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ÍNDICE

ABDELLAH KHOUZ, JORGE TRINDADE, PEDRO PINTO SANTOS, FATIMA EL BCHARI, SÉRGIO C. OLIVEIRA, RICARDO A. C. GARCIA, ASMA BOUGAYOU, MUSTAPHA IKIRRI, MOURAD JADOUD, SAID RACHIDI, AND BLAID BOUGADIR
Contributo de modelos estatísticos na avaliação da suscetibilidade a cheias na província de Essaouira, Marrocos
Contribution of statistical models in flood susceptibility assessment in Essaouira Province-Morocco

ASMA BOUGAYOU ; ABDELLAH KHOUZ ; FATIMA EL BACHARI; JORGE TRINDADE; MUSTAPHA IKIRRI; SIHAM AFRAOU; FARID FAIK; BLAID BOUGADIR
Avaliação do potencial de águas subterrâneas na área de Ait Abdellah com recurso à deteção remota e SIG
Assessment of groundwater potential in the Ait Abdellah area by using remote sensing and GIS

JOÃO CARRILHO, ABDELLAH KHOUZ, JORGE TRINDADE
Águas subterrâneas na governação do nexo Água-Energia-Alimentação em áreas periurbanas exteriores
Groundwater in the Water-Energy-Food nexus governance in outer peri-urban settlements

GUSTAVO DGEDGE, CELSO CHIVALE, JAIME MAGAIA, JORGE TRINDADE
Avaliação das áreas suscetíveis a cheias na sub-bacia do rio Revúboè, Moçambique
Assessing Flood Susceptibility Areas in the Revúboè river sub-basin, Mozambique

ANDREIA ALVES DA SILVA; LUÍS PEDRO ALMEIDA; ANTÓNIO H.F. KLEIN
Abordagem multiescalar baseada em dados de satélite para a análise de tendências da linha de costa em Portugal Continental
Satellite-driven multi-scale approach for shoreline trend analysis in Mainland Portugal.

ANDREIA ALVES DA SILVA, JORGE TRINDADE; JORGE ROCHA
Avaliação do perigo e da exposição à subida do nível do mar em Portugal Continental
Hazard and Exposure Assessment to Sea Level Rise in Mainland Portugal.

MOHAMED LOUAZANI, ABDERRAFIE EL MAKNISSI
Sistemas de gestão da água nos oásis saariano e o desafio da sustentabilidade face às alterações climáticas: estudo de caso dos oásis de Oued-Noun, sul de Marrocos
The Water Management Systems in Saharan Oases and the Sustainability Challenge in the Face of Climate Change: A Case Study of the Oued-Noun Oases, Southern Morocco.

RICARDO ACÁCIO XAVIER; PEDRO PINTO SANTOS; JOSÉ MANUEL MENDES
Risco de cheias em Moçambique: estratégias comunitárias para a redução da vulnerabilidade a partir de dois estudos de caso
Flood risk in Mozambique: communitarian strategies for vulnerability reduction from two case studies.

SUSANA PEREIRA; JORGE TRINDADE; ANDREIA ALVES DA SILVA; PEDRO PINTO SANTOS; EUSÉBIO REIS; JOSÉ LUÍS ZÊZERE
Perfis de risco de perigos costeiros em Portugal Continental à escala da freguesia
Risk profiles of coastal hazards in mainland Portugal at the civil parish level.

RECENSÕES

PAULO OSÓRIO

História do Pensamento Linguístico-Gramatical em Portugal e no Brasil de Batista, Ronaldo de Oliveira; Fernandes, Gonçalo; Bastos, Neusa Barbosa & Assunção, Carlos (eds) (2025).

JEFFREY CHILDS

Inventions of a Present: The Novel in its Crisis of Globalization, by Fredric Jameson

TESTEMUNHO(S)

HERMANO CARMO

Prémio Armando Rocha Trindade

Avaliação das áreas suscetíveis a cheias na sub-bacia do rio Revúboè, Moçambique

Assessing Flood Susceptibility Areas in the Revúboè river sub-basin, Mozambique

Gustavo Dgedge
Celso Chivale
Jaime Magaia
Jorge Trindade

Resumo

Este estudo avalia a suscetibilidade a inundações na sub-bacia do rio Revúboè, em Moçambique, utilizando o método Analytic Hierarchy Process (AHP) e Sistemas de Informação Geográfica (SIG). Foram integradas cinco variáveis condicionantes – declive, hipsometria, uso do solo, solos e precipitação – para produzir um mapa de suscetibilidade a cheias. Os resultados indicam que 55% da área apresenta suscetibilidade alta a muito alta, concentrada nas zonas baixas próximas de Tete e Moatize. A análise apoia o ordenamento do território e a redução do risco de desastres naturais.

Palavras-chave: Suscetibilidade a cheias; AHP; SIG; Rio Revúboè; Moçambique.

Abstract

This study assesses flood susceptibility in the Revúboè River sub-basin, Mozambique, using the Analytical Hierarchy Process (AHP) and Geographic Information Systems (GIS). Five conditioning variables – slope, hypsometry, land use, soils, and rainfall – were integrated to produce a flood susceptibility map. Results indicate that 55% of the basin has high to very high susceptibility, concentrated in low-lying areas near Tete and Moatize. The analysis supports land-use planning and disaster risk reduction, providing valuable insights for managing flood-prone areas in the Zambezi basin.

Keywords: Flood susceptibility; AHP; GIS; Revúboè River; Mozambique.

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Introduction

The Revúboè River sub-basin in Mozambique has a history of flooding, highlighting the importance of mapping hazard areas, which this study aims to identify. Flood maps are an important tool in preventing, controlling, and managing floods, as they allow for the definition of risk areas. They are also important in land use planning, particularly from the perspective of subsidising the prevention of natural disasters in the face of climate change, as well as helping to manage occupied areas. This research aims to identify the risk areas prone to flooding in the Revúboè sub-basin. These areas will be mapped using the AHP multicriteria analysis method and integrated into Geographic Information Systems.

Study Area Location

The study area comprises the Zambezi River basin, specifically the Revúboè River sub-basin. The Revúboè River sub-basin is in Mozambique, in the province of Tete. It flows into the Zambezi River immediately downstream of Tete City. The northern and eastern boundaries of the Revúboè sub-basin delimit the border between Mozambique and Malawi. To the west, it meets the Mavudzi River sub-basin, while to the south, the Revúboè River flows into the Zambezi River (Serafim, 2005). The study area covers six Tete province districts: Angónia, Chiuta, Cidade de Tete, Macanga, Moatize and Tsangano.

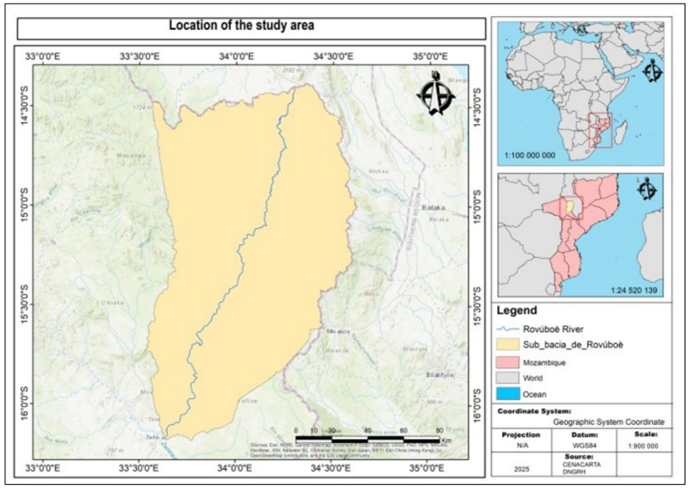


Figure 1. Location of the study area.
Source: CENACARTA edited by the Authors

Methodology

The methodology adopted used data geoprocessing to identify flood susceptibility areas in the Revúboè river sub-basin, backed by an extensive review of the specialised literature on areas of flood susceptibility. The thematic variables considered important to assess susceptibility are (slope, hypsometry, land use land cover, soils, rainfall). To assess exposure the variables considered important are road network, health care facilities, education facilities and population) were cross-referenced in a GIS (Geographic Information System) environment. flood susceptibility was assessed using the Analytical Hierarchy Process (AHP) method (Saaty, 2008).

i) Data sources and materials
Digital Elevation Model (MDE): was obtained from ALOS PALSAR, with a resolution of 12.5 meters. From this data, the sub-basin of the study area was delimited through automatic watershed delimitation using Hydrology ArcToolbox from ArcGIS 10.4.1.

This extension makes it possible to determine flow direction, calculate flow accumulation, delineate river basins and create drainage networks. The altitude and slope maps were also derived from this MDE, which were used to identify the lowest areas representing the greatest susceptibility of flooding in the study area due to the low altitude and the consequence of gravity draining the water to low areas and flatter slopes.

Soil distribution: the IIAM (Instituto de Investigação Agrária de Moçambique) geodatabase, originally at a scale of 1:1,000,000, was used to identify the distribution of soil types. Soil classes affect infiltration capacity and surface runoff and are essential to assess flood susceptibility.

Land use / Land cover (LULC): was obtained from the global land use raster database, originally from 2021 and at a resolution of 10m, provided by the European Space Agency, with 10 LULC classes, including vegetation type, exposed soil, crops and urban areas.

Rainfall distribution: was acquired from CRU (Climate Research Unit) Data, available at https://www.crudata.uea.ac.uk/cru/data/hgr/, originally with a spatial resolution of 0.5°. The geodata version used (CRU TS v. 4.06) was released on 26 May 2022, and this research included a 30-year time series (1991 – 2021) to create a matrix map of average annual rainfall. Data from the 2017 population census by INE (National Institute of Statistics) were used with geodata represented by village points with total population. Hospitals: A point location geodatabase from MISAU (Health Ministry) was used to locate health facilities.

ii) flood susceptibility assessment

flood susceptibility assessment in the Revúboè River sub-basin is based on the Analytical Hierarchy Process (AHP). AHP mathematically analyses paired comparisons between factors and experts' judgements and weights to evaluate qualitative or intangible criteria. Thus, factors or attributes are identified, which, when selected, are organised hierarchically, descending generally to the objective or solution to the problem(s) and down to the criterion, sub-criterion, and alternatives at various levels (Saaty apud Pimenta et al., 2019: 409). To determine the degree of importance and the weights of each criterion analysed, the methodology proposed by Saaty (2008) was used to structure the decision hierarchy, construct the paired comparison matrix, prioritise the alternatives and define susceptibility classes, which resulted in the definition of the susceptibility classes.

Reclassification and mapping of variables

Thematic maps of the independent variables are based on the methodologies described below. Weights were assigned to each class of the selected variables on a scale of 1 to 5, where 5 is the value with the greatest influence on flooding, and one is the lowest.

Hypsometry: The hypsometric map represents the variation in the altimetry of the morphology in the basin with the mean sea level as a reference. The map was obtained by classifying the MDE and then reclassifying it, where the altimetry classes were separated into an interval of 387.4 meters, giving a total of 5 classes. The weights assigned to the altitude classes were applied, as shown in Table 1.

Hypsometry class (m)	Slope (%)	Assigned Weight	Susceptibility Level
109 - 496	0 – 7	5	Very high
	7 – 20	4	High
496 - 884	20 – 39	3	Moderate
884 - 1.271	39 – 72	2	Low
1.271 - 2.046	>75	1	Very low

Table 1. Hypsometry and slope reclassification. Slope classes adapted from Leal et al. (2020).

Slope: The slope map represents the inclination of the land surface about the horizontal and is expressed as a percentage. The map was obtained by extracting the slopes from the raster generated from the MDE using the slope function in ArcMap, making it possible to discriminate the slope classes according to the IIAM classification (Table 1).

LULC: The land use and occupation map represents the different forms of land use and occupation in the study area. The ESA's global land use and occupation database was used for its preparation, and the images have a spatial resolution of 10 meters. The LULC information for the study area was extracted and classified in ArcGIS based on the legend provided on the ESA website. Table 2 shows the class's reclassification.

LULC class	Assigned Weight	Susceptibility Level
Permanent water bodies	5	Very high
Exposed soil	5	Very high
Built-up area	5	Very high
Shrub vegetation	3	Moderate
Cultivated land	2	Low
Pasture	1	Very low
Forest/tree cover	1	Very low

Table 2. Hypsometry and slope reclassification (Magaia, 2022).

Soils: the soil map classification is based on the pedological map of Mozambique, supplied by IIAM on a scale of 1:1,000,000, for which the study area was clipped. The weights for each soil class were applied according to Table 3.

LULC class	Assigned Weight	Susceptibility Level
Oxic red clay soils	5	Very high
Red clay soils	5	Very high
Shallow soils on non-calcareous rock	5	Very high
Black basaltic soils	5	Very high
Shallow soils on limestone	3	Moderate
Brown soils with a sandy texture	3	Moderate
Medium-textured red soils	3	Moderate
Lithic basaltic soils	3	Moderate
Lithic soils	2	Low
Greyish-brown sandy soils	1	Very low

Table 3. Reclassification of the soil map.

Rainfall: the average annual rainfall map was obtained using rainfall data (30-year series) from 1991 to 2021, obtained from CRU DATA - a high-resolution gridded time series climate data platform (Table 4).

The classification of annual precipitation in Mozambique can be adapted to reflect the specific climatic conditions of the country. According to the Mozambique Precipitation Atlas published by the National Institute of Meteorology (INAM), average annual precipitation varies significantly between regions, with values that can be less than 400 mm in some areas and more than 2000 mm in others.

Average annual rainfall class (mm)	Assigned Weight	Susceptibility Level
734 - 780	2	Low
780 - 828	3	Moderate
828 - 872	3	Moderate
872 - 908	3	Moderate
908 - 945	3	Moderate

Table 4. Reclassification of the average annual rainfall map.

Application of the multicriteria decision method

The flood susceptibility map will be the product of the spatial analysis of five variables, namely, slope, hypsometry, land use land cover, soils, rainfall. Variables represented in the thematic maps drawn up. It will involve two distinct phases of work: the theoretical phase, in which the weights will be assigned to the variables, and the operational phase, in which map algebra will be used to aggregate the thematic maps.

Theoretical phase: Weights were assigned to the variables using the AHP method and after expert consultation. A two-by-two comparison was made using a proposed scale where 1 is the minimum, and 9 is the maximum importance of one variable over another to define the relative importance of the criteria in terms of flood susceptibility. This is the most important part, as the values assigned to each variable directly affected the result obtained. Table 9 shows how weights were assigned as each element of the matrix indicates how important the variable in the left-hand column is to each corresponding variable in the top row. Therefore, when a variable is compared to itself, the only possible result is 1, which is equally important. As soon as all the variables intersect once, the matrix becomes simply the opposite of the initial procedure.

Vars	Slope	Hypso.	LULC	Soils	Prec.
Slope	1	3	4	5	7
Hypso.	1/3	1	3	4	5
LULC	1/4	1/3	1	3	4
Soils	1/5	1/4	1/3	1	3
Prec.	1/7	1/5	1/4	1/3	1
Total	1,93	4,78	8,58	13,33	20,00

Table 9: Example of variables in the pairwise comparison matrix.

With the relative importance values of the variables, it was possible to determine the statistical weights for each variable. The values were obtained manually by dividing each element by the sum of the elements in the column to which it belongs and averaging the columns to determine each weight, as shown in Tables 10 and 11.

Vars						Av	Weight (%)
Slope	0,52	0,63	0,47	0,38	0,35	0,47	47
Hypso.	0,17	0,21	0,35	0,30	0,25	0,26	26
LULC	0,13	0,07	0,12	0,23	0,20	0,15	15
Soils	0,10	0,05	0,04	0,08	0,15	0,08	8
Prec.	0,07	0,04	0,03	0,03	0,05	0,04	4
Total	1,00	1,00	1,00	1,00	1,00	1,00	100

Table 10. Determination of statistical weights for each susceptibility variable.

Variable	Weight (%)
Slope	47
Hypsometry	26
LULC	15
Soils	8
Precipitation	4

Table 11: Statistical weights of the risk variables.

To assess whether the weights calculated were true, it was necessary to calculate the consistency ratio (*RC* – Equation 1, which, according to Costa (2002), must be less than 0.10. The consistency ratio obtained was 0.06, attesting to the coherence of the hierarchy of the data classification.

$$IC = \frac{(\lambda máx - n)}{(n-1)} = \frac{(5{,}2865 - 5)}{(5-1)} = 0{,}0716$$

$$RC = \frac{IC}{IR} = \frac{0.0716}{1.12} = 0{,}064$$

Operational phase: One way to perform a multicriteria analysis is through map algebra: 1st by adding the weighted variables by criterion (Table 11) and 2nd For this stage, arithmetic operations were performed using the raster calculator tool of the ArcGIS software, where the reclassified flood susceptibility variables were associated. As a subsidy for this stage, the model presented by Equation was used.

$$S = (\omega D \times D + \omega H \times H + \omega LULC \times LULC + \omega Soil \times Soil + \omega R \times R)$$

ω - Weight of the respective parameter (obtained by AHP)

After obtaining the flood susceptibility map, flood susceptibility was reclassified into five hierarchical categories: very low, low, moderate, high and very high.

Results and Discussion

The multicriteria analysis method was used to calculate the maps of the conditioning variables, resulting in a flood susceptibility map (Figure 2).

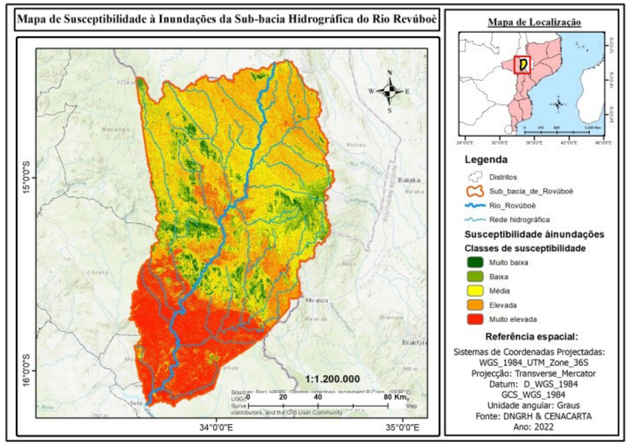


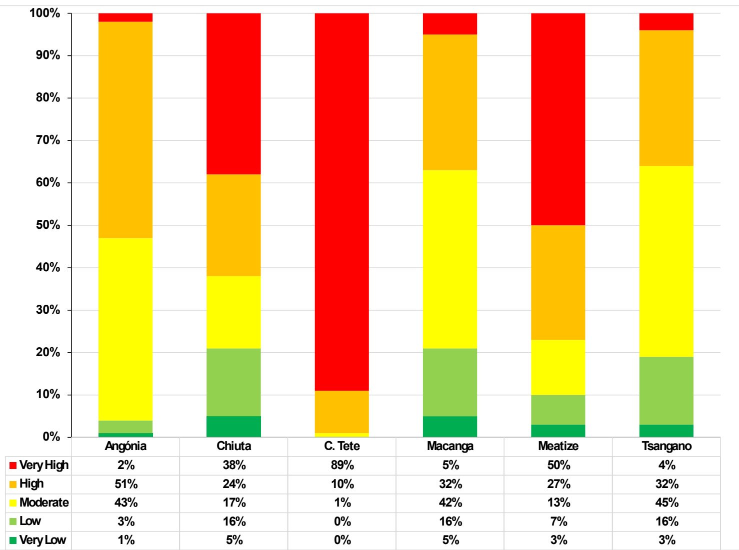
Figure 2. Flood susceptibility map of the Revúboè River sub-basin. Susceptibility classes shown from very low to very high

The map of areas susceptible to flooding was divided into five classes. Figure 2 shows the flood susceptibility map of the Revúboè River sub-basin. It can be seen that the areas considered to be of very high susceptibility are concentrated mainly in the lower regions of the sub-basin, evidently the location of the river mouth. The values are explained precisely by the fact that these levels of information present the greatest importance according to the paired comparison matrix, while the areas of low susceptibility are located in the middle course of the sub-basin, as they are areas with a mountainous slope. Analyzing the sub-basin area as a whole, the following indicators were obtained: Very low (3%), low (10%), Medium (32%), High (34%) and Very high (21%). It can be observed that the high susceptibility classes, followed by medium susceptibility, were predominant, representing, respectively, 34% and 31% of the total mapped area, showing that in general the sub-basin would have a high tendency to be flooded. The area with very high susceptibility was moderately significant, covering only 3,353.48 km², equivalent to 21% of the total area. The areas and percentages corresponding to the levels of flood susceptibility are summarised in Table 12.

Analysing the susceptibility map (Figures 2 and 3), Regarding the degree of susceptibility to flooding by districts of the Revúboè river sub-basin, the city of Tete in the 40.67 km²of the area covered by the sub-basin, 30.08 km², equivalent to 89% corresponds to the very high susceptib ility class, Moatize is mostly covered by very high susceptibility with 50%, corresponding to 2143 km² of the district's area. The district of Chiuta has a very high susceptibility level of 38%, equivalent to 894.55 km² of its total area.

Susceptibility Class	Area (km²)	%
Very low	462,3	3
Low	1726	11
Moderate	5074,25	31
High	5396,91	34
Very high	3353,48	21

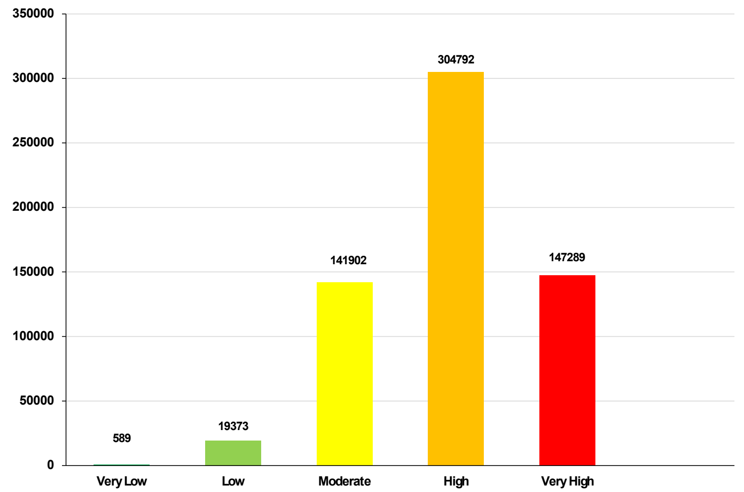
Table 12. Area covered by flood susceptibility classes.



Graph 1. percentages of area by degree of susceptibility in districts of the revúboè river sub-basin.

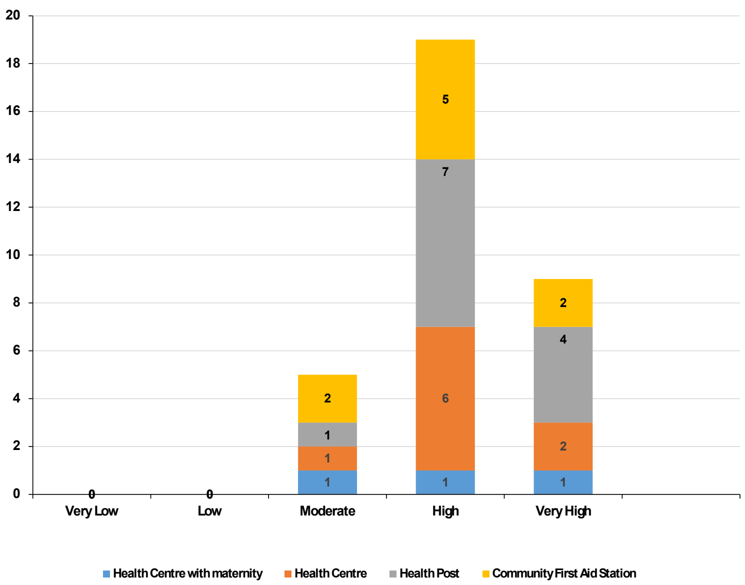
Exposed elements

Taking into account the number of inhabitants in susceptible areas, high susceptibility areas have the largest population with 304,792 inhabitants, followed by very high and medium susceptibility areas with 147,289 and 141,902 inhabitants, respectively. While 19,373 reside in low susceptibility areas, while very low susceptibility areas have 589 inhabitants.



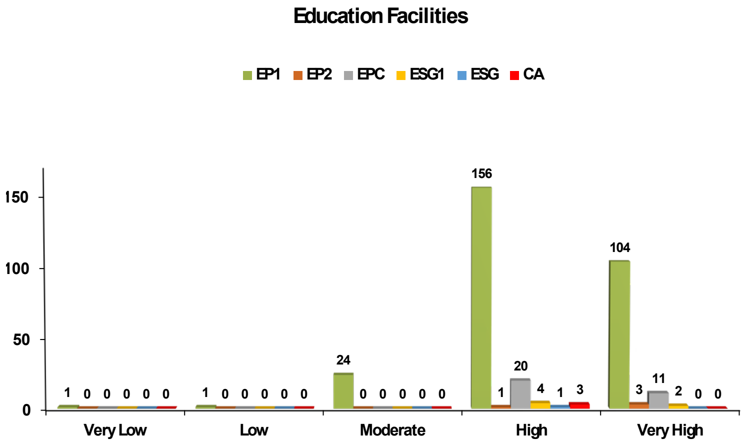
Graph 2. population distribution in relation to susceptibility levels

The very low and low susceptibility areas are not provided by any health services that may be affected by flooding. The medium susceptibility areas have 5 (five) health services that may be affected by flooding, namely one Health Centre with maternity ward, one Health Centre, one Health Post and two Community Aid Posts. The high susceptibility areas are well covered by health services, namely, 1 (one) Health Centre with maternity ward, 6 (six) Health Centres, 7 (seven) Health Posts and 5 (five) Community Aid Posts. In the very high susceptibility areas, 9 (nine) health services are affected by flooding, as illustrated in Graph 3.



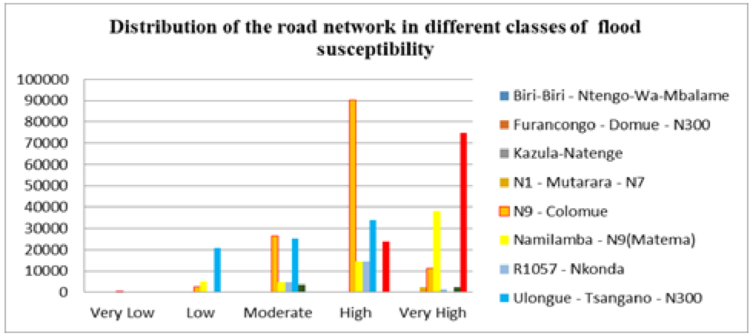
Graph 3. Distribution of Health Services in Susceptible Areas

Graph 4 shows the distribution of schools according to the level of education, with the majority of establishments being primary education institutions, the majority of which are in areas of high and very high susceptibility, with around 156 and 104 schools, respectively. 24 are located in areas of medium susceptibility, and only 1 school is located in areas of very low susceptibility, as well as in areas of low susceptibility.



Graph 4. Distribution of education facilities in susceptible areas

The Revúboè river sub-basin has a road network consisting of approximately 859.7 km of roads classified as primary, with the largest extension being in areas of high and very high susceptibility. The road that connects the districts of Tsangano and Angónia, in this case, the N9 – Colomue section, has 90.08 km in areas of high susceptibility and 11.42 km in areas of very high susceptibility, being the road with the largest coverage of susceptible areas. Another road that is heavily covered by areas of high and very high susceptibility is the Zobue – Tete – N6 section, which connects the city of Tete and the district of Moatize, 74.82 km of its extension are in areas of very high susceptibility and 23.87 km are in areas of high susceptibility.



Graph 5. Distribution of the road network in relation to susceptible areas

Conclusion

From this study it was possible to identify the areas susceptible to flooding in the Revúboè River sub-basin, Tete province. For this, the analytical hierarchical process (AHP) method and remote sensing technique were applied. To identify the susceptible areas, five variables were integrated: slope, hypsometry, land use and occupation, soil distribution and rainfall. The variables that most influenced the susceptibility analysis were slope and hypsometry, followed by land use, soil distribution and rainfall. The regions of very low susceptibility represent about 3% (462.3 km²) of the sub-basin area and are characterized by high altitudes and steep, mountainous slopes. However, the areas of very high susceptibility are concentrated near the mouth of the Revúboè River in low altitude areas ranging from 109 to 496.4 meters, and with flat and gently undulating slopes ranging from 0 to 7%, covering 3353.48 km² (21%) of the total area of the sub-basin. However, the areas at very high risk are low-lying areas and flat and gently undulating slopes, close to the mouth of the sub-basin. The areas most susceptible to flooding coincide with those flooded after the outbreak of Cyclone Idai in 2019 and Tropical Storm ANA in the first quarter of 2022, namely the City of Tete and the District of Moatize.

To analyze the exposure, the conditioning variables were the road network, the distance to health and education units and the population in relation to the susceptible areas. The flood susceptibility map studied from the algebraic integration of the reclassified maps of the conditioning variations, using the research (slope x hypsometry x land use and cover, soil x rainfall) According to the results, the very low and low risk areas represent 462.3 km² (3%) and 1726 km² (11%) of the total area of the sub-basin. The medium risk strongly covers the central to northern region of the sub-basin, covering about 5,074.25 km², equivalent to 31% of its area. The Tsangano district has the largest coverage of medium risk, covering 45% of its area, followed by the districts of Angónia and Macanga with 43% and 42%, respectively.

High and very high risk areas are located in areas with larger populations. Taking into account the number of inhabitants in susceptible areas, high susceptibility areas have the largest population with 304,792 inhabitants, followed by very high and medium susceptibility areas with 147,289 and 141,902 inhabitants, respectively.

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