days with rainfall amounts of 50 mm or more. Similarly, **Figure 8** illustrating the maximum rainfall amounts shows not only that these extreme values apply to all the months, but also that the maximums were recorded on 14 May 1950 (248 mm) and 14 September 1973 (239.6 mm).

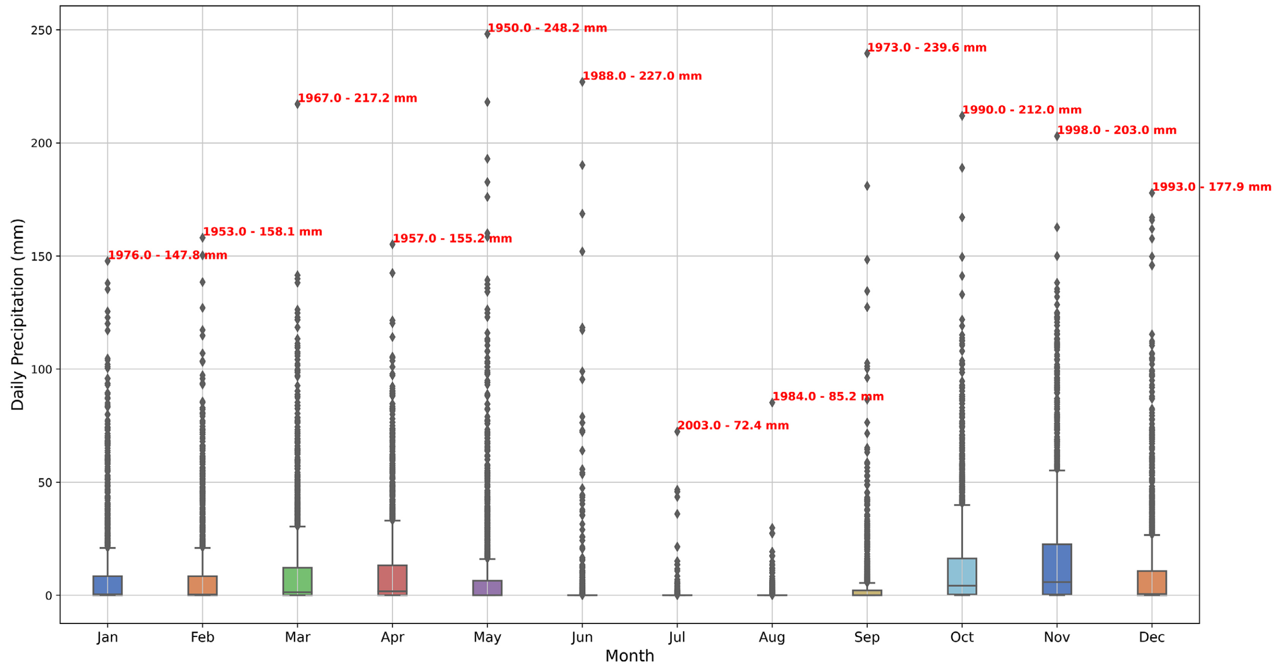


Figure 8. Absolute maximum daily precipitation on a monthly scale.

In a study of average annual rainfall in Gabon, Maloba Makanga (2010) calculated the Skewness coefficient, a shape parameter that measures the asymmetry of a distribution. This methodological approach stipulates that when the Skewness coefficient is zero, perfect symmetry is considered to exist. It emerges from this study, at an annual time step, that the Libreville coefficient (0.12), although reflecting positive skewness, remains close to zero. It should be pointed out that **Figure 8** shows monthly cigar boxes with little vertical extension, from which it can be deduced that the values analysed are mainly grouped around the median, which reflects low rainfall variability.

4. Discussion

Worldwide, more than 4000 non-earthquake landslides occur every year, causing the death of more than 5000 people. Similarly, in a context of global climate change, research tends to show that increased precipitation, coupled with a predicted rise in extreme rainfall events, could increase the frequency of landslides (IPCC, 2013; Gariano & Guzzetti, 2016; Souverijns et al., 2016; Thiery et al., 2016; Locat & Leroueil, 2019). It should also be noted that these events force the populations exposed to them to find new homes, following the example of the populations of the Kashmir region who were forced to move following landslides and flooding due to monsoon rains (https://www.iom.int/fr/news/les-glissements-de-terrain-et-les-inondations-font

-toujours-plus-de-morts-et-de-deplaces). These are phenomena whose occurrence can have a lasting impact on developing countries, which are more vulnerable (socially, economically and environmentally) to natural disasters (Kjekstad & Highland 2009; Jacobs et al., 2016; Alfieri et al., 2017; Kumar et al., 2017).

In addition to climate change, numerous studies show that the occurrence of landslides can be associated with climatic disturbances linked to ENSO phenomena. In Colombia and Venezuela, for example, the moderate El niño 2009 and la niña 2010 phases led to high landslide activity, peaking in November 2010 (Sepúlveda & Petley, 2015). Similarly, more than half of the landslides recorded in Brazil between 2004 and 2016 occurred between 2009 and 2011, with peaks in December 2009 and April 2010 in El niño years and January 2011 in la niña years (Palenzuela Baena et al., 2020). It is inevitable that the rainfall intensities associated with ENSO events have an impact on the occurrence of landslides.

In contrast, rainfall in central Africa is relatively independent of modes of variability such as El Niño (Maloba Makanga, 2000, 2015), even though dry anomalies have been observed on the west coast of central Africa during the April-June period in El Niño years (Camberlin, 2007). The sensitivity of rainfall to SST in the Atlantic Ocean is more obvious on the west coast of central Africa (Maloba Makanga, 2000, 2023). In fact, a prolonged rise in sea surface temperatures can significantly increase water vapour in the lower layers of the atmosphere and cause abundant rainfall in the sub-region. Rome et al. (2000) point out that in Central Africa, continental geographical conditions are still decisive in understanding the variety of hydrological responses to ocean forcing, and the influence of coastal relief, which strongly modulates atmospheric conditions, must be taken into account.

In recent years, the countries of sub-Saharan Africa have been confronted with the phenomenon of climate variability and the challenge of managing the ever-increasing risks that it brings (Kodja et al., 2013). However, if there is one aspect that has received little attention in studies of landslides in West Central Africa (Tchotsoua & Bonvallot, 1997; Depicker et al., 2021; Feukeng & Tchoukep, 2023), it is the environmental damage associated with the occurrence of these phenomena. They can lead not only to soil erosion but also to the destruction of vegetation and pollution of neighbouring watercourses as a result of land displacement. In West-Central Africa, even though landslides are strongly associated with high rainfall (Camberlin, 2007; Maloba Makanga & Samba, 1999), numerous studies have shown the impact of human activities or uncontrolled occupation in triggering these phenomena (Manefouet Kentsa et al., 2023; Mambou & Elenga, 2023). For example, the study by Depicker et al. (2021) revealed an increase in the population in the steep, mountainous regions of eastern DR Congo over the last 60 years. The results of this study showed that this human presence was unfortunately not without consequences. The landslide that occurred one year after the publication of this article in the scientific journal Nature Sustainability killed more than 400 people in South Kivu. In the same vein, in Cameroon, more precisely in Bafoussam, a landslide plunged several families into mourning on 30 October 2019. The toll was 43 dead and 11 injured (https://www.rfi.fr/fr/afrique/20191029-cameroun-dizaines-morts-apres-eboulement-terrain-bafoussam). The Republic of Congo is also affected by mass movements. For example, in January 2020, following heavy flooding on the River Congo, a landslide on the side of the Brazzaville corniche, bordering the river, caused the collapse of 180 m of the road, killing two people (https://www.adiac-congo.com/).

In Gabon, scientific work on climate variability has highlighted the risks of flooding (Mbadinga Igaly et al., 2019) and landslides (Kema Kema, 2011; Backita Moussounda, 2019; Mavoungou-Mavoungou, 2022). In the interior of the country, for example, a landslide that occurred on 24 December 2022 in the Offoué and Booué townships displaced 900 metres of track, severely disrupting rail traffic between Libreville and Franceville. In Libreville, the difficulty of accessing housing, which affects the whole country (Madébé, 2009), has led people to settle in areas where there is a high probability of mass movements.

One of the difficulties encountered in preparing this study was the paucity of data on landslides. Generally speaking, in Gabon, extreme phenomena following heavy rainfall are only reported by the media when they cause significant material and human damage. In Libreville, construction in a large part of the study area is taking place without any regulatory framework, making several neighbourhoods vulnerable to landslides (Ndong Mba & Beka Beka, 2019); while rainfall data from the meteorological station is archived at the Direction Générale de la Météorologie Nationale, there is no data archiving service for natural disasters.

In this context, this research relies in particular on satellite images, as earth observation technologies offer a sufficient spatial and temporal scale to reduce both the colossal efforts required by conventional data collection methods, particularly in the field, and the associated financial costs. This new approach facilitates decision-making and enables decision-makers to define appropriate strategies for achieving sustainable development objectives (Begni et al., 2005).

Overall, the various data used show not only the extent of human settlement between 1990 and 2020, but also that the spread of human settlements has been to the detriment of the plant cover that stabilises the slopes, among other things. Building on steeply sloping land and deforestation (which encourages water erosion) undermines the stability of the loose deposits covering the various slopes in the study area. Moreover, as Backita Moussounda (2019) has noted, the uncontrolled expansion of the city of Libreville has resulted in the presence of human settlements in non aedificandi areas.

This study also shows, based on statistics compiled from the written press, that every other year the city of Libreville, the most populous in the country, experiences landslides following torrential rains. Similarly, while landslides can be recorded in Libreville during the rainy period from September to May, the October-November rainy sequence, because of its prodigality, is the most favourable period for landslides. The study shows that the last two dekads of October and the first two dekads of November have the highest volumes of water of all dekads combined. It should be remembered that the city of Libreville records an average of 2800 mm of rainfall (1950-2018 period), a considerable volume of precipitation capable, in the long term, of triggering or amplifying mass movements. This heavy rainfall is also falling in an area that is experiencing a significant decline in its plant cover (the original forest area has been halved) as human settlements expand. These are a number of actions that could encourage erosion and landslides in a relatively steep area.

Furthermore, although the study focuses more on the role of precipitation, the intensity of which is a key factor in the occurrence of mass movements, it should also be pointed out that the amount of "antecedent" precipitation, which fell in the weeks preceding the triggering of the movement, is also a factor in increasing hydrostatic pressure. Fort et al. (2015) also point out that temporal variations in precipitation result in fluctuations in the water table recorded by piezometers, the rapid rise in level of which can also be a factor in triggering landslides. Consequently, in order to better understand the relationship between landslides and the characteristics of the main rainy season, other factors, particularly those relating to lithology and hydrology, should be taken into account, given the complexity of the interrelationships between the various components of the area affected by landslides in Libreville.

5. Conclusion

Generally speaking, erosion systems give landscapes their originality by shaping relief. Their action varies greatly depending on the climate. The rates of erosion are therefore very diverse, but everywhere they are considerably accelerated by human activity. Man has become the primary agent of erosion, often to his own detriment (Saur, 2012). Similarly, in a context of global climate change, which could increase the occurrence of landslides due, among other things, to increased rainfall, coupled with the predicted rise in extreme rainfall events, this study aims to understand spatial changes and the role of heavy rainfall in the frequent landslides that affect the eastern sector of Libreville, Gabon's most populous city.

This study carried out in a context marked by a low number of scientific publications on the subject and a scarcity of available data, was based on the one hand on statistics from the written press concerning landslides, on rainfall data from the National Meteorological Directorate and, on the other hand, on Landsat satellite data from 1990 to 2020.

A review of information on landslides reported in the written press has identified 23 events that occurred in Libreville between 1981 and 2022, an average of one every two years. A detailed analysis shows that the majority of these disasters occurred during the September-November season (the main rainy season), with October and November accounting for more than half of the events. A ten-day analysis shows that the last two dekads of October and the first two dekads of November are the wettest periods, and therefore the most likely to trigger landslides.

This high rainfall, averaging almost 2900 mm/year, has hit an environment that has been weakened by various human settlements in the eastern sector of Libreville, which was originally forested. A review of the spatial changes in the various land-use units between 1990 and 2020 shows a meteoric rise in human settlement (+102 hectares), while the forest area shrank by 94 hectares over the same period. However, this plant cover masks a relatively uneven topography, where erosion has revealed a number of ridges and spurs separated by valleys with marshes or swamps that are heavily populated: the city of Libreville has the highest population density per km^2 in the country. Characterised by a combination of fragile materials, steep slopes and significant differences in level, the topography appears unsuitable for construction in several places (Ndong Mba & Beka Beka, 2019). As the study area does not have a Land Use Plan, this human pressure is reflected in the anarchic occupation of the edges of the town's main relief. The local population has set up a number of economic activities, which are nevertheless exposed to the risk of landslides.

This study shows that, although landslides are natural disasters, they are exacerbated by the confused land situation in Libreville. It should be remembered that man's action on the rugged terrain is a source of slope fragility, which worsens with rainfall levels.

In short, these are the preliminary results of research aimed at providing decision-makers with decision-making tools to reduce the risk of landslides in urban areas in Gabon. Like the study on landslides in Bafoussam in Cameroon (Tangmouo Tsoata et al., 2020), our research, which uses geomatics among other tools, should eventually lead to the production of landslide susceptibility maps. This is an important tool in the planning of areas exposed to the risk of landslides.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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