

Antananarivo Facing Risks: A Study of Vulnerability and Resilience

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Abstract

Antananarivo faces recurrent natural hazards-particularly floods, landslides, and cyclonic events-that disproportionately affect its most vulnerable populations. This study analyzes the spatial variability of disaster impacts and household resilience across the districts of Renivohitra, Atsimondrano, and Avaradrano. Using a mixed-methods design combining a survey of 231 households with 28 semi-structured interviews involving local authorities, community leaders, and national institutions, the study identifies the main factors shaping vulnerability and adaptive behaviors.

Quantitative findings show significant differences across districts, with Renivohitra experiencing the highest levels of physical and infrastructural damage, while Avaradrano and Atsimondrano face greater disruptions to livelihoods and mobility. Principal Component Analysis reveals three categories of impacts-physical damage, socio-economic disruptions, and agricultural losses-that together explain most of the observed variance. Qualitative insights highlight persistent governance challenges, including fragmented responsibilities, limited preparedness, weak communication channels, and insufficient financial autonomy at municipal levels. Community solidarity networks and Fokontany-led initiatives emerge as important, though underutilized, contributors to local resilience.

The findings demonstrate that vulnerability in Antananarivo is shaped by the interaction of environmental exposure, socio-economic fragility, and institutional constraints. Strengthening resilience therefore requires a more coordinated and anticipatory governance system, the integration of community-based practices, improved early warning and preparedness, and greater investment in infrastructure maintenance and risk-informed urban planning. The study provides evidence to support more inclusive and context-specific disaster risk management strategies in rapidly urbanizing African cities.

Keywords

Vulnerability, Natural Disasters, Resilience, Adaptation, Risk Management

1. Introduction

Antananarivo, the capital of Madagascar, is increasingly exposed to natural hazards that threaten the wellbeing of its population and the functioning of its urban systems. Floods, landslides, and cyclonic events have become more frequent and severe over the past decade, driven by rapid urban expansion, inadequate land-use planning, environmental degradation, and the cumulative effects of climate change [1]. As a result, large segments of the population-particularly those living in low-lying areas, informal settlements, and peri-urban zones-experience recurring losses to housing, infrastructure, and livelihoods.

The vulnerability of Antananarivo is amplified by structural weaknesses in both infrastructure and governance. Ageing drainage networks, poor solid waste management, and insufficient flood-control structures contribute to recurrent inundations even during moderate rainfall. At the same time, institutional fragmentation, limited financial autonomy of municipalities, and weak coordination across national and local agencies reduce the effectiveness of disaster preparedness and response [2,3]. These governance challenges shape the ability of households and communities to anticipate, absorb, and recover from shocks, consistent with broader analyses of social and environmental vulnerability [4,5].

Despite numerous development programs and donor-supported initiatives, resilience in Antananarivo remains unevenly distributed across districts. Urban areas such as Renivohitra face chronic flooding due to high population density and extensive impervious surfaces, while peri-urban districts like Atsimondrano and Avaradrano confront mobility disruptions, agricultural losses, and limited access to public services. These spatial disparities echo findings from urban risk and resilience research in low-income developing country contexts [6].

Although several studies have assessed hazard exposure or socio-economic vulnerability in Madagascar, fewer have integrated household-level data with institutional perspectives to examine how governance structures, community practices, and socio-spatial dynamics jointly influence disaster outcomes. This reflects a broader gap in the literature on

multilevel risk governance and integrated vulnerability assessment frameworks [7,8]. In this context, this study provides an integrated, mixed-methods analysis of vulnerability and resilience across three districts of the Antananarivo agglomeration. It combines quantitative data from 231 households with qualitative insights from 28 key informants—including mayors, disaster management authorities, development program coordinators, and Fokontany leaders.

The objective of this research is to identify and explain the main factors shaping vulnerability and resilience in Antananarivo, and to assess the extent to which public policies, community initiatives, and socio-economic conditions contribute to the capacity of households to reduce risks and recover from disasters. By examining both structural constraints and adaptive practices, the study aims to inform more coherent, inclusive, and context-responsive strategies for disaster risk management and urban resilience in Madagascar's capital.

2. Theoretical Foundations: Understanding Vulnerability, Resilience, and Adaptation to Natural Disasters

Before proceeding to the empirical analysis, it is important to establish the conceptual and theoretical foundations underpinning this study. Disaster Risk Reduction (DRR) is now a major issue, aiming to limit population vulnerability and strengthen adaptive capacity to natural hazards [7,9,10]. This section explores the key concepts of vulnerability, resilience, adaptation, and risk, while highlighting the influence of socio-economic factors. It also draws on key theoretical approaches for in-depth analysis of these dynamics.

Vulnerability reflects the level of exposure and fragility of an individual or community to the impacts of natural disasters. It depends not only on physical conditions but also on economic, social, and political factors that influence the capacity to anticipate, withstand, and recover from shocks [4,11,12]. Rather than being a mere consequence of natural hazards, vulnerability results from complex social and structural processes shaped by interactions between local contexts and global dynamics [2,5,13].

Resilience is the capacity of a community or system to cope with a shock, maintain essential functions, and adapt to ensuing changes [14,15]. It extends beyond mere resistance to encompass a process of learning and transformation, enabling populations to better anticipate and manage future risks [8,16,17]. Key elements include the diversity of available resources, strong social support networks, and the capacity to innovate and adapt to challenges [18,19].

Adaptation encompasses the strategies implemented to reduce vulnerability and strengthen resilience to natural disasters [20,21]. It can take various forms:

- Technical (constructing protective infrastructure, early warning systems);
- Behavioural (income diversification, migration) [22,23];

Political (urban planning, sustainable natural resource management) [24,25].

Regarding disaster risk, it arises from the intersection of a potentially hazardous natural phenomenon, the fragility of exposed communities, and their degree of exposure to this hazard [26]. Three key approaches are essential for risk management: limiting exposure (e.g., avoiding construction in flood-prone zones); reducing population vulnerability (e.g., improving living conditions, economic status, and access to education); and managing the natural phenomenon itself through protective infrastructure [9,10].

Studies highlight the importance of socio-economic conditions in how populations are affected by natural disasters. Limited financial resources reduce the means to prepare or adapt, increasing dependence on the natural environment and exposure to climatic hazards [27,28]. Furthermore, limited access to education hinders risk understanding and informed decision-making, increasing community fragility [29,30]. Finally, social and gender inequalities also play a significant role: women, the elderly, and marginalized groups often have fewer resources and support, rendering them more vulnerable [23,31].

In developing countries, rapid and unplanned urban expansion fosters the emergence of informal settlements often located in hazard-prone areas [6,32]. Lack of urban planning, combined with ecosystem degradation—such as deforestation and soil erosion—further exacerbates these fragilities [33,34]. Concrete examples confirm these trends: in Bangladesh, the poorest families bear the brunt of flood consequences, with particularly heavy economic losses [35]; similarly, in India, droughts disproportionately affect women, who play a central role in household resource management [36].

Several theoretical perspectives offer insights into vulnerability and resilience mechanisms. Among them, the Capability Approach, proposed by Sen [37], focuses on developing individuals' essential capacities, such as education, health, and access to resources. According to this view, strengthening these basic capabilities enhances autonomy and the capacity to cope with disasters, emphasizing the importance of empowering populations to choose their lifestyles and develop adaptive skills.

These mechanisms can also be examined through other theoretical lenses. Dependency Theory [38] examines structural inequalities between developed and developing countries, highlighting how these imbalances exacerbate the vulnerability of populations in the Global South and critiquing economic models that perpetuate poverty and hinder adaptation. Political Ecology [39] explores the relationships between environment, economy, and politics in creating

vulnerabilities, emphasizing the need to identify the structural roots of environmental issues and implement inclusive solutions involving local and institutional stakeholders [3,25].

This conceptual review underscores that vulnerability to natural disasters is multifaceted, integrating environmental, socio-economic, and political elements. Understanding the situation in Antananarivo requires a comprehensive approach combining socio-economic analysis, urban planning, and adjustment policies. This research uses these concepts to examine disparities in vulnerability and resilience across urban, peri-urban, and rural areas of the Malagasy capital, focusing particularly on the adaptation tactics adopted by different households.

Despite existing studies on vulnerability and resilience, research gaps remain. Few studies have examined vulnerability and resilience across diverse geographical or socio-economic contexts, limiting the universality of findings [8,40]. Many focus primarily on the physical and financial aspects of disasters, overlooking the complex interactions between social and environmental factors affecting community resilience [5]. Finally, few studies adopt a participatory approach, directly engaging affected communities in problem identification and the co-development of solutions [41].

This study aims to address these gaps by comparing socio-economic vulnerability and resilience to natural disasters across three districts of Antananarivo, distinguished by their urban, peri-urban, and rural contexts. By combining quantitative and qualitative approaches, it seeks to enrich our understanding of ongoing dynamics while suggesting operational measures to strengthen community resilience. Furthermore, this study prioritizes a participatory approach, engaging local communities throughout the process, from data collection to interpretation, ensuring that findings are grounded in local realities and effectively contribute to improving residents' living conditions [19].

3. Materials and Methods

3.1 Study Area and Research Design

This study adopts a mixed-methods research design combining quantitative household surveys with qualitative key-informant interviews to examine vulnerability and resilience to natural disasters across three districts of the Antananarivo agglomeration. The selected areas represent contrasting socio-spatial contexts:

- Antananarivo Renivohitra (high-density urban core)
- Antananarivo Atsimondrano (peri-urban transition zone)
- Antananarivo Avaradrano (predominantly rural area)

This stratification allows the comparison of vulnerability patterns shaped by levels of urbanization, exposure to hazards, and socio-economic diversity. Such an approach is consistent with established frameworks in vulnerability and risk assessment that highlight spatial and socio-economic differentiation [5,12].

3.2 Quantitative Component: Household Survey

3.2.1 Sample Size and Sampling Procedure

A total of 231 households were surveyed across the three districts. The distribution reflects population size and exposure level:

- 195 households in Antananarivo Renivohitra
- 30 households in Atsimondrano
- 17 households in Avaradrano

A stratified random sampling approach was used. Strata were defined based on three criteria:

1. Degree of exposure to floods and cyclones
2. Type of settlement (urban/peri-urban/rural)
3. Socio-economic profile of households

The sample size was determined using Cochran's formula with a 95% confidence level and 5% margin of error, ensuring statistical representativeness for comparative analysis across districts.

3.2.2 Survey Instrument

Data were collected using a structured questionnaire covering socio-economic characteristics, past disaster experiences, perceived frequency and severity of hazards, adaptive strategies, and assessment of public policy performance.

The questionnaire included:

- Multiple-choice questions
- 5-point Likert scales (1 = never / very low; 5 = always / very high)

The instrument was organized into five modules:

1. Socio-economic characteristics (age, education, income, housing)

2. Risk perception and hazard exposure (frequency, severity, awareness)
3. Disaster impacts (damage to homes, crops, roads, public services)
4. Coping and adaptation strategies (savings, relocation, aid use, recovery actions)
5. Evaluation of public policies (early warning systems, flood management, local governance)

This structure reflects established analytical frameworks for disaster vulnerability, coping strategies, and livelihood responses [5,23].

3.2.3 Data Quality and Statistical Analysis

Data were analyzed using descriptive statistics (means, standard deviations, frequencies) and inferential procedures including:

- Principal Component Analysis (PCA)
- Correlation analysis
- ANOVA for inter-district comparisons
- Index construction (vulnerability index, resilience index)

The reliability of the multivariate analysis was validated using:

- KMO = 0.729, indicating adequate sampling adequacy
- Bartlett's Test of Sphericity: $\chi^2 = 929.774$, $df = 45$, $p < 0.001$, confirming factorability

These results justify the use of PCA to identify coherent categories of disaster-related damages, a technique frequently used in vulnerability measurement and risk analysis [12].

3.3 Qualitative Component: Key Informant Interviews

To complement quantitative data and understand institutional dynamics, 28 semi-structured interviews were conducted with key stakeholders.

Local Actors:

- 16 *Chefs de Fokontany* (local community leaders)
- Municipal authorities
- 4 Mayors:
 - Antananarivo Renivohitra
 - Sabotsy Namehana (Avaradrano)
 - Tanjombato (Atsimondrano)
 - Soavina (Atsimondrano)

National and International Institutions

- Senior officials from the BNGRC and CPGU
- Coordinator of the World Bank-funded PRODUIR project
- Task Team Leader (TTL) of PRODUIR
- Coordinator of the CAT-DDO project

The interview guide explored perceptions of disaster frequency, preparedness measures, communication systems, institutional coordination, and constraints facing local authorities. Interviews were recorded, transcribed, and coded thematically using approaches aligned with participatory and community-centered disaster research [19,41].

3.4 Data Triangulation and Integration

The mixed-methods design allowed a triangulation strategy:

- Quantitative data provided patterns of vulnerability and impacts
- Qualitative interviews explained institutional constraints, governance gaps, and local dynamics
- Field observations validated questionnaire responses

This integration strengthens the internal validity of the study and aligns with multi-level resilience assessment frameworks [2].

3.5 Ethical Considerations

Ethical approval was obtained from the Doctoral School Ethics Committee of the Catholic University of Madagascar. All participants-households and institutional actors-provided informed consent. Anonymity and confidentiality were fully ensured during all stages of the research, consistent with international research ethics standards.

4. Results

4.1 Socio-Economic Characteristics of Respondents

A total of 231 households were surveyed across the three districts of Antananarivo. The distribution reflects demographic dominance and urban density, with 195 households (84%) in Renivohitra, 30 households (13%) in Atsimondrano, and 17 households (7%) in Avaradrano. The majority of respondents were female (58%), with an average household size of 4.3 persons. These demographic patterns are consistent with previous studies on household characteristics in disaster-prone contexts in Madagascar [34].

Income levels were generally low across the sample: 64% earned less than 500,000 Ariary per month, mostly through informal activities such as street vending, domestic work, and small-scale commerce. Housing types differed significantly between districts: Renivohitra was characterized by dense, precarious settlements built with mixed materials, whereas Avaradrano and Atsimondrano displayed a higher proportion of semi-durable housing structures. Such disparities in housing quality are known to shape household vulnerability and exposure to shocks [2,5].

A one-way ANOVA confirmed significant differences in household income across districts ($F = 6.72$, $p < 0.01$), with Renivohitra households reporting higher income instability and more frequent work interruptions due to flooding. These results align with earlier work showing that poorer households often face recurrent productivity losses due to climate hazards [23,28].

4.2 Exposure to Natural Hazards

Floods emerged as the most frequent and severe hazard. Across the whole dataset:

- **82%** of households reported experiencing at least one major flood in the last five years
- **61%** reported multiple annual flooding episodes, particularly among residents of Renivohitra
- Cyclones and strong winds affected **47%** of households
- **29%** experienced drought-related impacts on livelihoods

These patterns align with national assessments highlighting Madagascar's multi-hazard environment and the chronic exposure of urban and peri-urban populations to hydrometeorological events [10,34,36].

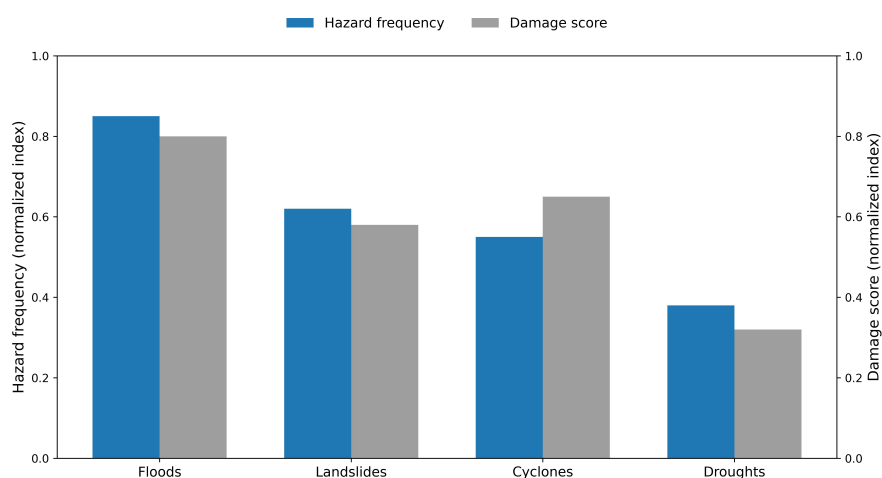


Figure 1. Figure 1 summarizes the Frequency and Damage Levels Associated with the Major Hazards Reported by Households

This figure summarizes the frequency of major hazards and the associated damage scores across surveyed households. Floods represent the most recurrent and severe events, followed by cyclones, landslides, and droughts, with clear variations between districts—patterns consistent with national hazard profiles documented for Madagascar [10,34].

A Kruskal-Wallis test showed statistically significant differences in flood occurrence across districts ($\chi^2 = 14.53$, $p < 0.001$), with Renivohitra being the most affected. This aligns with previous assessments showing that dense urban centers often face higher exposure due to inadequate drainage and high impervious surface coverage [2,6].

4.3 Damages to Infrastructure, Housing, and Livelihoods

Households reported severe impacts on a wide range of assets:

- **87%** reported damage to their homes
- **75%** reported damage to access roads
- **71%** indicated disruption of water or sanitation services
- **54%** lost crops or livestock (mainly in Avaradrano and Atsimondrano)

Such patterns reflect typical multi-sectoral disruptions documented in disaster-prone low-income settings, where both physical and socio-economic systems experience cascading impacts [7,23].

The most recurrent impacts were categorized using Principal Component Analysis (PCA), which identified three major components:

Component 1 – Physical and Environmental Damage (41% of variance)

Includes damage to:

- housing infrastructure
- drainage canals
- roads and bridges
- landslides and erosion

This component is strongly associated with Renivohitra's topography, population density, and rapid urbanization. Similar trends have been observed in other cities of the Global South where unplanned urban expansion amplifies hazard exposure [6,10].

Component 2 – Socio-Economic Disruptions (23% of variance)

Includes:

- income losses
- schooling disruptions for children
- temporary market closure
- reduced access to health facilities

These impacts were most severe in Atsimondrano due to recurrent flooding and poor road connectivity. Literature shows that such socio-economic disruptions often magnify long-term vulnerability by reducing livelihood stability and increasing recovery times [23,28].

Component 3 – Agricultural Losses (14% of variance)

Includes:

- crop destruction livestock mortality
- fishpond overflow

This component dominates in Avaradrano, where livelihoods depend strongly on farming and rice cultivation, reflecting the vulnerability of rural-based economies to climatic shocks [28,34].

Overall, the three components explain **78%** of the total variance, validating the PCA structure and confirming the multidimensional nature of disaster impacts on households [7].

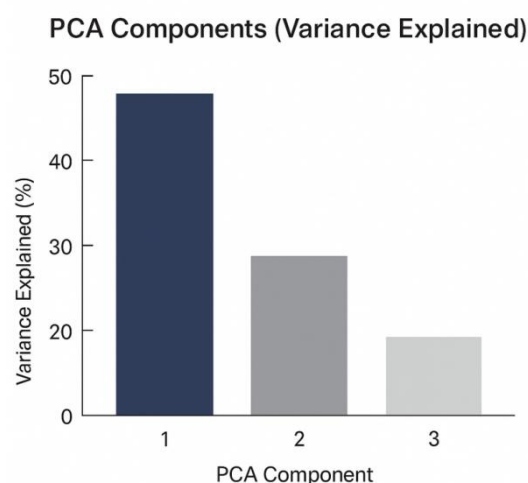


Figure 2. Figure 2 shows the Proportion of Variance Explained by the three Pca Components

4.4 Household Vulnerability Index

The bar chart illustrates the proportion of variance explained by the three principal components identified in the PCA: physical damage, socio-economic disruption, and agricultural losses. Together, these components account for most of the variance in disaster impacts, confirming the multidimensional nature of vulnerability and household exposure as documented in previous risk assessment studies [10,12].

Household Vulnerability Index

A composite vulnerability index was constructed from 16 variables capturing exposure, sensitivity, and adaptive capacity. Scores ranged from 0 (low vulnerability) to 1 (high vulnerability). This methodological approach aligns with established frameworks for vulnerability index construction, particularly those focusing on socio-economic and environmental sensitivity [4,5,12].

District-level averages reveal:

- Renivohitra: 0.72 (high vulnerability)
- Atsimondrano: 0.63 (moderate-high)
- Avaradrano: 0.58 (moderate)

These patterns reflect the differential exposure and adaptive capacity across the three districts. Renivohitra's high score is linked to its dense urban fabric, degraded drainage systems, and socio-economic precarity-factors commonly associated with elevated urban vulnerability [2,4]. Meanwhile, Atsimondrano's intermediate score reflects a mix of urban and peri-urban stressors, whereas Avaradrano presents lower overall vulnerability but higher agricultural sensitivity, consistent with findings in rural hazard-prone contexts [28].

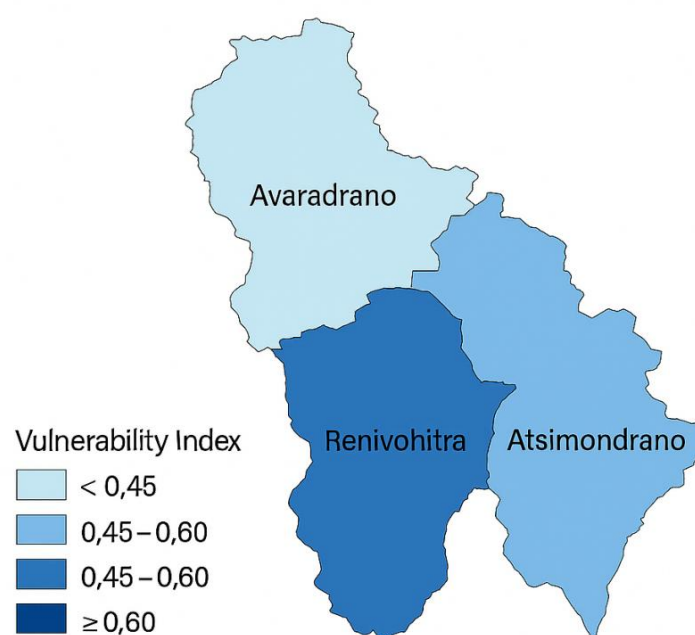


Figure 3. Figure 3 illustrates the Comparative Vulnerability Index across the three Districts

This figure presents the average vulnerability index for the three districts of Antananarivo. Renivohitra shows the highest vulnerability level, followed by Atsimondrano and Avaradrano, reflecting differences in exposure, infrastructure conditions, and socio-economic fragility-patterns already highlighted in previous vulnerability assessments [5].

An ANOVA test confirmed that these differences are statistically significant ($F = 11.84$, $p < 0.001$).

The higher vulnerability in Renivohitra is linked to dense settlements, poor drainage, and frequent inundation, consistent with findings that urban density amplifies exposure in low-income settings [2].

4.5 Coping and Adaptation Strategies

Households adopt a combination of temporary and long-term strategies, including:

- Reinforcing house structures (76%)
- Seeking emergency credit or family loans (61%)
- Temporarily relocating during heavy floods (43%)
- Cleaning drainage canals collectively (59%)
- Storing food or saving money as preparedness measures (29%)

These strategies mirror documented household-level responses to climate and disaster risks, especially in resource-constrained contexts [17,23]. Renivohitra showed higher adoption of collective actions due to high-density living, whereas Avaradrano households relied more on social networks and local authorities. Such behaviour aligns with community-oriented resilience mechanisms frequently observed in developing-country settings [19,41].

4.6 Perceptions of Public Policy Effectiveness

Respondents rated government intervention across five dimensions: preparedness, early warning, communication, evacuation management, and post-disaster support.

Results show generally moderate levels of satisfaction:

- Preparedness actions: $M = 2.8 / 5$
- Early warning systems: $M = 3.1 / 5$
- Evacuation management: $M = 2.5 / 5$
- Post-disaster response: $M = 2.3 / 5$
- Community involvement: $M = 2.9 / 5$

Correlational analysis indicates that higher satisfaction with public policies is significantly associated with lower vulnerability ($r = -0.46$, $p < 0.01$). This suggests a strong link between governance and household resilience—a relationship widely recognized in disaster governance literature [3,25]. Furthermore, satisfaction with early warning systems reflects the importance of clear, timely communication, a key factor in disaster preparedness [42].

4.7 Qualitative Insights from Key Informants

Insights from 28 interviews with mayors, development project leaders, disaster management authorities (BNGRC, CPGU), and 16 Fokontany chiefs reveal several institutional weaknesses:

(1) Coordination gaps

Local authorities emphasized overlapping mandates between BNGRC, CPGU, and municipal actors, leading to delays in emergency response—an issue frequently documented in centralized disaster governance systems [3].

(2) Budgetary constraints

Mayors stressed dependence on national transfers and donor-funded projects, limiting their ability to implement preventive measures. This reflects broader structural financing challenges in DRR across developing countries [25].

(3) Weak communication systems

Warnings are often late and not disseminated in accessible formats, leaving vulnerable communities unprepared. Prior research confirms that communication failures significantly heighten disaster impacts [30,42].

(4) High exposure of touristic and heritage areas

Both Renivohitra's historic center and the UNESCO site of Ambohimanga in Avaradrano face increasing flood risks, affecting local economic activities. This aligns with research on the vulnerability of cultural sites to climate change impacts [34].

(5) Community resilience mechanisms

Fokontany leaders described strong informal solidarity networks, canal-cleaning initiatives, and mutual aid systems that significantly shape resilience outcomes. Such community-led adaptation processes are consistent with participatory resilience frameworks [19,41].

These narratives complement the quantitative results and provide depth to the vulnerability diagnosis by highlighting institutional constraints, governance gaps, and localized resilience strategies.

4.8 Synthesis of Results

The combined quantitative and qualitative findings reveal that:

- Floods are the most widespread and destructive hazard in Antananarivo.
- Vulnerability varies spatially, with Renivohitra being the most exposed.
- Public policies have limited effectiveness, notably due to coordination failures and resource shortages.
- Household resilience is driven by both formal and informal mechanisms (governance + community action).
- Tourist and heritage areas are increasingly exposed, affecting local development potential.

These results form a solid basis for the discussion and policy recommendations, particularly regarding integrated governance, adaptive capacity, and multi-level coordination in DRR [3,17,21].

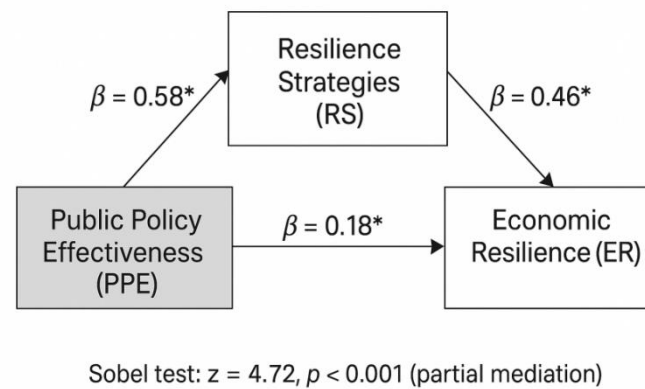


Figure 4. Figure 4 presents the Mediation Model Highlighting the Indirect Effects of Resilience Strategies on Economic Resilience

The diagram shows the mediating effect of resilience strategies on the relationship between hazard frequency/damage scores and economic resilience. Direct and indirect effects are displayed with standardized coefficients, and the Sobel test confirms a significant partial mediation.

5. Discussion

The results of this study reveal complex patterns of vulnerability and resilience in the Antananarivo agglomeration, influenced simultaneously by environmental exposure, socio-economic fragility, and governance performance. Rather than repeating the statistical findings, this discussion focuses on interpreting the mechanisms underlying these patterns and linking them with existing literature on disaster risk, urban resilience, and development planning.

5.1 Spatially Unequal Vulnerability and the Role of Urbanization

The study shows that Antananarivo Renivohitra concentrates the highest levels of vulnerability, largely due to dense settlement patterns, degraded drainage systems, and high exposure to recurrent flooding. This is consistent with global research indicating that urban density without adequate infrastructure amplifies disaster impacts in developing country cities [2,5,6]. The PCA results confirm that physical and infrastructural damages are the dominant sources of harm in the urban core.

In contrast, Atsimondrano and Avaradrano exhibit different vulnerability profiles, shaped less by density and more by mobility constraints, agricultural dependencies, and the weakness of rural–urban linkages. This aligns with studies showing that peri-urban and semi-rural areas face distinct challenges related to institutional presence, connectivity, and uneven public investment [22,28].

5.2 Socio-Economic Fragility as a Driver of Disaster Impacts

Low and unstable income levels across districts compound the impacts of hazards, limiting households' capacity to recover and adapt. This confirms arguments that poverty and vulnerability are mutually reinforcing drivers of disaster impacts [4,11]. Income instability in Renivohitra—documented in the ANOVA results—is tightly linked to service disruptions, market closures, and repeated repair costs.

Meanwhile, agriculture-dependent households in Avaradrano face recurrent crop losses, reinforcing findings that climate-related risks disproportionately affect primary sector livelihoods [28]. Household strategies identified—credit borrowing, temporary relocation, reinforcement of homes—mirror coping mechanisms commonly documented in vulnerable populations but rarely lead to long-term resilience [17,23].

5.3 Governance Gaps and Limited Public Policy Effectiveness

A central finding of this study is the moderate to low confidence expressed by respondents regarding public disaster management policies. Weak preparedness, limited communication, and inadequate post-disaster support reveal structural governance constraints.

Interview narratives highlight three key obstacles:

- 1. Fragmented institutional responsibilities** between BNGRC, CPGU, municipalities, and donors, creating overlaps and delays—an issue also emphasized in governance and DRR research [3,25].
- 2. Insufficient financial autonomy** of local governments, making them dependent on national allocations and donor projects, consistent with institutional vulnerability analyses [12,33].
- 3. Gaps in early warning dissemination**, especially for vulnerable populations in informal or isolated zones, confirming evidence that ineffective communication systems heighten disaster impacts [30,42].

These problems mirror findings from international literature showing that resilience depends not only on infrastructure but also on coherent, coordinated, multi-level governance systems [17,25].

5.4 The Growing Vulnerability of Touristic and Heritage Areas

Both Renivohitra's historic center and the UNESCO site of Ambohimanga in Avaradrano face increasing climate-induced stress. Flooding, erosion, and infrastructural decay threaten cultural assets, tourism income, and local identity. This dimension is often overlooked in urban resilience literature, yet heritage-based tourism plays a significant role in livelihoods.

The exposure of Ambohimanga highlights a critical gap in disaster planning: heritage sites are rarely integrated into DRR frameworks, despite their economic and symbolic importance. This finding expands resilience analysis by showing that disasters can jeopardize not only physical assets and incomes but also cultural continuity and long-term development potential [10,34].

5.5 Community-Based Resilience: A Critical but Underutilized Asset

Despite institutional weaknesses, the study identifies strong community resilience practices: canal clearing, informal financial support networks, *Fokontany*-led coordination, and mutual assistance during evacuations. These mechanisms align with participatory and community-centered resilience frameworks [19,41].

However, interviews reveal a lack of formal recognition and support for these initiatives. *Fokontany* leaders report limited involvement in planning processes, despite their proximity to communities. This disconnect underscores the need to link top-down DRR systems with bottom-up community capacity [19].

5.6 Integrating Quantitative Patterns and Qualitative Mechanisms

A major contribution of this mixed-methods approach is demonstrating that statistical patterns cannot be fully understood without institutional and contextual insight:

- Quantitative data show high vulnerability in Renivohitra → qualitative interviews reveal inadequate drainage budgets and overlapping mandates.
- Quantitative results show agricultural losses in Avaradrano → interviews reveal insufficient extension services and weak flood-control investments.
- Quantitative findings show moderate policy effectiveness → interviews highlight bureaucratic complexity and communication gaps.

This triangulation confirms that disaster vulnerability in Antananarivo is structural, shaped as much by governance limitations as by environmental hazards [10,25,42].

5.7 Contribution to the Literature

This study contributes to existing scholarship in three ways:

1. It provides an integrated analysis of hazard exposure, socio-economic fragility, and governance performance in a Sub-Saharan African capital city—an underrepresented region in DRR research [5,34].
2. It highlights the importance of institutional coordination, reinforcing evidence that governance quality is a core determinant of resilience outcomes [3,25].
3. It incorporates touristic and heritage vulnerability, a dimension seldom examined in urban resilience studies but essential for long-term development [10].

6. Conclusion

This study examined the differentiated impacts of natural hazards on households in Antananarivo and revealed the multiple factors that shape vulnerability and resilience across the urban, peri-urban, and rural districts of the metropolitan area. The findings show that exposure to floods, landslides, and cyclonic events intersects with socio-economic fragility, spatial inequalities, and institutional limitations, producing distinct vulnerability profiles in Renivohitra, Atsimondrano, and Avaradrano.

The analysis demonstrates that physical and infrastructural damages remain the dominant sources of harm in dense urban areas, while agricultural losses and mobility constraints are more pronounced in peri-urban and rural districts. The resilience strategies adopted by households illustrate both the resourcefulness of local communities and the limits of their adaptive capacity, particularly when coping mechanisms remain largely informal and unsupported. The role of community networks, *Fokontany* leadership, and local solidarity emerges as a critical but under-recognized pillar of resilience.

Institutional perspectives highlight persistent governance challenges, including fragmented responsibilities, insufficient financial autonomy, and limitations in early warning systems and preparedness. These constraints hinder the effectiveness of disaster risk management policies and restrict the ability of municipalities to implement preventive

actions. The growing exposure of historic and touristic sites, such as Ambohimanga, further underscores the need for integrated and forward-looking risk planning that protects both livelihoods and cultural heritage.

Overall, the findings suggest that building resilience in Antananarivo requires a shift toward a more coordinated, inclusive, and anticipatory governance framework. Strengthening local government capacities, improving inter-institutional collaboration, and formally integrating community-based initiatives into disaster planning are essential steps. Enhancing infrastructure maintenance, securing stable financing mechanisms, and aligning urban development policies with risk reduction objectives are equally critical.

By combining quantitative and qualitative evidence, this study provides a clearer understanding of the structural drivers of vulnerability and the opportunities for resilience in a rapidly growing African capital. Its insights can support decision-makers, practitioners, and development partners in designing interventions that are context-specific, equitable, and sustainable. The conclusions offer a foundation for future research exploring long-term adaptation pathways, governance reforms, and the resilience of socio-economic systems under intensifying climate-related risks.

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