Measurement scales in AHP multicriteria methodology for calculating and managing risks of natural disaster

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Highlights

- Step by step calculation for efficient management of risk disasters.
- Integration of the different dimensions of the risk disaster problem. The multicriteria view using AHP and ANP.
- How to calculate the threshold values for disaster risk assessment and decision-making.

ABSTRACT

This paper presents a refined approach to disaster risk management using the Analytic Hierarchy Process (AHP), emphasizing the use of rating mode with cardinal scales for more accurate and mathematically valid risk calculations. By integrating hazard, vulnerability, and resilience into a comprehensive disaster risk index, the model offers decision-makers a robust tool for evaluating and managing risks in public investment projects. The methodology corrects common issues with ordinal scales in risk assessments and introduces a new formula created by Claudio Garuti for calculating risk levels within normalized ranges. This approach ensures better prioritization of investments in disaster-prone areas, improving infrastructure resilience and decision-making efficiency.

Keywords (3-6): AHP, Disaster Risk Management, Cardinal Scales, Local and Global Thresholds.

1. Introduction

Natural disasters are a significant threat to public infrastructure and human well-being worldwide. With increasing frequency and intensity of such events due to climate change, it has become imperative to integrate disaster risk assessment into the different localizations, specifically for planning and evaluation of public investment projects. This integration is crucial not only to safeguard the physical infrastructure but also to protect vulnerable communities that depend on these services. Traditional project evaluation methods often overlook the multifaceted nature of disaster risk, focusing predominantly on measuring the probability of a hazard instead of its importance, or calculating this weighted importance, but using the wrong scales or common threshold setting methods that doesn’t adequate to the realistic scenario of nature. This gap underscores the need for a comprehensive risk assessment framework that incorporates multiple criteria with the right

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scales to evaluate the potential exposure, vulnerability, and resilience of projects to various natural disasters.

2. Literature Review

The Analytic Hierarchy Process (AHP) has been widely applied in disaster risk management and infrastructure decision-making due to its capacity to handle complex, multi-criteria problems. This article focusses on the correct use of cardinal scales in AHP to ensure the accuracy of disaster risk assessments, critiquing the use of ordinal scales, contributing to the development of a risk calculation model that integrates hazards, vulnerability, and capacity into a single and mathematically more precise index, facilitating better decision-making in public investments.

In contrast, both recent and more classical researcb provided by Morales and de Vries (2021) and Yadollahi and Rosli (2011) fall short in their scale usage and risk calculation precision. Morales and de Vries emphasize participatory decision-making which is correct but neglects the mathematical rigor that this article insists is necessary for valid risk assessment. Yadollahi and Rosli offer a practical method for prioritizing infrastructure projects, yet their model lacks cardinal scales and resilience measures critical in this comprehensive approach. Thus, the focus on using normalized cardinal scales and integrating a broader range of disaster management metrics improves the precision and robustness of AHP applications.

3. Hypotheses/Objectives

This paper aims to present a robust multicriteria methodology for assessing disaster risks, using the Analytic Hierarchy/Network Process (AHP/ANP). Furthermore, this paper introduces the concept of a Tolerable or Acceptable Risk Threshold (ART), which serves as a reference point for determining the acceptability of the calculated risk levels. Projects with risk levels exceeding ART may require further investment to enhance their resilience, while those below the threshold may proceed without additional risk management interventions. Since the local and global threshold values are calculated (instead of an arbitrary imposition), this approach can provide a clear, actionable framework for evaluating and an efficient management of risks disaster, contributing to more resilient infrastructure development and better-informed decision-making, that can be used in public project investments and others.

Given the above, the objectives of this report are as follows:

1) Correct the risk level calculation according to the principles of AHP, with special attention to the metrics and scales used.
2) Organize the risk management process and its application in a structured and logical manner through the corrected calculation of the risk level.
3) Select efficient and reasonable measures for not surpassing the global threshold value.

4. Research Design/Methodology

For the construction of the model for Risk of Disaster, a cardinal scale was used, capturing the extent of differences between values, assigning weights to different criteria or variables, reflecting their relative importance in the decision-making process. In the case of Risk measurement, the range must be a value between 0 and 1, a positive real number, as expressed by:

$$\mathbf{R = P \times I} \qquad \textbf{(1)}$$

Where: P = probability of the event occurring. Range between 0 and 1, a positive real number. (Stochastic indicator). I = intensity or importance of the event. Range between 0 and 1, a positive real number. (Stochastic indicator).

Given the above, the range of R must necessarily be a value that also goes from 0 to 1 ($0 \leq R \leq 1$). Any value outside this range (from 0 to 100%) has no logical or mathematically valid meaning in a risk calculation formula, particularly in disaster risk (how much is a 300%? of risk? what does it mean?). Another reason why it should be cardinal, and not ordinal, is that the ordinal scale does not constitute a metric, and its values are not numerically operable; for instance, in meteorology a hurricane level 2 and a hurricane level 3 do not make a hurricane level 5. (i.e., 2+3 is not 5). Therefore, all indicators used in risk calculation (threats, vulnerabilities, or capacities) must belong to a normalized cardinal scale and contain a proportional or absolute proportional metric if we wish to perform numerical operations with them.

In this way, each variable/indicator requires two properties for its application in the DSR calculation. First, it must belong to a normalized cardinal scale and second, it must belong to a range of variation between 0 and 1, a positive real number. This means that the classical formula:

$$\boldsymbol{R = H \cdot V / Cap} \qquad \textbf{(2)}$$

is no longer valid, since there’s no upper limit and there’s no restriction in the range, we can get results that exceed the normalized scale between 0 and 1 or even tending to infinite (for example, what means a risk equal to 121%, any value over 100% has no sense). In this classic formula H stands for hazards, an external factor of risk, represented by the potential occurrence of an event of natural origin or caused by human activity that may manifest at a specific location; V for vulnerability, an internal risk factor of a subject or system exposed to a hazard, which corresponds to its intrinsic susceptibility to being harmed; and Cap for resilience or capacity of a system, community, or society exposed to a hazard to withstand, absorb, adapt to, and recover from its effects in a timely and effective manner, including the preservation and restoration of its basic structures and functions.

To get a better understanding of disaster risk concept and how can be managed (and to correct the last formula), it is necessary first to calculate the base risk level that comes by multiplying the aggregated threat level H(j) by the vulnerability score V(j). This gives a measure of the risk without considering the capacity to mitigate the impact. We do that because threat and vulnerability are more persistent things on time, while capacity is something much more dynamic and is a variable where we can act and change in a relatively easy way to achieve an acceptable risk value. Thus:

$$\boldsymbol{BR} = \boldsymbol{H} \cdot \boldsymbol{V} \quad \textbf{(3)}$$

H and V came from its own hierarchy's models (or holarchy in the H case), the multiplication of these two vectors or arrays represent the base risk values of the territory mapped as different zones (expose to different hazards) and cells that belong to each zone.

The following equations represents the global evaluation (Agk) of an alternative being evaluated (the k cell mapped in the territory) across all the terminal criteria (j) for both (H and V) hierarchical decision-making models with (i) levels.

$$\boldsymbol{Ag^k} = \sum_j \left[\left(\prod_i \boldsymbol{w_{ij}} \right) \cdot \boldsymbol{S_j}\left(\boldsymbol{Al^k}\right) \right] \quad \textbf{(4)}$$

This is a weighted sum, where the weight is determined by the importance of each criterion in the hierarchy, and the evaluation is done using specific cardinal rating scales (it assesses how well the alternative performs according to that criterion). However, if the global weight of the terminal criterion (wj) is used instead, then equation (5) simplifies to (5.a).

$$\boldsymbol{Ag^k} = \sum_j \boldsymbol{w_j} \cdot \boldsymbol{S_j}(\boldsymbol{Al})^{\boldsymbol{k}} \quad \textbf{(5)}$$

Finally, the following equations are vital for the construction of the Vulnerability and Hazard models:

$$\boldsymbol{V}(\boldsymbol{i}) = \sum \boldsymbol{w}(\boldsymbol{i}) \cdot \boldsymbol{S_j}(\boldsymbol{i}) \quad \textbf{(6)}$$
$$\boldsymbol{C}(\boldsymbol{i}) = \sum \boldsymbol{w}(\boldsymbol{i}) \cdot \boldsymbol{S_j}(\boldsymbol{i}) \quad \textbf{(7)}$$
$$\boldsymbol{H}(\boldsymbol{i}) = \sum \boldsymbol{w}(\boldsymbol{i}) \cdot \boldsymbol{S_j}(\boldsymbol{i}) \quad \textbf{(8)}$$

The first one calculates the total vulnerability score V(i) for a specific model (e.g., social, economic, or infrastructure vulnerability) by summing up the weighted evaluation S_j(i) of each indicator i for each cell j. Equation (8) computes the total capacity score for a specific model, similar to how vulnerability is calculated, referring capacity as the ability of a zone to withstand or recover from a disaster. Finally, the third equation of the set calculates the overall threat or hazard value for a specific cell j in a zone by summing the weighted evaluations S_j(i) of each threat indicator i. It's important to notice here that only H stands for an exogenous variable, meanwhile the rest are endogenous (proper of the territory and not due to external factors).

5. Results/Model Analysis

Since the classic formula didn't respond adequately to the range condition, the capacity had to be adjusted into the accepted range (from 0 to 1). Therefore, the most appropriate formula would be then

$$\boldsymbol{GR} = (\boldsymbol{H}(\boldsymbol{j}) \cdot \boldsymbol{V}(\boldsymbol{j})) * (\boldsymbol{1} - \boldsymbol{Cap}(\boldsymbol{j})) \quad \textbf{(9)}$$
$$\textit{For } j = 1 \textit{ to \#cells in the territory under analysis}$$

By clearly identifying and quantifying the contributions of hazard, vulnerability, and capacity of each cell, this formula allows decision-makers to target specific areas for risk reduction. For instance, if capacity is low, efforts can be focused on building resilience and improving adaptive capacities.

The use of a cardinal scale allows to determine a threshold for each specific location, called disaster risk cells in the territory. Then, the maximum tolerable risk associated with a zone "i" sets a threshold for determining whether the disaster risk in each area is acceptable or not, and it´s given by:

$$\boldsymbol{MaxTR(i) = MaxTH(i) \cdot MaxTV(i)} \quad \textbf{(10)}$$

The first term represents the aggregated hazard assessment for zone "i". This is calculated as the weighted sum of different threat indicators times the local threshold within that zone:

$$\boldsymbol{MaxTH(i) = \sum[w(j) \cdot LT(j)]} \quad \textbf{(11)}$$
$$for\ j = 1, \dots, \#indicators\ in\ the\ threat\ model\ of\ zone\ "i"$$

The second term represents the aggregated vulnerability assessment. This is calculated as the weighted sum of different vulnerability indicators times its local threshold, quantifying the susceptibility or exposure of the zone to these hazards:

$$\boldsymbol{MaxTV(i) = \sum[w(j) \cdot LT(j)]} \quad \textbf{(12)}$$
$$for\ j = 1, \dots, \#indicators\ in\ the\ vulnerability\ model\ of\ zone\ "i"$$

By multiplying these two components, the equation reflects both the magnitude of the threat and the sensitivity of the zone to those threats given the maximum tolerable base risk value zone (the base risk value threshold for each zone). Notice that if the base risk of the cell j is lower than the maximum tolerable of the zone i, then the cell j in zone i has a tolerable risk, supposing its capacity = 0 (this is why it is called the base risk).
To calculate the local thresholds (LT's) you may use the Garuti's formula for cardinal scales in a risk model. In general, LT = 2LM/(L+M), with L and M the *Low* and *Moderate* levels of the scale. (*See reference 6 for more details of how to apply correctly the LT's formula in risks model).*

About the structure for managing risk of disaster, the first step is to design the management. Here, it is essential to set the objectives that are needed to achieve (to do meaningful efforts) and to define a specific strategy or strategies that will settle a line and a direction to accomplish them. After a complete design comes the application phase, where it's needed to try different alternatives implementing the strategy established, until choosing one. Finally, it comes management, where the implementation of the chosen alternative is measured. Here's a very important thing: "you can't manage what you can't measure" (*Peter Drucker and Lord Kelvin*). In other words, it's needed to measure in an accurate and appropriate way to succeed managing a risk of disaster project.

Regarding the procedure for calculating Disaster Risk in the territory, it can be instructed in 10 main steps, as follows:

1) 1. Define the Threat Model(s) According to the Study Zone. In other words, identify the types of hazards (e.g., floods, earthquakes, hurricanes) relevant to the study zone, where a zone is defined as a set of homogeneous cells (small areas or

sub-regions) within the territory that are subject to equivalent threats. For example, a coastal zone might face similar flood risks.

2) Define the Vulnerability and Capacity Models to identify how susceptible or exposed each zone or cell is to the defined hazards. and to Measure the ability of each zone or cell to withstand or recover from the impact of these threats.
3) Weight the Models. Meaning to assign weights to the different threats, vulnerabilities, and capacities according to their relative importance or influence on the overall disaster risk. Not all threats or vulnerabilities are equally important; weighting helps prioritize those that have a more significant impact on disaster risk in each zone. in the Threat model, pay attention to first weighs the different hazards in each zone from the "zone point of view", that is, compare the different hazards regarding the zone where they may appear (the priorities of the set of hazards should differ from zone to zone).
4) Define the Evaluation Grid. Set up a grid to evaluate the territory, determining how many zones are considered and how many homogeneous cells or sectors are within each zone.
5) Construct the Scales for All Models. Create consistent scales for evaluating threats, vulnerabilities, and capacities across all models. Standardizing scales ensures that assessments are comparable across different threats and regions, making the final risk analysis more reliable and valid.
6) Determine the Local Threshold (LT) of the Indicators for All Models. This is the maximum value that each indicator can take, based on its scale. Defining these thresholds provides a reference point for evaluating the magnitude of each indicator, allowing for consistent assessments of risk levels across different areas.
7) Calculate the overall Vulnerability for specific cells, the Maximum Vulnerability and the total Capacity score for the Vulnerability and Capacity Models, using vectorial equations since the variables are endogenous.
8) Calculate the overall Hazard level for specific cells, the Maximum Hazard, the Base Risk, the Global Risk and the Maximum Tolerable Risk
9) Compare BaseRisk(j) with MxR(z) (for each zone separately):
   - If: $Rb(j) < Rmax(z)$ then cell is below the maximum tolerable risk.
   - If: $Rb(j) \geq Rmax(z)$ then cell is facing a disaster risk and requires management!
10) Act (Do Management). Develop an urgency ranking, specifying the where (in which zone and cells) and the how much (what to do in those cells to reduce the level of intensity to an acceptable one, below the maximum tolerable risk).

Regarding the above, once the model has reached the management step, it's crucial to prioritize cells with high-risk indicators. A good idea is to start with those whose impact value exceeds the local threshold and at the same time the variable has high weight. In those case where the base risk is higher than the global threshold (BR>GT), management is mandatory, and the cell´s capacity needs to be improved until the base risk reaches an acceptable value.

A graphic (basic) example of the application of the above is displayed in the appendices section, where a territory is evaluated in terms of their disaster risk indices, divided by zones and cells. These cells may belong to different zones, because each cell can influence the importance of the different hazards of the territory (acting as alternatives that influence the importance of the set of criteria in a model). For example, it's not the same the importance of a tsunami near by the coast than to the interior. Thus, the location of each cell in the hazard model affects the weight of each hazard, making feedback between cells and the set of hazards (alternatives and the given hazard). This kind of model is called a holarchy (a hierarchy where the alternatives influence the primary criteria) . Thus, the cells identify the precise risk values in each zone, made with the equations.

6. Conclusions

In this paper we have presented a guide to assess the risk of disaster in a territory in a detailed way, correcting the classic formula and presenting a complete formulation (step by step) to calculate and manage the risk of disaster. The last (the management) is very important when the time comes to assign the resources (time, money and effort) in the most efficient way possible. This formulation and calculus give a precise value for the tolerable risk and the value for every cell that conform the territory, thus, indicating the specific location and the exceeded value (the risk extension value over the maximum tolerable value) of each cell. Moreover, this proceeding allows us to evaluate the different projects for capacity enhancement and evaluate which is the best course of action (which gave me the best result for unit of time, money or effort involved).
This process is based mainly in AHP (hierarchy and holarchy) in its absolute mode of measurement (the rating mode), without it most of this proceeding would be impossible to do.

7. Limitations

The conditions of this proceeding are strongly limited it by having a political support of the local or national agency involved, the group of technical professionals required (depending on the territory and hazards involved) and the database required to feed the models (mainly geographic map of disasters, and people and infrastructure affected).

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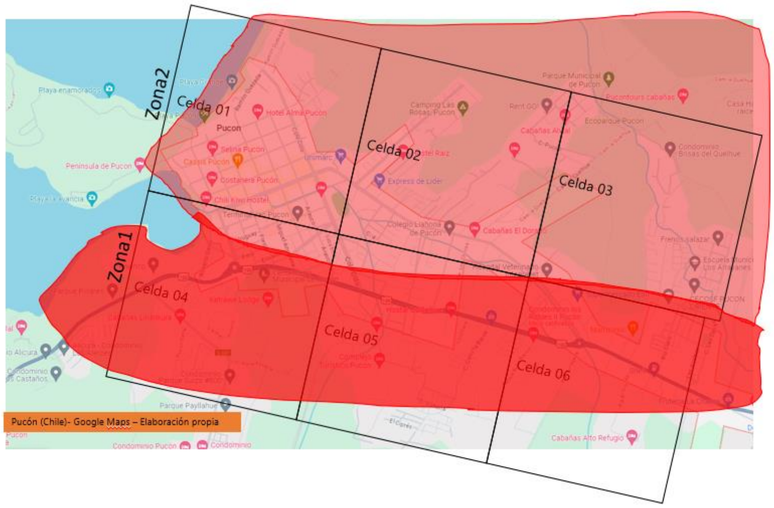
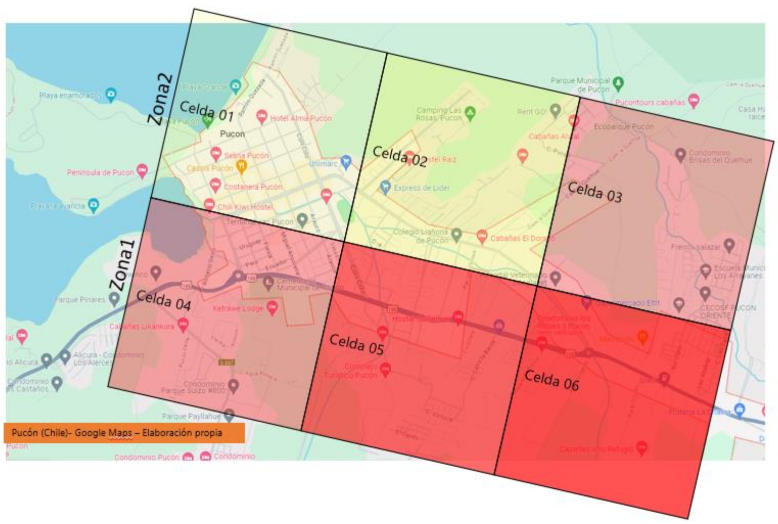
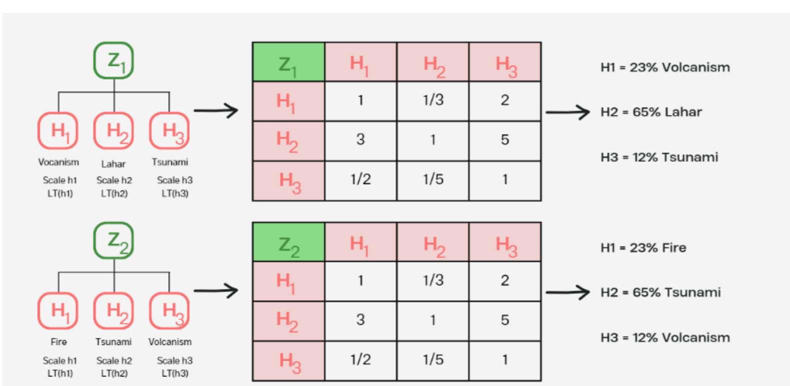
9. Appendices



Picture 1: Territory Risk Map



Picture 2: Zones and cells defined from the risk map



Picture 3: Example of a simplified pair-comparison matrix