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Mapping floods hazards in the department of Mono, Benin(West Africa)

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Abstract: West African country suffers from floods every year, either generally or locally. These disparities at the regional level are also observed at the local and national levels, and at a lower scale with enormous damage in several sectors. Mono Province is one of the areas in Benin affected by floods, which may be related to several factors. Thus, this study aims to elucidate the contribution of some combined parameters to floods in this department between the period 1960 and 2023. The method of mapping by combination of factors was used. The results showed that very high to high sensitivities occupies a proportion of 25% of the territory of Mono while the average one occupies a proportion of approximately 25% of the territory. In addition, approximately about 50% of the region is exposed to low risks of flooding. The districts of Athieme and Come are found to be under pressure of inundation whereas eastern part of the districts of Come and Grand-Popo underwent this pressure. The results of this work will make it possible to strengthen the development plan of the area but also to make better decisions by organizations or authorities in the event of flooding.

Key words: hazards events; inundations; department of Mono; West Africa; cartography

1 Introduction

Floods are dangerous events that are difficult to prevent. They cause a great deal of damage, including human, socio-economic, infrastructure and agricultural damage. Several factors contribute to the occurrence of these extreme events, including non-compliance with land-use planning or the uncontrolled settlement of populations. For example, the rising waters in the Ouémé rivers in central and south-eastern Benin and in the Mono and Couffo rivers in the south-west of the country, caused by torrential rains, resulted in at least one death by drowning and several other instances of material damage, particularly the destruction of several homes and large areas of food crops [1]. In order to reduce the effects of these events, particularly in the Mono department, it is essential to make a scientific assessment of the factors contributing to the increase in flooding. A study conducted in Mono Province, Benin [2] showed that in order to better manage the impact of climate change, the population of Koufu Province (border province) has adopted changes in farming practices, soil cover, planting of perennial species such as palm trees, orange trees, banana trees, and crop associations. These strategies have been proven effective, as they are still in force. However, they also have their limitations, as research has shown [2-4]. The work carried out [5] reveals that the strategy of occupying landscape units is not overly developed in the communes of Athiémé and Lokossa.

The Mono department comprises the communes of Lokossa, Athiémé, Grand-Popo, Houéyogbé, Comè and Bopa, and borders departments of Couffo, collines, Zou and Atlantique, as shown in Figure 1 below. It is located in south-west Benin between 6°15' and 7°45' north latitude and between 1°35' and 2°13' east longitude, covering an area of 1,605 km^2 with a population of around 4,972,403 according to the 2013 census by the National Institute of Statistics and Economic Analysis [6]. The Mono department has a sub-equatorial climate with a succession of four seasons, rainfall varying between 850 mm and 1,160 mm, temperatures of up to 27.9°C, relative humidity varying between 55% and 95% and an average annual insolation of 2,024 h/year [6].

The aim of the present study is to determine the degree of exposure of the department to flooding events based on a certain number of parameters, using cartography, and to bring out the related statistical values. A similar technique has been used to characterise a region in Morocco [7,8]. After an analysis of the individual contribution of the variables to flooding, a summary of the combination of these contributions will be presented to enable the area to be characterized.

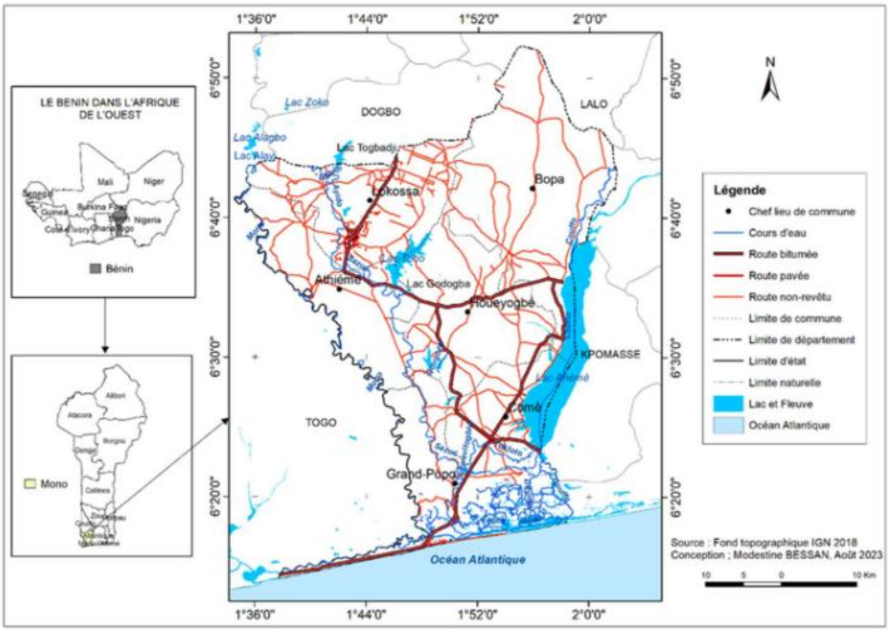

Figure 1. Location of the Mono department in Benin (yellow), enlarged on the right

2 Materials and methods

2.1 Equipment

2.1.1 Cartographic data

They include the data needed to map the hazards, issues and risks associated with flooding, and the data used to detect and analyse changes in land use. The basic data used consist of planimetric data, satellite data, demographic data and climatic data. These data are both quantitative and qualitative.

Planimetric data can be obtained from the USGS website;

The demographic data come from the General Census of Population and Housing carried out by INSAE, now INSTAD. These data were used to study the population dynamics of the research area and the human resources available to the sector;

Climate data refer to the precipitation data of rainfall stations in the study environment. We also used flat data. They mainly involve: 1/600,000 IGN terrain background, including road networks, rivers, and some villages in the research environment; 1/200,000 soil map covering the research environment; 1/200,000 geological map covering the research environment; Geographical map of Benin.

2.1.2 Data collected for land use mapping

Satellite data are used to assess land cover and extract the soil moisture index (NDWI). The NDWI assesses the state of a soil's water reserves in relation to its optimum reserves (useful reserves). When the soil moisture index (NDWI) is close to 1, the soil is moist (> 1, the NDWI indicates that the soil is tending towards saturation). Conversely, when it tends towards 0, the soil is in a state of water stress (below 0, it indicates that the soil is very dry) (OFB, 2022). DEM images were used to produce relief and slope maps. Various satellite images were used to achieve the objectives set. The satellite data used in this work include SRTM data on the research environment downloaded from dataexplorer.com and Landsat 9 images of scenes 192-55 and 192-56 B2 from the year 2023 with a resolution of 30 metres. The characteristics of the satellite images used are shown in Table 1.

Table 1. Characteristics of the satellite data used

Sensor	Acquisition date	Resolution	Number of bands
Landsat 9	January 2023	30m	11
SRTM	January 2022	30m	-

2.2 Methodology

2.2.1 Methods for processing and analyzing the various data collected

This section focuses on the various methods and models for processing and analyzing the rainfall, hydrometric, cartographic, temperature and socio-economic data collected during the surveys. It is based on an objective-based approach similar to that used in [9]. Air humidity was also analysed to understand atmospheric conditions in relation to rainfall. Satellite images were used to produce the land use map (COO), in order to identify potentially wet areas (NDWI), potential flood risk areas, and assess the morphology of the territory (MNT).

2.2.2 Approaches to analyzing flood triggers and amplifiers

The identification of the factors that trigger and amplify flooding is based on a study of rainfall and hydrometric variability, the dynamics of land use, the mapping of areas at risk of flooding, a study of population dynamics and an analysis of the dynamics of extreme events between 1960 and 2023.

2.2.3 Method for analyzing rainfall and hydrological variability

According to [10], the study of rainfall and hydrological variability requires the use of statistical tools such as central tendency and dispersion parameters and those for highlighting breaks and trends, which involves assigning values ranging from 1 to 5 to pixels that determine the sensitivity levels of the various risk factors [11]. It should be noted that this coding is generally carried out by experts, although it is validated by decision-makers. Here, risk is perceived as the possible occurrence of a hazard on potentially vulnerable issues. The aim here is to identify the factors that contribute to flooding. Depending on their importance, a coding system is applied to each hazard factor identified. To do this, flood factor maps are produced. These include relief, rainfall distribution, wetlands and drainage density. The various factor maps were cross-referenced in ArcGis software using the Weighted Sum tool.

Water flow velocity depends on slope. These slopes were generated automatically in Global Mapper 20 using the "slope" operation with SRTM as the input data. The lower the slope, the greater the risk of flooding, as low-lying areas are where the various watercourses converge. Soil type is a very important factor in determining the factors that favour flooding. The map derived from the soil factor was weighted and then converted to raster. The acquisition of satellite images was the first stage of this work, and the second was the pre-location of potential wetlands through these images using the NDWI (Normalised Difference Water Index) method. The NDWI methodology involves successive stages leading to the detection of three (03) types of wetland. It combined information from different neo-channels, thresholding, undirected classifications, the framework of which is constrained by the topographical index of [12]. In this respect, the method can be described as hybrid [13]. It consists of identifying open water surfaces using a specific NDWI index calculated as follows:

$NDWI = \frac{(\rho Green - \rho NRI)}{\rho Green + \rho NR}$ Green: reflectance corresponding to green spectrum or band 3, NRI: reflectance corresponding to near-infrared spectrum or band 5.

Drainage density is one of the morphometric indicators used to analyse a hydrographic network. It allows for the classification of terrain based on its ability to allow gravity water to flow more or less easily and rapidly in a natural manner [14]. This drainage density is generated and reclassified by the ArcGis "Spatial Analyst Tools". Figure 2 below describes the method diagram applied to hazards.

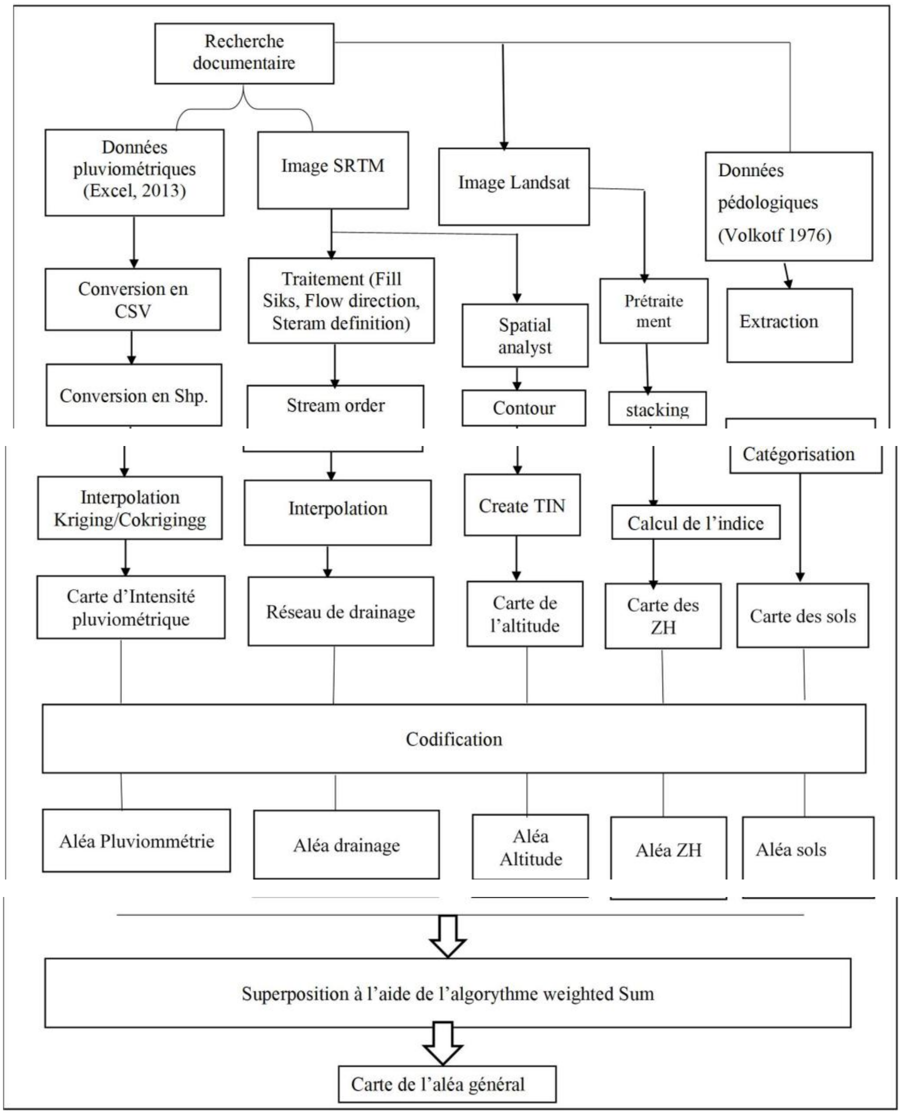

Figure 2. Methodological hazard diagram

2.2.4 Mapping vulnerability to flooding

The variables required to draw a flood vulnerability map include drainage density, drainage network, geology, topography, subsurface drainage, slope and induced permeability according to soil type [15]. Only data on the hydrographic network, drainage density, geology, slope and pedology are considered in this work due to the lack of data on the other parameters. On the basis of these data and data collected on past events in the study area and validated in the field, buffers were created around the Mono and Couffo rivers and their tributaries. The soil and topographical data and the drainage density map were combined with geological, permeability and slope data to produce a map of physical vulnerability to flooding. Figure

3 below summarizes the flood vulnerability mapping process.

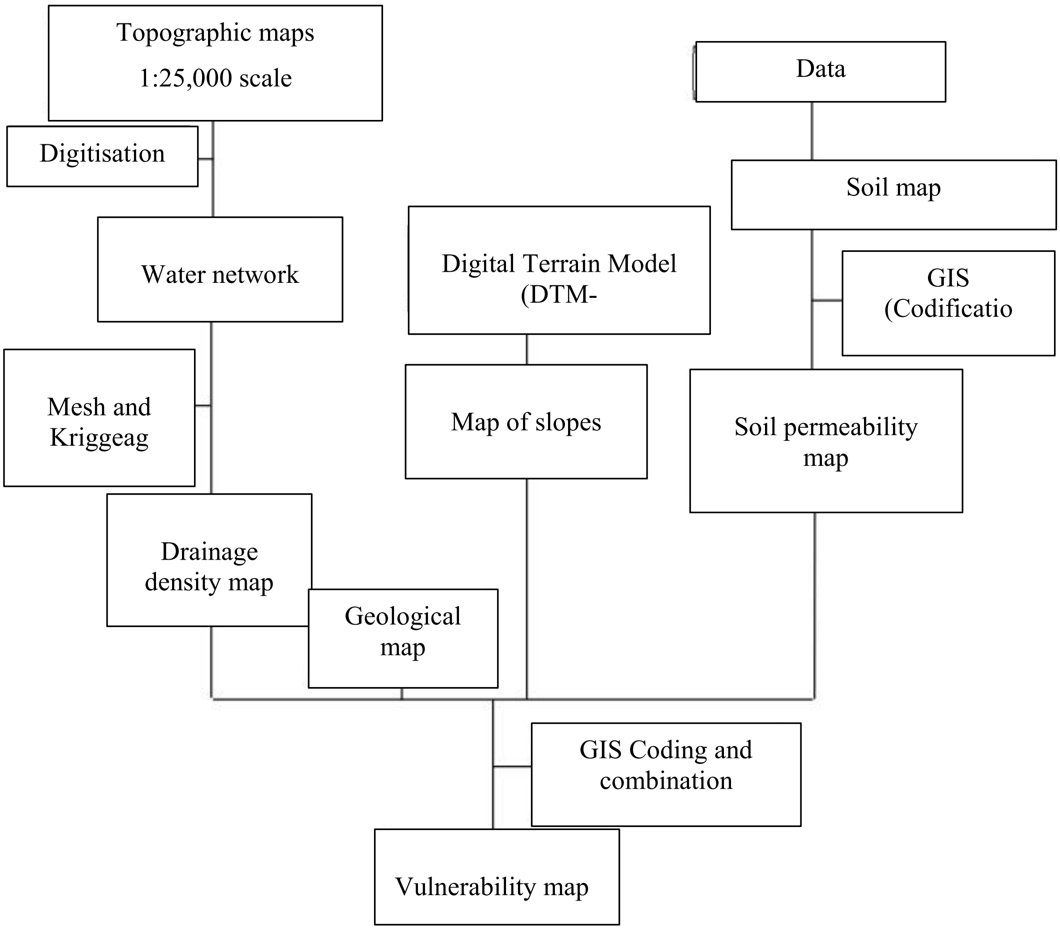

Figure 3. Method used to produce the flood vulnerability map

Source: adapted from [16] and completed by Bessan, 2020

By merging the hydrographic layers, topography, pedology and buffers, it was possible to define the flood vulnerability grid shown in Table 2.

Table 2. Grid of physical vulnerability to flooding

Level of vulnerability	Criteria
Fort	Presence of a watercourse, floodplain and high depression (slope < 5%) and hydromorphic soil and reduced impermeability with houses
Medium	Presence of a watercourse, depressed area near the floodplain and hydromorphic soil with an area of medium altitude and slope
Low	No major rivers, very low-lying areas, sometimes plateaux with moderately high slopes and altitudes.

Source: adapted from [17] and completed by Bessan, 2020

2.2.5 Mapping of flood risk areas

The map of areas at risk of flooding is obtained by cross-referencing the vulnerability map and the flood hazard map in a GIS because by definition, risk = hazard × vulnerability [18]. These two previously coded maps were used to generate the risk levels shown in Table 3.

Table 3. Flood risk assessment grid

Level of risk	Criteria
High	High hazard × Moderate, high and very high vulnerability
	Moderate risk × Very high vulnerability
	Low hazard × Very high vulnerability
Medium	Low and medium risk × Moderate and high vulnerability
Low	Low, medium and high hazard × Low and very low vulnerability

Source: adapted from [17] and completed by Bessan, 2023

3 Results

3.1 Terrain-related hazards

The different altitudes of the study area have made it possible to identify the relief hazard associated with the risk of flooding in this sector. Figure 4 illustrates this hazard.

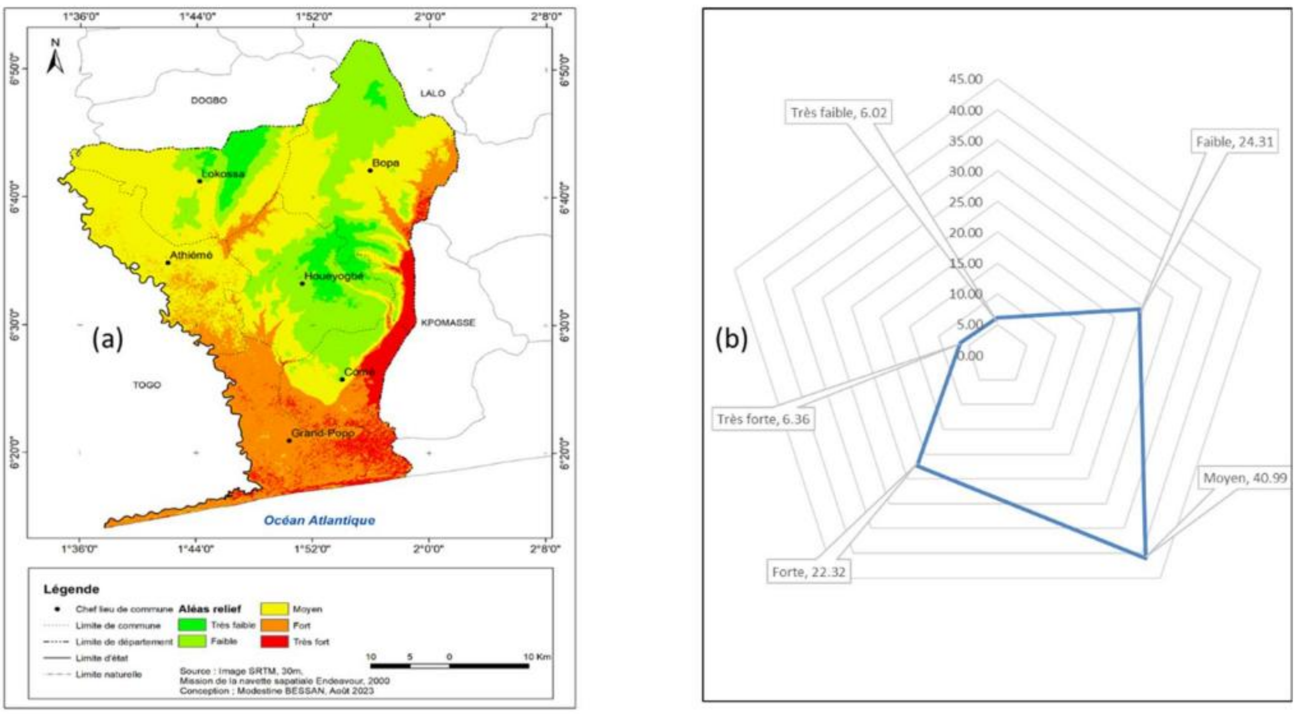

Figure 4. Map showing the distribution of (a) relief-related hazard and (b) the proportion of contribution to flooding

The relief-related hazard map shows a predominance of medium and low sensitivity. In addition, these sensitivities represent depressions or lower-lying areas. This is followed by high sensitivity, which occupies less surface area (Figure 4-a). Figure 4-b shows the proportions occupied by hazard sensitivities linked to relief in the Mono department. The proportions of the territory affected by the different sensitivities for this hazard are as follows: 40.99% for average sensitivity, 24.31% for low sensitivity and 22.32% for high sensitivity. The very strong and very weak hazards occupy 6.36% and 6.02% respectively.

3.2 Drainage density hazards

Data from the drainage density of the Mono department have made it possible to identify the different sensitivities of the hazard linked to this factor (Figure 5).

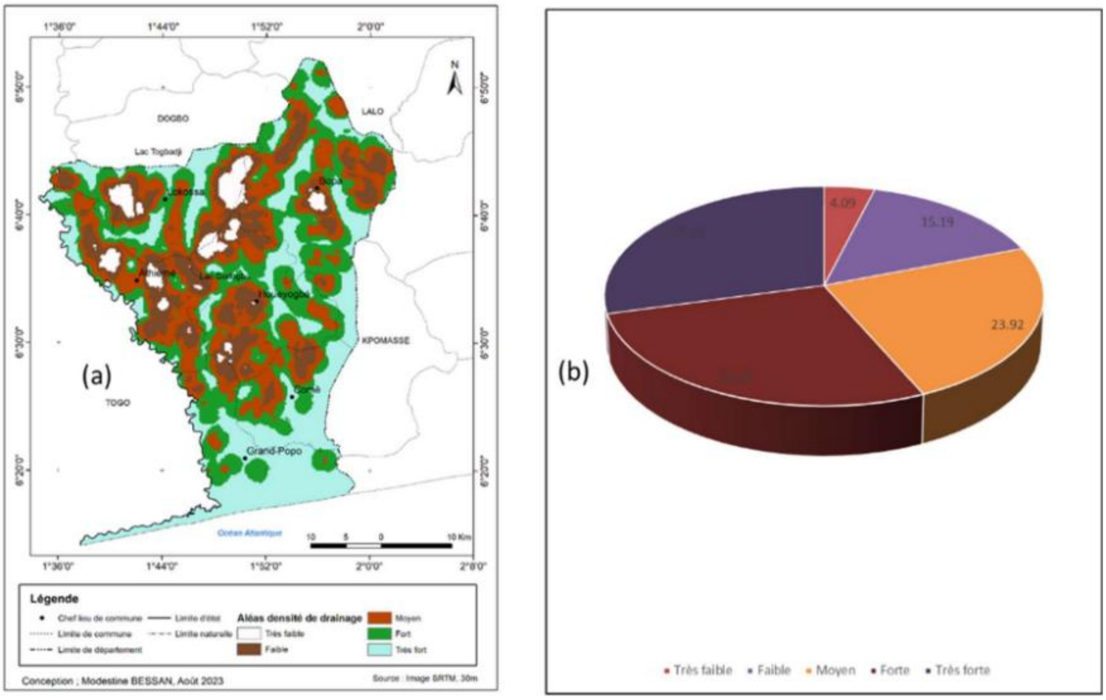

Figure 5. Map showing the distribution of (a) drainage-related hazard and (b) proportion of contribution to flooding

The drainage density hazard map shows a predominance of strong, medium and very strong sensitivities (Figure 5-a). Figure 5-b: proposed drainage density sensitivities. Strong sensitivities (strong and very strong) occupy 31.79% of the Mono territory. Medium sensitivity occupies 23.92% and low sensitivity (weak and very weak) occupies 44.29%.

3.3 Precipitation-related hazards

Precipitation is the main cause of flooding. In mono, flooding does not affect the whole territory in the same way (Figure 6-a).

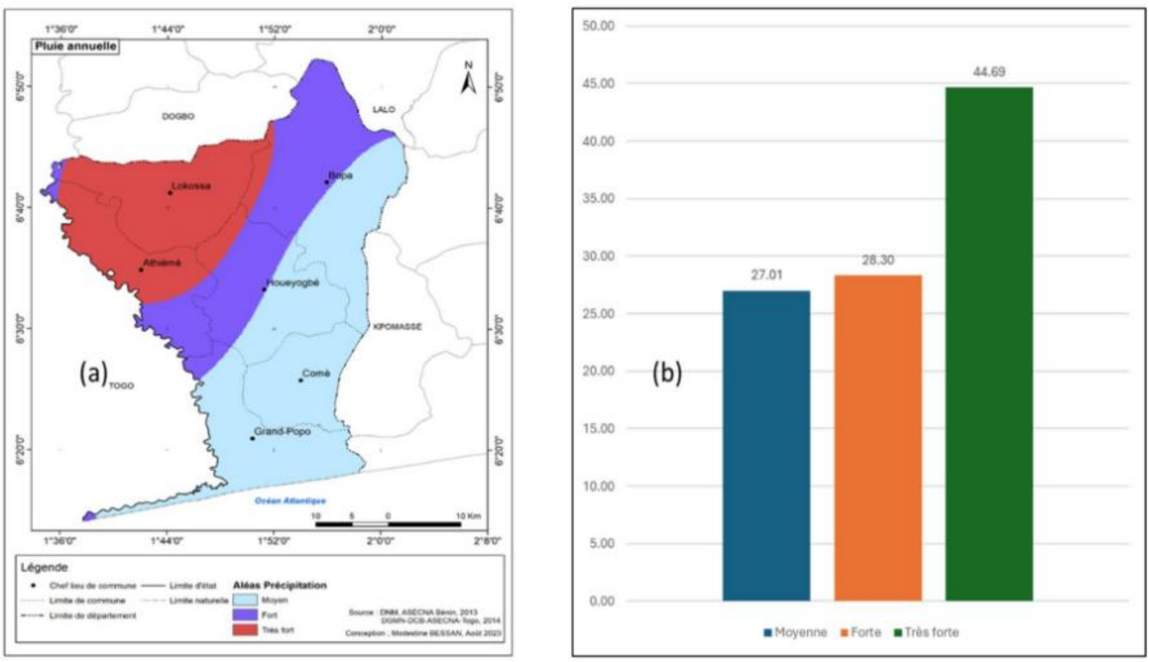

Figure 6. Precipitation-related hazard and (b) band diagram showing the proportions of contribution to flooding

Three levels of sensitivity are encountered in the area. These are medium, high and very high. Figure 6-b shows these sensitivities. Mono department is very well watered. High sensitivity (strong and very strong) covers 72.99% of its territory.

More than half of the territory is therefore susceptible to flooding due to heavy rainfall.

3.4 Soil moisture index hazards

Soil moisture index data for the Mono department have been used to identify the hazard associated with this factor (Figure 7). The hazard map linked to the soil moisture index shows a small part of the territory occupying strong sensitivities (Figure 7- b). Low sensitivity covers more than half of the area (68.36%). Medium sensitivity covers 27.55% and high sensitivity covers 4.09%. The wettest areas are located in the south of the county.

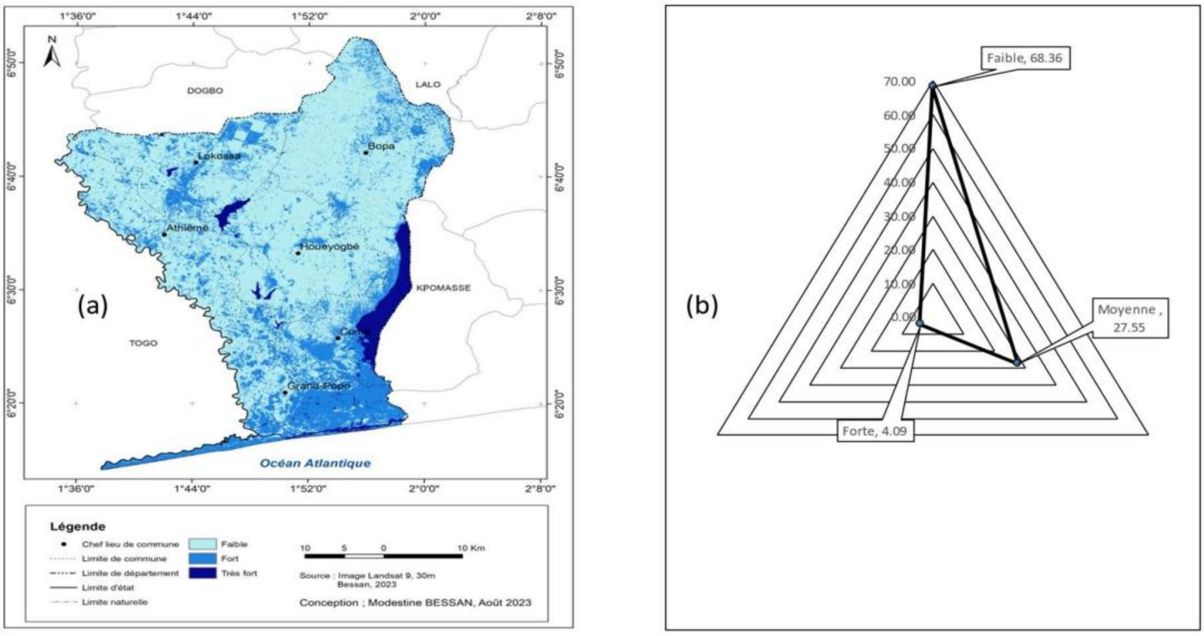

Figure 7. Soil moisture hazard

3.5 Soil-related hazards

Figure 8 shows the soil hazard map for the study area.

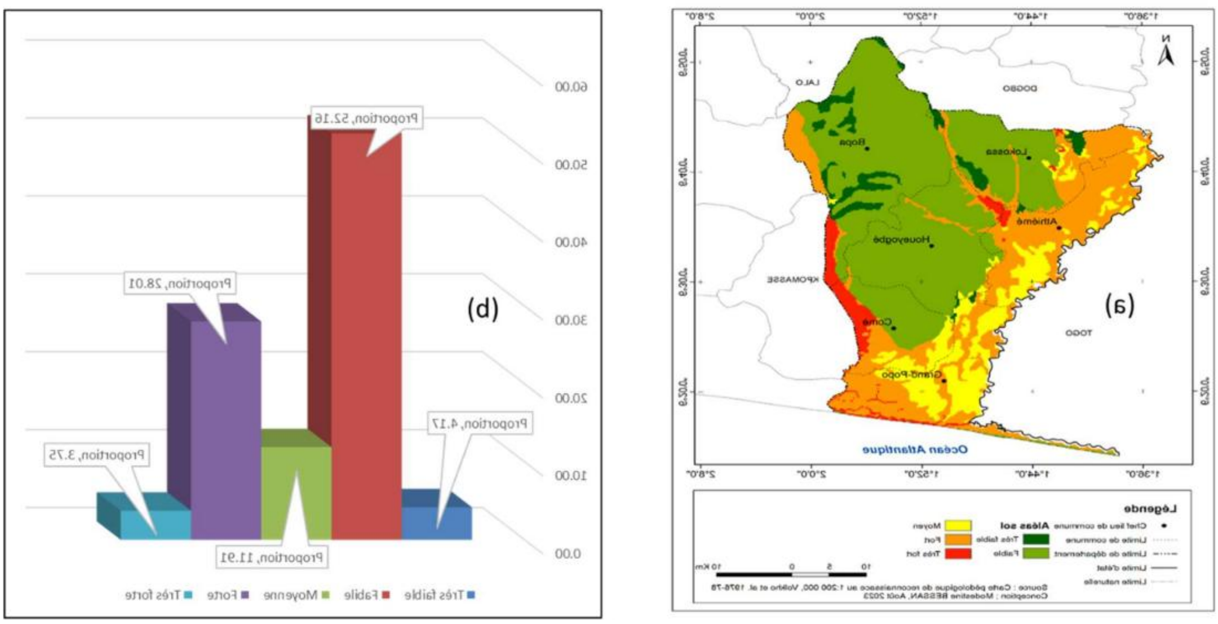

Figure 8. Soil type-related hazards

According to Figure 8-a, there are five (5) types of sensitivity: very low sensitivity, low sensitivity, medium sensitivity, high sensitivity and very high sensitivity. The areas occupied by each sensitivity are as follows (Figure 8-b). Analysis of Figure 5 shows the distribution of sensitivities related to soil types, with low sensitivity (very low and low) occupying more than half of the territory (56.33%), medium sensitivity covering 11.91% of the area, and high sensitivity (strong and very strong) covering 31.76%. Nearly a third of the department's total surface area has flood-prone soils.

3.6 Flood hazard distribution in Mono department

The individual hazards have been used to produce a summary map of flood-related hazards in the study area (Figure 9-a).

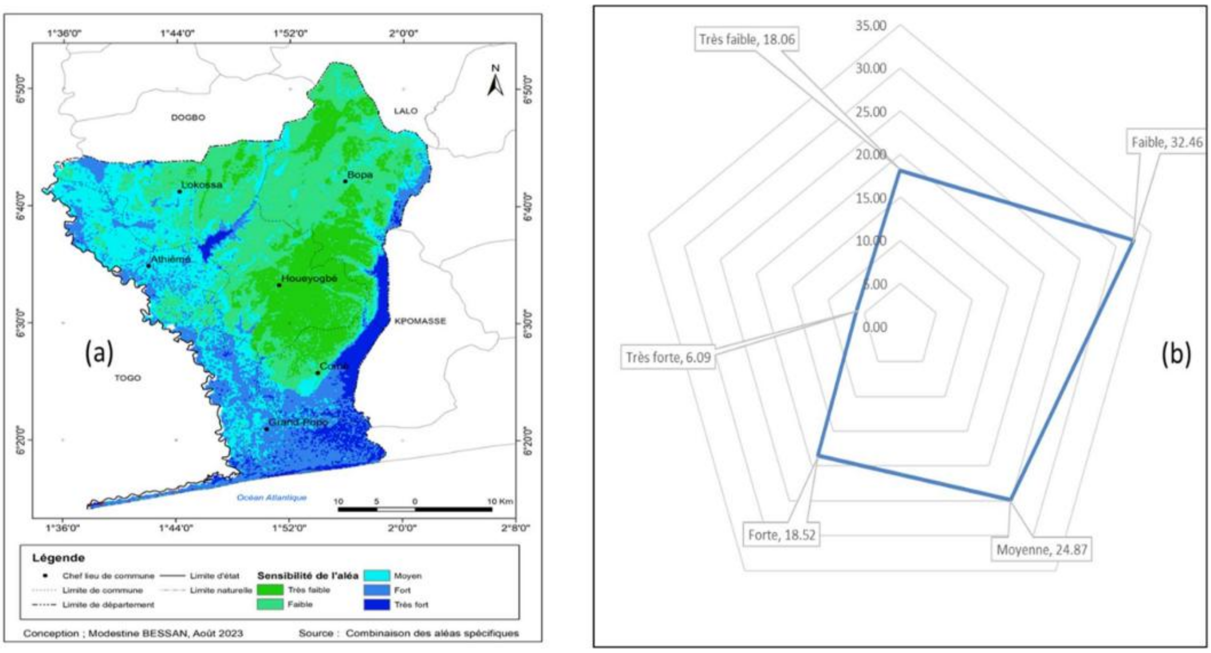

Figure 9. Flood hazard summary map of the Mono region

Figure 9-b shows the distribution of hazards according to five levels of sensitivity: very low, low, medium, high and very high. The proportions of the territory occupied by each sensitivity type are shown in Figure 9-a. The various flood hazard sensitivities in Mono occupy the following proportions:

Very high sensitivity, 6.09% of the Mono territory

High sensitivity, 18.52% of the Mono territory

Average sensitivity, 24.87% of the Mono territory

Low sensitivity, 32.46% of the study area

Very low sensitivity, 18.06% of the Mono territory

4 Discussions

The mapping of areas vulnerable to flooding in the Mono department revealed that areas at high risk of flooding occupy 31% of the study area and are located along rivers and water bodies with a high level of human activity (essentially agricultural areas with numerous grouped and precarious settlements), while areas at moderate risk of flooding occupy 48.32% of the Mono territory and are spread throughout the study area, mainly in medium-slope environments, not far from major river beds. Finally, areas at low risk of flooding occupy 20.67% of the territory, concerning medium to high slope environments, where there is little presence of watercourses; these are plateaus with very little agricultural activity and relatively solid houses (soil-cement mix). [19] Within the framework of studying the environmental factors involved in the flood process in the Maga region of Cameroon and its surrounding areas, it is shown that the natural conditions of the environment are very favorable for the flood process, and landscape changes related to land use changes directly affect the occurrence of floods. This led the authors to use remote sensing and GIS to map areas at risk of flooding. They found that 32.31% of the total area of Maga and its surroundings is at high risk of flooding, and that these areas correspond to territories with galloping demographics and intensive land use. Whereas 19.75% of Manga's territory is at medium risk of flooding and 47.94% is at low risk (areas where watercourses have less influence on activities) [19]. The results of these studies, carried out in Central Africa (Cameroon), are very similar to those of the present study, despite the difference in the study area (Central Africa: Sahelo-Sudanian climate, West Africa: sub-equatorial climate). This high degree of similarity is probably linked to the methodologies used, which are almost identical. [20] They reached similar conclusions when conducting flood risk area mapping research in the Tanger-T é touan area of the Matil River basin in northern Morocco. The authors' findings revealed that 14% of the total urban perimeter area of the Tangier-Tetouan region has a low vulnerability to flooding, while 51.8% of this area has a medium vulnerability to flooding, and the remaining 34.2% of the total urban perimeter area has the highest vulnerability to flooding. These results are in line with those of the present study, with the difference that the flood risk mapping work of [20] consisted in assessing the extent of flooding exclusively at the scale of the urban perimeter of the two cities of Tétouan and Martil, located between the Atlantic Ocean and the Mediterranean Sea. According to the authors, this explains why vulnerability to flooding is becoming more and more acute as urbanization continues to grow in both cities. Whereas in the present study, the mapping of flood risk zones has taken into account the urban, peri-urban and rural areas of the Mono department as a whole.

5 Conclusion

It is widely believed that these different works, including this paper, share a common similarity and diversity in providing reasonable territorial management tools to effectively prevent floods, as generally speaking:

Low risk areas involve areas recommended for normal and permanent human habitation;

Moderate flood risk areas include areas where personnel and their permanent activities may still be accommodated, but specific preventive measures must be considered and followed;

Areas at high risk of flooding are those in which permanent human occupation is strongly discouraged unless exceptional precautions are taken.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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