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Flood Risk Mapping of the Benin Municipalities at the Intersection of the Coastal Sedimentary Zone and the Crystalline Surface

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Abstract

Climate change and population growth have led to the increase and/or intensification of flooding becoming a major issue. The objective of this study is to visualize flooding risk of municipalities at the intersection of the coastal sedimentary zone and the crystalline surface. The methodology adopted is based on geomatic approach, which involves documentary research, processing and assisted classification using remote sensing images and multi-criteria analysis of the Geographic Information System (GIS). Flooding risk is very high at 8.85% in Djidja, Toffo, Zè and Bonou municipalities. In other municipalities such as Agbangnizoun, Abomey, Bohicon, Za-Kpota and Cove, it is high of 46.85%. To the Southeast of the study area, it is located on the eastern and western banks of Oueme Valley. The medium risk represents 26.35% and is located in the municipalities of Ouinhi and Adjohoun. The other municipalities have a low rate of 17.95%. Risk modeling has made it possible to access the various levels of rising water that can cause flooding. Land-use planning decisions can be influenced by the results of this study.

Keywords

Geomatic, Flood Risk, Contact Line, Municipalities, Benin

1. Introduction

Rise and/or intensification of flood is a major issue in land use planning and management due to climate change and population growth ([1]-[3]). Forecasts suggest that they will increase in number and intensity in the future with potentially catastrophic consequences for human societies [4]. Several studies have used radar and optical satellite images to assess the risk of flooding ([5]-[7]). Others have shown that population growth, the development of housing in remote areas and the general increase in built infrastructure have increased the potential impact of flood risk ([8] [9]). In Africa, the extent of flooding is relatively large in river catchments in general, especially in the minor and major river beds and their main tributaries. Benin is particularly affected, with flooding becoming increasingly recurrent since the 1980s [10]. Particularly in the north of the country, flooding is relatively high in the municipalities along the contact line between the sedimentary (coastal) basin and the crystalline basement. Several countries in the sub-region are experiencing the same situation. This is why studies need to be carried out on a regional scale to gain a better understanding of the determinants of the spatialization of flood risk. Despite the cascading impacts of flooding, existing platforms for climate adaptation do not yet fully understand the dynamics of urban communities due to the lack of detailed disaster management and effective evacuation plans at street level [11]. The objective of the present study is to visualize the flooding risk of municipalities at the intersection of the coastal sedimentary zone and the crystalline surface in Benin.

2. Material and Methods

The study area is located in Benin between 6˚35'00" and 7˚41'36" north latitude and 1˚36'10" and 2˚35'00" east longitude. It covers a total area of 6,883,647,063,873 m^2, or 688364.706 ha with a population of 1,188,750 inhabitants (RGPH, 2013) unevenly distributed across the communes bordering the contact line. The most populous is Bohicon (171,781 inhabitants) and the least, Bonou (44,345 inhabitants). There are several classified forests of varying sizes (**Figure 1**).

Data used in this study are presented in the methodological diagram. It will be complemented and updated by fieldwork. The methodology adopted is a geomatics approach based on documentary research, remote sensing image processing, image classification mapping, risk mapping and multi-criteria GIS analysis. Land use mapping is carried out by supervised classification using the maximum likelihood algorithm. The results obtained were evaluated using the confusion matrix. The latter was used to calculate errors of omission (EO), errors of commission (EC), class purity indices (CPI) and cartographic validity indices (CVI). The multi-criteria spatial analysis was carried out using the Saaty matrix and aggregation using weighted superposition [12]. The Euclidean distance to the water body is generated based on its geographical position relative to the various socio-economic infrastructures in the study area [13]. The prospects of flooding by overflowing watercourses after rainfall are assessed on the basis of a digital terrain model generated by SRTM images (30 m) and refined using lidar points extracted from a DJ Matrix 300 RTK drone image (5 m) of the study area using Global Mapper

17 software. To assess the risk of flooding from overflowing watercourses, the variables defined are drainage density, lithology, structural domain, underground drainage, slope, permeability induced by the fracture network, type of land use and rainfall intensity. The flood risk map is based on a hydrogeomorphological method [14], which consists of superimposing the hazard map onto the vulnerability map. For refinement, the Normalised Difference Water Index (NDWI) was used to extract water bodies [15] and the Differential Vegetation Index (DVI) was used to assess the biomass of vegetated and non-vegetated areas in order to better characterise flood-prone areas. To assess the likelihood of flooding, a simulation of the water level rise after rainfall is carried out on an SRTM image (30 m). The flood risk map is based on a hydrogeomorphological method [14], which consists of superimposing the hazard map onto the vulnerability map. The quantification of risk and the delimitation of areas according to their severity and frequency use the criticality grid [16] presented in the methodological diagram (**Figure 2**).

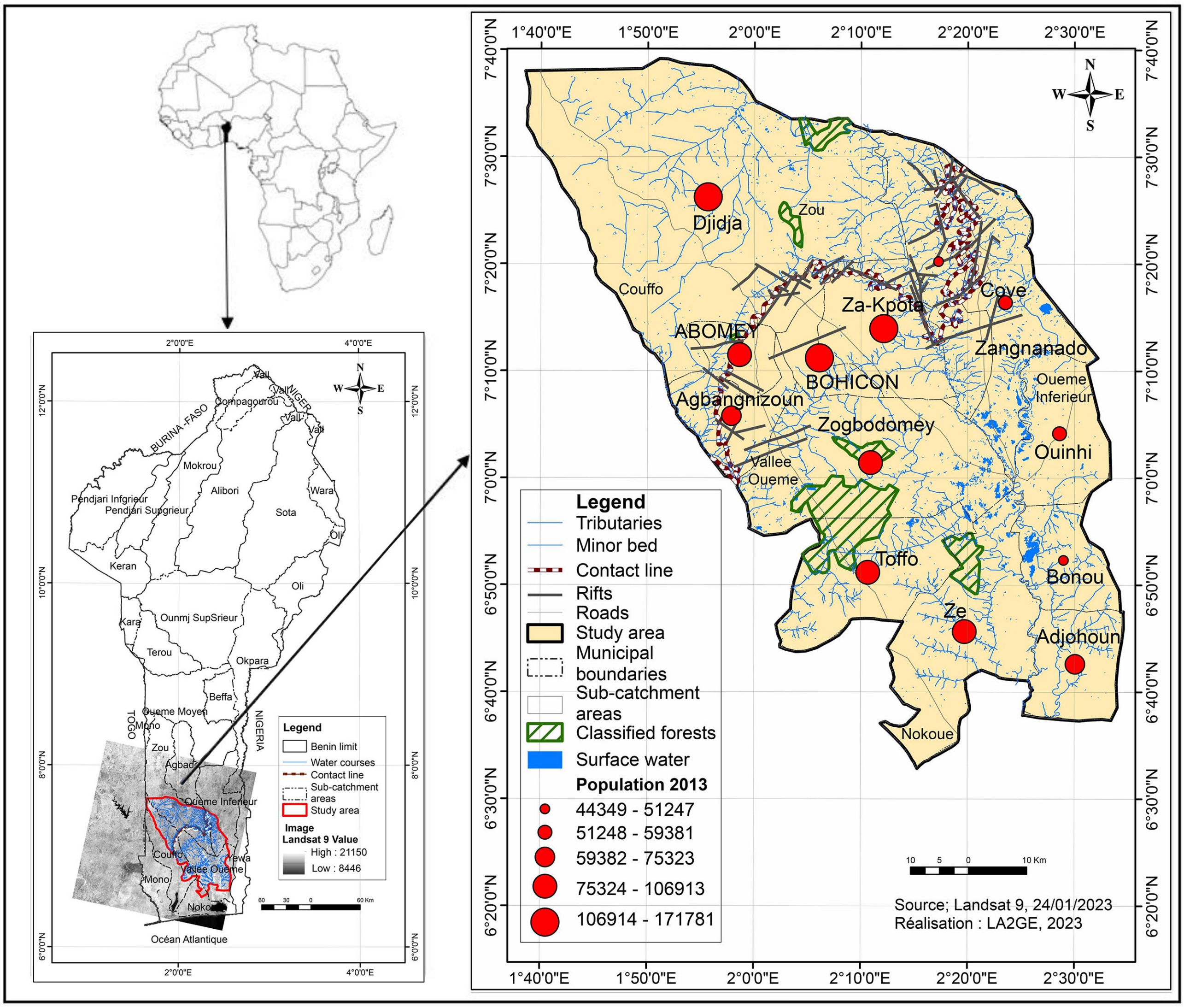

Figure 1. Study area.

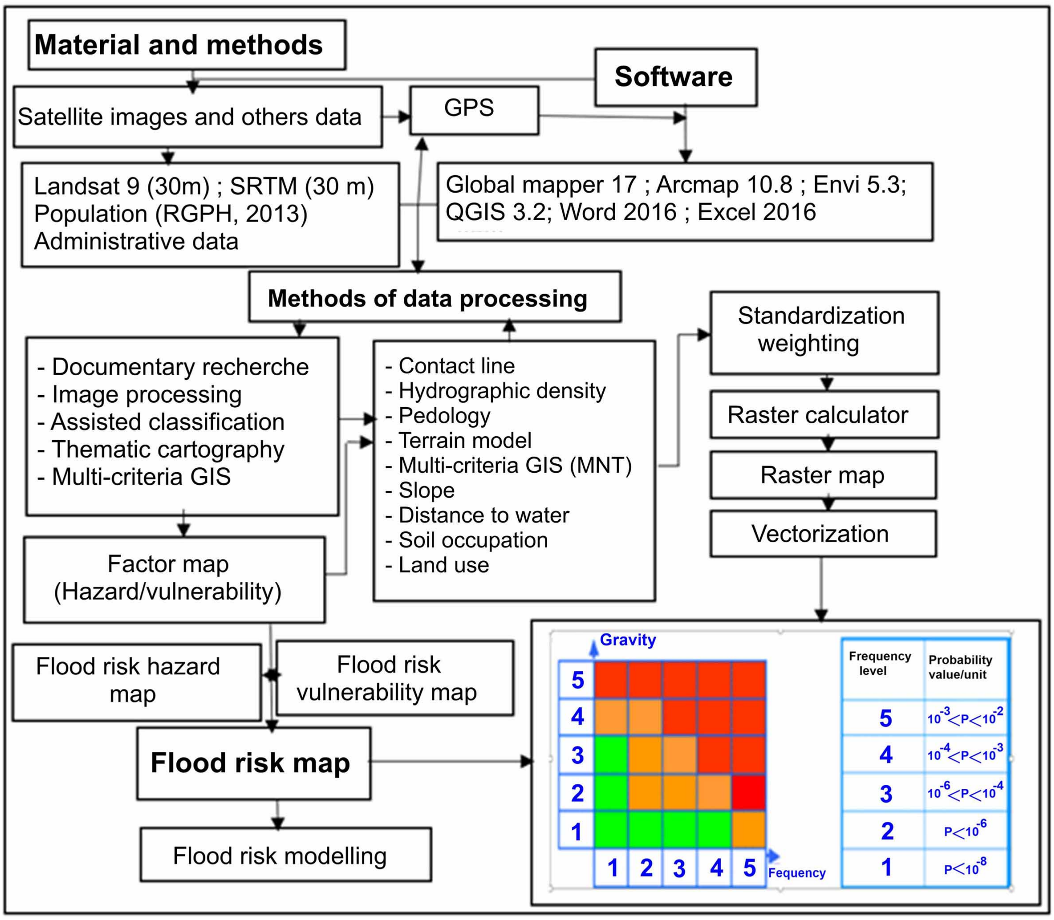

Figure 2. Methodology diagram.

This grid can be interpreted to divide the risk zones into three categories:

Red zone: The risk is frequent and very serious. This severity is linked to the type of damage recorded. These range from simple material losses to human fatalities.

Orange zone: This corresponds to areas of the city where the risk is of medium or even medium-high severity (minor material damage) and the return period is several years. These orange areas are difficult to develop and require sophisticated techniques to avoid or control the ever-present danger.

The **green zone** represents areas where the risk is of very low frequency and severity. Catastrophic events are rare and damage is easily repaired.

3. Results

3.1. Mapping the Flood Risk in the Study Municipalities

In the study area, the hazard is composed of the contact line, the hydrographic network at sub-catchments scale and its density, the distance from the water body and the type of soil drained (pedology), the relief (altitude and slope), the Normalized Differential Water Content Index (NDWI) and the Differential Vegetation Index (DVI).

3.1.1. Contact Line and Hydrographic Density

The contact line between sedimentary and crystalline rocks is located between 7˚00'00" and 7˚20'00"N and extends from west to east over a total length of 270,025 km. According to the work of [17] and the geological survey carried out by [18], it crosses several geological layers of different stratigraphy and lithology, characterised by NE-SW and NW-SE oriented tectonic faults. In the study area, exoreic soil drainage occurs in several sub-catchments, notably Couffo, Zou, lower Oueme, Oueme Valley and Nokoue (**Figure 3**).

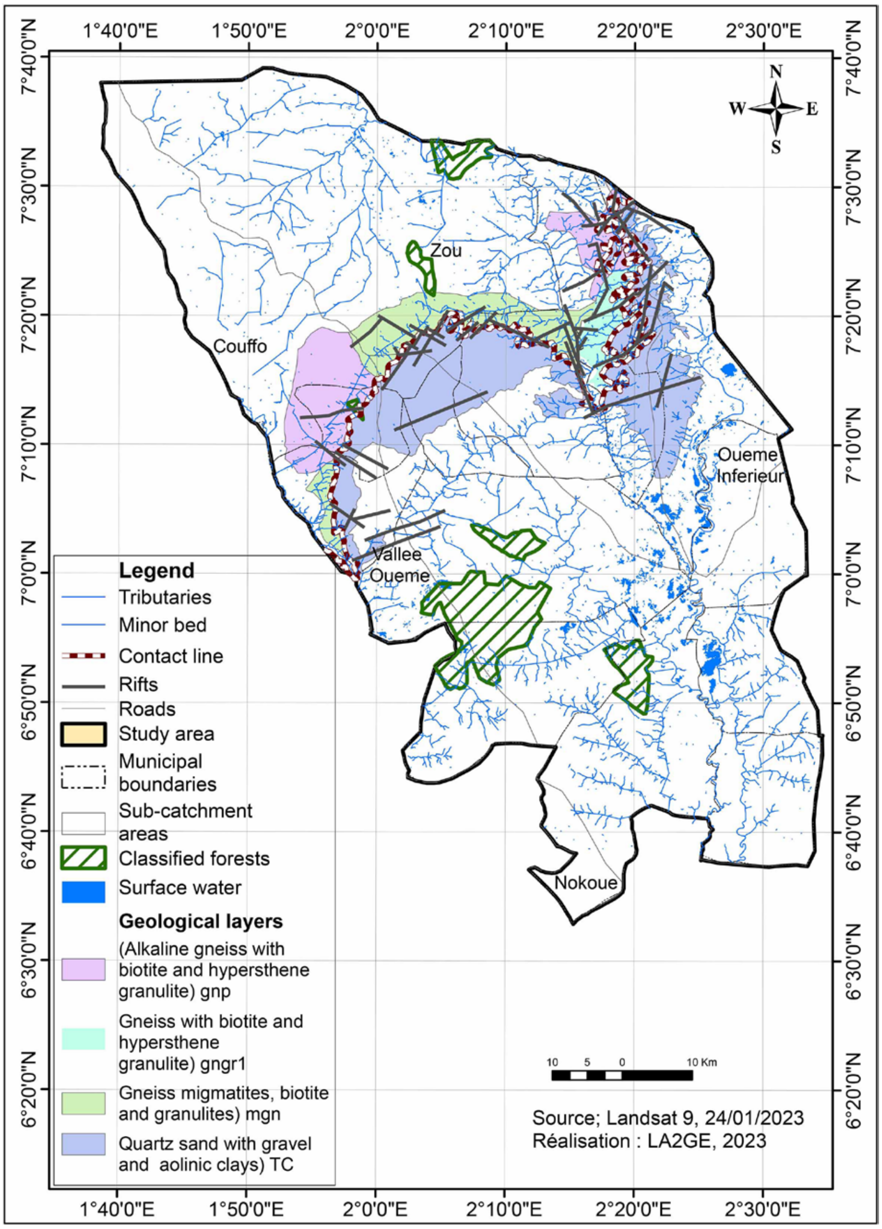

Figure 3. Contact lines.

Hydrographic network density is very high, at 15.32% in the north of the study area in the commune of Djidja, in the center in those of Zogbodomey and Toffo and around the contact line mainly in the Ouémé valley in the communes of Covè and Zagnanado. The high density is 21.27% and is found in the south-east of the study area in the communes of Toffo, Zè, Bonou and Adjohoun. Its average value (52.84%) characterizes the communes of Ouinhi and Zogbodomey. It is low in the south-east of Zogbodomey and in the north-east of Zagnanado and Cove (10.57%) (**Figure 4**).

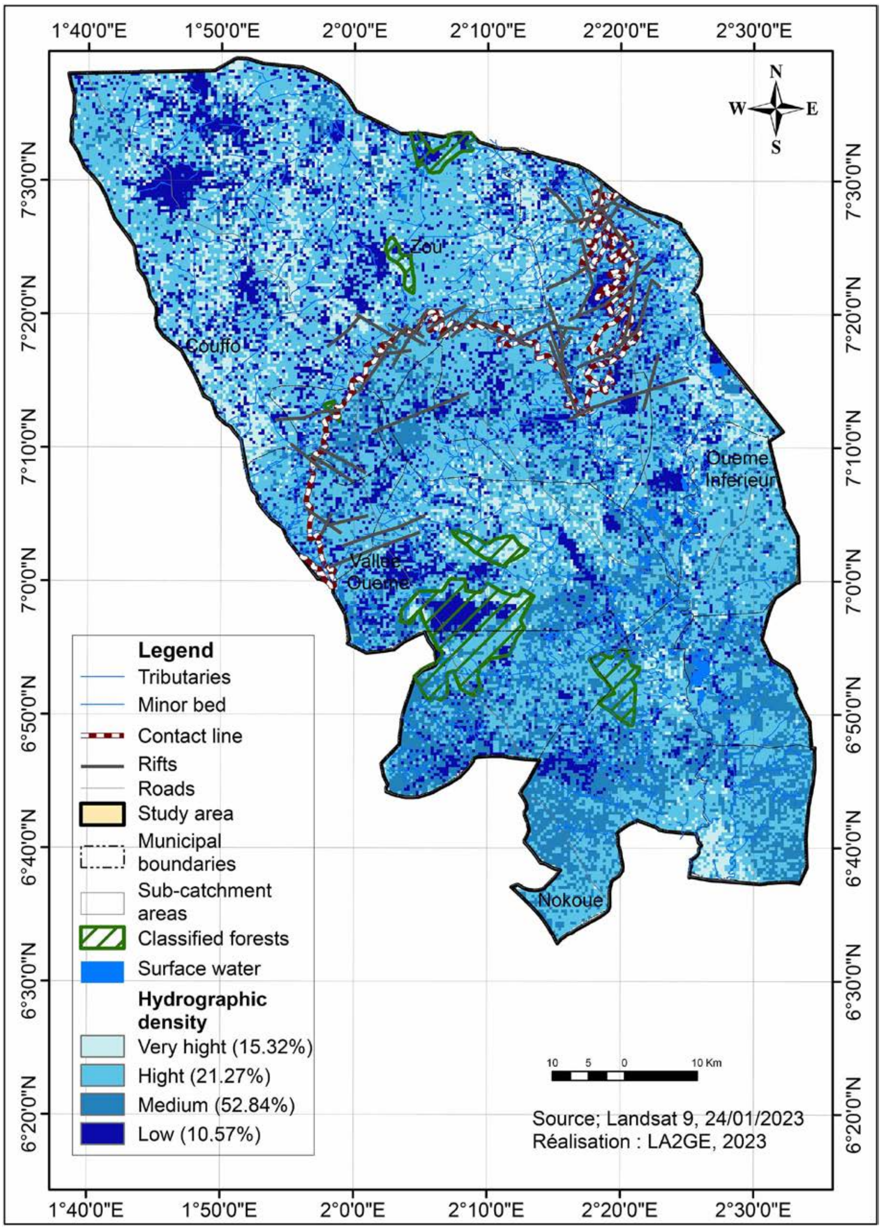

Figure 4. Hydrographic density.

3.1.2. Distance to Water and Drained Soil Types

In the study area, the Euclidean distance of flood-prone areas from a water body is evaluated on a four-level scale: 1000 m; 10,000 m; 20,000 m and 40,000 m. An analysis of the results obtained shows that when the measured distance of the settlements from the water bodies of the communes (Zagnanado, Ouinhi, Bonou, Adjohoun and Zè) is relatively short, between 0 m and 1000 m, the minor bed of the Ouémé and Zou valleys are more exposed to the risk of flooding due to the overflowing of water bodies and watercourses. On the other hand, between 1000 m and 10,000 m, the episodic and major beds of these valleys are periodically flooded by overflowing rivers and watercourses, especially after heavy rainfalls. However, if the distance from the watercourses varies between 10,000 m and 20,000 m, the communes bordering the contact line, such as those of Agbangnizoun, Abomey, Bohicon, Za-Kpota and Covè, are less exposed to flooding from the Ouémé and Zou rivers. When the distance from water bodies and rivers varies from 20,000 m to 40,000 m, only the commune of Djidja is exposed (**Figure 5**).

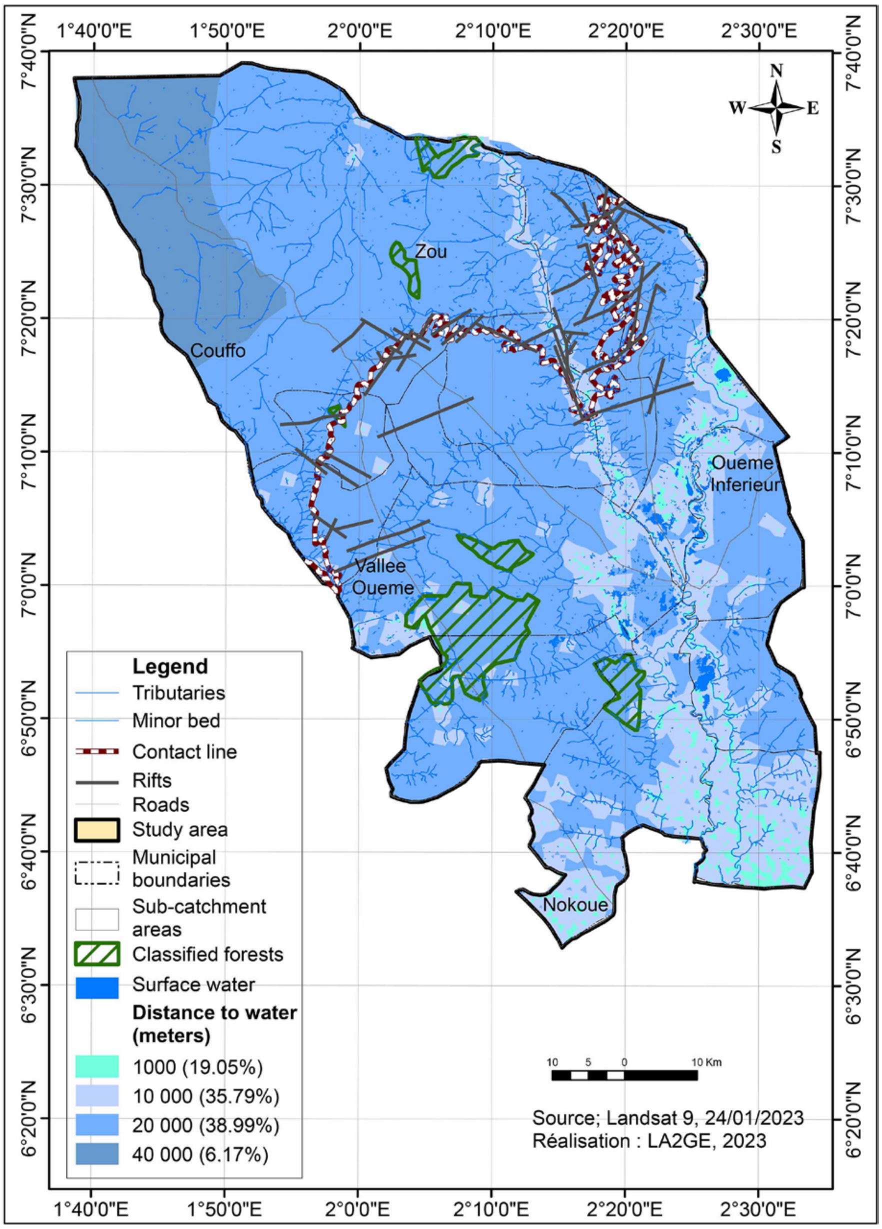

Figure 5. Distance to water.

The study area is covered by several soil types in varying proportions. Hydromorphic soils with low humus content (22.21%) cover the Ouémé valley and its alluvial depressions on both sides of the contact line. Tropical ferruginous soils (7.54%) cover the banks of the Ouémé and Zou river valleys. Impoverished ferruginous soils (54.86%) are the most important and are found in the south and center of the study area. Soils on sedimentary clay represent 15.39% and are mainly found in the north (**Figure 6**).

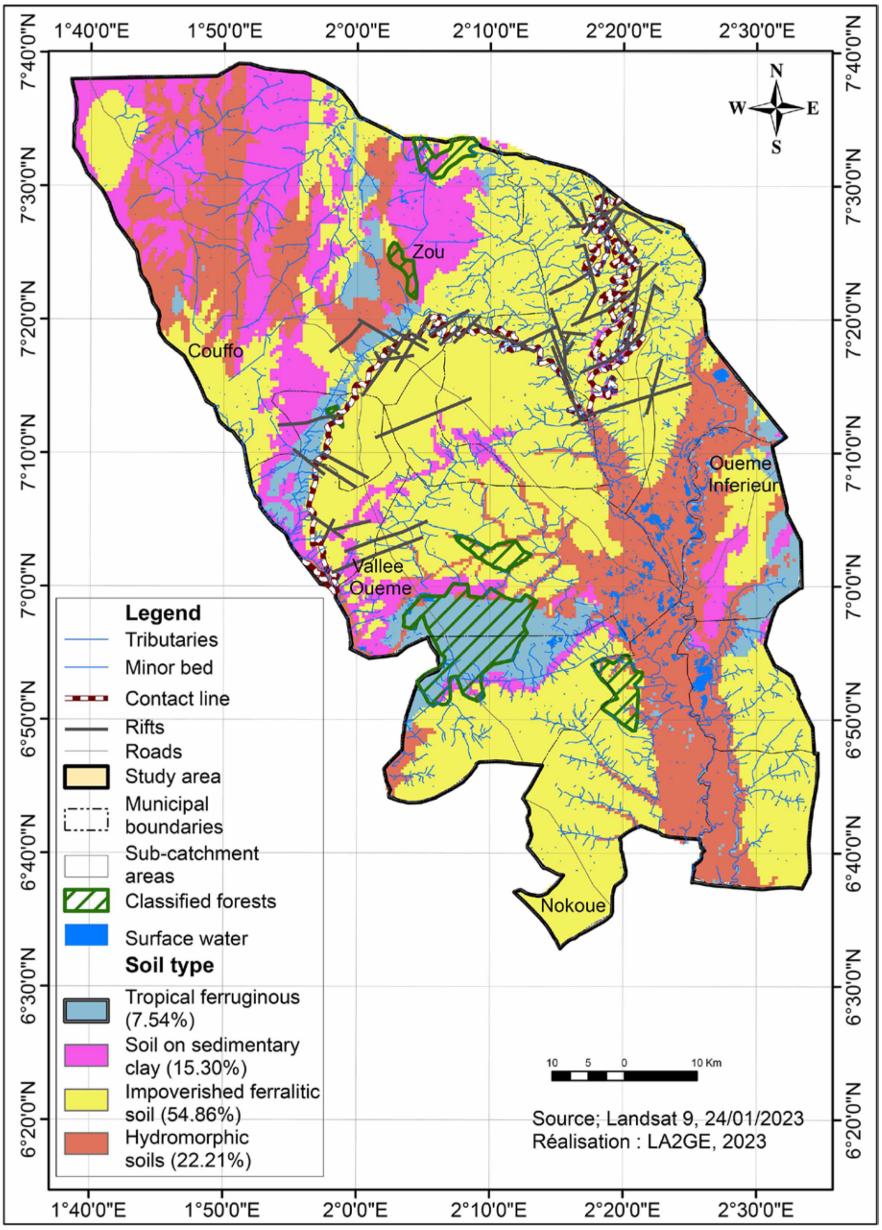

Figure 6. Soil type or pedology.

3.1.3. Digital Terrain Model and Slope

A reading of the digital terrain model shows that in the study area, altitudes generally vary from −5 m to +312 m above mean sea level. The study area is divided into two unequal parts by a major depression, the Ouémé valley. The altitudes observed on its banks are relatively high in the north-western communes of Djidja and Abomey, in the north-eastern communes of Covè and Zagnanado, and in the south-western commune of Toffo. To the east and west of the study area, the gradient is relatively low around the contact line (Figure 7).

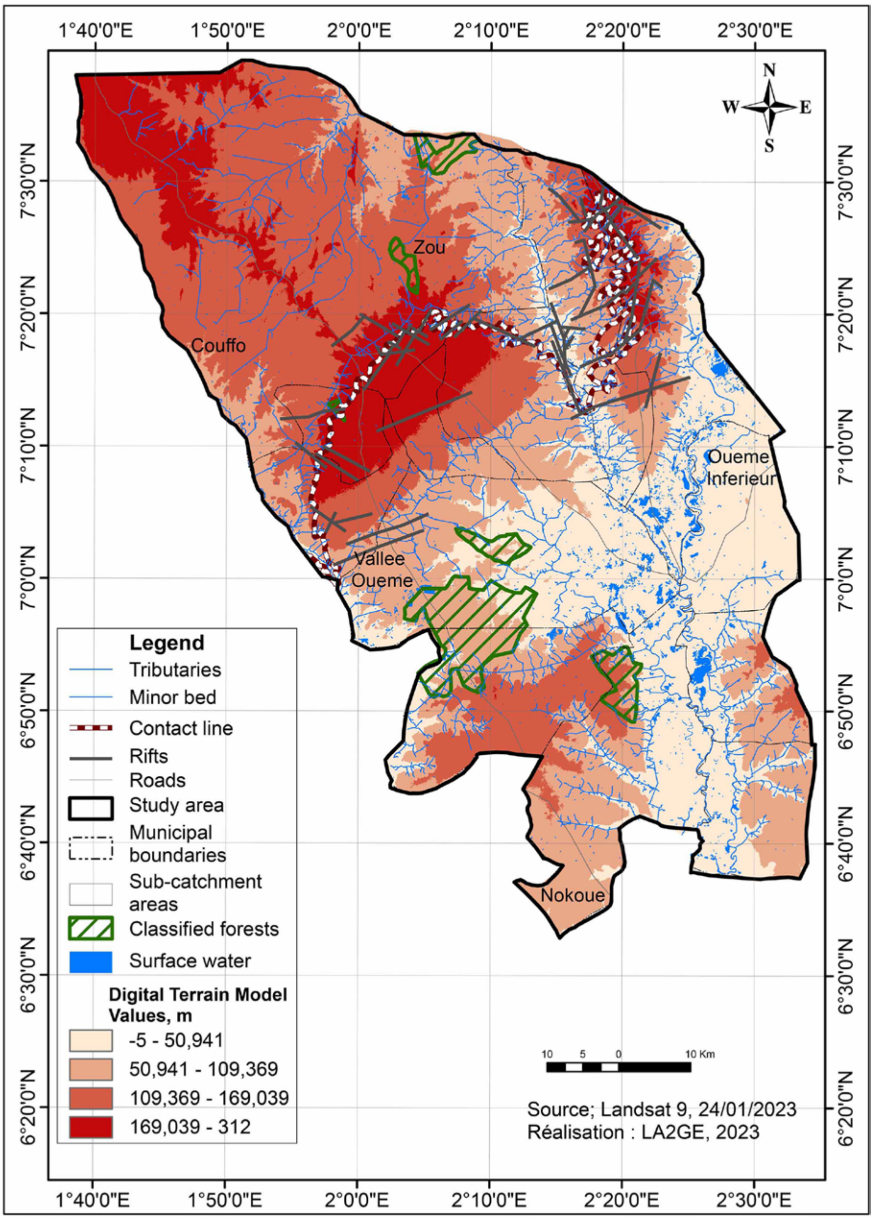

Figure 7. Digital terrain model.

In the study area, the gradient is highly localized and unevenly distributed. To the north-east, in the communes of Covè and Zagnanado, and to the south in those of Bonou, Adjohoun, Toffo and Zè, it is relatively steep. The slope is low and unevenly distributed in the Ouémé valley, particularly around the confluence and alluvial depressions. In the south, the slopes of this valley are marked by localized steep slopes, reflecting differential soil erosion, particularly visible in the communes of Toffo, Zè, Bonou and Adjohoun. Its value is relatively distributed on either side of the contact line. In the east-center, in the communes of Zagnanado and Za-Kpota, the alluvial depressions that shelter the tributaries of the river Zou are marked by steep slopes (**Figure 8**).

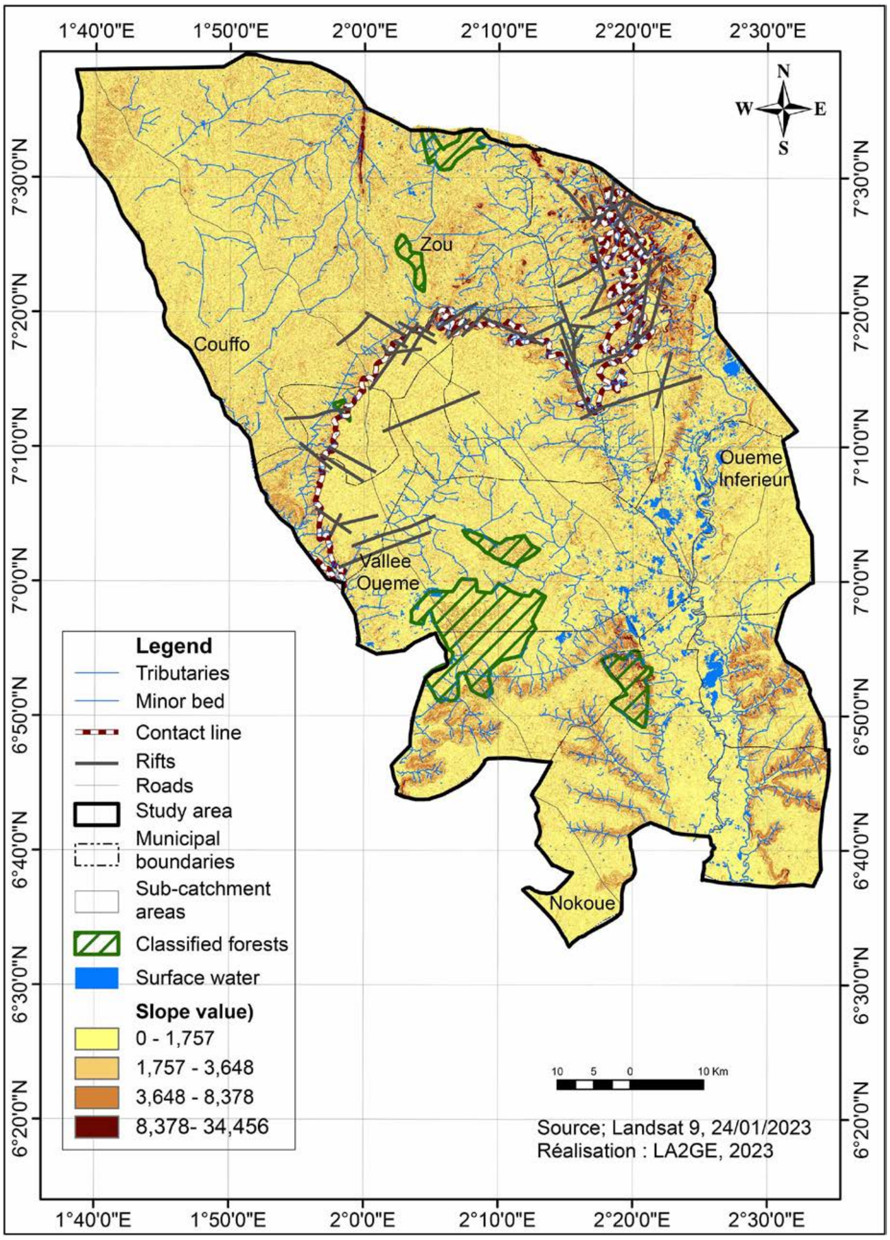

Figure 8. Slope.

3.1.4. Normalized Difference Water Index (NDWI) and Differential Vegetation Index (DVI)

The Normalized Difference Water Index (NDWI) measures the water stress of vegetation. It shows positive values for water bodies and zero or negative values for vegetation and bare soil. In the study area, they are positive with low, medium, high and very high intensities. This situation indicates the presence of a large mass of water due to the flooding of the main bed and the occupied or developed banks of the Ouémé valley (**Figure 9**).

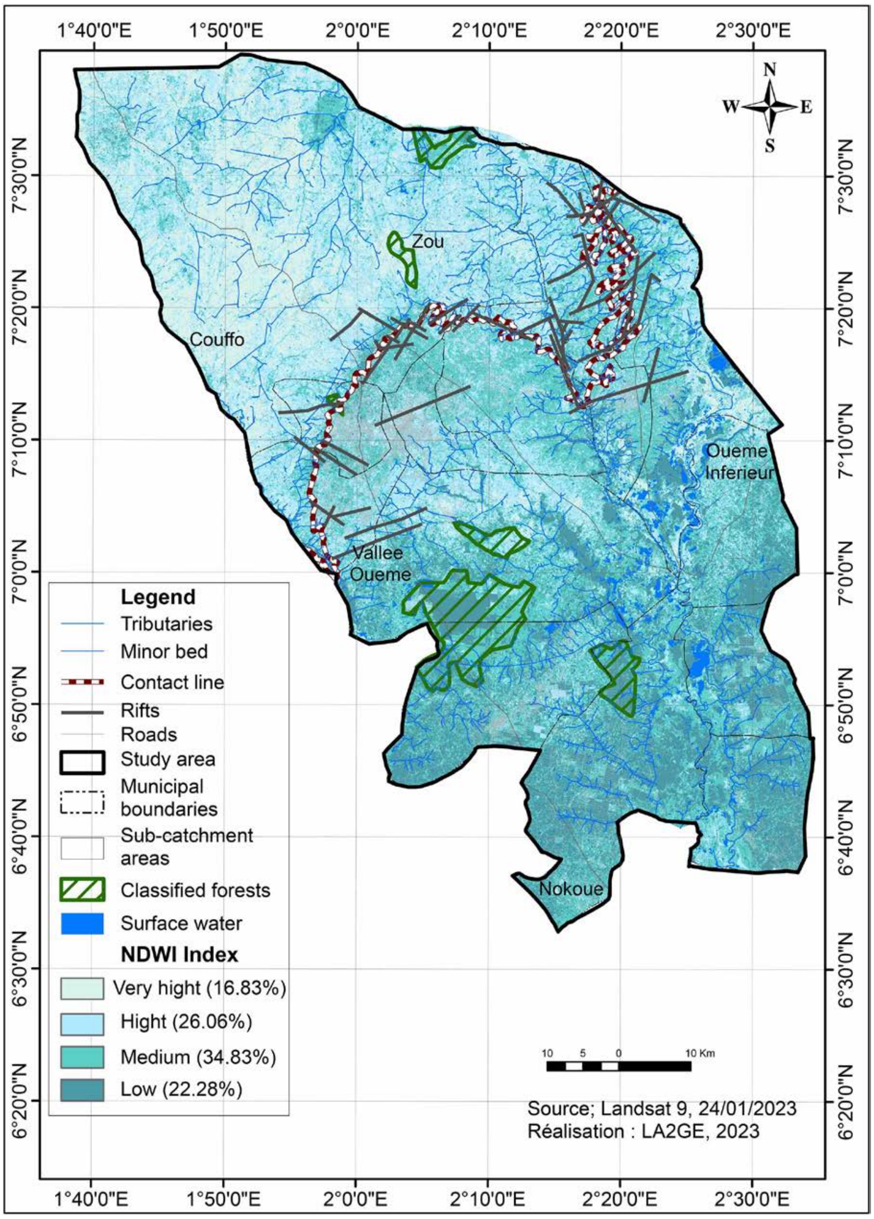

Figure 9. NDWI.

NDWI values between 0.174 and 0.236 are found in the commune of Djidja, indicating low flooding. On the other hand, values between 0.236 and 0.294 indicate medium flooding and are found in the communes of Abomey, Bohicon, Za - Kpota, Covè and Zagnanado. Heavy flooding is indicated by values between 0.294 and 0.326. These define the communes of Zogbodomey, Ouinhi and Zagnanado, located on both sides of the contact line. The communes of Zè, Toffo and Bonou, which developed on the southern bank of the Ouémé valley, were very severely flooded.

The average values of this index are found in the communes of Abomey, Bohicon, Za-Kpota, Covè and Zagnanado and indicate the presence of bare ground in areas with degraded vegetation. It can be seen that its low values are characteristic of crops, which are relatively important in the municipality of Djidja. The high values of this index are relatively distributed in the south and centre of the study area, particularly around the contact line in the communes of Zogbodomey, Toffo and Ouinhi. The very high values of the DVI index are poorly represented in the landscape and are found in the communes of Zè, Bonou and Adjohoun. Figure 10 shows the map of the Differential Vegetation Index (DVI 2), which is used to minimize the effect of bare soil on the spectral response of reflected vegetation.

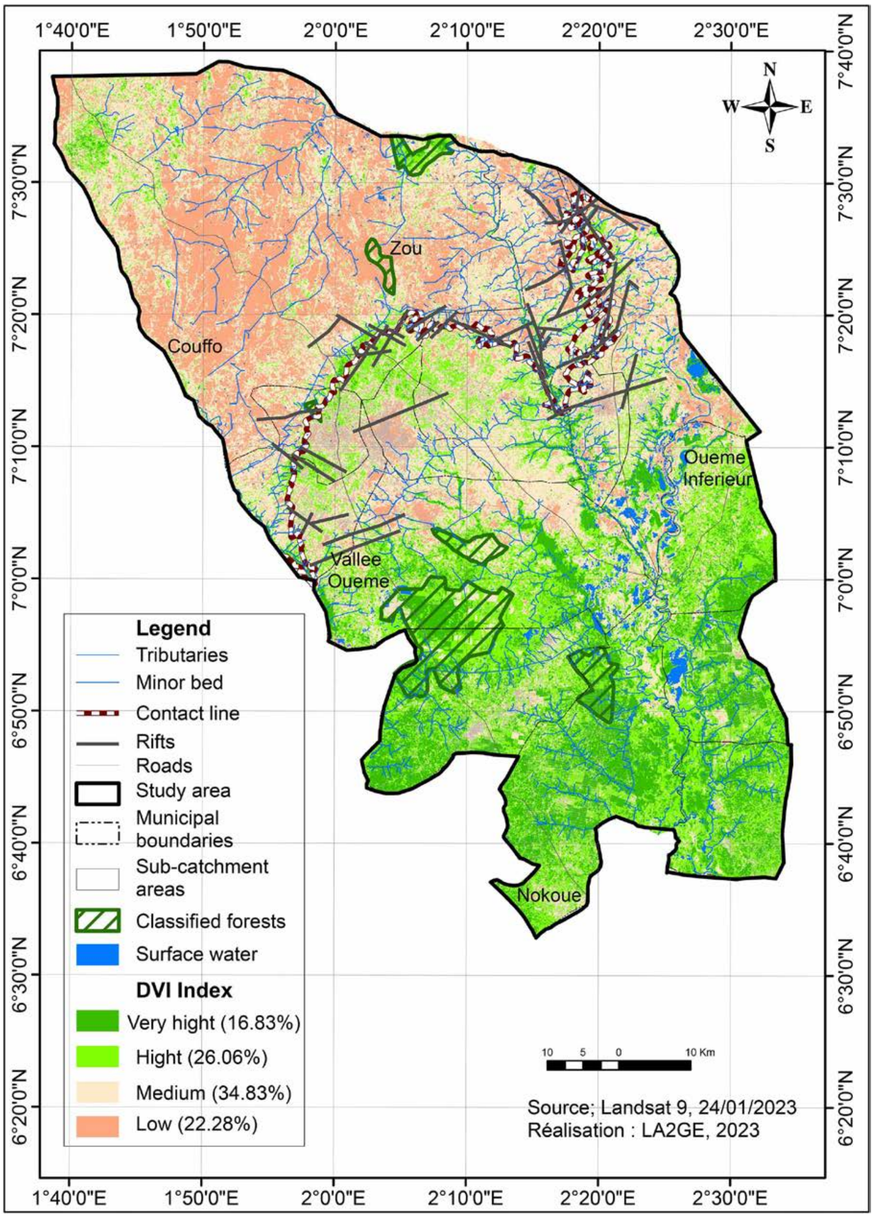

Figure 10. DVI index.

3.1.5. Land Use and Flood Risk Hazard in the Municipalities

Land use is one of the main hazards of flood risk. In the study area, it is characterized by a relatively large distribution of bare soil (24.55%), crops and fallow land (2.90%) surrounded by vast areas of wooded and shrub savannah (20.09%). This situation is particularly marked in the north of the study area in the communes of Djidja and Covè, and in the center in the communes of Abomey, Bohicon, Za-Kpota and Zagnanado. It reveals a significant anthropization of the landscape, which is at the root of its degradation. Open forest and wooded savannah (20.44%) are relatively important in the south of the study area, while dense forest (0.38%), which is relatively fragmented, characterizes the Ouémé valley in general and the classified Djigbe and Lama valleys close to the contact line in particular.

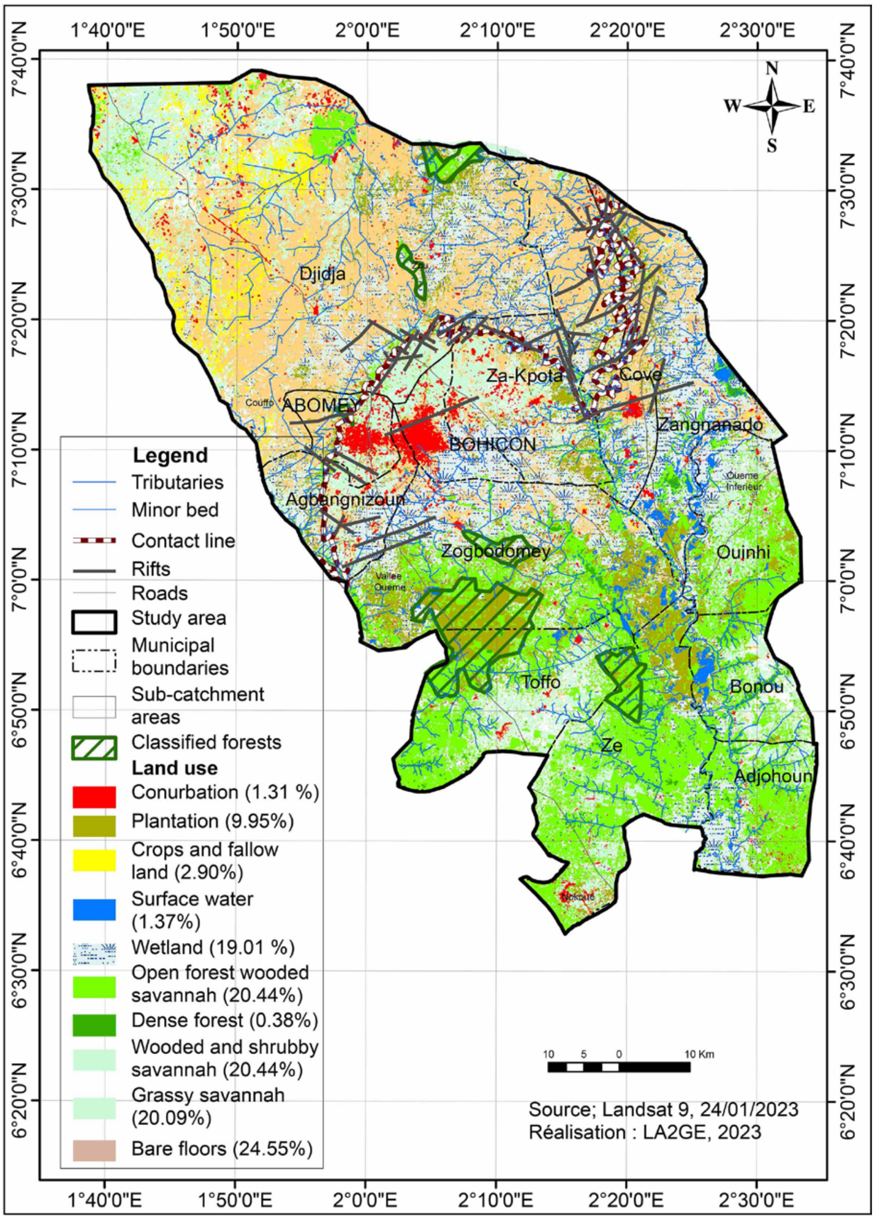

Figure 11. Land use.

Water bodies (1.37%) and built-up areas (1.31%) account for a relatively small proportion of the total. On the other hand, in the communes of Abomey and Bohicon, the latter is relatively important and express a conurbation of the secondary towns of Abomey and Bohicon, which is more pronounced at the latitude of 7˚10'00". In Covè and Zagnanado, the trend is less pronounced, reflecting an unbalanced spatial development. The density of the road network decreases progressively from south to north. It is relatively higher around the urban center in the eastern part of the study area (Figure 11).

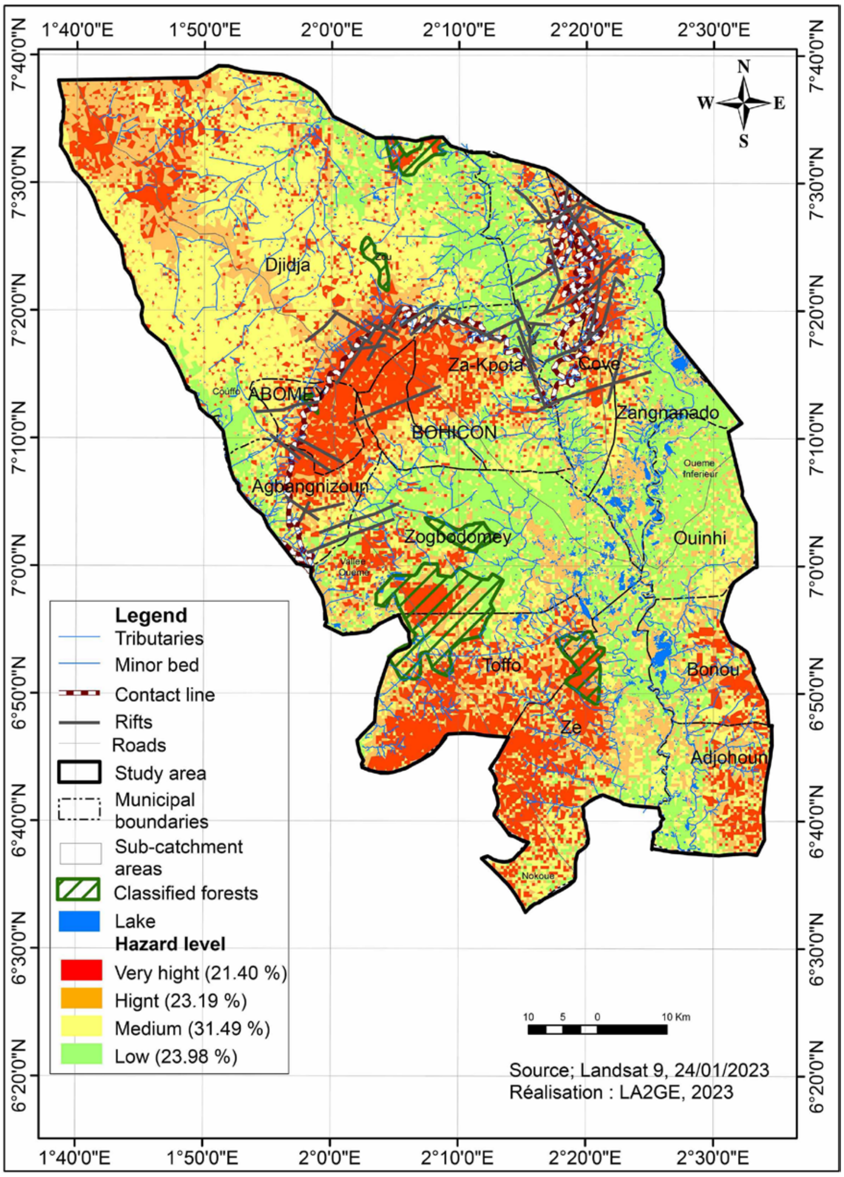

Figure 12. Flood risk hazard.

The flood risk is unevenly distributed. In the study area, it is very high (21.40%) and is most pronounced in the north-west in the commune of Djidja and in the center in the communes of Abomey, Bohicon, Za-Kpota, Covè and Zogbodomey along the contact line. Classified forests are particularly exposed. The communes of Toffo, Zè, Bonou and Adjohoun are particularly at risk (Figure 12).

3.2. Soil Use and Municipalities Flood Risk Vulnerability

In the study area, land use is made up of several elements in varying proportions: infrastructure (1.31%), which is relatively important on the contact line, plantations (9.95%), unevenly distributed in the south of the study area and particularly in the classified forests, agriculture (2.95%) dominant in the north of the study area in the communes of Djidja, Cove and Zagnanado, classified forests made up of remnants of dense forest (0.38%) unevenly distributed, open forest (20.44%) relatively concentrated in the south, wooded and shrub savannah (20.09%) and rural land (24.55%) which dominates the north of the study area in the commune of Djidja (Figure 13).

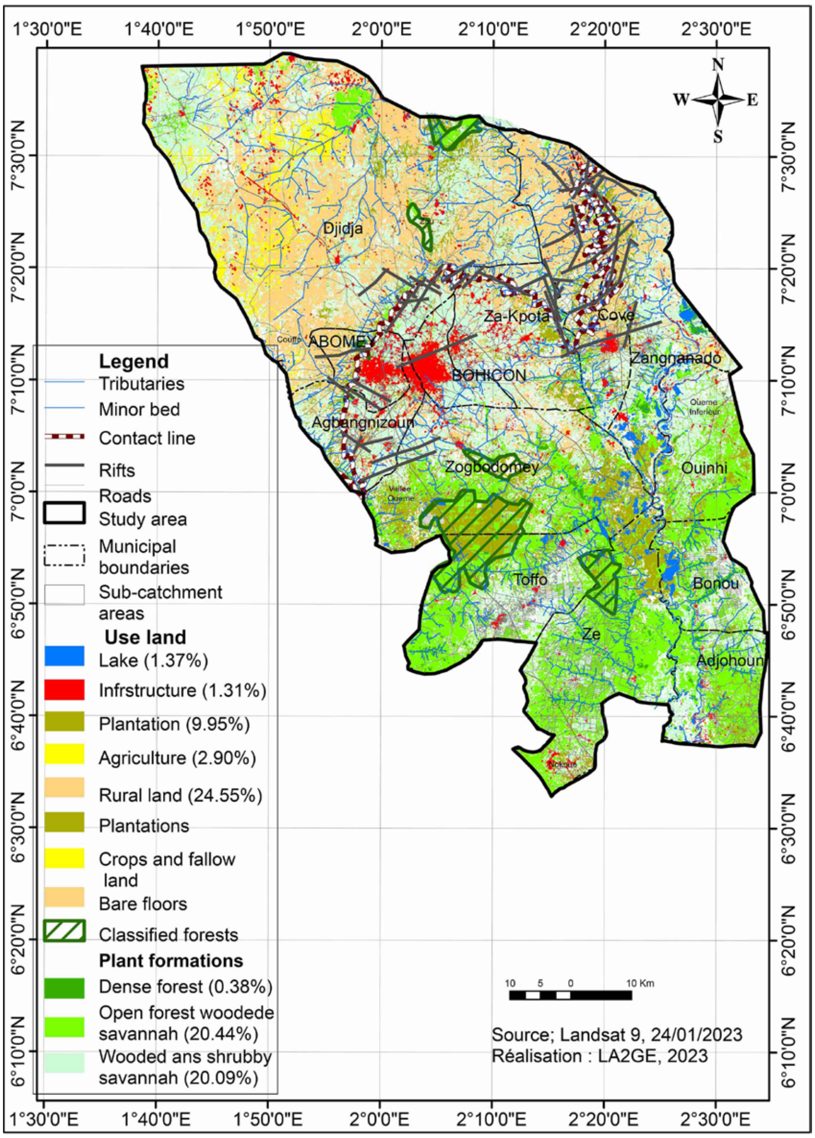

Figure 13. Soil use.

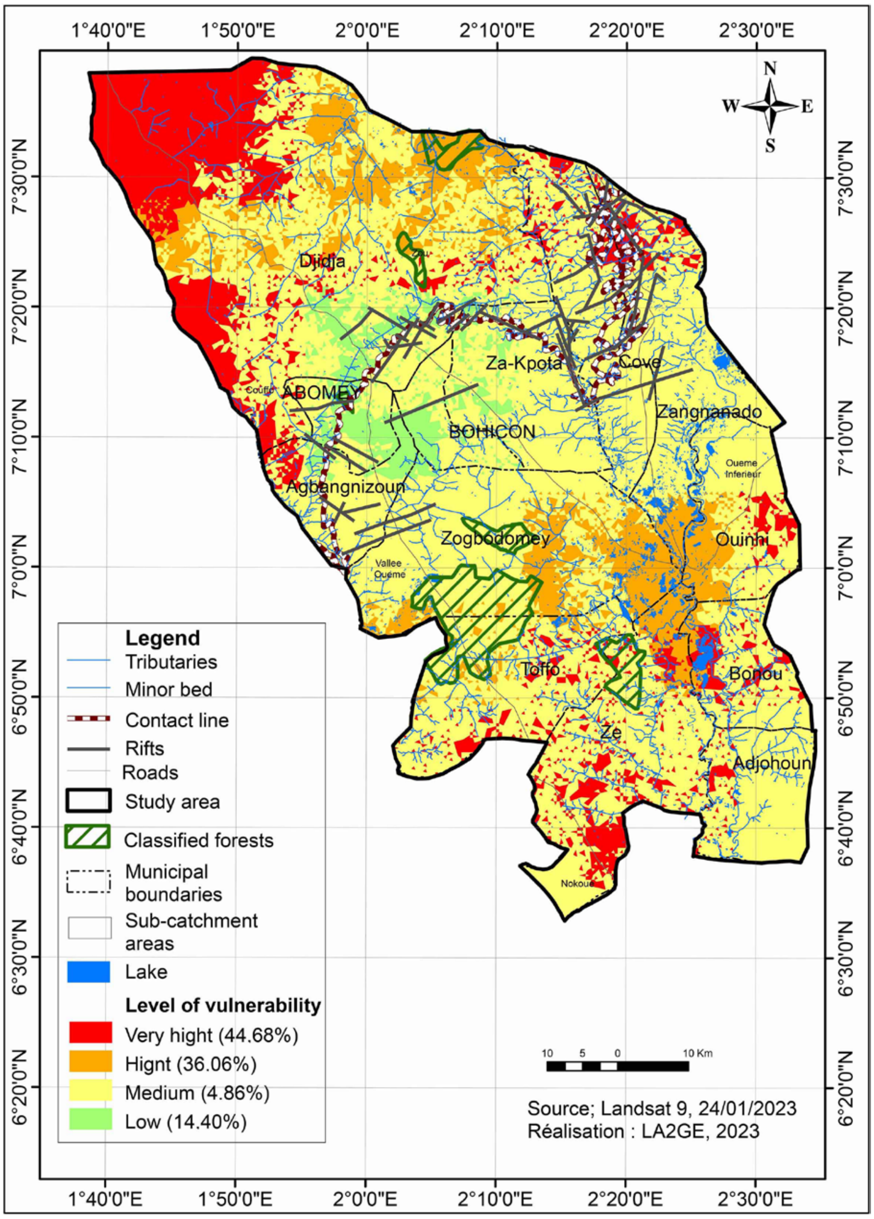

Figure 14. Flood risk vulnerability.

The analysis of the municipalities' vulnerability to the risk of flooding shows an uneven distribution. Very high vulnerability (44.68%) is relatively widespread in the north-west of the study area, in the communes of Djidja and Abomey, and in the north-east in Covè. In the south, it is found in Toffo, Zè, Ouinhi, Bonou and Adjohoun. High vulnerability covers 36.06% of the study area. It is found not only in the classified forests of the communes of Djidja and Toffo, but also to the south in the municipality of Zogbodomey, Ouinhi and Ze, particularly on the banks of the Ouémé valley. Vulnerability averages 4.86% and is highest in the municipalities located on south of the contact line in general and in Za-Kpota, Bohicon, Zagnanado, Zogbodomey, Toffo, Zè, Ouinhi, Bonou and Adjohoun in particular. The communes of Agbangnizoun, Abomey and Za-Kpota on the contact line are characterized by low vulnerability (**Figure 14**).

3.3. Mapping and Modelling of Municipalities Flood Risk

The spatialization of the flood risk in the municipalities around the contact line shows its uneven distribution (**Figure 15**).

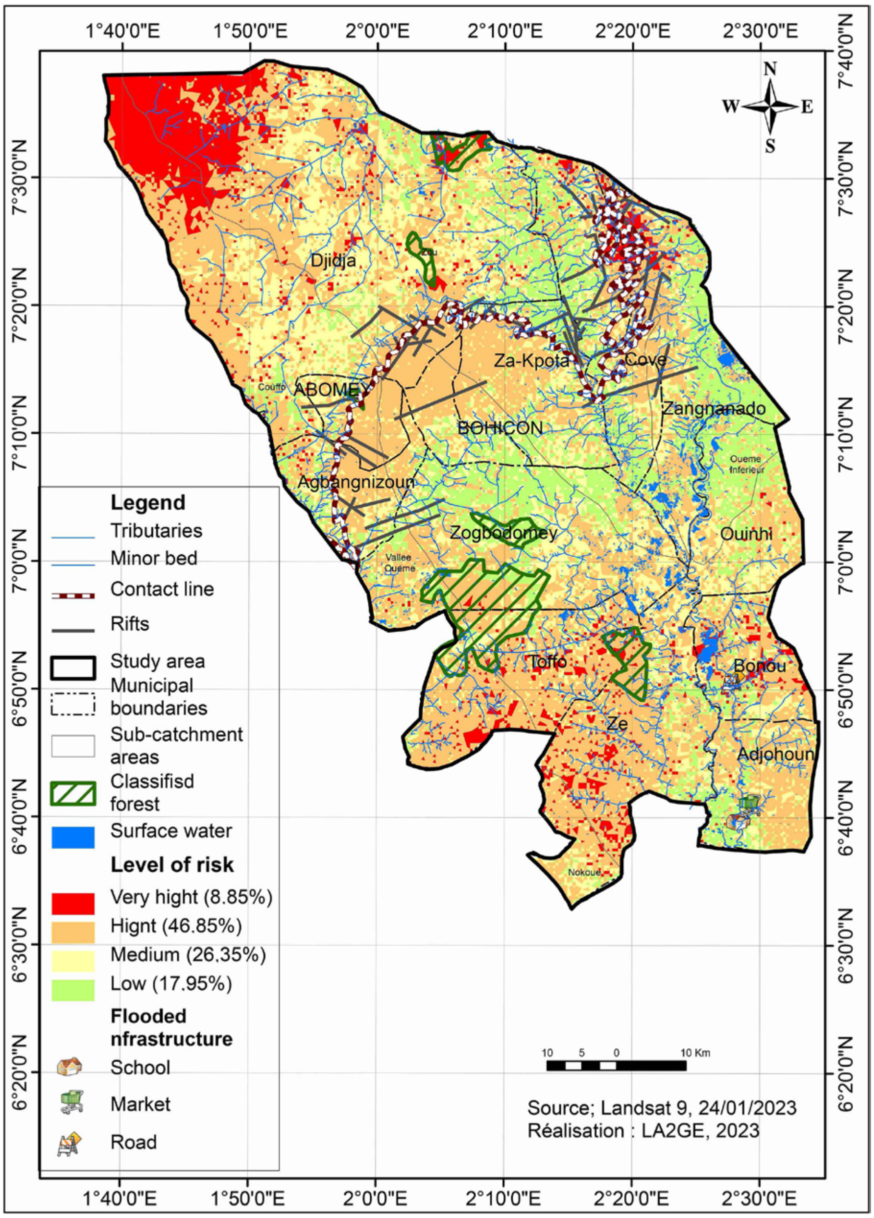

Figure 15. Flood risk spatialization.

It shows that the very high risk is visible in 8.85% of the study area, particularly in the north-west of the commune of Djidja, in the center in the classified forests and in the south in the communes of Toffo, Zè and Bonou. The highest level of risk (46.85%) affects the commune of Djidja in the north of the study area, and in particular the communes around the contact line, such as Agbangnizoun, Abomey, Bohicon, Za-Kpota and Covè. In the south, the risk is highest on the eastern and western banks of the Ouémé Valley, particularly in the communes of Toffo, Zè, Ouinhi, Bonou and Adjohoun. The medium risk is observed on 26.35% of the study area and can be seen to the north above the contact line in the commune of Djidja and to the south-east in the communes of Ouinhi, Bonou and Adjohoun. The low risk of 17.95% is particularly noticeable in the north-east of the communes of Covè and Zagnanado, in the center of Bohicon and Zogbodomey and in the south of the communes of Bonou and Adjohoun in the Ouémé valley.

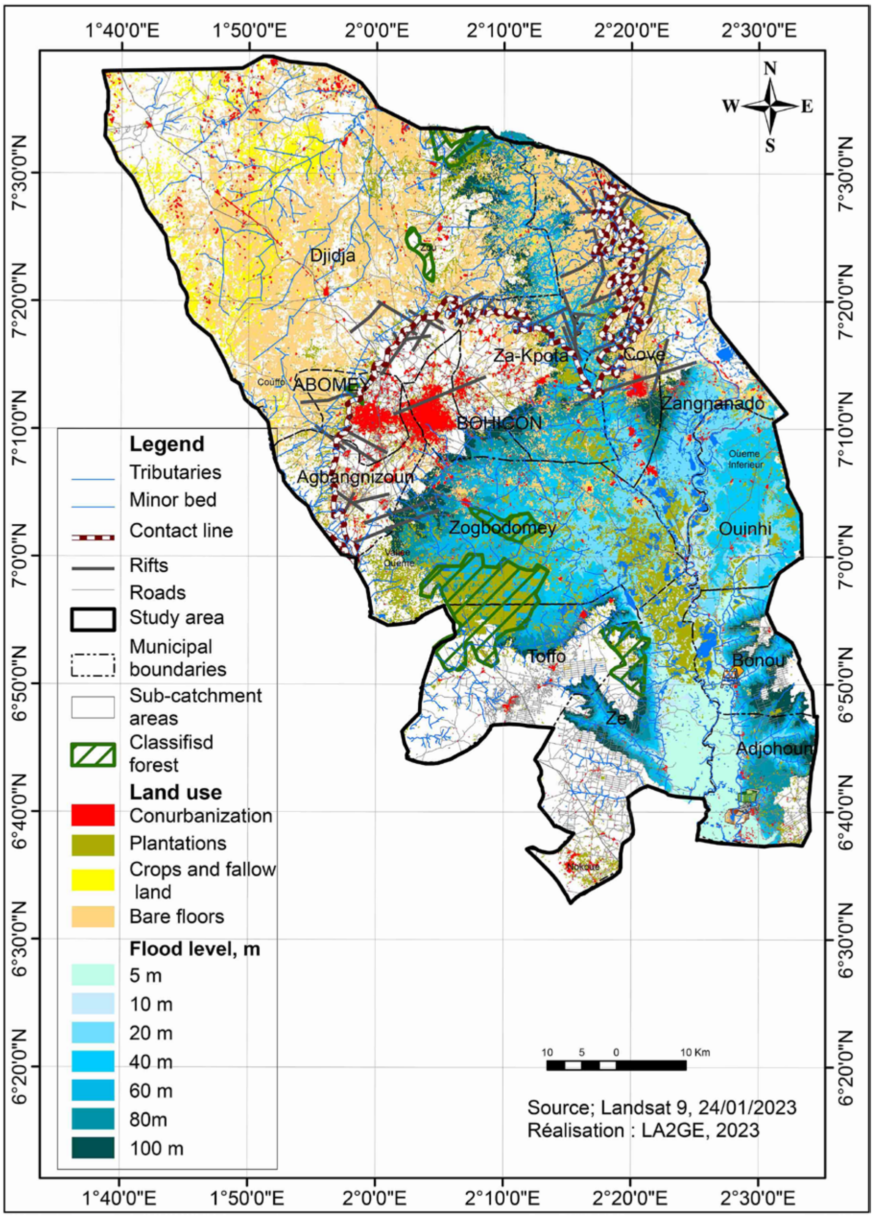

Figure 16. Flood risk modelling.

The simulation of flood by rising water shows that at a height of 10 m, the water is mainly in the Ouémé valley and in the alluvial depressions in the communes of Ouinhi and Zè. At 20 m, the episodic bed receives water and the main bed (developed and occupied banks) of the Ouémé valley is submerged. This situation is particularly characteristic of the communes of Ouinhi, Zagnanado and Zogbodomey. At a level of 40 m, the communes of Zè, Adjohoun and Bonou will be more severely flooded, particularly in the alluvial plains and on the banks of the Ouémé and Zou rivers on both sides of the contact line. At a height of 60 m, the banks of the Ouémé valley are flooded and the alluvial depressions in the communes of Zè, Bonou and Adjohoun are submerged. The communes most at risk in this scenario are Zagnanado, Ouinhi and Zogbodomey. If the water level rises by 80 meters, the communes of Adjohoun, Zè, Ouinhi, Zogbodomey, Zagnanado and Za-Kpota will be affected. Fieldwork has enabled us to identify the location of flooded infrastructure (markets, schools, roads, etc.) in the communes of Bonou and Adjohoun [19]. **Figure 16** shows a simulation of flood by rising water.

The model used to observe flooding by overflowing watercourses is validated by surveying the coordinates of flooded infrastructures in the field and projecting them onto the flood risk map (**Figure 15**, **Figure 16** and **Board 1**).

1) Latitude : 6° 39' 27" N
Longitude : 2° 28' 36" E

2) Latitude : 6° 39' 56"N
Longitude : 2° 29' 10" E

3) Latitude : 6° 49' 34" N
Longitude : 2° 30' 26" E

Photo taken by: Azize Ognondoun, 26 septembre 2023

Board 1. Illustration of the results of the model of the risk of flooding by overflowing after rainfall.

4. Discussion

According to [8], the main causes of changes in flood risk are climate change, changes in land use and other human interventions. All these factors exacerbate the phenomenon, making populations highly vulnerable to floods [1]. The work of [9] confirms this assertion by showing that vulnerability is the main concept in flood risk management. According to the latter author, four groups of methods are used to assess it: the curve method, the looser data method, computer modelling methods and indicator-based methods. The latter two are used in this study. The results show that the presence of a contact line between the sedimentary basin and the crystalline basement has a strong influence on the spatialization of the risk. Indeed, it is around the latter that the very high and high risks are identified. On a regional scale, the experience of Fiorillo *et al.*, 2010, p. 5, has shown that even in Sahelian countries in general and Niger in particular, floods can lead to severe degradation of land and vegetation. Several authors have stated in their work that flood risk depends mainly on hazard and vulnerability factors ([20] [21]). The work carried out in this study confirms this statement. In the event of a disaster, rapid evacuation routes for people and their property need to be identified and recommended for land use planning. Flood risk mapping could be used as a decision-making tool for this purpose.

The results of this study indicate that surface hydrodynamic processes significantly influence the fate of water in basement zones [22]. But the experience of [2] has shown that even in Sahelian countries in general, flooding can lead to severe degradation of land and vegetation.

5. Conclusion

The mapping showed that the commune of Djidja is particularly exposed to a very high risk of flooding. The communes on the contact line, such as Agbangnizoun, Abomey, Bohicon, Za-Kpota and Cove, are at relatively high risk. The contact metamorphism of the geological formations that structure them does not facilitate the infiltration of run-off water and explains this situation. Medium risk has been identified in the communes in the centre of the study area, particularly threatening the Toffo and Zogbodomey classified forests. Flood risk management at the sub-catchment level, particularly around the confluence of the Oueme and Zou rivers, is a key factor in supporting land-use planning decisions to reduce the vulnerability of the population and the impact of flooding. The simulation of the risk of flooding due to rising water indicates that, from a height of 40 m, flooding around the Oueme Valley is relatively significant, inundating the alluvial depressions on the banks on both sides of the contact line. For example, the Tillabéry and Zinder regions, located on the Liptako-Gourma and Damagaram-Mounio plinths, respectively, are characterized by flooding during the winter months and serious water shortages during the dry seasons. Mapping the risk of flooding in a bedrock environment is a decision-making tool for land-use planning. The limits of the study lie in the possibility of carrying out field surveys based on hydrogeological data in order to better characterize the causes of flooding on crystalline bedrock and in the sedimentary basin and to supplement the results of the present study.

Conflicts of Interest

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

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