Application of The AHP Method For Prioritizing Actions To Reduce Risk Associated With Gravitational Mass Movements In Areas Along The Margins of Watercourses of The City of Rio Branco, Brazil.

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APPLICATION OF THE AHP METHOD FOR PRIORITIZING ACTIONS TO REDUCE RISK ASSOCIATED WITH GRAVITATIONAL MASS MOVEMENTS IN AREAS ALONG THE MARGINS OF WATERCOURSES OF THE CITY OF RIO BRANCO, BRAZIL.

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ABSTRACT - Problems related to gravitational mass movements at the margins of water courses are present in different parts of the world, but in the Amazon, whose hydrological regime has unique characteristics, and whose socioeconomic situation may be considered as underdeveloped, such problems come into sharp focus. Rotational landslides and creeps on the ground are present with high frequency and magnitude in several municipalities in the Western Amazon. Such processes act in association and annually cause significant losses and material damage. In this context, this study proposes the structuring of a decision-making process that aims to assist in the indication of critical areas, as well as proposing possible actions to mitigate risks. The criteria and procedures adopted for risk-mapping in a portion of the urban center of Rio Branco-AC are described, herein. Risk was measured, based on the multicriteria analysis of attributes related to the physical, anthropic environment and the characteristics of the processes considered. The Hierarchical Analysis Method (AHP), was the technique adopted to structure the risk assessment model, which was later integrated into the GIS environment, to allow spatial analysis. The results were presented in the form of cartograms, descriptive tables and graphs, and aim to help control the mapped risks.

Keywords: Gravitational Mass Movement. AHP. Risk Mapping. Brazil.

1 INTRODUCTION

In Brazil, in particular and in the world, in general, uncontrolled growth and high rates of urbanization contribute to increasing the vulnerability of the exposed population and the potential for damage to infrastructure and facilities, which makes the issue of risk assessment and analysis an essential step for the adoption of policies aimed at reducing natural disasters.

As a result, several authors and entities (Cerri et al., 2007; Faria & Augusto Filho, 2013; Sobreira & Souza, 2012; Nola & Zuquette, 2021) have been developing methods and techniques (progressive detailing, experience of precedent etc.) to map risks, especially those related to external geodynamics processes.

In Brazil and in many other countries, risk mapping is based on predominantly qualitative assessments, in which the situational risk is diagnosed by the team that performs the mapping, based

on field surveys, through surface geological-geotechnical investigations (Cerri et al., 2007; Faria & Augusto Filho, 2013). However, more recently, several researchers (Vega & Hidalgo, 2016; Cascini et al., 2005; Jasiwal, 2011; Nola & Zuquette, 2021) have developed procedures to allow some quantitative risk assessment.

Observing the diversity of adverse processes (falls, landslides, creeps, inundations, flash floods etc.) and exposed elements (populations, properties and goods, economic and social activities etc.), it is possible for a specialist to understand that such a diagnosis needs to go through the evaluation of the phenomenon based on an appropriate interpretation of its controlling factors; there is a constant need to describe them in a systematic and way, compatible with the scale to be applied.

Therefore, it is essential that there is some prior knowledge about the dangerous event (its type, mechanism, material involved, magnitude, speed, trajectory, severity, destructive power etc.) and the vulnerability of the exposed element.

Even recognizing the inaccuracies and uncertainties inherent in qualitative assessments, Cerri et al. (2007) emphasize the importance of this activity for the effectiveness of an intervention policy.

To improve the risk mapping approaches Faria & Augusto Filho (2013), Vega & Hidalgo (2016), Cascini et al. (2005) and Jasiwal (2011) consider it pertinent to suggest and incorporate quantitative techniques that can contribute to reducing subjectivity.

Although the indeterminacy of an ideal solution may be evident, since there are no unique constraints, or even a single perception of the problem, it is essential that the diagnosis made presents some level of hierarchy regarding the solutions considered and generates assistance in allowing the validation of the results. This hierarchy should be based on qualitative criteria (type of movement, characteristics of land use and occupation, construction standards etc.) and quantitative criteria (number of properties and affected population, volume that can be moved, affected area, engineering intervention costs etc.).

In this sense, there is the perspective that the structuring of a decision-making process, based on the use of the decision support routine called Analytical Hierarchy Process - AHP, can simplify the

53 valuation of the conditions, reduce inconsistencies and provide assistance that allow a more objective
54 indication of risk situations.

55 The results presented in this article are related to a study developed with a focus on the indication
56 of critical areas regarding the risk of gravitational mass movements in areas adjacent to rivers and
57 streams in the Brazilian Amazon hydrographic system, especially creeps or rotational landslides.

58 This research has as its central premise the fact that the social and economic damages related to
59 such processes (creeps and rotational landslides) are significant in areas adjacent to the water courses
60 of Amazonian cities, and that knowledge regarding the mechanisms and principles that govern them
61 is still incipient ([Carvalho et. al., 2009](#); [Labadessa, 2011](#); [Matos & Cursinho, 2012](#); [Pacheco &](#)
62 [Brandão, 2012](#); [Magalhães & Gomes, 2013](#)).

63 The perception regarding the use and occupation of land in these areas, as well as the precarious
64 infrastructure and the lack of uniformity in the language and criteria adopted, has limited the
65 efficiency of the strategies necessary for adequate planning and coping with risk in these spaces.

66 In this context, the objective of this work was the development of a procedure based on the
67 Hierarchical Analysis Method, capable of evaluating, quantifying and hierarchizing, the conflicting
68 relationships between the use and occupation of areas along the margins of watercourses in
69 Amazonian cities and the magnitude of dangerous phenomena, to then indicate a set of mitigating
70 actions.

71 The research was carried out in a test area of the urban core of Rio Branco (AC), located in the
72 Northern region of Brazil. This area is known for presenting frequent creep movements and rotational
73 landslides, in an area with materials with geological and geotechnical characteristics that shows high
74 susceptibility to the occurrence of such gravitational mass movements ([Maia, 2003](#); [Oliveira &](#)
75 [Ferreira, 2006](#)), in addition to occupations with different patterns and stages of consolidation. The
76 results presented in the form of cartograms, descriptive tables and tables that aim to help control the
77 mapped risks.

2 THE HIERARCHICAL ANALYSIS METHOD (AHP)

The delimitation and assessment of areas subject to the occurrence of dangerous events and, therefore, areas with geological-geotechnical risk, depends on knowledge and surveying of the attributes that influence the predisposition and outbreak of the considered processes (Sobreira & Souza, 2012). The great challenge in this type of assessment consists in relating, in a systematic way, the characteristics of the physical environment and the anthropic actions, with the signs of movement identified to, then, indicate the potentialities and limitations of the different terrains. An important aspect to be considered with regard to the characterization of the physical environment refers to the identification of the processes responsible for the observed events, which are responsible for the appearance/creation of the areas of geological-geotechnical risk.

AHP has been applied in several areas of knowledge and has proved to be extremely useful in the analysis of geological-geotechnical risk of mass movements and in other natural disasters, especially in situations involving subjective judgments, as pointed out by the studies by Rodrigues & Zuquete (2006), Paula & Cerri (2012), Kayastha et al. (2013), Faria & Augusto Filho (2013), Intarawichian & Dasananda (2010).

AHP is a technique based on a decision tree, proposed by Thomas L. Saaty in the mid-1970s, which aims to reproduce human reasoning in the comparison of elements, as a tool to aid decision making in complex problems.

Despite the structuring of the problem in a more simplified form, the method does not rule out the need for specialists to carry out decision-making (specialist knowledge) in regard to the problem, but it has been used in several works cited in the academic literature.

The criteria are selected and arranged in a descending hierarchical structure in the form of an inverted decision tree (Figure 1), whose structure descends from the goal (objective) to the criteria, sub-criteria and alternatives, in successive levels.

Figure 1 - Typical hierarchy structure for an AHP

102 [Rodrigues & Zuquete \(2006\)](#) and [Paula & Cerri \(2012\)](#) summarize the recommended steps for
 103 applying the method:

- 104 i. Define the problem, that is, what one seeks to know (risk, susceptibility etc.);
- 105 ii. Create a hierarchical structure, by breaking down the problem into different levels, in
 106 which the top is occupied by the goal (general objective) and the last level by the more
 107 specific elements, such as attribute classes or intervention alternatives;
- 108 iii. Build decision matrices for each level, make parity comparisons and define the relative
 109 importance of each element. [Saaty \(1990\)](#) proposes that the importance of one element in
 110 relation to another, be defined based on a scale that varies from 1 to 9, where 1 refers to
 111 the elements in the matrix that present the same importance, and 9 when one element
 112 presents a higher degree of influence over another, to explain the problem;
- 113 iv. Check the consistency of the judgment in each matrix;
- 114 v. Obtain the vector of priorities for each matrix and perform the global assessment of the
 115 problem through the weighted linear combination of the various elements of each
 116 hierarchical level [Saaty \(1990\)](#).

117 Conducting a sensitivity analysis, in which the consistency of a positive reciprocal matrix requires
118 that its maximum eigenvalue (λ_{max}) is very close to the dimension of the matrix (n), results in a
119 greater consistency of the data, insofar as how much the closer λ_{max} is to n , the more consistent the
120 result will be (Gomes, 2009). The Consistency Index (CI) indicates how far the given value is away
121 from the expected theoretical value n , in which this difference is measured in relation to the number
122 of degrees of freedom of the matrix ($n - 1$). Thus, the Consistency Index is given by equation 1.

123
$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (1)$$

124 If CI is small enough, the decision maker's comparisons are likely to be consistent. The degree of
125 inconsistency is also verified by calculating the “Consistency Ratio” (CR) which is given by equation
126 2.

127
$$CR = \frac{CI}{RI} \quad (2)$$

128 Where RI is the random consistency index for the value n (matrix order number), which represents
129 the value that would be obtained in a reciprocal matrix of order n and in which no logical judgments
130 were made.

131 More fundamentals about AHP can be found in Saaty (1977), Saaty (1980), Saaty (1990) and Saaty
132 (2008).

133 3 MATERIAL AND METHODS

134 3.1 DEFINITION OF THE STUDY AREA

135 The study was applied to a portion of the urban core of Rio Branco (AC), in a representative region
136 of areas adjacent to rivers and streams in the Western Brazilian Amazon (Figure 2), where events
137 related to creeps and rotational landslides annually cause significant losses and material damage.

138 This area, with a surface area of approximately 1.1 km², involved the city's historic center, the
139 edge of the river Acre and five precarious settlements. It presents a sensitive diversity of densities
140 and occupation patterns, which are inserted in the same geomorphological context (Rio Branco
141 depression) and presents degrees of susceptibility, that vary from low, to high, to the development of

142 creeps and rotational landslides (Nascimento, 2016). This diversity of circumstances was considered
143 adequate for the simulation of different risk scenarios.

Figure 2 - Location of the study area.

144 To support the application of the proposed methodology, we initially sought to characterize the
145 types of gravitational mass movements (their typology, mechanisms and materials involved) based
146 on an integrated analysis of the components of the physical environment (relief, water courses,
147 scarring records) previous events and geological materials involved). In this context, two ranges of
148 land adjacent to the main water courses in the urban area of Rio Branco, the Acre River and one of
149 its tributaries, the São Francisco stream, were selected for this activity.

150 Through the use of techniques for physiographic compartmentalization of land and field work,
151 which involved the registration and the geological-geotechnical characterization of 73 features of
152 instability, the geotechnical zoning presented in Figure 3 was obtained, the steps, criteria and

153 procedures of which were used in its construction are detailed in Nascimento (2016) and Nascimento
154 & Simões (2017).

155 Based on the geological characteristics (type of geological material present), geotechnical (areas
156 subject to flooding, material parameters etc.) and geomorphological (longitudinal shape of the
157 margin) of each compartment, and considering the register of events that occurred in them (including
158 position and frequency), the degrees of susceptibility to the occurrence of new events were defined.

Figura 1 Geotechnical zoning of mass movements susceptibility.
Source: Nascimento (2016).

159 The mapping work was carried out by Nascimento (2016), in the zoning phase, which allowed us
160 to infer that creeping and rotational slides are the most significant processes, both by the frequency
161 with which they occur and by the magnitude of the registered events.

162 The creeps are associated with the plastic soils that cover the hills of the Solimões Formation,
163 occur more frequently in terrain with a slope greater than 12% and are not limited to the flooded
164 section of the channels.

165 According to Nascimento (2016), rotational landslides are frequently observed in flooded areas
166 and also on slope surfaces already weakened by the creep, which are often induced by the intense
167 fluctuations of river discharges that coincide with periods of intense and prolonged rain. There are
168 depressions between 0.4 and 2.2m high and traction cracks that are hundreds of meters long at the top
169 and mid-slope. The evidence of creeping is widespread, with an increase in its rate of displacement
170 in the rainiest quarter, evidenced by the misalignment of the foundations of wooden buildings, as can
171 be seen in Figure 4. The movements take place in predominantly clay-silty soils, as described in
172 Figure 5, which represents section AB (indicated in Figure 4), which was adapted from the work of
173 Nascimento (2016).

Figure 4 - Aspects and evidences of instability of mass movements registered by Nascimento (2016).

Figure 5 - Summary of physical characteristics observed in the study area by Nascimento (2016).

174 3.2 MATERIALS

175 The basic reference information obtained in this research comes from the Territorial Information
176 System (SITgeo) belonging to the Municipality of Rio Branco, whose database is from 2013. The
177 main materials obtained from SITgeo were:

- 178 • Digital mosaic of aerial photography from 2013, with a spatial resolution of 5 meters, on a scale
179 of 1:5000, developed by Aeroimagem S/A and obtained through a digital aerophotogrammetric
180 camera - LEICA ADS-80;
- 181 • Digital topographic map of the urban area, with contour lines equidistant at one meter on a scale
182 of 1: 5000, obtained by airborne laser profiling, in 2013;
- 183 • Registry map on a scale of 1: 5000, from the year 2013, containing information regarding plans
184 for public places, lots, paved roads, land use, rivers, neighborhoods and flood zones;
- 185 • Fluvimetric data from 1970 to 2014 provided by the State Civil Defense Coordinator;

- Geotechnical zoning database for susceptibility to gravitational mass movements developed by Nascimento (2016): shape files, topographical and geological feature records, field records, geological-geotechnical sections and 23 standard penetration test logs; and
- Google Street View images from the year 2012.

The Geographic Information System (GIS), of the ArcGIS 9.3 program, an ArcMap operations module developed by ESRI, was the tool used to manipulate all available or generated information plans. This took place by using projection “Universal Transversa de Mercator” - UTM, WGS-84, zone 19S.

3.3 STEPS AND METHODOLOGICAL PROCEDURES

The following is a detailed description of the methodological procedures used in carrying out the work.

3.3.1 E1 - Definition of the land unit

In general, the susceptibility maps provide important aid in planning the occupation of territorial space, especially with regard to the potential of a region's physical environment for the development of a given process.

However, it must be understood that these cartographic products have limitations related to the definition of actions necessary to mitigate geological risks and natural disasters. For there to be an indication of where, and what actions will be necessary to face the risk, in the short and medium term, it is necessary that the study be conducted on a higher, more detailed, scale, which in addition to the natural terrain susceptibility, also considers the degree of development of the processes and their relationship with anthropic induction factors and the vulnerability of the exposed elements.

Considering the diversity of uses, occupations, stages of consolidation, installed infrastructure, processes and their stages of development, it was decided to select a regular area, named cells, with dimensions of 50 by 50 meters, to represent the smallest unit of risk mapping, which allowed the tabulation and cross-indexing of information related to the criteria defined within the AHP

211 systematics, without the concern of overestimating or underestimating the extent of each evaluated
212 criterion.

213 The study area was, therefore, subdivided into 467 cells that constituted the information plan called
214 Regular Grid. This information plan was generated in vector format, in the ArcGis program, using
215 the Vector Grid operator of the GeoWizard 11.2 extension.

To tabulate the information related to the classes of the evaluated attributes, the table of attributes of the information plan of the Regular Grid was organized in a similar way to the example presented in Table 1.

Table 1 - Example of data storage on Regular Grid

Cell (code)	Attribute 1	Attribute 2	Attribute 3	Attribute n
Cell 1	Class A ₁	Class A ₂	Class A ₃	Class A _n
Cell 2	Class B ₁	Class B ₂	Class B ₃	Class B _n
Cell n	Class C ₁	Class C ₂	Class C ₃	Class C _n

216 3.3.2 E2 - Risk Breakdown

217 The decision problem (risk assessment) was broken down into four levels of hierarchy, as can be
218 seen in Figure 6. The first level was occupied by the components that determine the risk in the land
219 unit, that is, the Hazard Index (HI) and the Vulnerability Index (VI); the second level was composed
220 of the indicators of these components (Natural Susceptibility, Potential of Induction, Potential of
221 Destruction, Degree of Resilience and Potential of Damage); the third level was made up of the
222 attributes (natural, anthropic and process characteristics); and the fourth level, and last one, by the
223 classes of each attribute.

224 The susceptibility indicator was obtained by overlapping the Zoning Information plan with the
225 Regular Grid information plan. Although this indicator allows estimating favorable or unfavorable
226 characteristics to the development of the considered processes, the presence of signs of movement in
227 a given cell may indicate that it already has all the characteristics necessary for the development of a
228 geological mass movement.

Figure 6 - Adopted hierarchy structure.

In this case, the quantification of the hazard must consider the level of development of the process, which can be estimated based on signs of movement identified through fieldwork.

The information related to the signs of movement was obtained based on overlaps between the shapefile of Regular Grid, with the registration of unstable areas carried out by Nascimento (2016); the contour lines with a frequency of 1m and the orthophoto of 2013. This allowed identification of rugged regions, landslide features and those areas with evidence of creeping. The level of development of the mapped signs and evidences was based on the information contained in Nascimento (2016) field records.

The record of these occurrences in the geographic database was carried out by inserting a column for each attribute related to the characteristics of the mapped processes, in the information plan of Regular Grid. The magnitude of the evidence and the area of influence of these signals in the cell were considered as necessary attributes to estimate the Potential of Destruction indicator.

The magnitude of the signs of movement was assessed based on criteria presented by Cerri et al. (2007), as follows:

- Absent - there is no evidence of the development of instability processes;
- Incipient - evidence of instability suggests that the process is in an early stage, develops slowly or is dormant. In this case, monitoring is perfectly possible;

246   • Significant - there are indications that the process is in full development. There are diverse
247   abatement measures, cracks in the terrain and / or in buildings, or even scars from past landslides.
248   Monitoring of the area is still possible, but it is perfectly likely that landslides will occur during
249   intense episodes of rain and / or sudden variations in level in the watercourses; and

250   • Severe - the evidence or features of instability are expressive, indicating that landslides may
251   occur at any time, and it is not possible to monitor them.

252   For the evaluation of the area occupied by the signs or features of instability in the cell the
253   following classes were defined: absent; <25%; 25 to 50%; 50 to 75%; 75% to 100%.

254   From a different perspective, with the intention of estimating the interference of human action in
255   the evolution of processes (Potential of Induction), the possible damages to properties and goods as
256   a result of a destructive process (Potential of Damage) and the capacity that the population has to
257   restore its condition prior to a possible geological accident (Degree of Resilience), seven anthropic
258   attributes were defined (type of occupation, technical-constructive mode of implantation of buildings,
259   area occupied by buildings and infrastructure, occupation pattern, surface water concentration,
260   concentration of garbage / rubble on slope or escarpment and ground cover).

261   The information used for tabulation of classes related to anthropic attributes was obtained through
262   fieldwork and from orthophoto of 2013, information plans from the SitGeo database (lots, places,
263   buildings and road system) and Google Street View images from the year 2012. In Figure 7 there are
264   images that illustrate some of these observations.

Planned occupation, high pattern and well-structure occupation.

Detail fo some buildings present on cells 325 and 326 (Google StreetView, 2012).

Spontaneous occupation with poor pattern in an incipient infra-structured area

Detail of buildings present on cell 278

Figure 7 – Images that illustrate the method used for gathering information of anthropic attributes.

3.3.3 E3 - Valuation of risk

In this stage of application development, the comparison matrices were set up for each of the levels mentioned and represented in Figure 6. Then, comparisons were made between the elements of the same hierarchical level, with respect to the element of the higher level, defining, within a pre-defined scale of values (Table 2), the relative importance of a given element in relation to another.

In the peer-to-peer comparison, the weights of the elements of each matrix were defined by calculating the “given vector” or “priority vector”, while the verification of the coherence of the judgments was performed based on the results of the “given value” calculation.

The judgments made are essentially related to the authors' experience, aided by consultations with specialists in the region studied.

To obtain the normalized weights, the maximum given value, the consistency ratio (CR) and the consistency index (CI), we used the APH module, from the ASSISTAT 7.7 statistical program (Silva and Azeredo, 2009), using as input data the comparisons made in each matrix.

Table 2 - Scale of relative importance between factors.

Numerical Values	Terms	Comments
1	Equal importance	Both factors equally contribute to the event occurrence
3	Moderate importance	One factor is slightly favored when compared to other to event occurrence
5	Strong importance	One factor is strongly favored when compared to other to event occurrence
7	Very strong importance	One factor is very strongly favored when compared to other to event occurrence. This influence can be observed in practice
9	Extreme importance	One factor is absolute when compared to other, with a high certainty degree
2, 4, 6 and 8	Intermediate values	Used for intermediate importance on the previous definitions
Mutual of Values	Inverse values	Refers to inverse values

Scale of judgment of importance.

Source: SAATY, 1990 (adapted).

The parameter adopted to assess the consistency of the judgment made, was the Consistency Ratio with a value less than 0.1 (Saaty, 1990).

The values obtained in the priority vector of each matrix corresponded to the normalized relative weights assigned to each of the evaluated elements (classes, attributes, indicators and components).

After the tabulation of the attribute classes was completed, the Attribute Table of the Regular Grid information plan was exported to Microsoft Excel. Then, a spreadsheet was created containing the standardized weights of all attribute classes. With the aid of the Microsoft Excel VLOOKUP function, the attribute class contained in each cell was converted to its normalized relative weight.

The hazard (HI) and vulnerability (VI) indexes were obtained through the linear combination between the weights of the classes, attributes and indicators, according to equation 3.

$$IC = \sum_{i=1}^n RWI_i \times RWA_i \times RWC_i \quad (3)$$

Where: IC is the component's value (hazard or vulnerability) in cell i; RWI: normalized relative weight of the indicator present in cell i; RWA: normalized relative weight of the attribute in cell i; RWC: normalized weight of the attribute class present in cell i; n: refers to the number of criteria.

The columns of the Excel spreadsheet that contained the values of HI and VI were inserted in the table of attributes of Regular Grid and they were later converted to the matrix format, for subsequent overlaps.

295 This procedure was performed using the Spatial Analyst module (Feature to Raster) from the
296 ArcGis program. Subsequently, in the ArcGis program, the HI and VI values were divided into four
297 different ranges (Natural Breaks option), representing, in ascending order, the low, moderate, high
298 and very high classes for each component.

299 The results of this classification generated the Hazard and Vulnerability cartograms, which were
300 validated through the overlay of the orthophoto of 2013, the digital topographic map of the study
301 area, and to the register of instability features (Nascimento 2016), based on the scenarios presented
302 in Table 3 and Table 4.

Table 3 - Expected scenario for each hazard class.

Hazard Classes	Definition
Low	It is unlikely that a destructive event occur in a one-year period.
Medium	Hazard indicators are of medium potential to destructive processes. Building occupation and Consolidation of occupation should be carefully evaluated. The need for specific geotechnical design and monitoring must be adopted for high vulnerability areas.
High	Hazard indicators are of high potential, in way that the occurrence of an event sis very likely to occur in one-year period. New occupation areas, including buried infrastructure must be avoided. Monitoring must be constant and preferably performed by using instrumentation on more vulnerable units.
Very High	There are general evidences of creep and rotational mass movements. It is not possible to predict when new movements will occur.

Table 1 – Probable scenarios explanation for each vulnerability classes.

Vulnerability Classes	Definition
Low	Formed by non-occupied areas (buildings and infrastructure). Even if an event occur, it is unlikely that associated damage will occur.
Medium	Composed by open areas and areas with low consolidation levels. Damage associated with the occurrence of a event are of moderate severity.
High	Composed by consolidated or under consolidation areas. Damage associated to the occurrence of one instability process can result in human and material losses.
Very High	Composed by consolidated or under consolidation areas. Damages associated to the occurrence of one instability process are significant and are essentially related to the population high fragility occupying these areas.

303 The values of HI and VI were divided into four classes (low, moderate, high and very high), using
304 the Natural Breaks function, from ArcGis. The risk evaluation (RI) resulted from the combination of
305 these classes and was obtained through equation 4:

306
$$RI = HI \times VI \text{ (4)}$$

307 Where: RI is degree of risk in cell i; HI: weight of the class of the hazard component present in
308 cell i; VI is the weight of the class of the vulnerability component present in cell i.

309 The risk in a given cell was conditioned to the mutual existence of hazard and vulnerability. If
310 there is no propensity for damage to occur due to a particular physical event, there is no hazard and,
311 therefore, there is no risk. In order for this relationship to be translated into numerical terms, the
312 matrix shown in Table 5 was constructed.

313 In this sense, it was considered that risk situations only exist when one of these components is not
314 incipiently present, which is why a scale of 0 to 3 was defined.

Table 5 - Risk matrix

	Hazard (Score)				
	RI=HxV	Low (0)	Moderate (1)	High (2)	Very High (3)
Vulnerability (Score)	Low (0)	0	0	0	0
	Moderate (1)	0	1	2	3
	High (2)	0	2	4	6
	Very high (3)	0	3	6	9
		Low	Moderate	High	

315 The RI equal to 0 (low risk) indicates the least critical condition, in which, by maintaining the
 316 existing conditions, the possibility of social or economic damage is minimal, as it is unlikely that the
 317 event will occur, or due to the condition of low vulnerability of the exposed element. Areas with a
 318 low degree of hazard were considered to be stable.

319 The RI of 1 to 3 (moderate risk) indicates that, if the existing conditions are maintained, it is
 320 perfectly possible that social or economic losses will occur, especially in the months of more intense
 321 rainfall. It is, therefore, recommended to relocate buildings located in areas with a high or very high
 322 degree of hazard and to monitor those with a moderate threat potential.

323 The RI greater than 3 (high risk) indicates the most critical condition. The signs of instability are
 324 expressive, in number and / or magnitude. If the existing conditions are maintained, events with high
 325 destructive power are very likely to occur. Due to the conditions of vulnerability, significant social
 326 and economic damage is expected in these areas, which is why it is recommended to relocate the
 327 buildings that are present there.

328 Considering the situations described, it is considered extremely important that, concurrent with
 329 defining the degree of risk, the type of action and some deadline for its execution should also be
 330 defined.

331 The decision on the type of action and the respective deadline resulted from the cross-indexing the
 332 level of risk and the degree of hazard, as follows:

- 333 • Do not intervene - low risk and low hazard;

- Do not occupy - low risk and medium, high or very high hazard;
- Monitoring - moderate or high risk and medium hazard;
- Monitoring with scheduled relocation - moderate or high risk and high hazard;
- Immediate relocation - high risk and very high hazard.

4

5 RESULTS AND DISCUSSION

Considering the proposed system, the relative normalized weights for indicators (RWI), attributes (RWA) and classes (RWC) were defined using the AHP method, which were later related by means of a linear combination to support the evaluation of the risk components (HI - Hazard Index and VI - Vulnerability Index). The results of which are summarized in Table 6.

Table 6 - Indicators, classes and respective weights obtained throughout AHP for all components.

Comp.	Ind.	RWI (%)	Attributes	RWA (%)	Classes	RWC (%)
HAZARD (HI)	Susceptibility (SI)	38.79	Characteristics and behaviours of geological-geotechnical mapped units (Nascimento, 2016)	100.00	High	61.52
					Medium	31.88
					Low	6.60
	Induction Potential (IP)	14.26	Soil cover (SC)	25.00	Vegetal	7.96
					Urban	65.56
					Mixed	26.48
			Waste deposits on slope or cliffs (DS)	25.00	Very low or absent	5.72
					Low	11.01
					Medium	30.79
	Destruction Potential (DP)	46.95	Superficial water concentration due to leakage of sewage and water pipe system or absence of such systems (WS)	50.00	High	52.48
					Very low or absent	5.14
					Low	12.87
			Areas with instability signs (AI)	40.00	Medium	23.33
					High	58.66
					No evidence	3.57
			Events magnitude (EM)	60.00	<25%	9.89
					25 a 50%	16.01
					50 a 75%	26.38
					75 a 100%	44.15
					Absent	4.66
					Incipient (processes develops slowly and is possible to monitor)	12.84
					Significant (process is under full development and it is possible to monitor, but it is possible that mass movements occur during heavy rain periods or due to variations on drainage levels)	29.65
					Severe (High potential for mass movements to occur. It is not possible to monitor)	52.85

Table 6 – Indicators, classes and respective weights obtained throughout AHP for all components (Continuation).

VULNERABILIDADE (IV)	Potential Damage (PD)	20.00	Occupation Pattern (OP)	50.00	High	43.42
					Medium	28.24
					Low	16.38
					Very Low	8.50
					No Construction and Infrastructure	3.46
	Degree of Resilience (DR)	80.00	Area occupied by buildings and infrastructure (AO)	50.00	<5	6.04
					5-30	16.23
					30-60	28.79
					60-100	48.94
					Construction Quality (CQ)	50.00
			Some structures present	28.48		
			Well structured	15.95		
			No construction	4.30		
			Occupation Type (OT)	50.00	Subnormal urban agglomerate (slams, invasions etc.)	52.86
Residential and commercial areas		33.72				
Open areas		8.47				
No construction		4.95				
EQUATIONS ADOPTED FOR DEFINING VALUES FOR INDICATORS AND COMPONENTS						
$HI = 0.3879IS + 0.4695DP + 0.1426IP$				$VI = 0.8DR + 0.2PD$		
$DP = 0.6EM + 0.4AI$				$DR = 0.5CQ + 0.5OT$		
$IP = 0.5WS + 0.25DS + 0.25SC$				$PD = 0.5OP + 0.5AO$		

Figure 7 illustrates the overlapping of the geotechnical zoning information plan developed by Nascimento (2016) with the Regular Grid information plan. Approximately 53% of the assessed area was classified as having high susceptibility and the remaining regions as having low susceptibility. According to Nascimento (2016), high susceptibility is related to the slope of the compartments, which varies between 12 and 20% and the fluctuations of fluvial discharges, which act directly on the unconsolidated sediments and clay from the Solimões formation, generating several features of instability, as described. The regions with low susceptibility are above the flood zone, in compartments whose slope varies between 6 and 12%.

In Figure 9 and Figure 10, the cartograms related to the vulnerability and hazard components are presented, respectively.

Figure 8 - Regular Grid mesh with the overlapping of susceptibility classes defined for the area studied.

Figure 9 - Vulnerability chart.

Figure 10– Hazard chart.

354 The simulation carried out indicated that 79.87% of the investigated area has a high and very high
 355 vulnerability to the processes considered, as can be seen in Figure 11. An indication of very high
 356 vulnerability, in general, was associated, by the risk assessment model, to regions with a high
 357 concentration of subnormal settlements. There is, also, high vulnerability, on the other hand, of the
 358 historic and administrative center of the city, characterized by well-structured buildings and a greater
 359 concentration of installed infrastructure. Low vulnerability (17.77%), in general, was associated with
 360 areas devoid of occupations and infrastructure, normally located in the flood zones of the watercourse,
 361 while the average vulnerability was related to squares and open spaces, but endowed with some
 362 infrastructure.

363 Favorable conditions for the development of geological accidents (classes with high and very high
 364 AI) were observed in 38.76% of the investigated area, as can be seen in Figure 11. The Hazard
 365 cartogram indicated that cells with a higher level of hazard, concentrated in the concave section of
 366 the river, within the flood zones, since the level of high hazard was associated with the regions of

367 widespread evidence of creeps and abatement measures. Moderate hazard, in turn, was associated
368 with compartments with high natural susceptibility (Figure 8), in which the signs of instability were
369 observed incipiently or are absent. Low hazard was associated with the risk model, with
370 compartments of low natural susceptibility, and without signs or evidence of instability.

Figure 2 – Distribution of hazard and vulnerability classes, in percentage, for the study area.

371 The cartogram that expresses the risk (Figure 12) resulted from the cross-indexing of the RI (Figure
372 9) and HI (Figure 10) cartograms.

Figura 12– Mass movements risk chart.

373 From the data presented in Table 8, it can be seen that the most critical situations (classes with
374 moderate and high risk) were identified in 36% of the investigated area.

375 Table 8 - Distribution of risk classes.

Degree of risk	Area (m²)	Nº of cells	% of area
Low	720150	304	64,01
Moderate	154950	63	13,77
High	250000	100	22,22
Total	1.125.100	467	100,00

376 The decision on the type of action to be implemented, and the level of urgency for each action
377 resulted from the cross-indexing the risk cartography and the hazard cartography, the results of which
378 were summarized in Table 9 and represented in the cartogram in Figure 13.
379

380 Table 9 - Distribution of cells in accordance to mitigation actions.

Degree of risk	Degree of hazard				Action	nº off cells	% of area
	Low	Moderate	High	Very High			
Low	218	6	59	21	Without intervention	218	46,68
Moderate	0	62	4	0	Monitoring	62	13,28
High	0	0	73	24	Monitoring with scheduled relocation	77	16,49
					Immediate relocation	24	5,14
					Do not occupy	86	18,42

381 Figure 14 illustrates the overlapping of the information used to validate the risk model.

Figure 4 - Comparison between mitigation actions, instability (landslide) signs register and land use.

382 Based on the overlap of the registry of instability signs, the orthophoto mosaic and the actions
 383 indicated by the cartogram, we sought to subjectively assess the coherence between the action
 384 indicated by the model, the registered processes and the properties observed in each cell.

385 The emergency actions related to the immediate relocation occurred in 5% of the mapped area and
 386 correspond to the cells located in the vicinity of the largest channel bed, occupied by buildings with
 387 low construction standards, precarious infrastructure and, therefore, very vulnerable to the landslides
 388 frequently observed in this region.

389 As Figure 14 illustrates, the areas indicated for the programmed monitoring and / or relocation
 390 follow the same pattern as the occupations observed in the critical areas, however, they are
 391 concentrated in lands with less declivity and whose predominant movement is creeping.

392 6 CONCLUSIONS

393 This work sought to provide aid in assisting in the management of the risk associated with
 394 gravitational mass movements, composed of creeping and rotational landslides, along watercourse
 395 margins and urban areas of a municipality in the Western Brazilian Amazon. It is noteworthy that
 396 these processes are of common occurrence throughout the western region of the Amazon.

397 Due to the specificity of the theme, several criteria had to be developed or adapted in order for the
398 analysis to consider certain environmental, economic and social particularities of the region.

399 The Hierarchical Analysis Method was the technique adopted to structure the decision-making
400 process, so that the hierarchy of the problem and the prioritization of alternatives were based on the
401 logical and quantified judgment that the method provides.

402 In terms of use and occupation, especially the construction pattern and the level of income of the
403 population in the area studied, it was observed that the lower income population, characterized by
404 subnormal settlements that occupy riverside areas, is in fact, the most exposed to the processes
405 mapped. If, on the one hand, this population has developed ways to live with creeping (wooden
406 constructions, with limited dimensions, located in an area free from infrastructure, among others),
407 their physical and social condition makes them very vulnerable to landslides.

408 It was observed that the criteria and procedures described allowed the establishment of standards
409 for the collection, organization, management and validation of the decision-making process, which
410 contributes to the reduction of subjectivity in the identification of zones of different degrees of risk
411 and in the implementation of short-term and medium term actions to reduce geological accidents.

412 The results suggest that the methodological proposal can be applied in other areas, for the study of
413 the risk associated with other processes, which does not exempt it from the need for adequate
414 knowledge about those processes, their relationship with the physical environment and the exposed
415 elements.

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8 BIBLIOGRAPHIC REFERENCES

1. CARVALHO, J. A. L. De; IGREJA, H. L. S. Da; CUNHA S. B. Da; CARNEIRO D. S. Episódio de terras caídas no rio Amazonas: Caso Costa da Águia, Parintins-Am. In: XVIII Simpósio Brasileiro de Recursos Hídricos. **Anais...** Campo Grande, 2009.
2. CASCINI, L; BONNARD, CH.; COROMINAS, J; JIBSON, R. AND OLARTE-MONTERO, J. Landslide risk Management. Chapter: Landslide hazard and risk zoning for urban planning and development. Taylor & Francis. London. 199-235, 2005.
3. CERRI, L.E.S.; NOGUEIRA, F. R.; CARVALHO, C. S.; MACEDO, E. S.; AUGUSTO FILHO, O. Mapeamento de Risco em assentamentos precários no município de São Paulo (SP). **Geociências**, n. 26, v. 2, p. 143- 150, 2007.
4. FARIA, D. G. M. & AUGUSTO FILHO, O. Aplicação do Processo de Análise Hierárquica (AHP) no mapeamento de perigo de escorregamentos em áreas urbanas. **Revista do Instituto Geológico**, v. 34, n. 1, p. 23-44, 2013.
5. GOMES, M. F. M. **Metodologia de análise hierárquica aplicada para escolha do sistema de disposição de subproduto da mineração com ênfase nos rejeitos de minério de ferro**. 193p. Dissertação (Mestrado em Engenharia Geotécnica) - Universidade Federal de Ouro Preto, Ouro Preto, 2009.
6. INTARAWICHIAN, N. & DASANANDA, S. Analytical hierarchy process for landslide susceptibility mapping in lower Mae Chaem watershed, northern Thailand. **Suranaree J. Sci. Technol**, v. 17, n. 3, p. 277-292, 2010.
7. JASIWAL, J. **Landslide risk quantification along transportation corridors based on historical information**. Masster Thesis. Univeristy of Tweete, The Netherlands. 243 p, 2011.
8. KAYASTHA, P.; DHITAL, M. R.; DE SMEDT, F. Application of the analytical hierarchy process (AHP) for landslide susceptibility mapping: A case study from the Tinau watershed, west Nepal. **Computers & Geosciences**, v. 52, n. 0, p. 398 - 408, 2013.
9. LABADESSA, A. S. “Terras Caídas”, as causas naturais e antrópicas: uma ocorrência na comunidade de São Carlos - Médio Madeira/RO. **Geoingá**, Maringá, v. 3, n. 1, p. 45-61, 2011.
10. MAGALHÃES, R. C. & GOMES, R. C. M. Mineralogia e química de solo de várzea e suas susceptibilidades no processo de terras caídas na comunidade do Divino Espírito Santo - AM. **Sociedade & Natureza**, v. 25, n. 3, 2013.
11. MAIA, M. S. O. **Zoneamento geotécnico do sítio urbano do município de Rio Branco/AC e seus arredores, para fins de planejamento com ênfase à expansão urbana, através do sensoriamento remoto**. 116 f. Dissertação (mestrado). Instituto de Geociências e Ciências Exatas, Universidade Estadual Paulista, Rio Claro - SP, 2003.
12. MATOS, J. A. & CURSINHO, A. M. S. Caracterização geomorfológica das “Terras-Caídas” em área de várzea na comunidade Miracauera, Careiro da Várzea - AM. **Geonorte**, Edição Especial, v. 1, n. 4, p. 515 - 525, 2012.
13. NASCIMENTO, R. R. Do. Procedimento baseado em rotina de apoio à decisão aplicado à redução de risco de movimentos gravitacionais de massa em margens de cursos d’água: estudo de caso em Rio Branco/AC, 2016.

14. NASCIMENTO, R. R. Do. & SIMÕES, G. F. Avaliação da suscetibilidade a movimentos de massa gravitacionais em margens de cursos d'água da cidade de Rio Branco (AC). **Geociências**, v. 36, n. 2, p. 233-249, 2017.
15. OLIVEIRA, A. M.; FERREIRA, A. L. **Avaliação Geológico-Geotécnica da Cidade de Rio Branco; Relatório Final**. CPRM - Companhia de Pesquisa de Recursos Minerais. Vol I. 57p. Manaus, 2006.
16. NOGUEIRA, F. R. Gestão dos Riscos nos Municípios. In: CARVALHO C. S.; GALVÃO T. (orgs.) **Prevenção de Riscos de Deslizamentos em Encostas: Guia para Elaboração de Políticas Municipais**. Brasília, Ministério das Cidades, Cities Alliance, 2006, p. 26-45.
17. NOLA, I.T.S.; ZUQUETTE, L. V. Procedures of engineering geological mapping applied to urban planning in a data-scarce area: Application in southern Brazil. *Journal of South American Earth Sciences*, v. 107, p. 103141, 2021. doi.org/10.1016/j.jsames.2020.103141
18. PACHECO, J. D. & BRANDÃO, J. C. M. Geomorfologia fluvial do Rio Solimões/Amazonas: estratégias do povo vazeano do sudoeste do careiro da várzea. **Geonorte**, Edição Especial. Manaus. v.2, n.4. p.542 - 554, 2012.
19. PAULA, B. L. & CERRI, L. E. S. Aplicação do Processo Analítico Hierárquico (AHP) para priorização de obras de intervenção em áreas e setores de risco geológico nos municípios de Itapeçerica da Serra e Suzano (SP). **Geociências**, v. 31, n.2, p. 247-257, 2012.
20. RODRIGUES, B. B. & ZUQUETTE, L. V. Elaboration of gravitational mass movement predisposition chart based on decision support method: part of the city of Ouro Preto, State of Minas Gerais, Brazil. **IEAG: The Geological Society of London**. Paper n. 178, 2006.
21. SAATY, T. L. A scaling method for priorities in hierarchical structures. **Journal of mathematical psychology**, v. 15, n. 3, p. 234-281, 1977.
22. SAATY, T. L. How to make a decision: the analytic hierarchy process. **European journal of operational research**, v. 48, n. 1, p. 9-26, 1990.
23. SAATY, T. L. Relative Measurement and its Generalization in Decision Making: Why Pairwise Comparisons are Central in Mathematics for the Measurement of Intangible Factors - The Analytic Hierarchy/Network Process. **RACSAM-Revista de la Real Academia de Ciencias Exactas, Fisicas y Naturales. Serie A. Matematicas**, v. 102, n. 2, p. 251-318, 2008.
24. SAATY, T. L. **The Analytic Hierarchy Process**. McGraw-Hill. New York, 1980.
25. SILVA, F. A. S. & AZEVEDO, C. A. V. Principal Components Analysis in the Software Assistat-Statistical Attendance. In: **WORLD CONGRESS ON COMPUTERS IN AGRICULTURE**, 7, Reno-NV-USA: American Society of Agricultural and Biological Engineers, 2009. doi:10.13031/2013.29066
26. SOBREIRA, F. G. & SOUZA, L. A. Cartografia geotécnica aplicada ao planejamento urbano. **Revista Brasileira de Geologia de Engenharia e Ambiental**, São Paulo, n. 2, p. 79-97. 2012.
27. UNISDR - UNITED NATIONS INTERNATIONAL STRATEGY FOR DISASTER REDUCTION. **Como Construir Cidades Mais Resilientes - Um Guia para Gestores Públicos Locais**, Genebra. p. 90, 2012.

- 500 28. VEGA, J.A AND HIDALGO, C.A. (2016). Quantitative risk assessment of landslides
501 triggered by earthquakes and rainfall based on direct costs of urban buildings.
502 *Geomorphology*. 273:217-235. Doi: <https://doi.org/10.1016/j.geomorph.2016.07.032>