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Thesis title: Assessing vulnerability to Climate Change in Medellín, Colombia: A comparative analysis of exposure, sensitivity, and adaptive Capacity in 2014 and 2021.

Name: Natalia Arcila Yepes

Supervisor: Alberto Gianoli

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Institute for Housing and Urban Development Studies of Erasmus University Rotterdam

Summary

In Latin America, cities often face structural challenges such as the inequality gap, poverty, and informal urbanization processes where the individuals with fewer resources inhabit marginal lands more exposed to climate hazards and are more vulnerable or predisposed to be negatively affected by climate-related events. Without proper and targeted interventions, the increase in the vulnerability of these communities to climate change is imminent, bringing along a cost in terms of development.

In Medellín, the city expects an increase in frequency and intensity of precipitation, favoring floods and landslides and threatening low-income areas in comunas 1-Popular, 3-Manrique, and 8-Villa Hermosa. Understanding that resources are limited, and interventions must be of high impact, this research aims to determine the most influential factors affecting exposure, sensitivity, and adaptive capacity to climate change in the previously mentioned Comunas under the context of unplanned settlements, poverty, and informality. Analyzing 2014, when vulnerability reduction policies are approved, and 2021 for comparative purposes.

The index-based vulnerability assessment is conducted through Principal component analysis (PCA) using the software Stata, a statistical method for variables reduction to their essential features, finding the variables that can summarize the most relevant patterns in the data, and assigning weights to the indicators accordingly. The method is applied separately to each vulnerability component. The results reveal that most neighborhoods experienced vulnerability increasing between 2014 and 2021 due to higher sensitivity and decreased adaptive capacity. The vulnerability is primarily influenced by houses located in high landslide hazard areas, houses made with temporary materials, overcrowding, low income, high population below 14 years old, lack of access to public services, low formal land tenure, and low education level. The results highlight that addressing persistent structural conditions such as poverty and social inequality is crucial for reducing vulnerability. However, each neighborhood displays different challenges that range from low access to Wi-Fi to intra-urban displacements. In general terms, the decreasing adaptive capacity sets off the alerts because it entails the impact intensification, creating, in turn, the increase in sensitivity, also observed in the study area.

The index can be extended to the city and used as monitoring and assessing system, for urban planning purposes, for proposing strategies, for supporting community initiatives, and for targeting interventions and prioritizing resources in policies on education, poverty, and housing, to enhance adaptive capacity and minimize sensitivity.

Keywords

Latin América

Vulnerability

Adaptative capacity

Climate change

Principal Component Analysis (PCA)

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Abbreviations

AMVA	Área Metropolitana del Valle de Aburrá (Aburrá Valley Metropolitan Area)
CAP	Climate Action Plan
Comp	Principal Component
DANE	Departamento Administrativo Nacional De Estadística- National Administrative Department of Statistics
IHS	Institute for Housing and Urban Development Studies
IPCC	Intergovernmental Panel on Climate Change
MIB	Mejoramiento Integral de Barrios–MIB (Comprehensive Neighbourhood Improvement)
PCA	Principal component Analisys
PMGRD	Plan Municipal de Gestión del riesgo de desastres (Disaster management Plan)
POT	Plan de Ordenamiento Territorial (Land use Plan)
SIATA	Sistema de Alerta Temprana de Medellín y el Valle de Aburrá (Early Warning System for Medellín and the Aburrá Valley)
VI	Vulnerability Index

1. Introduction

1.1. Background

When it comes to the effects of climate change, disparities become apparent, and the consequences do not discriminate based on individual contributions. Natural processes, external forcings, or anthropogenic changes in the atmosphere composition generate a persistent and long-term variability of climatic properties (IPCC, 2022, p. 2902). However, the effects vary around the world, and the vulnerability or predisposition to be negatively affected by these variations increases with the high susceptibility and the lack of capacity to adapt often present in developing countries (Giri, Bista, Singh, & Pandey, 2021).

In Latin America, the urban poor often inhabit marginal lands and high-risk areas exposed to climate hazards. Since extreme weather events are becoming more frequent, severe, and prolonged because of climate change (IPCC, 2022), without proper interventions, the increase in the vulnerability of these communities to climate change is imminent. Disaster is a threat not only to people's lives and livelihood but also has a cost in terms of development. For instance, the Colombian Planning National Department-DANE calculated that the country lost 3,6 points of the PIB after la Niña in 2010-2011 (Municipality of Medellín, 2015b, p.2). This precedent set off the alarms of the potential threats of climate change on the country's future development and the necessity of adopting strategies to enhance adaptive capacity.

In Colombia, the city of Medellín is part of the Metropolitan Area of the Aburrá Valley-AMVA, where four manifestations of climate change as being identified by The AMVA and the National University of Colombia (2018) (as cited in Municipality of Medellín, 2021): Systematic increase in temperature, increase in the duration and frequency of dry seasons, increase in the duration and frequency of rainy seasons, and increase in intensity, magnitude, or frequency of storms. Accordingly, Medellín Climate Action Plan identifies two climate threats: rising temperatures and increased extreme precipitation events (Municipality of Medellín, 2021). Rising temperatures cause fires and Urban Heat Island effect, while extreme precipitation events cause landslides, floods, and fast floods. Furthermore, the Municipality of Medellín (2015b) states that the risk is increasing due to climate variability, growing urbanization, and inequality; and identifies that coping mechanisms come from different stakeholders apart from the institutionality and need to include every citizen.

In a context of inequality, the socio-economic conditions of poor urban communities play a significant role in their vulnerability to climate change. The legal status of the settlements affects the proper inclusion of communities, their participation in planning processes, and the availability of demographic data (McGranahan & Satterthwaite, 2014). However, Adger (2006) highlights that despite the limitations, in most cases, decision-makers have access to enough information about the vulnerability, and the most effective approach is to address vulnerability beneficiating all segments of society, which involve understanding additional challenges in a context of inequality. Along the same line, Doherty, Klima, and Hellmann(2016) argue that without the proper understanding of trade-offs, adaptation actions can come at the cost of the well-being of vulnerable communities. Consequently, social inequality is a barrier to effective adaptation, and urban management strategies to reduce vulnerability will require focusing on characterizing and addressing these issues that in many cases of a structural nature.

1.2. Problem statement

Medellín's urban area is divided into six zones, each formed by comunas. In zones 1 and 3 are located comunas 1-Popular, 3-Manrique, and 8-Villa Hermosa, which account for approximately 60% of the population and exhibit high densities, lower living conditions, and increased risks. For instance, comunas 1-Popular and 3-Manrique are the most densely populated and present the highest risk in the city, highly impacted by socio-natural phenomena and vulnerability due to living conditions (Municipality of Medellín, 2015b, pp. 1-2). Moreover, through a city-scale vulnerability to climate change assessment, the Municipality of Medellín (2021) concluded that the neighborhoods with higher climate risk are low-income areas in the upper part of the comunas 1-Popular, 3-Manrique, and 8-Villa Hermosa. Consequently, this research focuses on the three comunas and the factors affecting vulnerability in each area.

As stated before, Medellín is facing an increase in the duration and frequency of rainy seasons and an increase in the intensity, magnitude, or frequency of storms, worsening existing challenges in landslides and flood management. Causing significant concern since the highest-risk areas match the lowest living conditions. For Example, during 2008, 2010, and 2011, the most common event was landslides reaching 46% of reported events and the highest percentage of losses in terms of lives and livelihoods (Municipality of Medellín, 2015b, p. 8). Due to the high occurrence of precipitation-related events in high-slope areas, one of the characteristics of the study area, this research will focus on landslides and floods.

In short, the city of Medellín faces structural challenges such as the inequality gap, poverty, the development of precarious settlements in high-slope areas, and informal economies; furthermore, the city is exposed to natural events related mainly to rainfall, of which an increase in frequency and intensity is expected (Municipality of Medellín, 2021). Given the circumstances, Medellín initially incorporated climate adaptation challenges in its Land Use Plan, POT 2014-2027, and the Municipal Disaster Risk Plan, PMGRD 2015-2030. Later, the Climate Action Plan, CAP 2020-2050, was approved and articulated with the early plans, setting the path of mitigation and adaptation to climate change. Despite the climate adaptive-related policies adoption, it is unclear if the vulnerability to climate change in Medellín is decreasing. Following the previous timeline is relevant to identify a baseline in 2014, before the POT and PMGRD adoption, and conduct the same analysis for 2021, a year after the execution of an administrative period or the short-term execution of both plans.

In addition, similar problems do not necessarily imply the same priorities or the same intervention strategies in different areas; moreover, the system responses can also differ. At the same time, cost-effective approaches to handle critical vulnerabilities are largely unknown; thus, the evaluation of available data can help direct limited resources to address critical issues (Doherty et al., 2016) . Even though comunas 1-Popular, 3-Manrique, and 8-Villa Hermosa share characteristics such as lower socio-economic conditions and their location in a steed rural-urban border, each area must be studied separately under the understanding that the dynamics between nature and society as well as the exposure, sensitivity, and adaptive capacity to climate change effects can differ even within communities (Ford et al., 2010) .Without this approach, adaptive actions tend to benefit those better positioned to access or take advantage of governance institutions rather than effectively reducing vulnerability for marginalized and often most vulnerable undervalued segments of the system (Adger, 2006). In that sense, identifying opportunities for enhancing adaptive capacity and reducing vulnerability and sensitivity in specific locations requires the acknowledgment of critical factors for each community.

1.3. Relevance of the research

This research analyzes the most influential factors affecting vulnerability to climate change in the Comunas 1-Popular, 3-Manrique, and 8-Villa Hermosa of Medellín and contributes to the scientific understanding of the localized impacts of climate change through the examination of the relationship between precipitation-related hazards, such as landslides and floods, and socio-economic conditions faced by marginalized and vulnerable communities, providing valuable insights into the complex and unique dynamics between nature and society and the varying levels of exposure, sensitivity, and adaptive capacity to climate change.

The potential for climate-resilient development pathways varies within territories with distinct development contexts and vulnerabilities (IPCC, 2018). Despite the shared characteristics in the study area, similar problems may require setting different priorities and intervention strategies. This research identifies critical factors for enhancing adaptive capacity and reducing vulnerability, ensuring that policymakers can direct limited resources towards effectively increasing adaptive capacity and reducing sensitivity and, ultimately, climate vulnerability in marginalized populations.

Finally, by analyzing data from 2014 as a baseline and comparing it to 2021, the research aims to assess the effectiveness of the implemented climate adaptation policies and provides valuable insights for policymakers, urban planners, and stakeholders involved in addressing climate change impacts. Furthermore, using open data generates the possibility of replicating the study and evaluating the indicators to monitor the behavior of critical factors over time.

1.4. Research objective

The main objective of the research is to determine the most influential factors affecting exposure, sensitivity, and adaptive capacity to floods and landslides due to increasing precipitation in Comunas 1-Popular, 3-Manrique, and 8-Villa Hermosa in the city of Medellín, under the context of unplanned settlements, poverty, and informality. The results are expected to provide insights that can guide policymakers, stakeholders, and communities to improve the adaptive capacity and reduce the vulnerability of urban poor communities in Medellín, Colombia. The following specific objectives are part of the research to support the fulfillment of the main objective:

- Compare and analyze the changes and significant behaviors in the key factors of exposure, sensitivity, and adaptive capacity in two specific years, 2014 and 2021. Creating a baseline in 2014, before the POT and PMGRD adoption, and conducting the same analysis for 2021, after the short-term execution of both plans.
- Explore the potential interactions between exposure, sensitivity, and adaptive capacity factors to understand their role in determining vulnerability to climate change in the study area.
- Investigate the possible explanations and influences behind the changes in vulnerability to climate change in Medellín between the years 2014 and 2021.

1.5. Research questions

In line with the research objectives, the primary aim of this research is to answer this question:

- What are the most influential factors affecting exposure, sensitivity, and adaptive capacity to climate change in Comunas 1-Popular, 3-Manrique, and 8-Villa Hermosa of Medellín?

To answer the main research question, the following sub-questions will be answered as well as part of the investigation:

- What are the main changes and relevant behaviours in the key factors of exposure, sensitivity, and adaptive capacity comparatively in 2014 and 2021?
- What are the potentially relevant interactions between exposure, sensitivity, and adaptive capacity factors in determining vulnerability to climate change in the study area?
- What are the possible explanations and influences for the changes and the influential factors in the vulnerability to climate change in Medellín?

2. Literature review

As a foundation for this study, this chapter provides an overview of vulnerability assessment based on existing research. After a brief introduction to urban and socio-ecological systems, this chapter will proceed with the initial section, where the theoretical foundations of vulnerability to climate change will be explored. Secondly, the definition of exposure, sensitivity, and adaptive capacity is provided. In addition, interactions between vulnerability components in the context of urban areas in developing countries will be discussed to assess their strengths and limitations in Reducing vulnerability. Lastly, this chapter will conclude with a conceptual framework summary presented as a diagram representing the expected relations between the concepts including in this chapter.

In urban areas, different dynamic elements take place and interact with each other. Elements such as the local environment, ecosystems, and natural resources are part of Socio-ecological systems and are connected and predisposed by the social system and external components such as people, physical infrastructure, wealth, demographics, institutional arrangements, and social and economic dynamics (Kumar, Geneletti, & Nagendra, 2016). In that sense, the system will have reciprocal feedback due to the interaction between elements and external components.

In the case of urban areas, other elements are included as an extension and not an exclusion of socio-ecological systems. According to the Intergovernmental Panel on Climate Change- IPCC (2022), in the context of urban systems define three city elements: “a) encompass physical, built, socio-economic-technical, political, and ecological subsystems; b) integrate social agent/ constituency/processes with physical structure and processes; and c) exist within broader spatial and temporal scales and governance and institutional contexts” (p. 2926). Each element has multiple dimensions and characteristics, and understanding the connections between these elements is essential for policymaking and urban planning.

2.1. Vulnerability to climate change in urban systems

Urban systems can be subjected to different pressures and increasingly vulnerable to the changes in the state of the climate or climate change. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change defines vulnerability as “The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt” (IPCC, 2022, p. 2253). Other definitions are found in the literature and include from one perspective or another the relations between exposure, sensitivity, and adaptive capacity. In the IPCC definition, exposure is the predisposition to be adversely affected by climate hazards, sensitivity denotes the system's susceptibility to those hazards, and adaptive capacity represents the ability to cope or adapt.

In addition to the IPCC's definition, the literature offers alternative perspectives and additional aspects of the vulnerability of urban systems facing climate change. For instance, Coulibaly et al. (2015) state that in the presence of environmental stress, the predisposition to be affected is revealed through the interaction between social and biophysical subsystems on a spatial scale, including the socioeconomic condition of the individuals affecting their ability to adjust. In that sense, vulnerability has a continuously evolving state and arises due to a lack of adaptation-related responses (Giri et al., 2021). Therefore, adaptation requires a focus on the properties that prevent the system adaptation instead of the threat itself.

Consequently, vulnerability research aims to determine who or what is at risk and explore the reasons behind their susceptibility while identifying the limitations and capabilities to enhance adaptation and policy interventions (Ford et al., 2010). Answering those questions requires the consideration of the ongoing interactions between climate change, the physical environment, and the social and economic factors that shape vulnerability in a specific area.

2.2. Vulnerability components

2.2.1. Exposure

The IPCC(2022) defines exposure as "The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected" (p.2899). From this perspective, the characterization of the exposure considers the assessment of climate-related events and determining the magnitude and frequency to which the components in the system are subjected (Kumar et al., 2016). Along with sensitivity, understanding this component is crucial for evaluating the potential impacts on elements such as people and both public y private property exposed to climate hazards.

2.2.2. Sensitivity

For the second component of vulnerability, sensitivity, the IPCC (2022) uses the following definition: "the degree to which a system or species is affected, either adversely or beneficially, by climate variability or change." (p. 2922). In other words, the characteristics, factors, or attributes of the elements in the system that make them more susceptible to direct or indirect effects of the hazards or to be harmed (Giri et al., 2021). In that regard, under the same magnitude of exposure, the system's conditions can reduce or worsen the impact (Coulibaly et al., 2015).

2.2.3. Adaptive capacity

While the literature shows a consensus regarding the definitions of exposure and sensitivity, the third component of vulnerability, adaptive capacity, has different approaches in the literature. Some definitions focus on the adaptive capacity of systems, institutions, and humans, while others approach natural and human systems separately. The distinctions suggest the possibility of examining adaptive capacity from different perspectives and scales. However, the definitions have several similarities with the ones provided by the IPCC. The organization defines adaptive capacity as "the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities or to respond to consequences" (MA, 2005, as cited in IPCC, 2022, p. 2899). The definitions acknowledge that adaptive capacity not only involves taking action to reduce the negative effects of climate change but also taking advantage of opportunities that arise from changing circumstances.

Actions taken to enhance adaptive capacity may range from policy decisions to involuntary responses generated by ecological, market, or welfare changes (Ford et al., 2010), demonstrating the changing nature of adaptive capacity and the influence of a wide range of factors, such as social, economic, and environmental. Therefore, the capacity to adapt is impacted by local resources, conditions, and specific characteristics of the system or element that limit or support the capability to adapt (Adger et al., 2005, as cited in Kumar et al., 2016). This demonstrates the context-specific nature of adaptive capacitive.

Given the characteristics of adaptive capacity, in the context of urban areas of developing countries, Flórez Bossio, Ford, and Labbé (2019) identify three levels of adaptive capacity: coping, adapting, and transforming. The first level refers to the ability to deal with short-term climate threats with concrete actions as a respond to the events. Adapting describes longer-term efforts to prepare for potential climate change risks or to take advantage of potential opportunities. Finally, transforming refers to the ability to change structural conditions. Placing climate actions in one of these categories would facilitate cost-benefit analysis and decision-making.

2.3. Interactions between exposure, sensitivity, and adaptive capacity in the context of urban areas in developing countries.

As shown in Figure 1, vulnerability is shaped by the combined influence of exposure, sensitivity, and adaptive capacity. Additionally, exposure and sensitivity determine the level of impact, while adaptive capacity influences the system or population's ability to cope and recover from these impacts. In this regard, Kumar et al.(2016) highlight the interaction between exposure and sensitivity in determining climate change impacts in cities, without being influenced by the system coping capacity. That means the impacts on the systems are predominantly related to extreme events and the susceptibility to be affected by them.

On the other hand, focusing on Adaptive capacity in urban areas of developing countries, Flórez Bossio et al. (2019) warn about the importance of recognizing that some urban population groups present inherent vulnerabilities and may be more negatively affected by climate change. These groups tend to have higher levels of sensitivity and lower levels of adaptive capacity, which aggravates circumstances that favor sensitivity.

In terms of exposure and adaptive capacity, the interaction between these components is usual in urban informal settlements. Areas occupied by the poor are often in ecologically sensitive and marginal areas (Wekesa et al., 2011 as cited in Giri et al., 2021) . In those cases, the location reduces the adaptive capacity, increases vulnerability and exposure to climate-related hazards, and exacerbates existing inequalities through the interaction with the lack of resources, assets, and facilities.

2.3.1. Important factors on Reducing vulnerability and enhancing adaptive capacity in urban informal settlements.

Whether vulnerability is associated with exposure to a transitory risk, or is a chronic state, reducing vulnerability is usually related to social vulnerability. However, the term cannot be seen as the same as poverty. In a vulnerability assessment is imperative to recognize that certain population groups divided by income, race, gender, or age are more susceptible to climate change impacts. For instance, groups such as the elderly, children, women, and marginalized communities possess inherent vulnerabilities (Flórez Bossio et al., 2019). Still, enhancing adaptive capacity and reducing vulnerability in informal urban areas require addressing poverty and social inequalities and ensuring equitable access to resources and infrastructure. Poruschi and Ambrey (as cited in Doherty et al., 2016) point out that social inequality is a major barrier to effective adaptation and suggests that remedying social inequalities favors pro-environmentally behavior in vulnerable populations. As emphasized by Adger (2006), though income level may be a key parameter in vulnerability reduction, it also requires a focus on general well-being.

Along the same line, enhancing current and future adaptive capacity is possible by addressing social inequalities and incorporating equity into infrastructure and urban design, as stated by Giri et al.(2021). For instance, the program Comprehensive Neighbourhood Improvement (Mejoramiento Integral de Barrios–MIB) focuses on less consolidated or informal areas of Medellín by focusing on reducing inequality and socially constructed vulnerabilities by providing drinking water among other interventions (Garcia Ferrari, Crane De Narváez, Castro Mera, Velásquez, & Bain, 2022). Some interventions such as access to information, education, and resources also play an important role in enhancing adaptive capacity. A lower education level limits the ability to access and understand technical information and to effectively use early warning systems, forecasts, and reading materials (Coulibaly et al., 2015).

Interventions and adaptive actions can generate unintended harm and consequences to vulnerable populations due to the uncertainty and lack of understanding of trade-offs. When trying to enhance adaptive capacity there is a need for trade-off analysis. Households' efforts to adapt can come at the expense of other aspects of human welfare, reinforcing poverty traps and leading to inequity in the burden of risk management (Eakin et al., 2016 as cited in Doherty et al., 2016; Flórez Bossio et al., 2019). Furthermore, enhancing adaptive capacity requires understanding the dynamics of collective action, political will, and citizen participation and a holistic understanding of the vulnerable population.

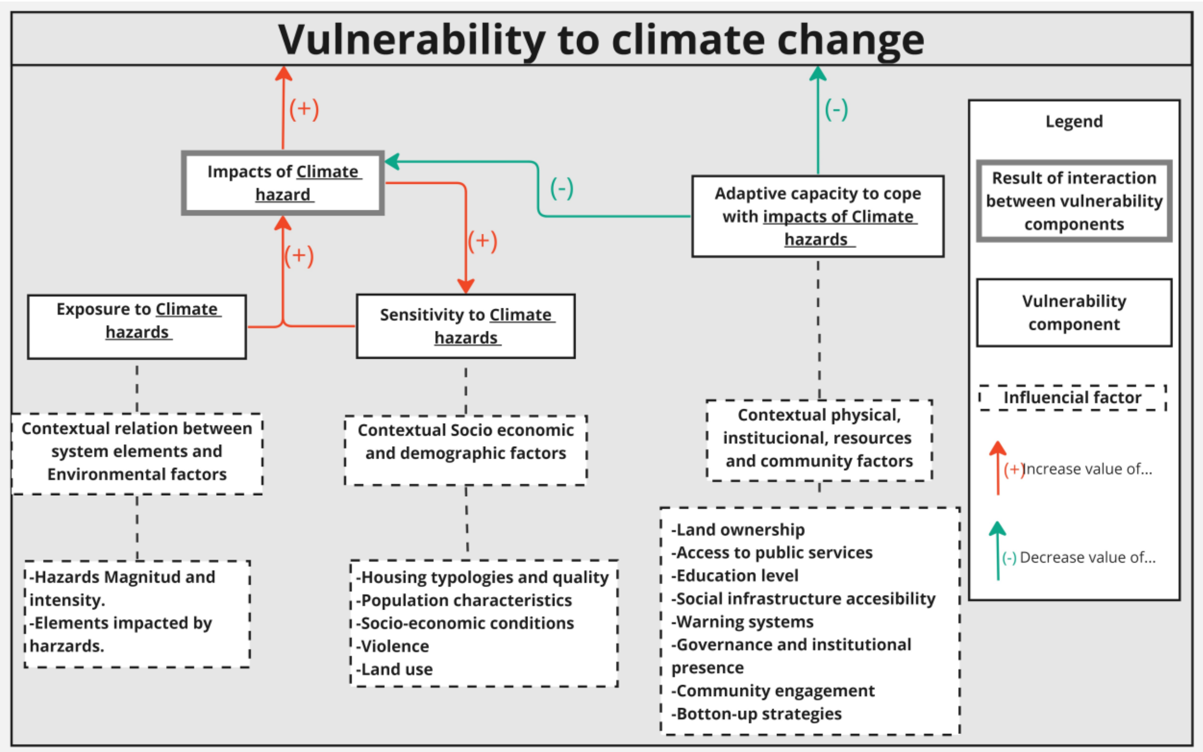
To conclude, the key elements and actions to reduce vulnerability are closely related to the specific physical and socioeconomic context; however, urban informal settlements shared some elements that can enhance adaptive capacity such as addressing social inequalities and ensuring equitable access to resources and infrastructure, recognizing that certain population groups possess inherent vulnerabilities, incorporating equity into infrastructure and urban design, and providing access to information, education, and resources. However, the action's effects must be evaluated while looking for possible trade-offs, as adaptive efforts may reinforce poverty and inequities.

2.4. Conceptual framework

The vulnerability conceptual framework in Figure 1 illustrates the concepts and their expected interaction developed throughout the literature review. At the top, as the core of the framework, is the concept of vulnerability representing the propensity or predisposition of the system to be adversely affected (IPCC, 2022, p. 2253) and determined by the interactions of three components: exposure, sensitivity, and adaptive capacity. In this research, exposure refers to the magnitude and frequency to which the components in the system are exposed (Kumar et al., 2016). Sensitivity represents attributes of the elements in the system that make them susceptible to the effects of the hazards (Giri et al., 2021). Ultimately, adaptive capacity reflects the ability of a system, community, or individual to adjust and respond to climate change impacts (MA, 2005, as cited in IPCC, 2022, p. 2899). The components are shaped and influenced by different contextual factors, such as socio-economic, institutional, demographic, and environmental conditions. Figure 1. Associates general factors to a specific component; however, depending on the context, the interaction between the factors and/or factors and components can vary. The factors used for this research can be seen in more detail in the subdimension in the operationalization in Table 1

Vulnerability is influenced by the components' interactions. Impacts on the systems are related to extreme events and the susceptibility to be affected by the hazards. Therefore, the impacts are the result of the interaction between exposure and sensitivity (Kumar et al., 2016). The vulnerability increases with the impacts and decreases with adaptive capacity, which means, it is positively affected by impacts and negatively affected by adaptive capacity. At the same time, the impacts exacerbate existing inequality and socio-economic disadvantages, increasing sensitivity and creating a feedback loop where impacts make the system more sensitive, and sensitivity increases the impacts. On the contrary, the adaptation capacity decreases both impacts and vulnerability.

Figure 1 Vulnerability conceptual framework



3. Research design, methodology

3.1. Description of the research design and methods

This research aims to find the most influential factors affecting vulnerability to climate change; therefore, the method used to perform an index-based vulnerability assessment should be able to find the variables that can summarize the most relevant patterns in the data and assign weights to the indicators accordingly. Principal component analysis (PCA) was selected for that purpose. PCA is a statistical method for reducing a high number of variables to their essential features or principal components, where the principal components are linear combinations of the variables that account for most of the variance in the data set (Greenacre et al., 2022, p. 1). Furthermore, PCA has been applied as an alternative to equal weighting in vulnerability assessment because of its ability to deliver comparable and reliable results that can be used for urban planning and to minimize hazards in cities in Latin (Inostroza, Palme, & De La Barrera, 2016).

This quantitative research establishes a Vulnerability Index (VI) using PCA and incorporates social, economic, and physical factors connected to vulnerability to climate change. The increasing precipitations are expressed in floods and landslide events, and a total of 51 indicators are used to assess exposure, sensitivity, and adaptive capacity in three Comunas (forty-five neighborhoods) in 2014(y1) and 2021(y2). The methodology has three major steps:

1. Identify from the literature review potential categories representing vulnerability to climate change in the context of informality and poverty at different scales: global south, Latin America, Colombia, and Medellín.
2. Define and process appropriate sub-variables and indicators for exposure, sensitivity, and adaptive capacity.
3. Perform PCA to identify the most influential factors affecting the three variables: exposure, sensitivity, and adaptive capacity.

3.1.1. Indicator selection and dataset generation

Based on the literature review a first exploratory definition of sub-variables and indicators for exposure, sensitivity, and adaptive capacity is created. The indicators in Table 1 are the input to the PCA and are selected due to data availability in terms of desirable scale and time. Within the framework of Law 1712 of 2014 on transparency and access to Colombian public information, this research relies on open data from the municipality of Medellín, including but not exclusively, the POT GDB and the life quality survey, the Aburrá Valley Early Warning System- SIATA, the IDEAM- and the National Department of statistics-DANE. Some indicators and indexes are subtracted directly from the sources while other data is processed to calculate indicators using the software QGIS and Stata for spatial and quantitative analysis. The resulting data matrix has a total of 44 indicators for 45 neighbourhoods located in three Comunas, each indicator has data available for the years 2014 and 2021.

3.1.2. PCA Vulnerability Index

The dataset with the indicators in Table 1 is prepared for the PCA. The first step is to normalize the data for each variable: exposure, sensitivity, and adaptive capacity. When necessary, the data is transformed to a normal distribution and then standardized to obtain a mean of 0 and a deviation of 1 (Bucherie et al., 2022). Then, the PCA is performed in Stata to reduce the number of indicators per variable due to high correlation while retaining as much information as possible (Abdrabo et al., 2023). After, a PCA is conducted on Stata on each variable and year, 2014 and 2021.

Once the PCA analysis is complete, Stata provides the eigenvalues, indicating the variance explained by each principal component. Components with an eigenvalue close to or higher than 1 were integrated, understanding that the components explain a significant portion of the total variance (Bucherie et al., 2022). Subsequently, Stata calculates the loadings and compute the scores for each retained principal components. The sign of the loadings indicates whether the correlation is positive or negative (Aroca-Jimenez, Bodoque, Garcia, & Diez-Herrero, 2017) and higher component scores indicate higher vulnerability. Performing the PCA allows the identification of the most influential factors affecting exposure, sensitivity, and adaptive capacity in Comunas 1-Popular, 3-Manrique, and 8-Villa Hermosa and the changes in two points in time, 2014 and 2021. Higher component scores indicate higher vulnerability, while loadings indicate the relationship between variables and components. After the PCA, the KMO test is applied for sampling and checking model robustness. Following Abdrabo et al. (2023) categories are defined as: 0.90 (marvellous), 0.80 (meritorious), 0.70 (middling), 0.60 (mediocre), 0.50 (miserable), and below 0.50 (unacceptable).

The individual values for exposure, sensitivity, and adaptive capacity, are calculated as shown in Equation 1 Dimension vulnerability Index (Bucherie et al., 2022):

Equation 1 Dimension result

$$D_b = \sum_{i=1}^{n} (\alpha_i * PC_{bi})$$

Where PC_{bi} is matrix of each principal component i, weighed for individual neighbourhood b by the percentage of variance explained of each principal component (α_i). Finally, The Vulnerability to climate change follows an adaptation of Inostroza, Palme, and De La Barrera (2016) equation:

Equation 2 Vulnerability index

$$VI_b = E_b + S_b - AC_b$$

Where the Vulnerability Index (VI) is the sum of exposure (E) and sensitivity (S) minus the adaptive capacity (AC) for individual neighborhood b.

3.2. Operationalization: variables, indicators

The three selected dimensions are the components of vulnerability: exposure, sensitivity, and adaptive capacity. Exposure is measured using three sub-dimensions and 11 indicators, sensitivity with five sub-dimensions and 24 indicators, and adaptive capacity with six sub-dimensions and 16 indicators. The dimensions, sub-dimensions, and indicators are grouped in Table 1 and are based on the finding from the literature review, summarized in Figure 1.

Table 1 Operationalization table: Dimensions and indicators.

Dimension	Subdimension	Cod	Indicators	Data source	Literature
Exposure	Precipitation	E11	Total Annual days of rain	Open data IDEAM	Huynh, Do, and Dao (2020) Kumar, Geneletti, & Nagendra (2016) Giri et al. (2021)
		E12	Average deviation of monthly accumulative precipitation from the 30-year average		
		E13	Number of fatal accidents due to precipitation		
	Flooding	E21	Number of Buildings affected by flooding	MEData: open data municipality of Medellín (Quality of life survey)	Coulibaly et al. (2015) Huynh et al. (2020) Giri et al. (2021)
		E22	Percentage of land with flooding high hazard	GeoMedellín: Spatial open data from Municipality of Medellín (flood hazard and administrative division)	
	Landslides	E31	Number of Buildings affected by landslides	MEData: open data municipality of Medellín (Quality of life survey)	
		E32	Percentage of land with landslides high hazard	GeoMedellín: Spatial open data from Municipality of Medellín (GDB_POT). Cadastre requested to the Municipality of Medellín	
Sensitivity	Housing typologies	S11	Percentage of houses with transitory materials on the walls	MEData: open data municipality of Medellín (Quality of life survey)	Kumar et al. (2016)
		S12	Percentage of houses with transitory materials on the floor	MEData: open data municipality of Medellín (Quality of life survey)	
	Population	S21	Percentage of population between 0-14 years old	National Census-DANE	Huynh, Do, and Dao (2020) Inostroza, Palme, & De La Barrera (2016) Kumar et al. (2016) Coulibaly et al. (2015)
		S22	Percentage of the population between 15-64 years old		
		S23	Percentage of the population 65 years old or more		
		S24	Female ratio		
		S25	Population density (people/ha)		
		S26	Percentage of disabled population	MEData: open data municipality of Medellín (SISBEN III)	
		S27	Percentage of indigenous population		

		S28	Percentage of Afro-descendant population	MEData: open data municipality of Medellín (Quality of life survey)	
		S29	Percentage of people arriving in the city due to public order problems		
		S210	Total Population	National Census-DANE	
	Socio-economic conditions	S31	Percentage of Overcrowded households	MEData: open data municipality of Medellín (SISBEN III)	Roncancio, Cutter, & Nardocci (2020) Giri et al. (2021) Huynh et al. (2020) Sarkodie and Strezov (2019)
		S32	Households with an income below legal minimum wage	MEData: open data municipality of Medellín (Quality of life survey)	
		S33	Households with an income between 1 and 2 minimum wages		
		S34	Gini coefficient	MEData: open data municipality of Medellín	
	Violence	S41	Number of females with a suspicious diagnosis of public health surveillance of gender violence.	MEData: open data municipality of Medellín	Adger (2006)
		S42	Number of cases of Intra-urban Forced Displacement		
	Land use	S51	Percentage of Built areas on land with flood high hazard	GeoMedellín: Spatial open data from Municipality of Medellín (flood hazard, Cadastre, and administrative division)-request for additional data to Municipality of Medellín	Kumar et al. (2016)
		S52	Percentage of Built areas in land with landslide high hazard		
Adaptive capacity	Land tenure	A11	Percentage of houses formally owned	MEData: open data municipality of Medellín (Quality of life survey)	Sarkodie and Strezov (2019)
		A12	Percentage of houses occupied with no legal rights		
	Public services	A21	Percentage of households having drinking water connection	MEData: open data municipality of Medellín (Quality of life survey)	Huynh, Do, and Dao (2020) Inostroza, Palme, & De La Barrera (2016) Kumar et al. (2016)
		A22	Percentage of households connected to electricity		
		A23	Percentage of households having wastewater drainage connection		
		A24	Percentage of households with waste collection service		
		A25	Percentage of households with wifi		
	Education	A31	Percentage of the population with no years of education	MEData: open data municipality of Medellín (Quality of life survey)	Coulibaly et al. (2015)
		A32	Percentage of the population with primary education		
		A33	Percentage of the population with secondary education		
		A34	Percentage of the population with university education		
	Infrastructure	A41	Public space per inhabitant (m2/inhab)		Huynh, Do, and Dao (2020)

		A42	Distance from the neighborhood to an educational facility	GeoMedellín: Spatial open data from Municipality of Medellín (GDB-POT)	Kumar et al. (2016) Giri et al. (2021) Sarkodie et al. (2019)
		A43	Distance from the neighborhood to a health facility		
		A44	Distance from the neighborhood to a community facility		
		A45	Distance from the neighborhood to a recreation and sports facility		
	Warning systems	A51	Number of pluviometric stations	SIATA	Flórez Bossio, Ford, and Labbé (2019) Coulibaly et al. (2015)

3.3. Expected challenges and limitations.

This research relies mostly on open data, making use of Law 1712 of 2014 on access to public information in Colombia; however, some relevant indicators are not included in the index due to the lack of data availability in formats, scale, or years required. In some cases, alternatives were found by requesting the responsible entities. Elements such as access to communication technologies (Bucherie et al., 2022; Inostroza et al., 2016) are not incorporated even though can be measurable under a quantitative approach, the above due to the absence of information available for the baseline year. Additionally, some topics might require a qualitative or mixed approach. In this sense, the research does not include indicators focused on community engagement and button-up adaptive action (Garcia Ferrari et al., 2022; Núñez Collado & Wang, 2020) and governance (Adger, 2006). The same applies to the analysis of Trade-offs resulting from interventions focused on improving socio-economic conditions, infrastructure, and interventions focused on mitigation or adaptation to climate change (Flórez Bossio et al., 2019). This analysis would allow conclusions on the effects of government interventions and policy implementation.

In other cases, the period comparison was not feasible because the data was unavailable for one of the years to analyze. Therefore, data was allowed within the range 2012-2014, for year 2014; and 2017-2021, for y2=2021. These ranges maintained the measurements before the POT and PMGRD. It is also relevant to inform that under the established methodology, tendencies are unknown because the index only compares two moments in time; therefore, there is no information on how a shock such as covid-19 and other aspects may have influenced the indicators for 2021.

Similarly, the information did not always correspond to the neighborhood scale but to the Comuna scale. This scale may not fully reflect the conditions of the analyzed neighborhood, especially knowing that areas close to the edge present a high social vulnerability (Municipality of Medellín, 2014, 2015, 2021). Another limitation is that the municipal statistics follow a political-administrative division and ignore the informal occupation of an urban nature on administratively rural land, preventing an accurate characterization of the neighborhood areas in the urban-rural border.

A better understanding of the potentially relevant interactions between exposure, sensitivity, and adaptive capacity factors in determining vulnerability to climate change and possible explanations and influences for the variations in 2014 and 2021 will require approaching academics, public officers, community leaders, and study area inhabitants the sector would be more enlightening. Additionally, due to the impossibility of traveling to Medellín, observations and fieldwork are not part of the research; nevertheless, the author has experience in the planning department of Medellín, which can help the analysis while being aware that it can generate bias.

4. Results, analysis, and Discussion

4.1. Study area and temporality

The district of Medellín in Colombia with an area of 376,3995 km2 from which 263,0411 km2 are urban according to the land use plan and a population of 2.6 million for 2022. The study area is defined according to previous analyzes carried out by the municipality of Medellín (2014, 2015, 2021), where Comuna 1-Popular (C1), Comuna 3- Manrique (C3), and Comuna 8-Villa Hermosa (C8) were selected as the most vulnerable areas natural disasters and climate change.

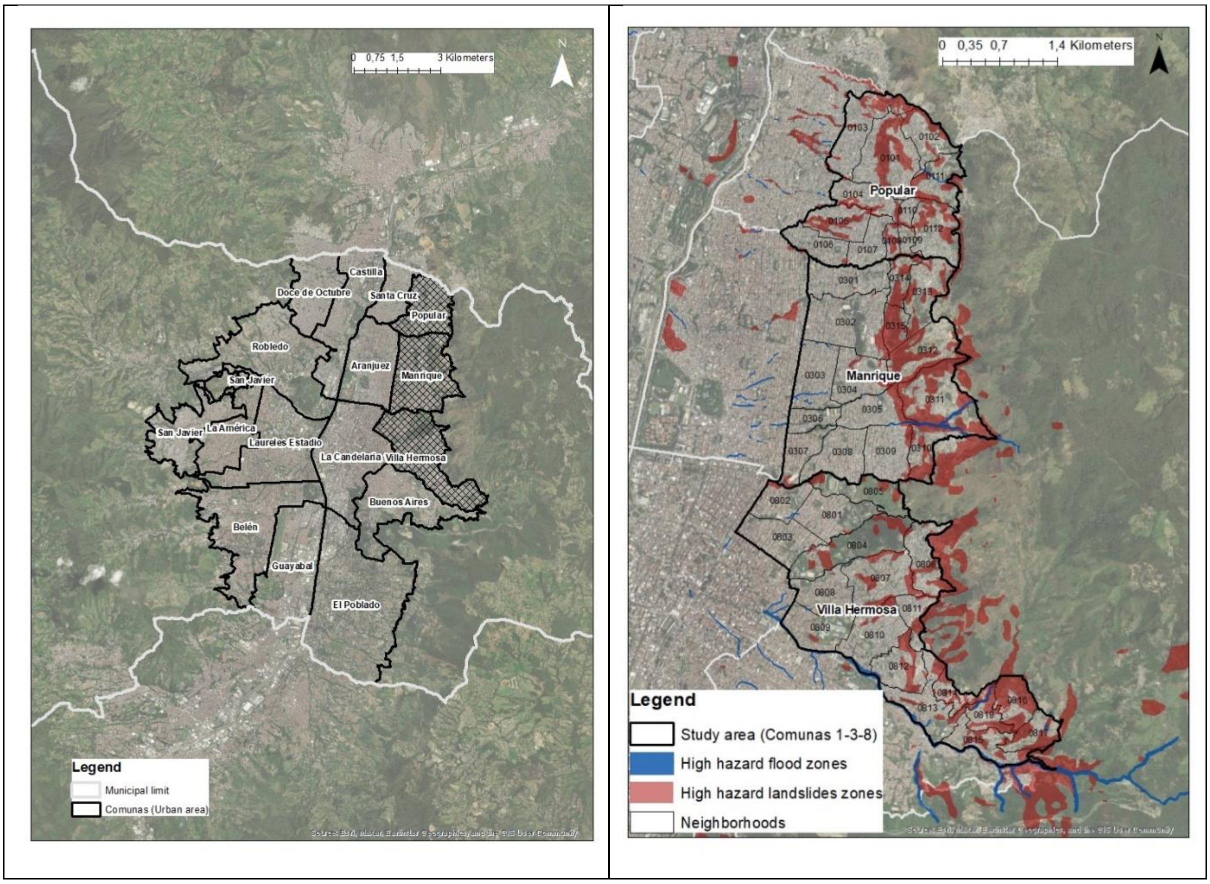
The left side of Figure 2 shows Medellín administrative division and the right side shows the study area. Each comuna is analyzed in the context of the increasing intensity and frequency of precipitation, which materialized in floods and landslides. The comunas were examined using high and middle flood and landslide hazards to identify the neighborhoods with possible affectations. In some of the neighborhoods, the hazard layer only coincides with a small percentage of land, but all are exposed to at least one hazard. For this reason, a total of forty-five neighborhoods are part of the study area, without exclusions.

In addition to the study area, temporality is a core research element based on the municipal risk management legal framework. Law 1523 of 2012 establishes the national disaster risk management policy and the National Disaster Risk Management System, acknowledging climate change risks and connecting land use planning and disaster management. Consequently, in 2014 and 2015, Medellín adopted the articulately formulated Disaster Risk Management Plan (PMGRD) and Land Use Plan (POT). Within the POT implementation, the Climate Action Plan (CAP) was adopted in 2020.

The POT has a minimum of three periods of execution: short-term 2016- 2019, medium-term 2020 -2023, still ongoing, and long-term 2024- 2027. After each period, the revision of structural content is feasible in order to meet the plan objectives, including objective 4: "Promote the development of a resilient territory that gives priority to attention to risk factors and situations in areas of greater social vulnerability, favoring the implementation of mitigation measures" (Municipality of Medellín, 2014, p. 11). This research seeks to compare the year of the POT's approval, 2014, and the year after the POT short-term and CAP adoption, 2021.

The characterization of relevant factors in the vulnerability in the context of urban irregular settlement in Medellín aligns with the literature on that matter. The PMGRD identified comunas 1-Popular, 3-Manriqur y 8-Villa Hermosa for their vulnerability to socio-natural phenomena and due to living conditions. Along the same line, the municipality of Medellín(2021) in its CAP highlights the relation between inequality and high vulnerability in urban areas and identifies as recurrent factors of vulnerability to climate change the low educational level, malnutrition, deficit in access to basic services, development of precarious settlements in high-slope areas, multidimensional poverty, low household income, informal economies, and prevalence of certain age groups, as children. Furthermore, comunas 1-Popular, 3-Manrique y 8-Villa Hermosa are the most vulnerable to climate change in terms of precipitation, causing landslides and floods in the steed areas.

Figure 2 Medellín and study area



Source: Generated using open data from geographical catalog of Municipality of Medellín (2023). On the left: Medellín map. Right: Study area and high and medium flood and landslide hazard.

From a spatial perspective, the occupation of high-slope areas in the urban-rural border is a structural challenge in the city. The instrument for land use and spatial planning, POT, proposes to limit growth on the hillsides and promotes an inward growth model. Ambitious Comprehensive Neighbourhood Improvement projects, among other urban strategies, have also opened space for debate, exercises of co-production, and other mechanisms of social participation including multiple stakeholders. Contributing included the participation of the community in monitoring risks and in the construction of small-scale mitigation works as self-build processes (Garcia Ferrari et al., 2022).

Slum upgrading programs present a unique opportunity to improve conditions of poverty, inequality, and segregation. However, equitable Urban Planning and participatory planning still have room for improvement in the city. According to Pratt(2022), in Medellín projects that include interventions that have improved accessibility and infrastructure that can resist heavy rains, have also excluded residents from participating and forced them to relocate. This reinforces the necessity to understand and analyse the trade-off of institutional intervention in the framework of climate change planning and learn from each experience to build capacity and avoid creating more vulnerability.

4.1.1. Historical social patterns in Urbanization process in comunas 1-popular, 3-Manrique and 8-Villa hermosa

Assessing vulnerability in the Colombian context demands understanding social and historical patterns impacting the configurations of the territories. For instance, rural populations displaced by political and violent conflicts often migrate to peripheral and informal urban areas lacking basic infrastructure and services, with limited social investment and development opportunities, increasing their vulnerability to natural disasters (Roncancio, Cutter, & Nardocci, 2020). Medellín is an example of complex social configuration influenced by historical social mobility patterns.

Comunas 1-popular, 3- Manrique, and 8-Villa Hermosa are the most vulnerable to climate change. Therefore, understanding unplanned urbanization in the area is relevant to this research. According to the municipality of Medellín (2015a), the urbanization process in Comuna 1-Popular began in 1960. The first inhabitants arrived, mostly from the rural areas of the Department of Antioquia, forced by political violence. From its beginnings, there was no planning, urban structure, or formal possession. Between the 1960s and 1970s, the neighborhood consolidation developed, while the flows of the migrant population continued to increase. This process continued during the 1980s, due to intra-urban displacement. In this way, the Comuna is consolidated as a receiving territory for the low-income population.

The Local Development Plan of Comuna 3-Manrique shows different elements in the urbanization process (Municipality of Medellin, 2019). The first important expansion happened with the arrival of hundreds of people in search of better opportunities because of the growing industrialization in Medellín and the construction of working-class neighborhoods during the urbanization boom in the early 1920s. The second moment is after the installation of the tramway as the main mean of transportation and events such as partisan violence, which exiled thousands of people from a large part of eastern Antioquia during the 1950s. As the population began to increase the new unplanned neighborhoods too. Same as Comuna 1-Popular, Comuna 3-Manrique suffered urban violence in the 80s with the phenomenon of drug trafficking and urban warfare, generating many people displaced from their territories and forced to relocate to informal settlements, many of them in high-risk areas.

According to Quiceno, Montoya, and Muñoz(2008), the urbanization of Comuna 8-Villahermosa started with low-income families in 1920 but the densification of the sector corresponds, same as in Comuna 3-Manrique, to the acceleration of migrations between the 40s and 50s due to industrialization. However, in the 1950s, there was a notorious increase in subdivisions with informal properties, some of the themes being legalized between the 1960s and 1980s. The area continues to be subject to invasions and in the 1990s, new irregular settlements of the displaced population occurred in the urban-rural border. In the context of the urbanization processes in the three comunas, displacement migration, and violence is a pattern, so for this research victimization and violence are part of the sensitivity analysis.

4.2. Results

This session starts with a short introduction to the indicator's correlation. Subsequently, the results of each PCA and the selected principal components will be shown, as well as the variables that explain the major variation for exposure, sensitivity, and adaptive capacity. Finally, the vulnerability mapping displays the final calculation for each neighborhood in 2014 and 2021.

4.2.1. Indicators correlation analysis

The data set should not have highly correlated indicators to avoid redundancy and find the accurate set of variables that explain the maximum variance. Therefore, one of the preliminary steps for PCA is to clean the data set from highly correlated indicators within the same category. For instance, for sensitivity, indicator S11- Percentage of houses with transitory materials is highly correlated to S12- Percentage of houses with transitory materials on floors. Additionally, other indicators were excluded because of low relevance in the study area; for example, S27- Percentage of the indigenous population with mode 0 and mean 0,7%. Moreover, other excluded variables are not correlated to any indicator, such as A45- Distance from the neighborhood to a recreation and sports facility.

After cleaning the database, a second exploratory analysis of the 29 resulting variables is performed using the correlation coefficient matrixes in Figure 3. For the exposure subdimension, the areas prone to flood and landslides and the number of buildings affected by both hazards have positive correlations; however, the correlation coefficients point to a low correlation which might indicate that the variables have weak or no linear relationships.

For sensitivity, there is not a consistent pattern of predominantly positive or negative correlations, indicating complex interactions because some variables exhibit positive correlations with certain indicators and negative correlations with others. Most of the positive correlations in this dimension are associated with the percentage of the population between 0-14 years old is correlated to houses with transitory material (0,59), overcrowded houses (0,67), and households with income below legal minimum wage (0,47). On the contrary, the percentage of the population 65 years old or more is negatively correlated with the same variables.

Lastly, the correlation matrix of adaptation capacity also indicates complex interactions and some weak relationships. The highest negative and positive correlations are related to the percentage of the population with secondary education. Showing a positive correlation to the percentage of households with Wi-Fi (0,49) and a negative correlation to the population with primary education (-0,53).

Figure 3 Correlation matrix

EXPOSURE

		E13	E21	E22	E31	E32
Number of fatal accident s due to precipitation	E13	1,00				
Number of Buildings affected by flooding	E21	0,18	1,00			
Percentage of land with flooding high hazard	E22	-0,11	0,03	1,00		
Number of Buildings affected by landslides	E31	-0,07	0,12	0,16	1,00	
Percentage of land with landslides high hazard	E32	-0,28	-0,17	0,23	0,25	1,00

SENSITIVITY

		S11	S21	S23	S25	S26	S28	S29	S210	S31	S32	S34	S41	S42	S51	S52
Percentage of houses with transitory materials on walls	S11	1,00														
Percentaje of population between 0-14 years old	S21	0,59	1,00													
Percentaje of population 65 years old or more	S23	-0,45	-0,83	1,00												
Population density (people/ha)	S25	-0,43	-0,15	0,11	1,00											
Percentage of disabled population	S26	-0,16	-0,41	0,58	0,06	1,00										
Percentage of Afro-descendant population	S28	0,25	0,29	-0,28	-0,02	-0,08	1,00									
Percentage of people arriving in the city due to public order	S29	0,46	0,50	-0,47	-0,03	-0,18	0,50	1,00								
Total Population	S210	-0,14	0,03	-0,04	0,21	-0,27	-0,14	-0,11	1,00							
Percentaje of Overcrowded households	S31	0,39	0,67	-0,60	0,01	-0,30	0,17	0,27	0,22	1,00						
Households with an income below legal minimum wage	S32	0,42	0,47	-0,36	0,13	-0,03	0,21	0,38	-0,32	0,33	1,00					
Gini coefficient	S34	-0,04	-0,19	0,16	-0,47	0,07	0,03	-0,15	0,00	-0,17	-0,24	1,00				
Number of females with a suspicious diagnosis of public	S41	-0,21	-0,23	0,22	0,41	0,33	0,03	0,08	-0,33	-0,29	0,18	-0,26	1,00			
Number of cases of Intra-urban Forced Displacement	S42	0,12	0,34	-0,30	0,09	-0,29	0,06	0,16	0,50	0,29	0,09	-0,08	0,10	1,00		
Percentage of Built areas on land with flood high hazard	S51	-0,44	-0,37	0,40	0,27	0,16	-0,12	-0,22	0,22	-0,29	-0,28	-0,14	0,21	0,06	1,00	
Percentage of Built areas in land with landslide high hazard	S52	-0,14	0,09	-0,07	0,57	0,00	0,09	0,14	0,17	0,12	0,14	-0,30	0,21	0,13	0,03	1,00

Colour scale: 1, 0,75, 0,50, 0,25, 0, -0,25, -0,50, -0,70, -1

ADAPTIVE CAPACITY

		A11	A21	A22	A23	A25	A32	A33	A41	A51
Percentage of houses formally own	A11	1,00								
Percentage of households having drinking water connection	A21	-0,19	1,00							
Percentage of households connected to electricity	A22	-0,02	0,23	1,00						
Percentage of households having waste water drainage connection	A23	-0,25	0,22	0,04	1,00					
Percentage of household with wifi	A25	-0,26	0,27	0,04	0,40	1,00				
Percentage of population with primary education	A32	0,01	-0,15	-0,27	-0,22	-0,29	1,00			
Percentage of population with secundary education	A33	-0,28	0,18	0,06	0,29	0,49	-0,53	1,00		
Public space per inhabitant (m2/inhab)	A41	0,11	0,18	0,05	0,10	0,35	-0,27	0,20	1,00	
Number of pluviometric stations	A51	0,20	-0,02	-0,14	-0,07	0,08	-0,01	-0,10	0,32	1,00

4.2.2. Outcomes of PCA-driven method

The PCA vulnerability index was calculated in Stata for each of the three dimensions: exposure, vulnerability, and adaptive capacity. The 44 indicators included in Table 1 Operationalization table: Dimensions and indicatorsTable 1 (7 for exposure, 20 for sensitivity, and 17 for adaptive capacity) were subjected to prior analysis to spot indicators highly correlated or not suitable for PCA. The Kaiser–Meyer–Olkin (KMO) for sampling adequacy to perform the component analysis was implemented. A KMO index higher than 0.80 is desirable and below 0.50 is considered unacceptable for PCA (Abdrabo et al., 2023). In this research, datasets with a KMO index greater than 0.50 were considered suitable for PCA, being preferable values greater than 0,70; however, the average KMO score was 0,64. Accordingly, the PCA was performed for a total of 29 indicators (5 for exposure, 15 for sensitivity, and 9 for adaptive capacity) in Table 3, Table 5, and

Table 7.

The retention of the principal components follows the following standard: eigenvalues greater than 1 (Abdrabo et al., 2023) or than accounting for more than 70% percent of the total variance (Inostroza et al., 2016). The observation of the Scree Plot that shows the eigenvalues for each PC was applied as a complementary inspection. A total of twelve components (3 for exposure, 5 for sensitivity, and 4 for adaptive capacity) were retained, explaining 71,27% of the total variance, as shown in Comp1 shows as influential factors the percentage of land with high flooding and landslide probability, while Comp2 groups the Percentage of Buildings affected by both flooding and landslides. Although the study area has a certain level of exposure, the exposure maps in Figure 4 show low exposure in most of the study area and high levels only in the inhabited areas close to the border, with high slopes and a high probability of floods or landslides.

Table 2

4.2.2.1. PCA exposure dimension

In this research, the exposition is made of three sub-dimensions: Precipitation, flooding, and landslides. Comp1 shows as influential factors the percentage of land with high flooding and landslide probability, while Comp2 groups the Percentage of Buildings affected by both flooding and landslides. Although the study area has a certain level of exposure, the exposure maps in Figure 4 show low exposure in most of the study area and high levels only in the inhabited areas close to the border, with high slopes and a high probability of floods or landslides.

Table **2** shows the resulting five Principal Components (Comp) as well as the percentage of variance explained, and Eigenvalues associated with each component. The three first components were retained, explaining 72,6% of the variance and a value of 0.57 in the KMO test. Analyzing the loading factors associated with the indicators and the retained components in Table 3, the indicators with higher loadings for each component are the percentage of land with landslides high hazard, the number of Buildings affected by flooding, and the percentage of land with flooding high hazard. Comp1 shows as influential factors the percentage of land with high flooding and landslide probability, while Comp2 groups the Percentage of Buildings affected by both flooding and landslides. Although the study area has a certain level of exposure, the exposure maps in Figure 4 show low exposure in most of the study area and high levels only in the inhabited areas close to the border, with high slopes and a high probability of floods or landslides.

Table 2 Percentage of variance explained and Eigenvalues for each component in the exposure dimension.

COMPONENT	EIGENVALUE	DIFFERENCE	% VARIANCE EXPLAIN	CUMULATIVE % VARIANCE EXPLAIN
Comp1	1.59906	.407761	0.3198	0.3198
Comp2	1.19129	.351772	0.2383	0.5581
Comp3	.839522	.0758494	0.1679	0.7260
Comp4	.763673	.157219	0.1527	0.8787
Comp5	.606454	.	0.1213	1.0000

Table 3 Loading factors of indicators associated to Comp1, Comp2 and Comp3 in the exposure dimension.

SUB DIMENSION	INDICATORS	COMP1	COMP2	COMP3
Precipitation	Number of fatal accidents due to precipitation	-0.4859	0.3299	0.1147
Flooding	Number of Buildings affected by flooding	-0.2313	0.7057	-0.0163
Flooding	Percentage of land with flooding high hazard	0.4214	0.3189	0.8209
Landslides	Number of Buildings affected by landslides	0.3844	0.5391	-0.5420
Landslides	Percentage of land with landslides high hazard	0.6206	-0.0291	-0.1380

4.2.2.2. PCA sensitivity dimension

The sensitivity dimension is made of five sub-dimensions: Housing typologies, Population characteristics, Socio-economic conditions, Violence, and land use. Table 4 displays the resulting fifteen Components and each associated percentage of variance explained, and Eigenvalues. The five first components were retained, explaining 71,9% of the variance and a value of 0.71 in the KMO test. The indicators with higher loadings for each component in Table 5 are Percentage of the population between 0-14 years old, Population density (people/ha), Households with an income below the legal minimum wage, Percentage of Afro-descendant population, and Number of cases of Intra-urban Forced Displacement Medellín.

Table 4 Percentage of variance explained and Eigenvalues for each component in the sensitivity dimension.

COMPONENT	EIGENVALUE	DIFFERENCE	% VARIANCE EXPLAIN	CUMULATIVE % VARIANCE EXPLAIN
Comp1	4.26126	1.81993	0.2841	0.2841
Comp2	2.44133	.366266	0.1628	0.4468
Comp3	2.07507	.987288	0.1383	0.5852
Comp4	1.08778	.157725	0.0725	0.6577
Comp5	.930054	.117435	0.0620	0.7197
Comp6	.812619	.0838158	0.0542	0.7739
Comp7	.728803	.158194	0.0486	0.8225
Comp8	.570609	.100101	0.0380	0.8605
Comp9	.470508	.0368829	0.0314	0.8919
Comp10	.433626	.0449115	0.0289	0.9208
Comp11	.388714	.0955786	0.0259	0.9467

Comp12	.293135	.0572178	0.0195	0.9662
Comp13	.235918	.0795235	0.0157	0.9820
Comp14	.156394	.0422124	0.0104	0.9924
Comp15	.114182	.	0.0076	1.0000

The subdimension of violence is part of the sensitivity dimension due to the social patterns in urbanization processes in the study area since many households had to relocate to informal settlements, many of them in high-risk areas, because of the partisan violence and drug trafficking during the second half of the 20th century (Municipality of Medellin, 2019; Municipality of Medellín, 2015a; Quiceno et al., 2008). The context matches the variables through which Comp1 explains sensitivity, including the percentage of houses with transitory materials on the walls, overcrowded households, and people arriving in the city due to public order problems. Along the same line, Comp 4 groups percentage of people arriving in the city due to public order problems and Afro-descendant population. For instance, the neighbourhoods 0814- San Antonio, 0111-La Avanzada, and 0819-Villa Lilliam have between 20% and 40% of both the Afro population and displacement communities. Figure 4 displays the vulnerability maps, including the mentioned neighbourhoods located close to the urban-rural border and within the vulnerability categories high and very high vulnerability in 2014 and 2021.

Table 5 Loading factors of indicators associated to Comp1, Comp2, Comp3, Comp4 and Comp5 in the sensitivity dimension.

SUBDIMENSIONS	INDICATORS	COMP1	COMP2	COMP3	COMP4	COMP5
Housing typologies	Percentage of houses with transitory materials on the walls	0.3428	-0.1910	0.1573	-0.0077	0.2277
Population	Percentage of the population between 0-14 years old	0.4407	0.0297	-0.0282	-0.0720	0.0798
Population	Percentage of the population 65 years old or more	-0.4216	-0.0260	0.0828	0.0724	0.0394
Population	Population density (people/ha)	-0.0892	0.5552	-0.0135	-0.1114	-0.2051
Population	Percentage of disabled population	-0.2474	0.0096	0.3401	0.0366	0.1205
Population	Percentage of Afro-descendant population	0.2022	0.0387	0.2070	0.6266	-0.3624
Population	Percentage of people arriving in the city due to public order problems	0.3087	0.0993	0.2186	0.4015	-0.0726
Population	Total Population	0.0134	0.1475	-0.5927	0.1429	0.0014
Socio-economic conditions	Percentage of Overcrowded households	0.3477	0.0704	-0.1630	-0.2042	-0.0378
Socio-economic conditions	Households with an income below the legal minimum wage	0.2619	0.1519	0.3433	-0.2070	0.1941
Socio-economic conditions	Gini coefficient	-0.0808	-0.4149	-0.0807	0.3348	-0.1475
Violence	Number of females with a suspicious diagnosis of public health surveillance of gender violence.	-0.1271	0.3461	0.3603	0.1569	0.3714
Violence	Number of cases of Intra-urban Forced Displacement Medellín	0.1701	0.2137	-0.3276	0.3195	0.5240
Land use	Percentage of built areas on land with flood high hazard	-0.2499	0.2186	-0.1474	0.2763	0.2539
Land use	Percentage of built areas in land with landslide high hazard	0.0382	0.4551	-0.0036	-0.0426	-0.4574

4.2.2.3. PCA Adaptive capacity dimension

The sensitivity dimension is made of five sub-dimensions: Land tenure, public services, Education, Infrastructure, and Warning systems. Table 4 presents the resulting nine components and each associated percentage of variance explained, and Eigenvalues. The five first components were retained, explaining 77,3% of the variance and a value of 0.66 in the KMO test. The indicators with higher loadings for each component in

Table 7 are percentage of household with Wi-Fi, number of fluviometric stations, percentage of households connected to electricity, and percentage of population with primary education.

Table 6 Percentage of variance explained and Eigenvalues for each component in the Adaptive capacity dimension.

COMPONENT	EIGENVALUE	DIFFERENCE	% VARIANCE EXPLAIN	CUMULATIVE % VARIANCE EXPLAIN
Comp1	2.57819	1.08291	0.2865	0.2865
Comp2	1.49528	.320535	0.1661	0.4526
Comp3	1.17475	.190867	0.1305	0.5831
Comp4	.983883	.258566	0.1093	0.6925
Comp5	.725317	.0858551	0.0806	0.7730
Comp6	.639462	.0515527	0.0711	0.8441
Comp7	.587909	.10974	0.0653	0.9094
Comp8	.478169	.141136	0.0531	0.9626
Comp9	.337033	.	0.0374	1.0000

A positive adaptive capacity reduces the vulnerability value. The incorporation of equity into infrastructure plays an important role in reducing vulnerability in informal settlements (Giri et al., 2021). Comp1 integrates public services like wastewater drainage connection, drinking water connection, and Wi-Fi and links access to those services to the completion of secondary education. That correlation became apparent during the preparation for the PCA, where the correlation between the percentage of the population with a university education and the percentage of households with Wi-Fi was 0,72. In the context of risk management, among the many benefits of access to education, according to Coulibaly et al. (2015), a lower education level limits the ability to access and understand technical information and effectively use early warning systems.

In general, the resultant loading factors of the retained components for this dimension support the connection between the reduction of inequality and socially constructed vulnerabilities by providing public services such as drinking water, among other interventions (Garcia Ferrari et al., 2022). For instance, comp4 integrates the percentage of households having drinking water and electricity connections, while Comp3 associates the connection to electricity and the legal tenure of homes. Similarly, Comp2 integrates the number of pluviometric stations, public space per inhabitant (m2/inhabitant), and percentage of houses formally own, which is consistent with the indicators that show that formal areas have not only more access to public services but also more public space per inhabitant.

Table 7 Loading factors of indicators associated to Comp1, Comp2, Comp3, and Comp4 in the adaptive capacity dimension.

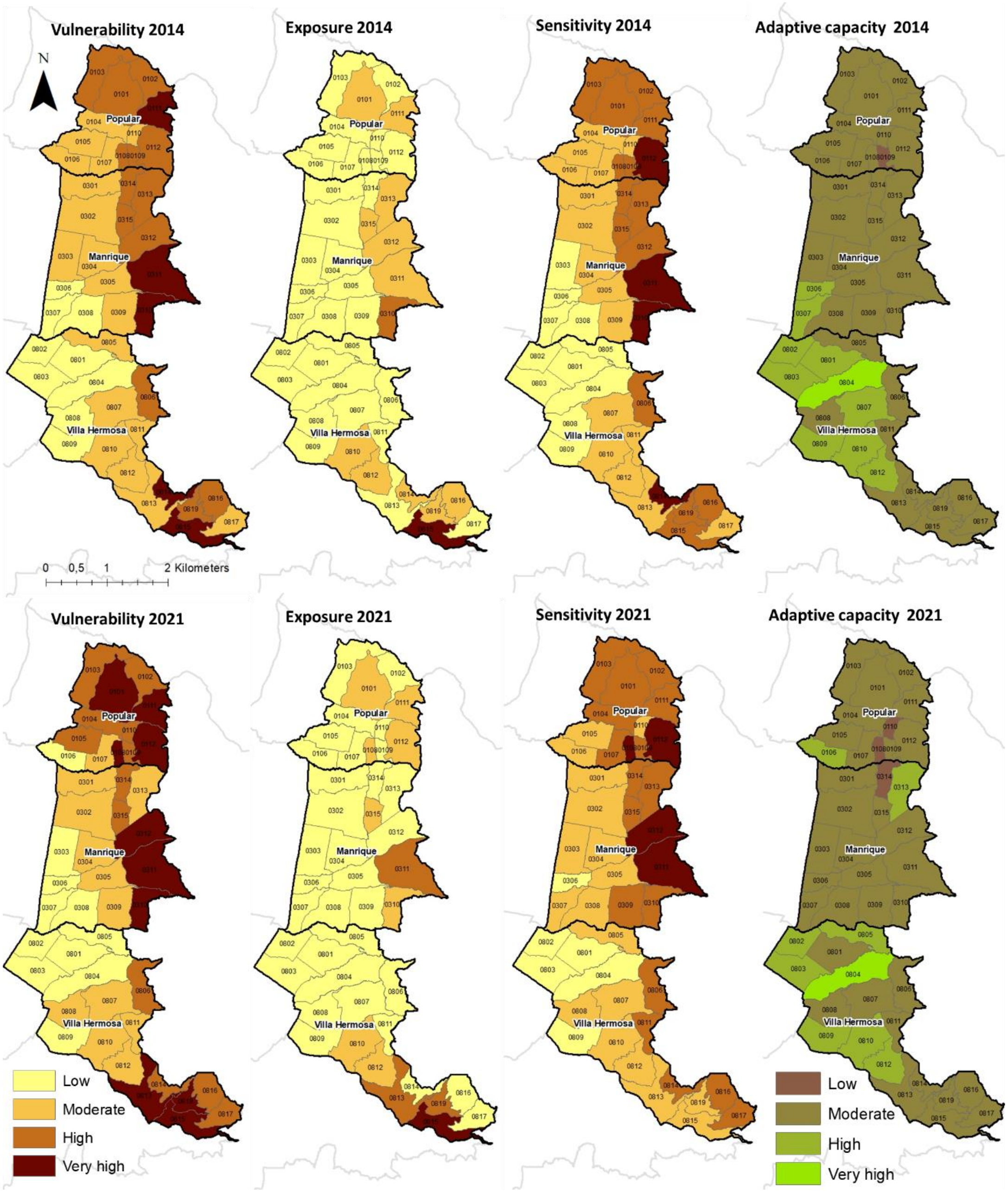
SUBDIMENTIONS	INDICATORS	COMP1	COMP2	COMP3	COMP4
Land tenure	Percentage of houses formally own	-0.2445	0.4690	0.3309	-0.1662
Public services	Percentage of households having drinking water connection	0.3085	-0.0687	0.1687	0.6863

Public services	Percentage of households connected to electricity	0.1674	-0.1229	0.7479	0.2052
Public services	Percentage of households having wastewater drainage connection	0.3663	-0.1471	-0.2508	0.1186
Public services	Percentage of household with Wi-Fi	0.4718	0.0914	-0.2649	0.0499
Education	Percentage of population with primary education	-0.4029	-0.1282	-0.3554	0.4529
Education	Percentage of population with secondary education	0.4702	-0.0636	-0.0649	-0.4268
Infrastructure	Public space per inhabitant (m2/inhab)	0.2768	0.5575	0.0182	0.1169
Warning systems	Number of pluviometric stations	-0.0140	0.6315	-0.1967	0.2041

4.3. Analysis

4.3.1. Vulnerability mapping

Figure 4 Maps overall vulnerability and three dimensions (vulnerability, exposure, and adaptive capacity)



Source: Generated in ArcMap using open data from geographical catalog of Municipality of Medellín (2023) and outcomes from PCA analysis in Stata after applying Equation 1 and Equation 2.

The total vulnerability for Comunas and their neighborhoods was found to replace the weighed factors from each dimension (Equation 1) in Equation 2. In terms of vulnerability, exposure, and sensitivity increase vulnerability, and adaptive capacity reduces vulnerability; that means high and very high levels of adaptive capacity help to reduce vulnerability.

The two vulnerability index outputs and the results for each dimension for 2014 and 2021 are presented in the maps in Figure 4, elaborated using ArcMap. For 2014, 19 out of 45 neighborhoods are classified with high or very high vulnerability, which corresponds to 35% of the total population and 40% of the surface of the study area. The vulnerability, exposure, and sensitivity show a concentration of high values in the upper neighborhoods close to the urban-rural border. In 2021, 22 neighborhoods had a high or very high vulnerability, which corresponds to 43% of both the total population and the surface of the study area. The vulnerability, exposure, and sensitivity show a concentration of high values in the upper neighborhoods close to the urban-rural border.

4.3.2. Vulnerability spatial distribution

At the comuna scale, vulnerability does not present major changes. Table 8 shows the three Comunas keep their exposure, sensitivity, and adaptive capacity category level for 2014 and 2021. However, in terms of numerical values, for every comuna, the average sensitivity in 2021 is greater or equal to the average sensitivity in 2014, while the average adaptive capacity is less in 2021, leading to higher vulnerabilities for all the comunas in 2021. The exposure is relatively stable, showing a small increase in Comunas 1-Popular and 8-Villa Hermosa and a small decrease in Comuna 3-Manrique.

Table 8 Main changes in exposure, sensitivity, and adaptive capacity

Year	Comuna	Exposure (+)	Sensitivity (+)	Adaptive capacity (-)	Vulnerability
2014	1	Low	High	Moderate	High
	3	Low	Moderate	Moderate	Moderate
	8	Low	Moderate	Moderate	Moderate
2021	1	Low	High	Moderate	High
	3	Low	Moderate	Moderate	Moderate
	8	Low	Moderate	Moderate	Moderate

The changes at the neighborhood scale become more noticeable, the Table 9 summarizes the different cases that lead to vulnerability variations. Vulnerability decreased in 26% of the neighborhoods. Different combinations of exposure, sensitivity, and adaptive capacity lead to this change; however, those combinations can be divided into two main cases. For 15% of the neighborhoods, the vulnerability reduction is due to an increase in adaptive capacity. Conversely, in 11% of the neighborhoods, both adaptive capacity and exposure were reduced, generating a vulnerability decline. The last case could present a risk in future periods, given the intensity and frequency of rainfall tend to increase as well as the risks associated with flooding and landslides, enabling the exposure and vulnerability to increase because of the low levels of adaptive capacity.

For the remaining 73% of neighborhoods in the study area, the vulnerability became more intense. For 60% of the neighborhoods, sensitivity increased, and adaptive capacity decreased. For 11% of the neighborhoods, the capacity to adapt increased; but this increase was not enough to support the increase in exposure or sensitivity or both. For the remaining 2%, both sensitivity and adaptive capacity decreased.

Table 9 Changes in vulnerability in 2014 and 2021: exposure, sensitivity, and adaptive capacity.

Vulnerability bahavior from 2014 to 2021	Changes in exposure, sensitivity, and adaptive capacity	% Neibourhoods	Comuna 1	Comuna 3	Comuna 8
Reduced (26,67%)	Increased or equal exposure and sensitivity, and increased adaptive capacity	2,22%	1		
	Higher or equal exposure and sensitivity, and increased adaptive capacity	8,89%	1	1	2
	Reduction of exposure, sensitivity, and adaptive capacity.	4,44%		1	1
	Reduced exposure and sensitivity, and increased adaptability	4,44%	1		1
	Exposure reduction by more than half, higher sensitivity, and lower adaptive capacity.	6,67%	1	1	1
Increased (73,33%)	Exposure reduction most of the times by more than half, higher sensitivity, and lower Adaptive capacity.	26,67%	2	4	6
	Exposure and sensitivity increase and adaptive capacity decreases	33,33%	4	6	5
	Exposure is maintained or increased, slightly higher Sensitivity and adaptive capacity	4,44%	1	1	
	Exposure increases, sensitivity decreases or stays the same, and adaptive capacity increases.	6,67%	1		2
	Reduction in exposure, sensitivity, and adaptive capacity	2,22%		1	

4.3.2.1. Comuna 1-Popular

For 2014 in Comuna 1-Popular, 7 out of 12 neighborhoods are classified with high or very high vulnerability, which corresponds to 57% of the comuna population and 66% of the comuna area. For 2021 the comuna experiences a vulnerability increase with ten neighborhoods with high or very high vulnerability classifications, 82% of the comuna population, and 85% of the comuna surface. For both periods studied, Comuna 1-Popular has the highest levels of vulnerability. Although the exposure levels are not among the highest, the sensitivity is high, and the adaptation capacity is the lowest of the three comunas.

In 2014, the Comuna reported the lowest levels of adaptation capacity with all the neighborhoods at low and moderate levels, and by 2021 an increase in sensitivity is visible. Even so, four neighborhoods manage to reduce their levels of vulnerability: 0102-Santo Domingo Savio No.2, 0106-Villa Guadalupe, 0109-Aldea Pablo VI, and 0111-La Avanzada, being the only one to achieve the reduction of the vulnerability category 0106-Villa Guadalupe due to the increase in its adaptation capacity, as the vulnerability maps in Figure 4 indicate.

According to Medellín Climate Action Plan-CAP, the most vulnerable neighbourhoods in terms of flooding and landslides due to climate change are Santo Domingo Savio no.1 and Popular. Table 10 Vulnerability classification Comuna 1-Popular, 2014 and 2021Table 10 shows the vulnerability classifications for both years, 2014 and 2021, placing both neighbourhoods in high and very high vulnerability, and bringing attention to others very high vulnerable sectors close to the urban-rural border: 108-El Compromiso, 0111-La Avanzada, and 0112- Carpinelo.

Table 10 Vulnerability classification Comuna 1-Popular, 2014 and 2021.

Neigbourhood ID	Neigbourhood Name	Category 2014	Category 2021	Change in category
0101	Santo Domingo Savio No.1	High	Very high	Increased
0102	Santo Domingo Savio No.2	High	High	
0103	Popular	High	High	
0104	Granizal	Moderate	High	Increased
0105	Moscú No.2	Moderate	High	Increased
0106	Villa Guadalupe	Moderate	Low	Reduced
0107	San Pablo	Moderate	Moderate	
0108	El Compromiso	High	Very high	Increased
0109	Aldea Pablo VI	High	High	
0110	La Esperanza No.2	Moderate	High	Increased
0111	La Avanzada	Very high	Very high	
0112	Carpinelo	High	Very high	Increased

4.3.2.2. Comuna 3-Manrique

In 2014, 6 out of 15 neighborhoods in Comuna 3-Manrique are classified with high or very high vulnerability, which corresponds to 19% of the comuna population and 37% of the comuna area. For 2021 the comuna experiences a vulnerability decrease down to 5 neighborhoods with high or very high vulnerability classifications, corresponding to 15% of the comuna population, and 31% of the comuna surface. However, 3 out of 4 neigborgood with low vulnerability in 2014 rose to moderate. For Comuna 3-Manrique the vulnerability, exposure, and sensitivity show a concentration of high values in the upper neighborhoods close to the urban-rural border noticeable in the respective maps in Figure 4.

According to Medellín Climate Action Plan-CAP, in Comuna 3-Manrique the most vulnerable neighbourhood is 0312-Oriente. Table 10 Vulnerability classification Comuna 1-Popular, 2014 and 2021**Table 11** shows the vulnerability classifications for both years, 2014 and 2021, placing the neighbourhoods in high and very high vulnerability for each year, and bringing attention to others very high vulnerable zones close to the urban-rural border: 0310-Versalles No.2, 0311-La Cruz, and 0312-Oriente.

Table 11 Vulnerability classification Comuna 3-Manrique, 2014 and 2021

Neigbourhood ID	Neigbourhood Name	Category 2014	Category 2015	Change in category
0301	La Salle	Moderate	Moderate	
0302	Las Granjas	Moderate	Moderate	
0303	Campo Valdés No.2	Moderate	Low	Reduced
0304	Santa Inés	Moderate	Moderate	
0305	El Raizal	Moderate	Moderate	
0306	El Pomar	Low	Low	
0307	Manrique Central No.2	Low	Low	
0308	Manrique Oriental	Low	Low	
0309	Versalles No.1	Low	Moderate	Increased
0310	Versalles No.2	Very high	Very high	
0311	La Cruz	Very high	Very high	
0312	Oriente	High	Very high	Increased
0313	María Cano-Carambolas	High	Moderate	Reduced
0314	San José La Cima No.1	High	High	
0315	San José La Cima No.2	High	High	

4.3.2.3. Comuna 8-Villa hermosa

For 2014 in Comuna 8-Villa Hermosa, 6 out of 18 neighborhoods are classified with high or very high vulnerability, which corresponds to 35% of the comuna population and 28% of the comuna area. For 2021, the comuna experiences a vulnerability increase with seven neighborhoods with high or very high vulnerability classifications, corresponding to 40% of the comuna population, and 31% of the comuna surface. This is the largest commune in area and its upper neighborhoods have some of the highest population densities in the study area. Furthermore, its results in each dimension are the most diverse. The vulnerability, exposure, sensitivity, and adaptive capacity show a great difference between the neighborhoods at the bottom and those at the top, reaching the urban-rural border.

According to Medellín Climate Action Plan-CAP, the most vulnerable neighbourhoods in terms of flooding and landslides due to climate change are Las Estancias, Villa Liliam, Llanaditas, and Villa Turbay. Table 10 Vulnerability classification Comuna 1-Popular, 2014 and 2021**Table 12** shows the vulnerability classifications for both years, 2014 and 2021, placing the four neighbourhoods in high and very high vulnerability and bringing attention to 0814-San Antonio, which, as for the neighbourhoods that require attention in the other communes, is a highly vulnerable area close to the urban-rural border.

Table 12 Vulnerability classification Comuna 8- Villa Hermosa, 2014 and 2021

Neigbourhood ID	Neigbourhood Name	Category 2014	Category 2015	Change in category
0801	Villa Hermosa	Low	Low	
0802	La Mansión	Low	Low	
0803	San Miguel	Low	Low	
0804	La Ladera	Low	Low	
0805	Batallón Girardot	Moderate	Low	Reduced
0806	Llanaditas	High	High	
0807	Los Mangos	High	Moderate	Reduced
0808	Enciso	Moderate	Moderate	
0809	Sucre	Moderate	Moderate	
0810	El Pinal	Moderate	Moderate	
0811	Trece de Noviembre	Moderate	Moderate	
0812	La Libertad	Moderate	Moderate	
0813	Villatina	Moderate	High	Increased
0814	San Antonio	Very high	High	Reduced
0815	Las Estancias	Very high	Very high	
0816	Villa Turbay	High	High	
0817	La Sierra	Moderate	High	Increased
0819	Villa Lilliam	High	Very high	Increased

4.3.3. Important factor in High vulnerability neighbourhoods

The ten neighbourhoods with very high vulnerability to climate change due to the increasing precipitations are listed in the bottom right corner of Figure 5. The indicators in the same figure represent most of the variance in exposure, sensitivity, and adaptive capacity. In the case of the indicators of exposure and sensitivity (Codes starting with E and S), values below the average for the study area as desired. On the contrary, for indicators of adaptive capacity (Codes starting with A), the values above the main of the study area consider enhancing adaptive capacity.

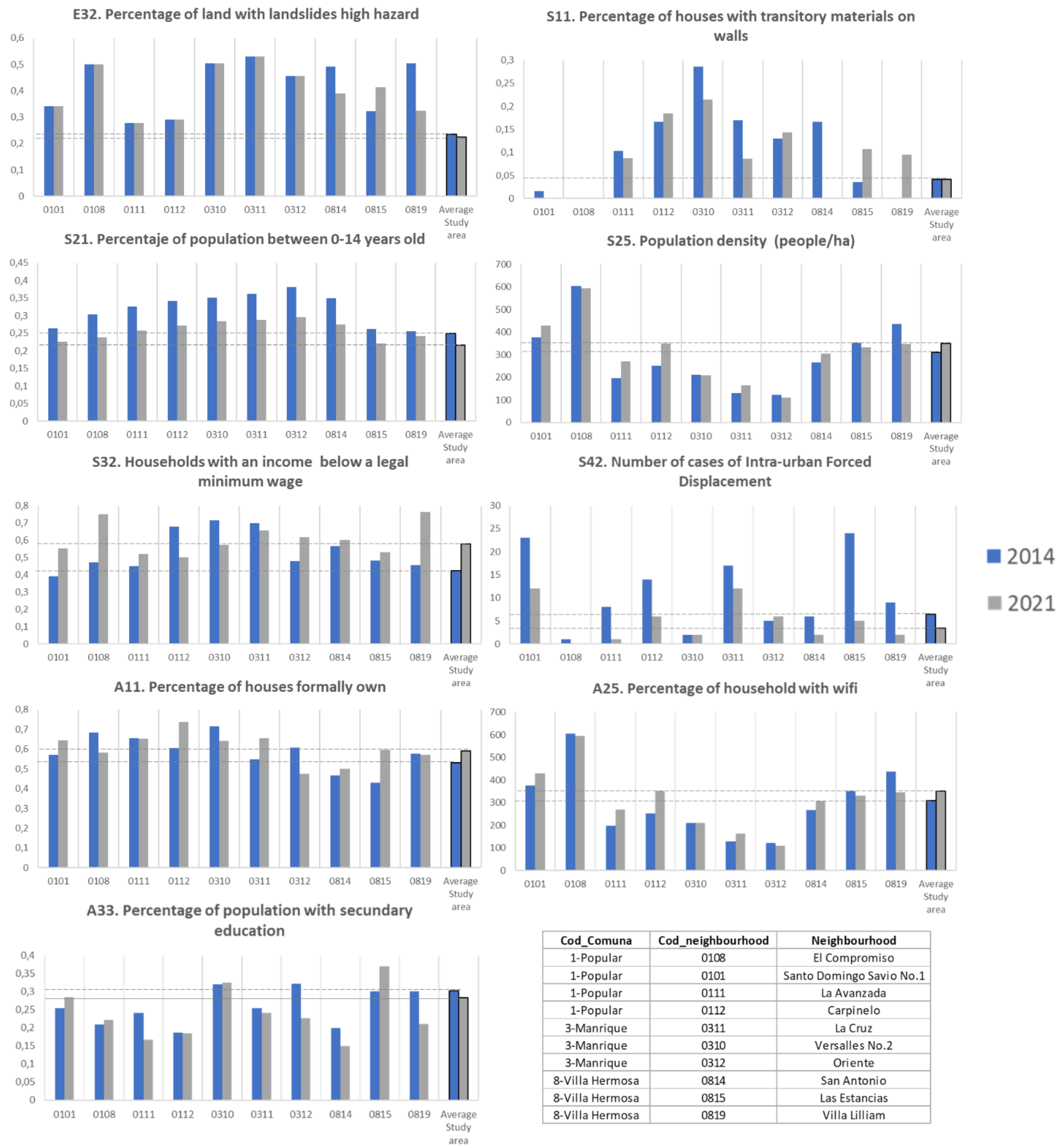
From 2014 to 2021, the indicators with a desired behaviour in the study area were the percentage of land with landslides high hazard, the percentage of the population between 0-14 years old, the number of cases of intra-urban forced displacement, the percentage of houses formally own, and the percentage of houses with Wi-fi.

The neighbourhoods with very high vulnerability share characteristics such as higher values of the percentage of land with landslides high hazard, the percentage of the population between

0-14 years, the households with an income below the minimum wage, and the percentage of houses formally own. The last indicator can show an increase in the adaptive capacity that might be a consequence of formalization processes.

Despite the similarities, the indicators' values vary, showing the possible focus of intervention for specific areas. For instance, 108-El Compromiso combines high population density and a high percentage of land with landslides high hazard and population between 0-14 years. Conversely, 310-Versailles No.2 reveals a high percentage of land with landslides high hazard, income below the minimum wage, houses with transitory material, and population between 0-14 years. While 815-Las Estancias shows the same factor as 310 Versailles No.2, adding urban forced displacement, and 311-La Cruz also incorporates access to Wi-Fi and low education level.

Figure 5 Indicators that explain most of the variance and values for very high vulnerability neighbourhoods.



Cod_Comuna	Cod_neighbourhood	Neighbourhood
1-Popular	0108	El Compromiso
1-Popular	0101	Santo Domingo Savio No.1
1-Popular	0111	La Avanzada
1-Popular	0112	Carpinelo
3-Manrique	0311	La Cruz
3-Manrique	0310	Versalles No.2
3-Manrique	0312	Oriente
8-Villa Hermosa	0814	San Antonio
8-Villa Hermosa	0815	Las Estancias
8-Villa Hermosa	0819	Villa Lilliam

4.4. Discussion

This section interprets the results, starting with the most influential factors affecting exposure, sensitivity, and adaptive capacity to climate change in the study area and the interaction between these components that led to vulnerability changes between 2014 and 2021, placing the finding in the conceptual framework in Figure 1. Subsequently, an examination of the main changes and relevant behaviors in 2014 and 2021 and possible explanations and influences is conducted through a spatial and temporal interpretation of the results based on the vulnerability mapping on Figure 4.

4.4.1. Vulnerability as an interaction between exposure, sensitivity, and adaptive capacity

This research successfully conducted a vulnerability assessment at a neighborhood scale for 2014 and 2021, applying PCA, under the understanding that the dynamics between nature and society can differ even within communities (Ford et al., 2010). Consistent with this guideline, the analysis reveals differences for every scale and year analyzed. At the commune scale, vulnerability categories remain almost constant, but at the neighborhood scale, changes become more noticeable. For most of the neighborhoods, vulnerability increased due to higher sensitivity and decreased adaptive capacity. In the neighborhoods that experience a vulnerability reduction, the causes are improvements in adaptive capacity (15%) or a decline in exposure.

The high sensitivity, the limited increase in adaptation capacity, and, in some cases, the vulnerability reduction without increasing adaptive capacity indicates a lack of impact reduction between 2014 and 2021, potentially increasing long-term sensitivity and generating a feedback loop between sensitivity and impacts as shown in Figure 1, and exhibiting that despite of having policies and plans focused on risk and vulnerability reduction and adaptation to climate change, the vulnerability in the area is increasing, and the study area is not prepared for the increment in the intensity of precipitation that can lead to an increase in exposure. In that sense, in the context of adaptive capacity levels in urban areas of developing countries stated by Flórez Bossio et al. (2019), Medellín primarily demonstrates coping with short-term climate threats but lacks long-term adaptation and transformation due to persistent structural conditions such as poverty, inequality, and location of marginal communities in risky areas.

In terms of the factor influencing vulnerability, the principal components selected through PCA display crucial aspects in the study area. First, for exposure, Comp1 identifies factors such as high flooding and landslide probability, while Comp2 considers the percentage of buildings affected by these hazards. In this case, exposure can decrease in some areas even though the hazard areas do not decrease significantly in the study area, according to Figure 5. Therefore, depending on the precipitation patterns and the events of each year, the exposure could decrease without decreasing sensitivity or increasing adaptive capacity.

Secondly, sensitivity is influenced by the social patterns of urbanization in the area. Many households relocated to informal settlements due to historical violence, often inhabited in high-risk areas. Variables such as transitory materials on walls, population below 14 years old, overcrowded households, low income, and people arriving in the city due to public order problems also contribute to sensitivity. Given the above, might be a connection between forced displacement and inadequate socio-economic and habitability conditions in the area, showing disadvantages from historical patterns in the conformation of the territory. To reduce sensitivity, it would be worth studying the connection between these variables and, if applicable, finding priority areas for intervention in the areas most affected by this phenomenon.

Third, adaptive capacity, the component that reduces vulnerability and impacts (Figure 1), is highly influenced by the access to public services (wastewater drainage, drinking water, and Wi-Fi), land tenure formality, and the education level, which according to Coulibaly et al. (2015) also works as a tool to access and understand technical information and effectively use early warning systems, promoting resilience. Thus, adaptive capacity aligns with city challenges in developing countries and with the sustainable development goals agenda.

4.4.2. Spatial and temporal interpretation of the results

The vulnerability to climate change assessment for 2014 and 2021 in the 45 neighborhoods in three comunas provides insights into the vulnerability patterns and specific factors contributing to high vulnerability. For the study area, the vulnerability, exposure, sensitivity, and adaptive capacity mapping in Figure 4 shows high exposure, sensitivity, and vulnerability near the urban-rural border. However, Sensitivity is often moderate and high in the study area, and the adaptive capacity has a more homogeneous spatial distribution, displaying mostly a moderate classification across the whole area. Based on historical patterns in the formation of communes and socioeconomic conditions, this may be evidencing the socioeconomic vulnerability of the population and the infrastructure deficiencies in the area.

The changes over time in vulnerability for each commune differ from each other. Comuna 1-Popular consistently exhibits the highest levels of vulnerability and lower valuer of adaptation capacity, with an increase from 2014 to 2021. In Comuna 3-Manrique, there was a decrease in vulnerability, even though the reduction is predominantly due to exposure, and the high vulnerability persists in upper neighborhoods. Ultimately, Comuna 8-Villa Hermosa shows an increase in vulnerability, with the most diverse results in the three comunas. The lower area of Comuna 8-Villa Hermosa consistently displays lower exposure and sensitivity and higher adaptive capacity for both years, with slight deterioration of adaptive capacity and higher sensitivity in 2021. These findings emphasize the ongoing vulnerability challenges in these comunas and highlight the need to address structural challenges to reduce vulnerability to climate change.

The common characteristics of very highly vulnerable neighborhoods are land hazards, high young population, low income, and low education. Further, each area has additional factors. For instance, El Compromiso: population density and land hazard, Versailles No.2: transitory housing, Las Estancias: urban displacement and transitory housing, and La Cruz: low access to Wi-Fi and education level. The variations of these factors between 2014 and 2021 are minimal; however, a reduction in intra-urban displacements stands out, but given the scope of this analysis, a reduction in the levels of violence cannot be affirmed.

The population under 14 years of age accounts for more variation in vulnerability. The correlation analysis (Figure 3) shows the correlation between this population's transitory housing, overcrowded houses, and households with income below the legal minimum wage. One possible explanation is the higher levels of sensitivity and lower levels of AC to climate change in specific population groups, including children and marginalized communities (Flórez Bossio et al., 2019). However, more than the sensitivity inherent to this group of populations, the result might show a greater, more elevated presence of the young population in the poorest areas, favoring social vulnerability.

The predominance of elements associated with social and economic vulnerability supports the idea that reducing vulnerability requires addressing poverty and social inequality (Doherty et al., 2016). Targeted interventions and prioritization of resources to reduce vulnerability and enhance adaptive capacity require more knowledge and participation of each community, but knowing specific areas of intervention generates an excellent starting point.

5. Conclusions

In Latin America, low-income families often inhabit marginal lands exposed to climate hazards, and the effects on already vulnerable communities tend to grow with more frequent extreme weather events. In Medellín, the Disaster Risk Management Plan (PMGRD-2014) and Land Use Plan (POT-2015) classified Comunas 1-Popular, 3-Manrique, and 8-Villa Hermosa as the highest vulnerability areas due to the combination of risky location and the lowest socio-economic conditions. In 2020, the city adopted the Climate Action Plan (CAP), reaffirming the high vulnerability of these areas and warning about its future increase.

Reducing vulnerability with few public resources is a challenge that requires prioritizing interventions and strategies that effectively benefit the most vulnerable. Expecting to provide insights that can guide policymakers, stakeholders, and communities to reduce vulnerability, the purpose of this research is to determine the most influential factors affecting exposure, sensitivity, and adaptive capacity due to increasing precipitation in the neighbourhoods in Comunas 1-Popular, 3-Manrique, and 8-Villa Hermosa and compare and analyse the changes between 2014 and 2021, exploring interactions between exposure, sensitivity, and adaptive capacity and possible explanations to provide a priorities for strategies, interventions, and complementary studies.

This research delivers four main conclusions as a result of the vulnerability assessment. First, between 2014 and 2021, vulnerability increased in most neighbourhoods due to higher sensitivity and decreased adaptive capacity, showing a clear pattern of high exposure, sensitivity, and vulnerability, in upper areas near the urban-rural border, supporting that areas occupied by the poor are often ecologically susceptible, exacerbates existing inequalities and increasing sensitivity (Wekesa et al., 2011 as cited in Giri et al., 2021). Furthermore, the study area presents homogeneity in the adaptability but higher sensitivity in the border; the lower vulnerability levels in Comuna 3-Manrique and the lower part of Comuna 8-Villa Hermosa show less exposure and sensitivity, which could support that intervention and adaptive actions in Comuna scale risk to benefit the best located instead of the most vulnerable (Adger, 2006). A reason to select areas of intervention and ensure impacts in priority areas.

In addition, very highly vulnerable neighbourhoods share common characteristics such as high land hazards, high young population, low income, and low education. Elements with low variation during the studied years, although there was a general increase in families that lived with less than a current minimum wage, and the most vulnerable neighbourhoods show low levels in two correlated variables, internet connection, and low educational levels, showing that access to all kind of public services support social vulnerability reduction (Garcia Ferrari et al., 2022).

Secondly, vulnerability increased in most neighbourhoods due to higher sensitivity and decreased adaptive capacity, suggesting an existing feedback loop between adaptive capacity, sensitivity, and impacts in the study area. As stated in the conceptual framework in Figure X, the decreasing adaptive capacity sets off the alerts because it entails the impact intensification, creating, in turn, the increase in sensitivity, also observed in the study area. This reinforces the understanding that vulnerability has a continuously evolving state and arises not because of the threat itself but due to a lack of adaptation-related responses, as stated by Giri et al. (2021), and the adaptive capacity reflects the ability to adjust and respond to climate change impacts (IPCC, 2022). These interactions evidence that both adaptive capacity and sensitivity must be addressed; otherwise, actions focused on reducing sensitivity will not always be reflected in the target populations.

Third, the possible interpretations for the increase in vulnerability lie in the factors that influence vulnerability. The persistent structural conditions of poverty, lack of access to public services, low education levels, and the location of marginalized communities in risky areas align with the approach of Poruschi and Ambrey (2016) of reducing vulnerability in informal urban areas without addressing poverty and social inequalities and ensuring equitable access to resources and infrastructure, and the connection between the reduction of social vulnerabilities and the provision of public services stated by Garcia Ferrari et al. (2022). Addressing these factors will allow for enhancing adaptive capacity in the study area and shift from coping with short-term climate threats to long-term adaptation and transformation of structural conditions.

The population under fourteen years has a large influence on the vulnerability variation. This could be due to an exaggeration in the weight of the variable in the PCA. However, the areas with the highest vulnerability consistently present this group of populations above the average values of the study area, and the variable is correlated to transitory housing, overcrowded houses, and low income. These factors reflect low economic status and could suggest that low incomes families tend to have a higher natality, although that assertion cannot be affirmed by this research. But if it was possible to establish the call made by Flórez Bossio et al. (2019) to recognize that some urban population groups may be more negatively affected by climate change and groups such as children in marginalized communities possess inherent vulnerabilities.

Lastly, the research show that the most influential factors affecting exposure, sensitivity, and adaptive capacity due to increasing precipitation in the neighborhoods in Comunas 1-Popular, 3-Manrique, and 8-Villa Hermosa are the houses located in high landslide hazard areas, houses made with temporary materials, overcrowding, low income, high population below 14 years old, lack of access to public services, low formal land tenure, and low education level. The results highlight that addressing persistent structural conditions such as poverty and social inequality is crucial for reducing vulnerability. However, each neighborhood displays different main challenges that range from low access to Wi-Fi to intra-urban displacements. Furthermore, the relationships between these factors presented in previous points could suggest that the intervention approach in the most vulnerable areas must be integral instead of through sectoral policies applied on larger geographical scales.

Limitations and potential applications

The vulnerability assessment in this research focuses on understanding the most influential factors that affect exposure, sensitivity, and adaptive capacity and their behavior between 2014 and 2021 through the PCA statistical technique. Despite the preparation to ensure the data set was suitable for PCA, the final average KMO test score is 0.64, indicating the data set is acceptable but without reaching a desired value of 0.8. Regardless, the results are consistent with the general vulnerability classification of the Medellín Climate Action Plan and bring further information that can complement decision-making and serve as a starting point to define priorities for strategies, interventions, and complementary studies.

When having limited resources and issues of greatest need, as in the Medellín context, the adaptation strategies must address critical vulnerabilities, and measurement and evaluation of available data and metrics are handy (Doherty et al., 2016). Consequently, this research was carried out using only open data, which indicates the possibility of creating monitoring systems that support decision-making for urban planning, policies or strategies; for supporting community initiatives, and for prioritizing interventions in sectoral policies on education, poverty, and housing. The above, without being unaware that this institutional approach needs to be complemented with knowledge of the specific intervention areas such as education, public services, and social sciences.

Although the study responds to a need for the assessment of vulnerability, for improving future studies results, technical clusters before PCA, expert reviews, or a mix of qualitative research approaching the communities might provide more detailed information on community engagement, button-up adaptive, and trade-offs resulting from previous interventions, favoring adaptation processes and analysis of the results. That approach aligns with the challenges for vulnerability research to develop measures, including perceptions of vulnerability, and promote adaptive community action and resilience.

Finally, due to the increasing vulnerability and the reduction in adaptive capacity, an initial intervention is proposed in the ten neighborhoods with very high vulnerability (Figure 5), focusing on adaptive capacity to reduce impacts and avoid the exacerbation of the sensitivity. The institutional approach would promote access to essential public services, including internet connectivity, hoping for a positive effect in terms of access to education and land formalization programs. However, the second approach would be to use the findings to conduct participatory discussions to improve adaptive capacity and study the dynamics of the communities to generate and strategy to encourage collaboration between community members, local authorities, and relevant stakeholders to develop context-specific interventions and solutions leading to empowering communities and favoring long-term adaptation. Still, sensitivity also plays an important role in vulnerability and addressing poverty and social inequality is crucial for reducing vulnerability and efforts towards these challenges should be maintained and increased by maintaining a permanent focus of attention.

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