International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-12 Issue-2, December 2022

Climate Vulnerability of Photovoltaic Energy Systems using GIS: Case of the Plateau Department

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***Abstract**: Benin has a large potential (3.5-5.5 kWh/m²/day) for solar photovoltaic energy production. This daily energy production, which mainly depends on solar radiation, also varies considerably, depending on climatic parameters. The Plateau department is an industrial zone where mainly clinker and cement are mined and processed. In such an environment of dust production, meteorological data are very dynamic and act as input parameters or sometimes disruptors of the photovoltaic energy conversion chain. The aim of this paper is to determine the appropriate location of the photovoltaic field for optimal production of electrical energy, in the plateau department of Benin. The analysis is based on the multicriteria decision-making method (MCDM) and Analytic Hierarchical Process (AHP), using a Geographic Information System (GIS). ArcGIS 10.8 software was used to classify and weight the different vulnerability criteria (Global Horizontal Irradiation, Temperature, Wind Speed, Wind Direction, Precipitation, Relative Humidity, Cloud cover, and Aerosol), in order to determine the optimal photovoltaic power generation area by overlaying the layers. The result shows that solar irradiation is the most important criterion for better production of photovoltaic energy whose weight of 46.06% is the highest, and aerosol (dust), the lowest weight of 2.43%, considerably reduced energy production. The northern zone from 7°35'0"N-7°39'0"N of the commune of Ketou is therefore the best site for optimal production, considering the parameters studied.*

***Keywords**: AHP, Benin, Environment, Multicriteria, Optimal, Renewable.*

I. INTRODUCTION

To prevent the earth from heating up by more than 1.5°C by 2050, 70-85% of electricity production must come from renewable energy (GEIC. 2018) [1]. The Beninese government adopted (October 2020) the National Renewable Energy Development Policy (PONADER), with the aim of making renewable energies the priority source of sustainable and optimal satisfaction of national energy needs by 2030 [2]. The emphasis is then placed on photovoltaic (PV) production, given the large solar energy potential of the country (3.5-5.5 kWh/m2/day).

In Benin, despite the need to exploit solar PV, especially in the plateau, the environmental conditions of the area can be a blockage. Environmental and meteorological data are very dynamic and act as input parameters or sometimes disruptors of the photovoltaic energy conversion chain. The main meteorological parameters are sunshine, temperature, precipitation, wind speed, humidity, and cloud cover. Dust density, an environmental parameter, is also very important to take into account because of the activities developed in the area for the choice of the site. The energy received by the solar cells is very variable because of the disturbances of the light rays by climatic and environmental parameters. The light rays are either partially or totally absorbed or deviated depending on the season by these parameters. To better estimate the influence of these criteria on photovoltaic production, the collection, classification, and weighting of climatic data by geographical area are essential. The technique based on the Analytical Hierarchy Method (AHP) in a Geographic Information System (GIS) environment is often used [3], [4].

Therefore, a multi-criteria analysis of the influence of climatic and environmental parameters is essential to better appreciate the choice of PV energy production sites [5]. This AHP method was developed by Thomas Saaty in 1975 [6]. Several climate criteria are used in the literature for peer comparison analysis, but they are often not exhaustive.

This paper aims to elaborate a vulnerability map of a photovoltaic energy source to the variability of climatic and environmental criteria, using a multi-criteria decision support technique, based on the AHP method. This would enable the choice of the best site for the production of electric energy. No study of this nature has been carried out in this area despite the importance and nature of the industrial activities developed in the area, especially cement production.

The remainder of the work, presents in the second part, a literature review; details in the third part, the materials and methods used for the determination of the most vulnerable locations. The fourth part of the work presents the discussions of the obtained results, and finally, the conclusion and research tracks.

Manuscript received on 16 November 2022 | Revised Manuscript received on 20 November 2022 | Manuscript Accepted on 15 December 2022 | Manuscript published on 30 December 2022.

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II. LITERATURE REVIEW

Some studies in the literature using the AHP method, have been based on a variety of criteria, for the selection of the photovoltaic power generation site. The following criteria are the most studied, and influence the photovoltaic energy yield:

- Global Horizontal Irradiation (GHI)

A study carried out shows that, the best location for a photovoltaic field is the area where the GHI power is high [7].

- Temperature

The performance of a PV system increases at temperatures below 25°C, but each 1°C increase results in a 0.4% to 0.5% reduction [8].

- Relative humidity

The shortwave radiation is absorbed by aerosol and water vapor particles [7], [8]. Water droplets can cause a large accumulation of dust on the PV surface, resulting in poor performance of the PV panel [9].

- Average annual precipitation

The energy production of solar PV fields decreases as a function of average annual precipitation because part of the shortwave solar radiation is absorbed by water droplets [10].

- Wind speed

The wind speed plays an important role in the heat removal from the surface of the PV cell [9], which in turn leads to better efficiency. In addition, there is a sharp decrease in the performance of solar cells during low wind [11]. Ahmad Vasel and Frantzis Iakovidis [12], recommend the realization of PV plants, not equipped with a solar tracking system, in the northern hemisphere, and sites with strong and frequent southern winds.

- Wind direction

If the wind direction faces the surface of PV cells, the air movement will remove some of the dust particles accumulated on it [13]. Therefore, the more the dominant wind direction from the south faces the surface of PV cells installed in the northern hemisphere, the more solid particles are removed [14].

- Cloudiness

Clouds reflect shortwave solar energy, on average 21% [15]. Therefore, the high cloudiness values, cause a decrease in the energy production of PV modules.

- Dust density

PV module performance decreases exponentially with dust accumulation [16]. The high values of higher rank classes correspond to the low performance of PV modules.

Other MCDM techniques are also used, such as weighted linear combination (WLC), elimination and choice translation reality (ELECTRE), and technique for order preference by similarity to ideal solution (TOPSIS) [17]. The AHP method is more practical and more used to obtain a decision with an accepted consistency ratio.

III. MATERIALS AND METHODS

A. Study site

The study area (Fig. 1) selected for this study is the Plateau department, covering an area of 3264 Km², equivalent to 3% of the country's surface. It is located, between the meridians 2°24' and 2°47' East longitude and the parallels 6°32' and 7°39' North latitude, and has a 58% electricity coverage. It is bordered to the East by Nigeria, to the West by the department of Zou, to the North by the department of Colline, and to the South by the department of Oueme. The department of the plateau is subdivided into 5 communes: Adja-Ouere, Ifangni, Ketou, Pobe, Sakete [18]. The total population is 407,116 inhabitants with a density of 125 inhabitants/km² [18]. The department enjoys a subtropical climate with two rainy seasons (April to mid-July) and two dry seasons (mid-September to October) in the year [19]. The soil is very rich in limestone and clay. The government has given authorization to two mining companies for the exploitation and production of clinker and cement.

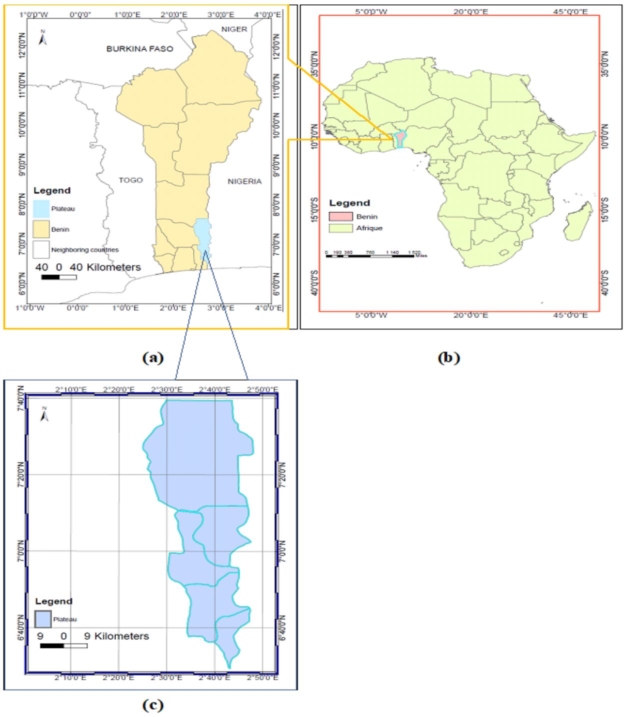

Fig. 1. Study area location map (a) Map of Benin (b) map of Africa (c) Map of Plateau department

B. Study Materials

The data used in this study are obtained by downloading from the various sites of NASA (National Aeronautics and Space Administration) [20], in Geo TIFF format and IEA (International Energy Agency) in Net CDF (Network Common Data Form) format [21]. The set of data sources with shapefile layer GIS files for the mapping of Africa and Benin is contained in Table I. The Plateau Department in Benin with the five communes are extracted from ArcGIS 10.8 software [22], [23].

Table- I: Data sources

Nr.	Data format	Data source
1	Shapefile	https://www.diva-gis.org/gdata
2	Shapefile	https://open.africa/dataset/africa-shapefiles
3	Geo TIFF	https://neo.gsfc.nasa.gov/view.php
4	Net CDF	http://weatherforenergydata.iea.org/

Retrieval Number:100.1/ijeat.B39211212222
DOI: 10.35940/ijeat.B3921.1212222
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C. The Work Plan

To determine the most suitable location for maximum production, parameters influencing PV production were identified. Eight criteria (Table II) were selected because of their dominant influences on the performance characteristics of the PV modules.

The proposed methodology consists of:

- To identify in the literature the comparison values by pair of criteria used by international experts in similar studies and the weights obtained from these criteria by the AHP method, of Thomas Saaty [6], for the determination of the best location of a PV field.
- Extract and classify the raster data for each criterion in the study area on a scale of 1 to 5 (very low, low, moderate, high, and very high) using Spatial Analyst tools in ArcGIS 10.8 software.
- Elaborate the comparison matrix by Thomas Saaty [6] criteria, using the axioms of reciprocity and consistency.
- Normalize the comparison matrix, and determine the weight of each criterion by the AHP method. Check if the consistency ratio (CR) is less than 0.1, then the comparison is consistent; if not, repeat the comparison matrix.
- Establish the vulnerability mapping by overlaying the raster layers of each criterion, using the AHP method of ArcGIS 10.8.

Fig. 2, summarizes the different steps of the geoprocessing process.

Table-II: Criteria

Nr.	Criteria	Sub-criteria	Unit
1	Climate	Wind direction	Degree, 0° East
2		Wind speed	m/s
3		Precipitation	mm
4		Global Horizontal Irradiation (GHI)	J/m²/h
5		Temperature	°C
6		Cloud cover	%
7		Relative humidity	%HR
8	Environment	Aerosol	µg/m3

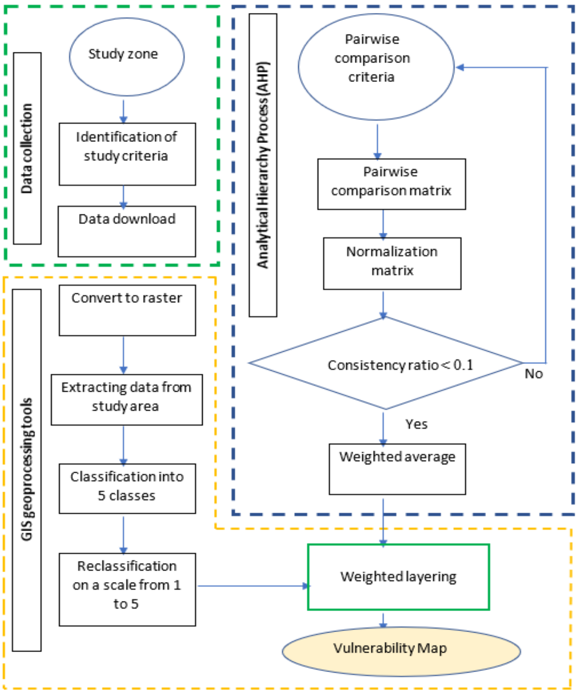

Fig. 2. Data processing flow diagram

D. The AHP-MCDM Method

Given the variability of the solar deposit, the yield to be obtained varies according to time and space and becomes uncertain. To obtain maximum energy production, an analysis of the climatic and environmental criteria acting on the photovoltaic conversion chain becomes essential. Several meteorological and environmental parameters, which vary greatly, influence photovoltaic production. The multi-criteria or multi-dimensional analysis becomes complex to identify the most appropriate location for the implementation of a photovoltaic field.

The AHP method, developed in 1975 by T. L. Saaty [6], is used to solve this problem. The method is based on a comparison by pair of criteria, to obtain values according to a nine-point scale, contained in Table III. The process of developing cell vulnerability indices is carried out in 5 steps:

1)-Elaboration of the comparison matrix by pair of criteria

These values lead to a positive reciprocal square dominance or weight matrix A for establishing a relationship between the criteria [6].

$$A = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} \quad (1)$$

According to Saaty's theory of reciprocity,

$$a_{ij} \succ 0, \forall (i,j), a_{ij} \times a_{ji} = 1 \quad (2)$$

The advantage of this method is that it allows verification of the consistency of the judgment between the criteria. For this, the matrix is said to be consistent [6], if:

$$\forall (i,j,k), a_{ik} \times a_{kj} = a_{ij} \quad (3)$$

But this equation is not often verified, and Thomas Saaty introduced a notion of a reasonable level of inconsistency acceptable by the calculation of the Coherence Ratio (CR).

2)-Normalization and standardization

After the constitution of this comparison matrix by pair of criteria, the normalization consists in dividing the values of each column by the sum of the values of the same column. This yields a normalized matrix whose values $\overline{a_{ij}} \prec 1$.

$$\overline{a_{ij}} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad (4)$$

3)-Weighted average

The weight of each criterion is obtained by averaging the new values of each row of the normalized matrix.

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$$\overline{w_i} = \frac{\sum_{i=1}^{n} \overline{a_{ij}}}{n} \quad (5)$$

4)-Consistency ratio

To ensure that the pairwise comparison between the criteria is consistent, the consistency ratio CR is calculated.

$$CR = \frac{CI}{RI} \quad (6)$$

with

$$CI = \frac{\lambda_{\max} - n}{(n-1)} \quad (7)$$

CI is the random index (Table IV), n, the number of criteria and λ_{max}, the maximum eigenvalue of the comparison matrix. If the $CI \prec 0.1$, then the degree of consistency is considered satisfactory [24].

5)-Vulnerability indices

For each pixel *k* of the study area, the vulnerability index vm is calculated by applying the following formula [3]:

$$vm_K = \sum_{i=1}^{n} x_{ki} \times w_i \quad (8)$$

x_{ki} is the rank of each criterion i, after classification, on a scale of 1 to 5 (very low, low, moderate, high, and very high), w_i, is the weight of the corresponding criterion, obtained after the normalization of the comparison matrix by pair of criteria.

Table-III: Thomas Saaty scale

Scale intensity value (a_{ij})	Definition
1	Criteria i and j are of equal importance
3	Criterion i is of moderate importance more than j
5	Criterion i is of strong importance than j
7	Criterion i is of very strong importance than j
9	Criterion i is of extreme importance than j
2,4,6,8	Intermediate values between two judgments in case of need for compromise

Table- IV: Random indices (RI) of different number

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

IV. RESULTS AND DISCUSSIONS

The values of pairwise comparison are collected in the matrix in Table V and validated by consistency ratio CR according to the AHP method. The value of the random consistency index (RI) used for 8 criteria, to calculate CR, is 1.41. The study carried out in the Plateau Department in Benin using the AHP method, is approved by a CR consistency rate of 4.2%. The accepted consistency threshold is 10%. As the matrix is approved, the geoprocessing tools of ArcGIS are used with the weights obtained to overlay the different layers and the resulting layer by the AHP method. The most important criterion for better production of photovoltaic energy is solar irradiation with the highest weight (46.06%) among other criteria studied, followed by temperature with a weight coefficient of 21.09% (Table VI). The criteria such as aerosol, humidity, and cloudiness obtained the lowest weight value, 2.43%, 3.86%, and 3.92%, respectively, after the pairwise criteria comparison. These weight values confirm that, these 3 criteria (aerosol, humidity, and cloudiness) considerably reduce the production of photovoltaic energy. The results presented in Fig. 3, Fig. 4, Fig. 5, and Fig. 6, show the classification of each layer into 5 classes using the ArcGIS geoprocessing tools. The weighting and classification results obtained from all criteria are presented in Table VI.

Fig. 7, shows the resulting map of the overlay of the different maps (Fig. 3, Fig. 4, Fig. 5, and Fig. 6) of criteria classifications. The final map is obtained from the following equation, with the corresponding weight coefficient as calculated by the application of AHP:

$$vm_k = (46.06 \times I_k + 21.09 \times T_k + 11.40 \times S_k + 6.68 \times D_k)\% \quad (9)$$
$$+ (4.80 \times P_k + 3.63 \times H_k + 2.43 \times A_k + 3.92 \times C_k)\%$$

where vm_k is the final weighting value of the raster cell k, according to the AHP calculation method; I_k, T_k, S_k, D_k, P_k, H_k, A_k, C_k, are respectively the rank of Global Horizontal Irradiance, Temperature, Wind Speed, Wind Direction, Precipitation, Relative Humidity, Aerosol, and Cloud Coverage for each cell k. The result is classified into 3 main zones: the center from 6°50'0"N-7°35'0"N, a southern zone below 6°35'0"N-6°50.0"N, and a northern zone 7°35'0"N-7°39'0"N, which are respectively less, moderately, and highly indicated for photovoltaic production, with a cell weighting value from lowest to highest.

Table V: Comparison matrix of selected criteria

Criteria	I	T	S	D	P	H	A	C
Global horizontal irradiation (I)	1	5	5	6	8	7	9	9
Temperature (T)	1/5	1	3	4	5	5	4	4
Wind Speed (S)	1/5	1/3	1	2	3	5	5	3
Wind Direction (D)	1/6	1/4	1/2	1	2	2	3	2
Precipitation (P)	1/8	1/5	1/3	1/2	1	2	3	1
Relative Humidity (H)	1/7	1/5	1/5	1/2	1/2	1	2	2
Aerosol (A)	1/9	1/4	1/5	1/3	1/3	1/2	1	1/2
Cloud cover (C)	1/9	1/4	1/3	1/2	1	1/2	2	1

V. CONCLUSION

In Benin, the rate of electrification in general, and in rural areas particularly, is very low. It is therefore important to increase energy production through renewable energy sources. The present study has shown that the most suitable location in the Plateau Department, for better production of photovoltaic energy, taking into account the influence of the variability of the climatic and environmental parameters studied, is a northern zone, from 7°35'0"N-7°39'0"N in the commune of Ketou, located in the north of the Plateau Department. In this study, the technique of multicriteria decision support with the AHP method of comparison by pair of criteria (GHI, temperature, wind speed, wind direction, precipitation, cloud cover, humidity, aerosol) is used in a geographic information system environment and allowed the identification of areas by order of convenience according to the weighted values of vulnerability calculated by the geoprocessing tools of ArcGIS 10.8. Fig. 7 shows the ranking of the areas according to the vm_k weight values of the geographical cells.

Retrieval Number:100.1/ijeat.B39211212222
DOI: 10.35940/ijeat.B3921.1212222
Journal Website: www.ijeat.org

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The south and the extreme north, have more favorable photovoltaic energy production conditions than the center of the Plateau department. Beyond this mapping (Fig. 7), as a decision support tool, elaborated from the analysis of climatic and environmental criteria, to choose the best location for the installation of a solar power plant, other social and economic studies are also necessary to make the investment profitable.

Table- VI: Criteria classification and weighting

Criterion	Unit	Class	Class ranges and ratings	Class rantings	Weight (%)
Global horizontal irradiation	j/m²/h	<709 839	Very Low	1	46.06%
		709 839,18 - 710 882,87	Low	2	
		710 882,87 - 731 495,65	Moderate	3	
		731 495,65 - 755 761,34	High	4	
		755 761,34- 776 374,12	Very high	5	
Temperature	°C	<26,94	Very high	5	21.09%
		26,94 - 27,31	High	4	
		27,31- 27,87	Moderate	3	
		27,87- 27,90	Low	2	
		27,90 - 27,98	Very Low	1	
Wind speed	m/s	<1,69	Very Low	1	11.40%
		1,169 -1,80	Low	2	
		1,80 -1,88	Moderate	3	
		1,88 - 1,98	High	4	
		1,98 - 2,60	Very high	5	
Wind direction	°	<40,57	Very Low	1	6.68%
		40,57 - 43,65	Low	2	
		43,65 - 47,12	Moderate	3	
		47,12 - 49,44	High	4	
		49,44 - 51,93	Very high	5	
Precipitation	mm	<0,031	Very high	5	4.80%
		0,031 - 0,034	High	4	
		0,034 - 0,045	Moderate	3	
		0,045 - 0,066	Low	2	
		0,066 - 0,091	Very Low	1	
Relative humidity	%	<68,14	Very high	5	3.63%
		68,14 - 70,61	High	4	
		70,61- 73,75	Moderate	3	
		73,75 - 78,62	Low	2	
		78,62 - 82,44	Very high	1	
Aerosol	Ug/m³	1 - 25	Very high	5	2.43%
		25 - 50	High	4	
		50 - 98	Moderate	3	
		98- 192	Low	2	
		192- 255	Very Low	1	
Cloud coverage	%	<56,10	Very high	5	3.92%
		56,10 - 56,98	High	4	
		56,98 - 58,10	Moderate	3	
		58,10 - 59,55	Low	2	
		59,55 - 59,84	Very Low	1	

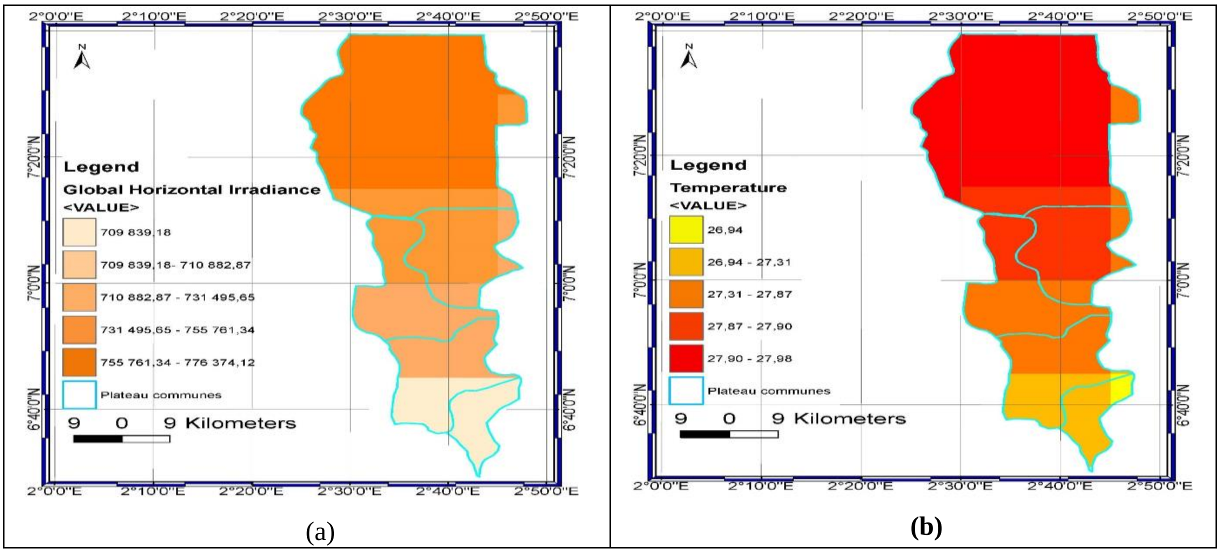

Fig. 3. Classification of criteria (a) GHI (b) Temperature

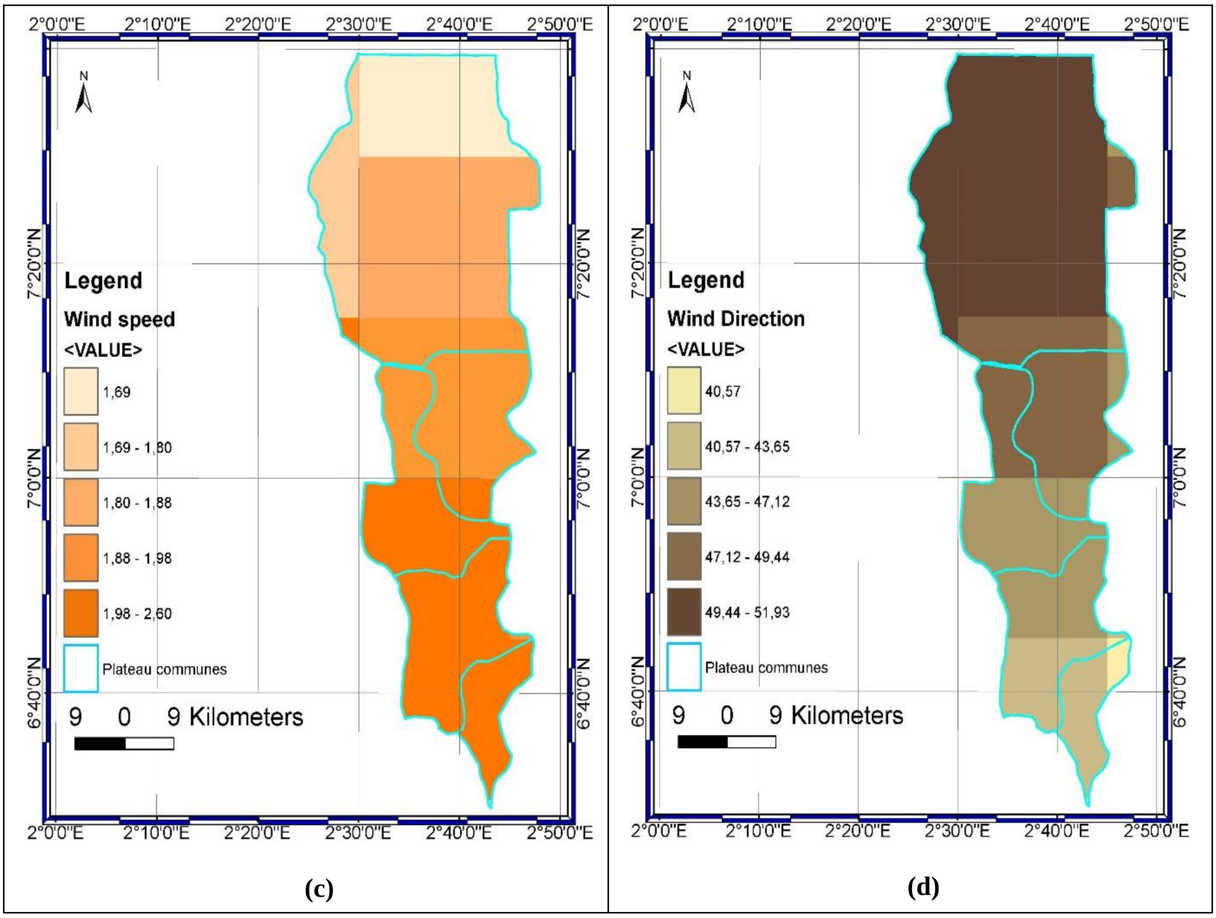

Fig. 4. Classification of criteria (c) Wind speed (d) Wind direction

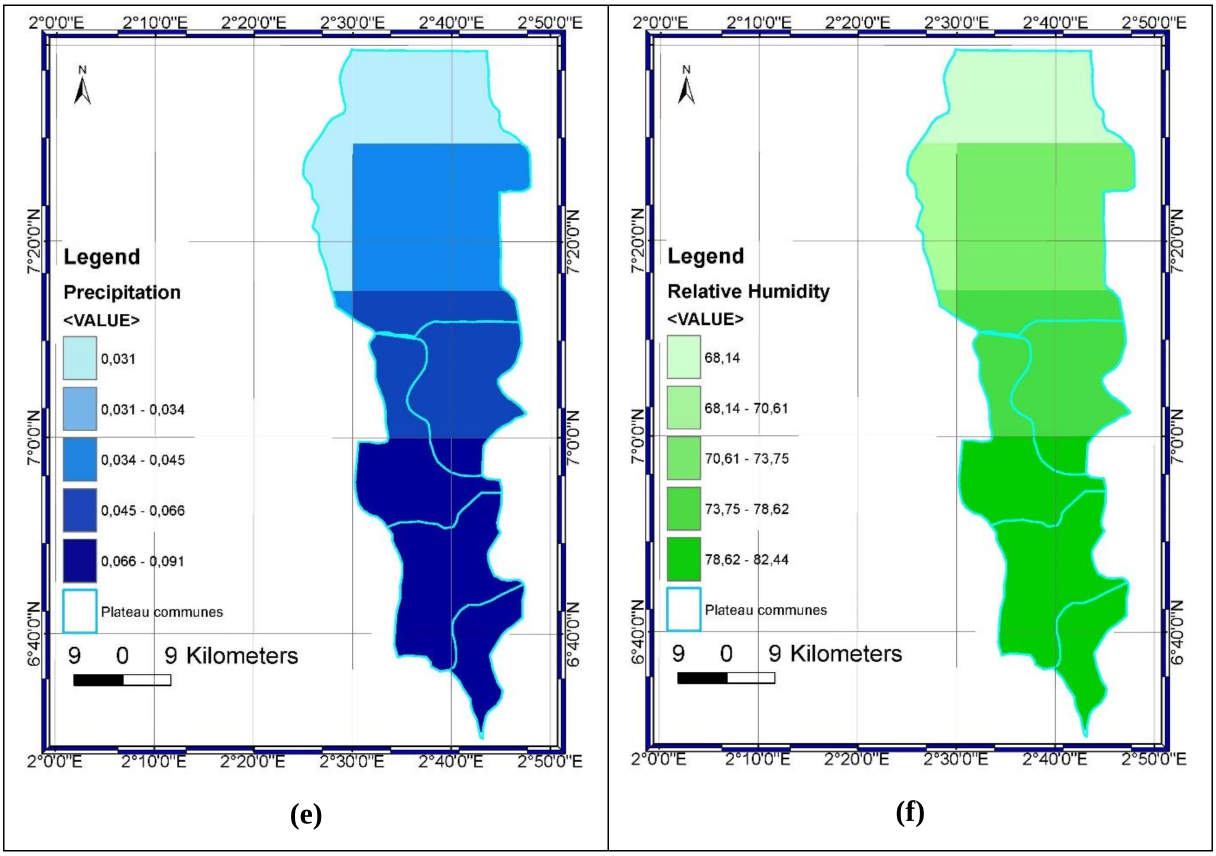

Fig. 5. Classification of criteria (e) Precipitation (f) Relative humidity

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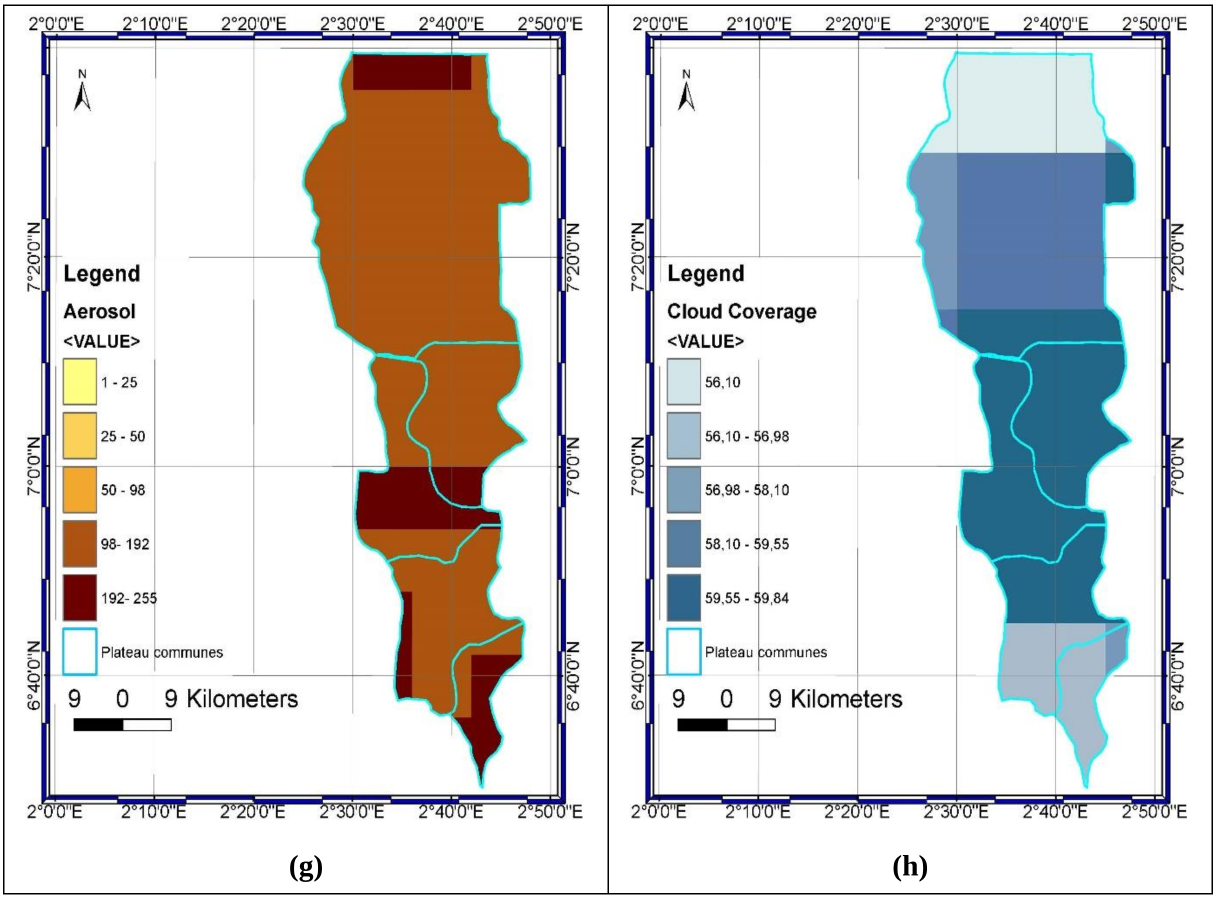

Fig. 6. Classification of criteria (g) Aerosol (h) Cloud coverage

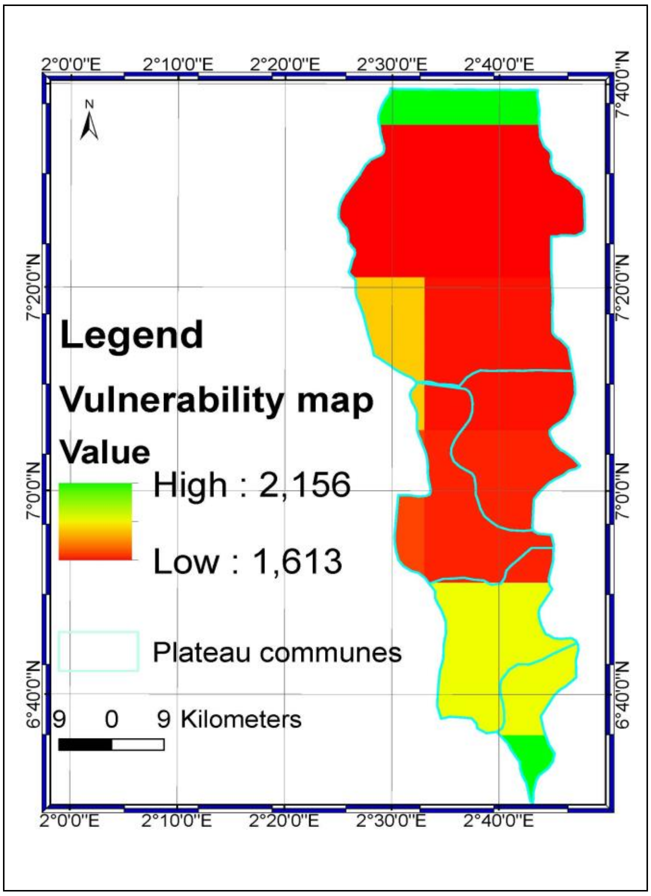

Fig. 7. Vulnerability map

DECLARATION

Funding	Not funding.
Conflicts of Interest/ Competing Interests	Not conflicts of interest to the best of our knowledge.
Ethical Approval and Consent to Participate	Not relevant.
Availability of Data and Material/ Data Access Statement	Not applicable.
Authors Contributions	Yao Gnagbolou, Thesis Student, declare to be the Correspondence Author. Macaire B. Agbomahena, Thesis Director, declare that l contributed to the proofreading of this article. Gabin Koto N'gobi, Thesis Supervisor, declare that l contributed to the proofreading of this article. Maurel Richy Aza-gnandji, Thesis Supervisor, declare that l contributed to the proofreading of this article.

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