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Contribution of GIS and Multi-Criteria Analysis to the Assessment and Prevention of Flood Risks in the Municipality of Kaffrine, Senegal

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Abstract

Floods are an increasingly recurring phenomenon throughout the world, in Africa and in Senegal. The Kaffrine's municipality is not spared from this phenomenon which is often the cause of environmental disasters, economic and human lives losses. Despite the strategies put in place, this phenomenon still persists, particularly in Kaffrine's municipality. Our objective is to contribute to the assessment and prevention of flood risk in the municipality of Kaffrine, through multi-criteria analysis and the geographic information system. The data used comes from surveys, ground surveys, satellite images and public institutions. The use of Saaty's multi-criteria analysis and the geographic information system made it possible to process and analyze the data. Crossing the vulnerability map and the hazard map made it possible to produce the flood risk map. A significant part of the population (nearly 30%) is exposed to high or very high risk of flooding. This proportion is higher in the north of the study area.

Keywords

GIS, Hazard, Vulnerability, Risk of Flooding

1. Introduction

Since the 2000s, there has been a return of rains with its attendant floods. According to an IFRC report published in 2020 (IFRC, 2020), in recent years there has been an increase in natural disasters, 83% of which are caused by extreme climatic and meteorological phenomena, such as heavy rains, storms and heat waves. These natural phenomena, particularly floods, have always been part of human daily life in certain regions of the world (Akindele & Todome, 2021). These are natural disasters with very serious human and material consequences, which the authorities face every year.

West Africa is one of the most vulnerable areas to climate change (Bognini, 2011). For three decades with the return of rains in West Africa and Senegal, the number of households subject to recurring floods continues to increase (Cissé et al., 2018). Senegal is one of the areas where enormous material and human losses are noted. Indeed, according to Schwarz et al. (2017), "torrential rains in 2005 caused floods in Dakar, bringing out 46 deaths, a cholera epidemic and the evacuation of 60,000 people. In 2009, floods destroyed 30,000 homes in Dakar, affected more than half a million people and caused damage and losses estimated at 44.5 billion US dollars" p 7. Still in 2009, the cost of the flooding in Senegal is estimated at 103 million USD (Government of Senegal, 2010).

Other cities in Senegal are not spared from this scourge. This is the case of the municipality of Kaffrine, which has been facing floods for decades, particularly in 2013, 2014 and 2016. Indeed, the municipality is located in a basin that constitutes an area of accumulation of runoff water. It also suffers from the inadequacy of the sanitation network. Flood management thus represents one of the major challenges for this municipality.

Certainly, strategies have been proposed to decision-makers for centuries by engineers, in particular the construction of the sanitation network, the displacement of populations occupying non-aedificandi zones, etc., to try to contain these floods. However, these strategies have so far not been able to relieve the populations (Dauphine & Provitolo, 2007) and flooding problems persist, particularly in the municipality of Kaffrine.

Any flood control strategy must be based on relevant data, in particular, spatial data at a fine spatial resolution. It must also take into account the best scale of manifestation of the phenomenon (Poulard et al., 2009). Unfortunately, most municipalities in Senegal suffer from the lack of this data. In the municipality of Kaffrine, the problem of flood risk data is even more glaring. The failure of the proposed strategies is partly linked to this problem. The production of information on the spatial distribution of flood risks is, therefore, necessary to develop assessment and prevention strategies in this municipality with very limited resources. Risk prevention is the first step in a risk management approach, because it would contribute to considerably reducing damage in the event of an occurrence (N'Guessan Bi et al., 2014).

Our objective is to contribute to the assessment and the prevention of flood risks in the municipality of Kaffrine, by producing risk indicators at a fine spatial resolution. The production of this type of information is important because it allows better targeting of interventions in space.

The data used come from surveys, ground surveys, satellite images and public institutions, producers of routine data. The use of Saaty's multi-criteria analysis (Saaty, 1977) and the geographic information system made it possible to process and analyze the data.

2. Methodology

2.1. Study Area

The municipality of Kaffrine is a locality located in the heart of Senegal, on the Dakar-Tambacounda axis, 258 km from Dakar. It is part of the department of the same name and is surrounded by the rural commune of Kahi (**Figure 1**). It currently consists of nine (9) official neighboroods (Escale Est, Escale Ouest, Diamaguéne TP, Diamaguéne centre, Diamaguéne Ndiobéne, Pèye, Mbamba, Kaffrine II Nord and Kaffrine II Sud). Its surface area is 440 ha.

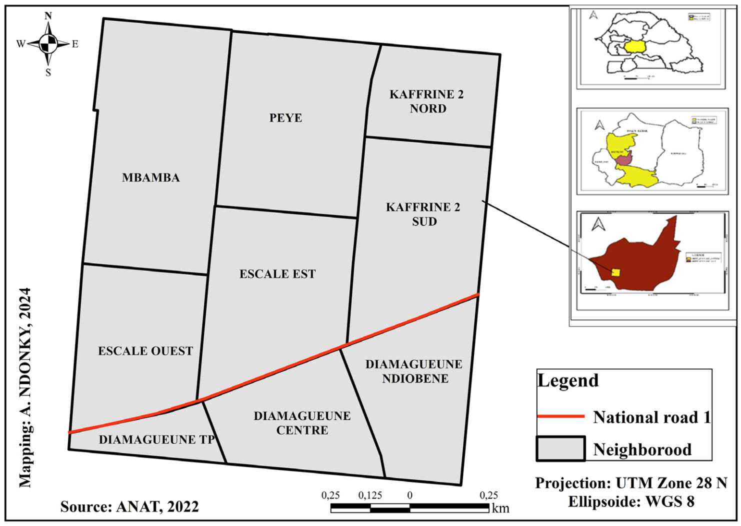


Figure 1. Location map of Kaffrine municipality.

In 2023, the population of the municipality of Kaffrine is 57,307 according to the general census of the population and housing of Senegal of 2023 (National Agency of Statistics and Demography (NASD), 2024). The economy is dominated by agriculture, livestock and forestry. It rains on average 800 mm per year; however, there is interannual variability. Temperatures are generally high, with significant variations. They fluctuate between 26 and 39˚C with an average of 29˚C.

The city is located in a vast lowland with flat relief. The contour lines determine a relief of slight depressions and mounds. Its relief constitutes to a certain extent, a difficulty for the installation of a sanitation network.

The main types of soils found in the municipality of Kaffrine are: sandy soils (Deck), clayey soils (Dior), silico-clayey soils, and lateritic soils which shelter quarries in certain places. These soils do not have the same sensitivity to the risk of flooding.

The hydrography is essentially made up of the Saloum Fossil Valley. As for groundwater, the city is irrigated by the Maestrichtian aquifer which is nearly three hundred (300) meters deep.

2.2. Definition of Concepts

2.2.1. Hazard

Hazard is a threatening event or a probability of occurrence in a region and during a given period of a phenomenon that could cause damage. It is a phenomenon resulting from factors or processes that escape, at least in part, human control (Géoconfluences, 2019). It is a natural (atmospheric, hydrological, geological or geomorphological processes), technological or geopolitical phenomenon which can occur in a given space.

Hazard is a threatening phenomenon of natural and/or anthropogenic origin, likely to affect a given space, in particular by the nature and value of the exposed elements that this space supports (people, goods, activities, etc.). It is characterized by its nature, its identity, its probability of occurrence and its frequency when it can be estimated (Gbeassor et al., 2006). According to the United Nations Disasters Relief Co-Ordinator (UNDRO, 1979), hazard can be defined as a threatening event or a probability of occurrence in a region and during a given period of a phenomenon that could cause damage. Hazard is linked to the notion of chance. In the field of risk study, hazard is defined as the probability of occurrence of a phenomenon. It is often a physical, lithospheric or climatic process.

2.2.2. Risk

The notion of risk is very close to that of uncertainty. The notion of risk is therefore relative and depends on the way in which societies conceive their fragility in the face of perils (Hangnon, 2009), refers to the possibility of a loss (Fournier d'Albe, 1979). It follows from this that risk is the probability that a potentially dangerous phenomenon will occur, and which by its characteristics can cause damage and harm in a given space, at a given moment. The concept of risk includes two explanatory factors: on the one hand, the frequency and amplitude of events that can cause damage and on the other hand, the potential for damage or vulnerability that depends on the type, value and exposure of the elements affected by these hazards. It thus joins the usual definition proposed by MATE (2001) on the concept of natural risk which is the product of hazard and vulnerability: Risk = Hazard × Vulnerability. Vulnerability is defined as a degree of damage (Veyret & Reghezza, 2005). In this study, we consider risk as the product of hazard and vulnerability.

The flood risk factors that are the subject of this study are as follows: slope, rainfall, soil type, altitude, building density, population density and level of coverage by rainwater drainage network.

Rainfall is a measure of the intensity of rain that brings water that can cause flooding. Given the unavailability of rainfall data by district and the small size of the study area (very low internal variability), we used the amounts of rainfall that fell in 2019, 2020 and 2021. In this way, we were able to measure the effect of the rain. The slope is one of the factors directly linked to the cause of flooding, because it facilitates the runoff of rainwater towards the lowlands. The type of soil plays a major role in the occurrence of floods (Guelbeogo & Ouedraogo, 2022). Altitude is an important factor, because the speed of water circulation also depends on altitude (Guelbeogo & Ouedraogo, 2022). Building density is a factor in flooding. Indeed, studies have shown that the characteristics of residential buildings can influence the occurrence or intensity of flooding (Wilhelmi & Morss, 2013; Tanguy, 2012). Population density plays a fairly significant role in the occurrence of floods, because it leads to a reduction in free space, soil compaction, which can slow down the infiltration of rainwater, prevent or slow down the runoff of the latter. The level of coverage of the rainwater drainage network is a factor to be taken into account. Indeed, the failure and lack of coverage of this essential infrastructure can therefore be a factor aggravating the vulnerability of the population (Pageon, 2008; Nicholls & Small, 2002).

2.3. Types of Data and Their Collection

Three types of data were collected. These are data on the natural physical environment (topography, rainfall, soils), urban data (population and level of coverage in the sanitation network), data on the relative importance of risk factors.

To collect the first data type, we used satellite images, Master Plan for the evacuation of rainwater for the municipality of Kaffrine and the data provided by the National Agency for Civil Aviation and Meteorology (NACAM). As for the second data type, they were collected from the NASD, the Regional Development Agency (RDA) and the National Sanitation Office (NSO). To collect the third data type, we conducted a survey of experts and stakeholders in the fight against flooding. A sample of 30 local authorities and experts was chosen to comment on the relative importance of flood risk factors. The survey consists of comparing two by two the different risk factors (hazard and vulnerability), by filling out a hazard and vulnerability matrix, presented in the form of a table. Each survey assigns a weight from one (1) to nine (9) according to the scale proposed by Saaty (1991). The survey was conducted using a tablet equipped with the Kobocollect application. This application is reliable and easy to use.

2.4. Data Processing and Analysis

2.4.1. Physical Environment Data Processing

To process and analyze physical environment data (altitude, slope), we followed the following steps. First, we made a digital terrain model (DTM) from 30 m resolution SRTM rasters provided by NASA. This model was validated by comparing the ground data with the DTM data. To do this, we used a sample of 43 ground control points spread out across the municipality and on which GPS surveys were made to measure altitude values. A correlation coefficient between the altitude values taken in the field and those obtained from the rasters was calculated. The result obtained is 0.773, closer to 1; which allowed us to validate the DTM.

The next step was to project a regular grid of 30 m × 30 m cells onto this raster to extract topographic data such as slope and altitude for each cell of the grid, by using zonal statistics method. The choice of cell size is based on the resolution of the raster used (30 m).

The topographic surveys allowed us to generate a linearization of the two existing networks using the Covadis software. The use of Google Earth Pro was necessary to obtain the topographic profiles of the area. The soil type of each neighborood was classified into categories according to its level of sensitivity to flooding using the Qgis software. Finally, for rainfall, the data was segmented into three years (2019, 2020 and 2021).

2.4.2. Multi-Criteria Analysis (MCA) to Measure the Relative Importance of Risk Factors

MCA is a method that was invented by the mathematician Thomas Saaty (Saaty, 2000; Saaty, 2008). It is intended to help the decision-maker refine his decision-making process by examining the coherence and logic of his preferences. It is a method that can be used in the quantification of qualitative criteria, through weighting. It has already been applied in different fields with success (Ramos et al., 2014; Corvin, et al., 2021; Kumar et al., 2010; Le Gallic et al., 2006). This method is able to identify and take into account the inconsistencies of decision-makers.

MCA is a rigorous method that includes a series of important steps: structuring the hierarchy, establishing priorities, and verifying the logical consistency of the analysis (Saaty, 2008). It allows for measurement of the criteria of a given situation, based on the derivation of relative priorities from pairwise comparisons sharing a common attribute (Saaty, 1994; Kendrick, 2007). **Table 1** is used to calculate the weight of each flood criterion (factor).

Table 1. Comparison matrix and calculation of its eigenvector

	C1	C2	…	Cn
C1	**1**	a12		a1n
C2	a21 = 1/a12	**1**		a2n
…			**1**	
Cn	an1 = 1/a1n	an2 = 1/a2n		**1**

In the hierarchical analysis process, the relative importance of component or criterion *i* with respect to component *j* (a_{ij}) is determined using the Saaty scale (Saaty, 1991) and is assigned to the (*i*, *j*) th position of the pairwise comparison matrix. Automatically, the inverse of the number associated with the (*j*, *i*) th position can be calculated according to the following rule (Chang et al., 2007):

$$a_{ij} > 0, a_{ji} = \frac{1}{aij}, a_{ii} = 1 \forall i \tag{1}$$

To calculate the weights of each factor, we first calculated the average of the fourteen (14) matrices called the raw value matrix proposed by the people surveyed to obtain a single matrix. This operation is valid for hazards and vulnerabilities. We then added the values of each cell for each column to obtain the total value of each column. Finally, to obtain the normalized matrix, we divided the value of each cell by the total of each column.

Once the raw matrix is filled, we add up each row. To obtain the weight of each factor, we divide each cell in the row sum column by the number of factors (hazard or vulnerability). The eigenvector (weight) indicates the order of priority or hierarchy of the characteristics studied. This result is important for the evaluation of the probability, since it will be used to indicate the relative importance of each operating criterion.

The eigenvector of the matrix can be found by the following formula:

$$Wi = \left(\prod_{j-1}^{n} a_{ij} \right)^{1/n} \quad (2)$$

Furthermore, it must be normalized so that the sum of its elements is equal to unity. To do this, simply calculate the proportion of each element to the sum using the following equation:

$$T = \left| W1/\sum Wi W2/\sum Wi \cdots Wn/\sum Wi \right| \quad (3)$$

Let T be the normalized eigenvector used to quantify and evaluate the importance of each criterion. The latter will be multiplied by the vector of weights of each factor to give the ratio of the weighted sums of the factors, the average of which gives the maximum eigenvalue (4).

$$\lambda \max = T \cdot w \quad (4)$$

where w is calculated by adding the columns of the comparison matrix.

In order to check the consistency of the response given by the respondents, Saaty (1977) proposes to calculate the CI (5). The next step is to calculate the consistency index (CI):

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)} \quad (5)$$

where, $\lambda_{\max}$: maximum eigenvalue of each factor in the matrix table and n the size of the matrix. The eigenvalue is the measure that will allow to evaluate the consistency or the quality of the solution obtained. To calculate the eigenvalue, we multiply each cell of the raw matrix by each value of the vector of the sum of the rows; which allows to obtain the vector of the sum of weighted values.

The following table shows the different values of the RI according to the number of factors.

The next step is to calculate the consistency ratio (CR) between the consistency index and the random consistency index using the following equation:

$$CR = CI/RI \quad (6)$$

where, CR is the ratio between CI and the random consistency index (RI). The RI index presented in (**Table 2**), comes from a sample of 500 positive reciprocal matrices managed randomly, whose size reaches 11 by 11.

Table 2. Random index of consistency (RI) for n = 1, 2…8 (Saaty, 1977).

n	1	2	3	4	5	6	7	8
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41

To validate the survey matrix, the *CR* is calculated (6). According to the work of Yurdakul and Tansel (2004), the *CR* value must be less than 0.1 to conclude that the pairwise comparison judgments are consistent. On the other hand, if the *CR* value is greater than 0.1 the coefficients of the matrix are inconsistent and cannot be used for the analysis (Wong & Li, 2007).

2.4.3. Database Development and Mapping

The data comes from different sources, spatial scales and different formats. It was therefore necessary to integrate them into a geographic information system. To do this, we first created a grid with cells measuring 30 m on each side to respect the 30 m resolution of the raster. This grid covers the entire extent of the municipality of Kaffrine.

We transferred the population data of the neighboroods to the cells of the generated grid, by multiplying the population density of the neighborood by the area of each cell of this neighborood. The values of the indicators of the different hazard factors (slope, soil, and altitude) were also transferred to the cells of the grid by superimposing the raster file (30 m) already corrected with the grid created and using the area statistics method. For the rainfall data, we discretized the statistical series into 3 classes representing each of the 3 years (2019, 2020 and 2021), then assigned the scores to each year according to the recorded rainfall intensity.

For the rainwater drainage network service level data, we first determined the centroids of each cell, then calculated the distance between these centroids and the nearest network line, using the distance matrix tool. Finally, the inverse of this distance was used to measure the level of rainwater drainage network coverage of each grid cell.

After entering the values of all the hazard and vulnerability factors for each grid cell, we weighted the values of each factor using the weights obtained from the multi-criteria analysis.

To map the indicators obtained, we created percentiles. The creation of percentiles consists of arranging the values of the hazard and vulnerability variables into five levels framed by the minimum and maximum of each variable and for each of the three years.

2.4.4. Validation of the DTM

We used the Shuttle Radar Topography Mission (SRTM) data (30 m spatial resolution raster) provided by NASA to generate the Digital Terrain Model (DTM) (altitude map). To verify the validity of the results obtained, we took 43 ground control points, where altitudes were measured by a differential GPS. The altitudes obtained from the SRTM data were compared with those from the measurements taken at the ground control points, by calculating the Pearson correlation coefficient. The result obtained is 0.77, closer to 1; hence the validation of the DTM.

2.4.5. Validation of Flood Risk Maps

To validate the flood map, we took altitude measurements of 30 points well distributed in the study area. These points were projected onto the flood risk maps.

The result shows that low-lying points are mostly located in high flood risk areas. This allowed us to validate our flood risk maps.

3. Results

3.1. Weight of Risk Factors

The results of the survey on the perception of experts and stakeholders on the relative importance of flood risk factors are contained in Table 3 and Table 4.

Regarding the hazard factors, the results indicate a greater importance given to rainfall and slope/altitude (Table 3). The water retention capacity of soils also has a significant weight, but lower than those of the previous factors. The factor with the lowest weight is the level of soil impermeability. Table 4 contains the results of the measurement of vulnerability factors. According to these results, the density of buildings has the greatest weight, followed by population density. The level of coverage by rainwater drainage network comes last.

Table 3. Matrix of hazard factors.

Factors	Rain	Slope/ altitude	Water holding capacity	Soil impermeability level	Sum for each line	Weight of each factor	Weighted sum of values	Ratio of weighted sums	Lamda Mmax
Rain	0.522	0.643	0.471	0.400	2.035	0.509	2.596	5.103	4.21
Slope/ altitude	0.17	0.214	0.353	0.300	1.041	0.260	1.276	4.904	
Water holding capacity	0.174	0.071	0.118	0.200	0.563	0.141	0.564	4.006	
Soil impermeability level	0.130	0.071	0.059	0.100	0.361	0.090	0.258	2.856	

Table 4. Vulnerability factors matrix.

Factors	Population density	Building density	Level of coverage in rainwater drainage network	Sum for each line	Weight of each factor	Weighted sum of values	Ratio of weighted sums	Lamda Mmax
Population density	0.65	0.69	0.56	1.9	0.63	1.78	2.81	3.11
Building density	0.22	0.08	0.33	0.63	0.21	0.82	3.91	
Level of coverage in rainwater drainage network	0.13	0.08	0.11	0.32	0.11	0.28	2.61	

To validate the survey matrix on the perception of the relative importance of the weights of flood risk factors, we calculated the consistency index (*CI*) and the consistency ratio (*CR*). The results are contained in **Table 5**. They show that the *R* has a value lower than 0.1, which allows us to say that our consistency matrix is valid. Indeed, according to the Saaty method (Saaty, 1977), when the value of *R* is lower than 0.1, we can conclude that the pairwise comparison judgments are consistent.

Table 5. Values of the validation indicators of the survey matrix on the perception of the relative importance of the weights of flood risk factors.

Indicators	Vulnerability	hazard
CI	0.053	0.072
RC	0.092	0.080

3.2. Very High Hazard in the Northeast, in the Center

Knowing that we have only one rainfall station in the municipality of Kaffrine, the rainfall data for a single year do not experience any intra-municipal variation. Also, to have a variation in these data, we used the rainfall data for three years (2019, 2020, 2021). In addition, it should be noted that rainfall often changes from one year to the next. This allowed us to highlight the effect of rain on the occurrence of floods.

The additive combination of the hazard factor layers gives the maps below. These maps were developed for the years: 2019, 2020, 2021 (**Figure 2**) to be able to follow the dynamics of the phenomenon over time. We can see that the hazard is very high over the entire northwest part, part of the south and the center of the municipality. The North-East, East, South-East and South-West parts are weakly exposed to flood hazard.

The results obtained also show that the hazard factor is almost the same in space for the years 2019, 2020 and 2022. The temporal dynamics do not seem to have an influence on the probability of flooding in the city of Kaffrine.

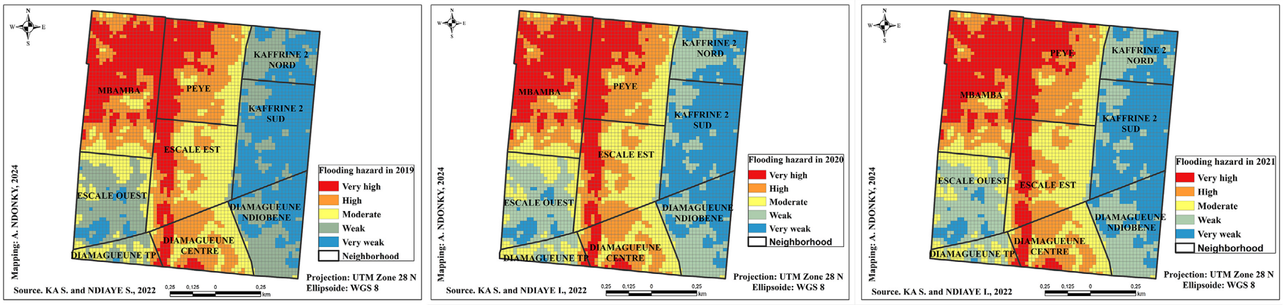
3.3. Higher Vulnerability in the North

According to the results of our field investigations, the vulnerability factors did not change significantly during the three reference years (2019, 2020 and 2022). Therefore, we considered it more relevant to produce a single vulnerability map for these three years.

Figure 3 highlights the spatial distribution of the level of vulnerability to flooding in the city of Kaffrine. It can be seen, in general, that the level of vulnerability is higher in the north, while the south records low levels of vulnerability. The southern part of the city records the lowest risk levels. In addition, there are pockets of very low vulnerability in the center and enclaves of high vulnerability in the southwest.

3.4. Proportion of the Population Exposed to Different Risk Levels

Table 6 contains the percentage of the population exposed by risk level and by year. In 2019, 13.64% of the population was exposed to a very high-risk level and 15.28% to a high level of flooding. Almost the same proportions are observed in 2020 and 2021. A significant share of the population (nearly 29%) is exposed to high and high-risk levels.



(a) (b) (c)

Figure 2. Hazard maps (2019-2020-2021).

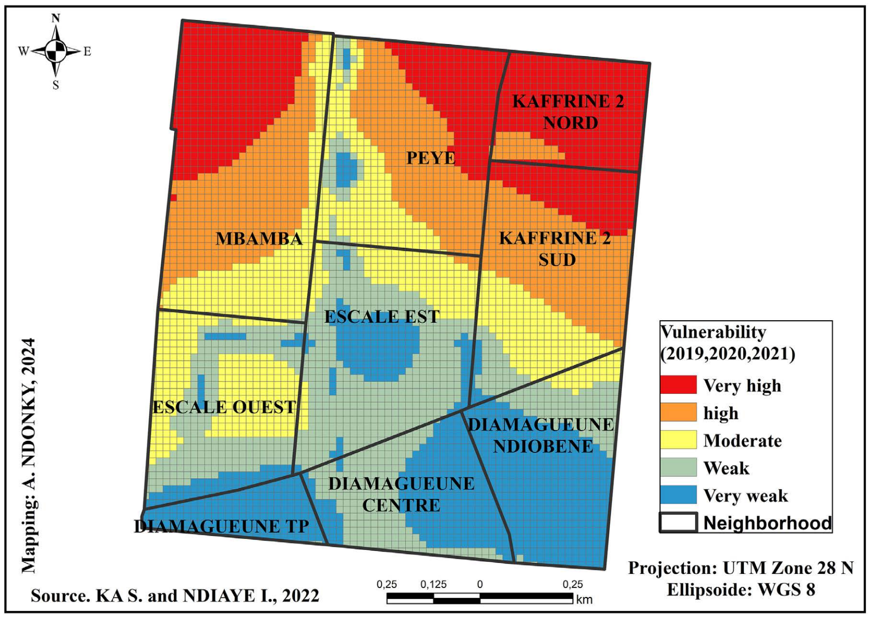


Figure 3. Vulnerability map.

Table 6. Percentage of population exposed to the risk of flooding.

Risk level	Percentage of population exposed		
	2019	2020	2021
Very high risk	13.64	12.08	12.72
High risk	15.28	17.28	16.31
Moderate risk	11.66	11.13	11.55
Weak risk	17.18	17.36	17.34
Very weak risk	42.23	42.15	42.08
Total	100	100.00	100.00

3.5. Higher Risk in the Northwest

As a reminder, this risk map results from the cross-referencing of the hazard map with the vulnerability map. By applying the percentile method, we distinguished 5 levels of flood risk: very high, high, moderate, low and very low. Figure 4 shows the spatial distribution of the flood risk level in the municipality of Kaffrine.

In general, we note that the flood risk level is higher in the northwest, particularly in the neighboroods of Mbamba, Peye, part of Diamagueune Centre. We also note pockets of very high flood risk level in the southwest, particularly in the neighboroods of Diamagueune centre and Escale ouest.

The areas that record the high flood risk level are found further northeast and north-central, particularly in the neighboroods of Bamba, Peye and in the northeast, particularly in the neighboroods of Kaffrine nord and Kaffrine sud. Moderate risk is recorded further north-east and in the centre, especially in the districts neighboroods of Kaffrine Nord and Kaffrine Sud, Escale Est, Escale Ouest.

Low risk areas mainly concern the neighboroods of Diamagueune Centre, Kaffrine Nord and Kaffrine, Escale Est, Escale Ouest. As for very low risk areas, they are found further south, in the center and center-west; they concern in particular the neighboroods of Diamagueune Ndiobéne, Diamagueune TP, Kaffrine Sud, Escale Est, Escale Ouest.

4. Discussion

In this study, we used multi-criteria analysis (Saaty, 1977) combined with GIS to obtain results that allow us to assess and prevent the risk of flooding in the municipality of Kaffrine.

The GIS made it possible to take into account the spatial interactions between factors, as well as to effectively visualize several risk factors. Multi-criteria analysis offers the possibility of simultaneously taking into account the relative importance of several risk factors. The combination of these two methods made it possible to produce risk maps. The concordance of the risk maps with field observations shows the validity of our results and tends to support our methodological choices.

The areas most exposed to the risk of flooding are located in the north and center. Indeed, these areas are located in areas of lower altitudes (4 m), low slope, and clayey soils impermeable to rainwater infiltration. In addition, these neighbor

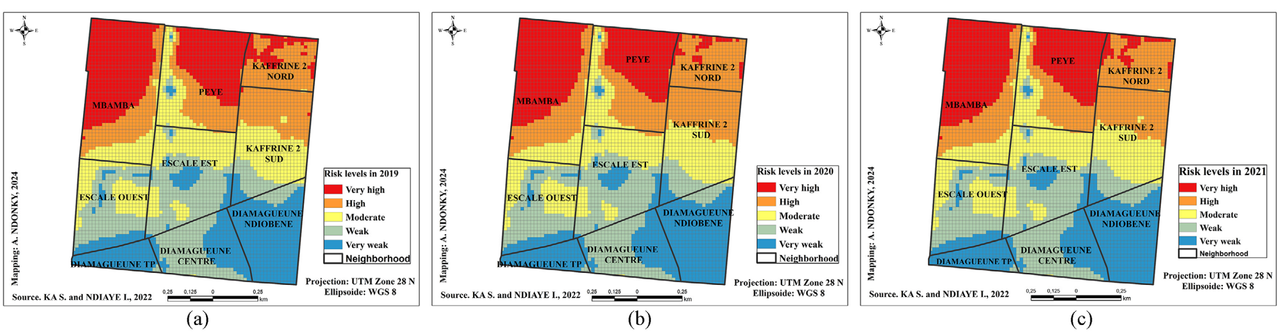


Figure 4. Risk maps.

hoods suffer from the absence of a rainwater drainage network. On the other hand, the neighboroods located in the south of the city are exposed to a low risk. This is explained by the presence of sandy soils permeable to rainwater, steep slopes and high altitudes.

Our study has limitations. First, there is the weakness of NACAM rainfall data, since the latter do not allow us to capture the intra-municipal variability of the amount of rain that has fallen. Then, the second limitation is the lack of socio-economic data, the poor characterization of the built environment (functions/activities) that would have allowed us to refine the assessment of vulnerability factors. Finally, the small size of the study area did not allow us to take into account the spatial variability of the effects of certain factors such as rain.

Given the research objective and the methodology used, these limitations can be considered negligible. To our knowledge, this type of study has never been conducted in the municipality of Kaffrine; which makes it difficult to compare its results with those of other studies on the same theme and the same zone. Nevertheless, we will compare them with those of studies carried out elsewhere.

Thus our results can be compared to those of the work of Lai et al. (2015) on the Dongjiang River basin (China), which also revealed that high risk areas have low altitudes, gentle slopes, suitable for receiving runoff water. Like us, these authors used the Geographic Information System, multi-criteria analysis to assess the flood risk. For validation, if we used ground control points, these authors, on the other hand, used historical data. Criado et al. (2019) also used the GIS tool to assess the flood risk in Spanish urban areas, particularly in Salamanca.

Nanfack (2021) used hierarchical multi-criteria analysis to assess flood vulnerability in Cameroon. His study made it possible to spatialize flood vulnerability. The specificity of our study compared to the latter is that ours made it possible to assess, at both vulnerability and hazard. Guélbéogo and Ouédraogo (2022) also used hierarchical multi-criteria analysis and GIS to map flood risks in the Kou watershed in Burkina Faso. In this study, they combined seven factors (rainfall, slope, altitude, topographic humidity index, soils, land use, and distance to drainage) in a geographic information system (GIS) environment. However, the authors did not say anything about the validation of the results. Similarly, they did not assess the relative importance of flood factors to each other. Therefore, our study has a clear advantage over that of these authors.

Using field surveys, hydrodynamic modeling, and remote sensing, Tanguy (2012) mapped urban flood risk adapted to crisis management in the municipality of Saint-Jean-sur-Richelieu, located in southern Quebec. This mapping, like our results, made it possible to locate populations exposed to flood risk.

Mojaddadi et al. (2017) combined the frequency ratio and the support vector machine (SVM) method to estimate flood risk in the Damansara watershed in Malaysia. These authors, like us, used altitude, slope, and soil type as flood factors to assess flood risk. For flood risk mapping, they, like us, used percentiles (5 classes). These results tend to reinforce the relevance of our methodological choices.

Ndour et al. (2020) used a multidisciplinary approach to study flooding in the Sampathé neighborood of Thiès (Senegal). In this study, only topographic factors and soil type were taken into account. Our contribution to the work of these authors is that we took into account vulnerability factors, assessed the relative importance of each risk factor rigorously, using the Saaty method (Saaty, 1977).

Akallouch et al. (2024) highlight areas exposed to the risk of flooding, particularly in the river valley (low altitude areas). This study, like ours, shows the importance of GIS in the production of useful information for understanding the spatial dimension of various phenomena and decision-making. However, our study has an advantage over that of these authors. Indeed, in this study, the authors used only the GIS, while ours combined the GIS and the MCA to take into account the difference in the weight of risk factors, and thus better enrich the results. In addition, we have produced maps showing different levels of risk, the percentages of population exposed by level of risk, which makes it possible to refine knowledge of risk and better plan intervention actions.

Our results have provided a better understanding of the flood phenomenon in the municipality of Kaffrine, since to our knowledge no study of this kind has been conducted in this locality. Therefore, our study is an important scientific contribution.

The results of this study may be useful for the prevention and control of floods in Senegal, particularly the municipality of Kaffrine. Indeed, the methodology of flood assessment and mapping is, with the development of geographic information systems and spatial analysis in recent years, a popular tool in natural risk management and urban planning. Thus, the identification of high flood risk areas has made it possible to produce important information to target interventions in space. From this point of view, our study is an important contribution to decision-makers.

5. Conclusion

The objective of this study was to show the contribution of GIS and multi-criteria analysis to the assessment and prevention of flood risks in the municipality of Kaffrine. It was a question of producing the flood risk map by taking into account the interaction of several flood risk factors simultaneously. This objective was achieved because at the end of our study, we can retain the following lessons.

The study made it possible to establish the flood risk map in the municipality of Kaffrine, to highlight the different categories of flood risk space, in particular the areas at high risk of flooding. The risk associated with the type of soil is higher than that relating to the slope.

From a methodological point of view, the use of a method combining GIS and multi-criteria analysis, by allowing the consideration of several factors and their interaction in space, made it possible to enrich the results.

Concerning flood control policies, this study provides important elements to better assess and prevent floods. It also allows to better target intervention areas, to correct socio-spatial inequalities of exposure to flood risks. Indeed, the flood risk maps produced constitute useful instruments for organizing flood prevention and control actions at a local level.

In view of the limitations highlighted above, improvements can be made to refine flood risk mapping. Thus, in future studies, it will be necessary to refine the spatial resolution of population data, buildings, rainfall, and soil type to improve the measurement and analysis of risk indicators. It is also important to take into account socio-economic aspects, and the functions of buildings in order to improve the measurement of hazard risk and, more generally, flood risks. The development of dynamic risk maps would also be very beneficial for local authorities involved in flood control.

Finally, given that our approach has been validated in the case of the commune of Kaffrine, it could, from a comparative perspective, be applied to other communes in Senegal.

Conflicts of Interest

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

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