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MULTISCALAR ANALYSIS OF FLOODING IN URBAN AND RURAL AREAS FOR RESILIENT TERRITORIAL PLANNING: THE CASE STUDY OF COTOPAXI (ECUADOR)

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JOHANA CALLES-ORTIZ [2]
EMILIA ROMÁN-LÓPEZ [3]
GUSTAVO ROMANILLOS-ARROYO [4]

1 This article is part of the doctoral thesis “Resilient Territorial Planning for Floods in Urban and Rural Areas: The Case of Cotopaxi (Ecuador).”

2 Arquitecta
Estudiante programa de Doctorado “Sostenibilidad y Regeneración Urbana, Departamento de Urbanística y Ordenación del Territorio” de la Escuela Técnica Superior de Arquitectura de Madrid
Universidad Politécnica de Madrid, Madrid, España
https://orcid.org/0000-0001-8619-3787
jp.calles@alumnos.upm.es

3 Doctora Arquitecta
Profesora Contratada Doctora, Escuela Técnica Superior de Arquitectura de Madrid
Universidad Politécnica de Madrid, Madrid, España
https://orcid.org/0000-0001-6746-2793
emilia.roman@upm.es

4 Doctor en Geografía
Profesor Contratado Doctor, Departamento de Geografía
Universidad Complutense de Madrid, Madrid, España
https://orcid.org/0000-0001-5098-8596
gustavro@ucm.es

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Las inundaciones en las áreas urbanas y rurales de la provincia de Cotopaxi son recurrentes y generan múltiples impactos negativos a nivel ambiental, social y económico. Esta investigación pone el foco en los factores que intervienen en las inundaciones pluviales y fluviales en tres escalas: territorial, urbana/rural y local. A través de una metodología mixta, apoyada en métodos cualitativos y técnicas de análisis espacial, se realiza un análisis multiescalar con relación a las inundaciones en áreas urbanas y rurales. Esta metodología se puede extrapolar a otras áreas con características similares y se nutre de tres procesos: revisión y recopilación documental, caracterización del territorio, a través de Sistemas de Información Geográfica y producción de cartografía y por último, análisis de normativas e instrumentos técnicos de planificación territorial. Como resultado, se describen cuatro factores macro de inundaciones, siendo el cambio en el uso y la cobertura del suelo el más relevante de todos, que afectan en mayor medida a la escala urbana/rural, convirtiéndola en una escala clave en la gestión del riesgo de inundación. Finalmente, esta metodología ha permitido identificar el origen de las inundaciones según la escala de análisis y, además, establecer las problemáticas específicas, las posibles vías de acción y las competencias con el fin de reducir la vulnerabilidad de las áreas afectadas.

Palabras clave: inundaciones, áreas urbanas, riesgo de inundación, análisis multiescalar, cambio climático

Flooding in urban and rural areas of the Cotopaxi province is a recurring problem that has had multiple adverse effects on the environment, society, and the economy. This research focuses on the factors involved in pluvial and river flooding at three scales: territorial, urban/rural, and local. Using a mixed-methods approach, supported by qualitative methods and spatial analysis techniques, a multiscale analysis of flooding in urban and rural areas is conducted. This methodology can be extrapolated to other areas with similar characteristics and includes three processes: documentary review and compilation; characterization of the territory through Geographic Information Systems and cartography; and, finally, analysis of regulations and technical instruments for territorial planning. As a result, four macro factors of flooding are described, with the change in land use and cover being the most relevant, affecting the urban/rural scale to a greater extent, making it a key scale in flood risk management. Ultimately, this methodology has enabled identifying the origin of floods according to different scales of analysis and, in addition, establishing specific problems, possible solutions, and competencies to reduce the vulnerability of affected areas.

Keywords: floods, urban areas, flood risk, multiscale analysis, climate change

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I. INTRODUCTION

Climate change has intensified many meteorological phenomena worldwide (The Intergovernmental Panel on Climate Change [IPCC], 2023). Climate-related threats, such as floods, droughts, heat waves, etc., have highlighted the vulnerability and exposure of some ecosystems and human settlements to current climate variability. As a result, this series of impacts has generated diverse problems, including damage to infrastructure and settlements, health, human well-being, and the economy (IPCC, 2014).

In the last three decades, water-related disasters accounted for 88% of the climate-related events in Latin American and Caribbean countries, 77% of the reported economic costs, and 89% of the people affected by all disasters registered in the region (Saravia Matus, 2024). In Ecuador, floods are a constant threat due to different factors, including the general atmospheric circulation, air masses, and the influence of ocean currents, such as the El Niño Phenomenon (Pourrut & Gómez, 1998). In coastal cities, there is evidence of an increased risk due to the territory's conditions, which is further exacerbated by the expected rise in temperatures over the coming decades. However, there are also inter-Andean cities that, lacking a coast or proximity to the ocean, are affected by recurring floods. This circumstance in urban and rural environments has not been investigated in depth, highlighting the lack of attention to the prevention, preparation, and reduction of disaster risk.

In this context, this research, considering the current situation of mitigating flood risk through the recovery of ecosystems and the use of green and sustainable solutions based on nature, aims to highlight the universe of factors involved in floods in urban and rural inland areas, including various aspects, such as: green infrastructure, urban rivers, informal settlements, hydraulic works for flood control, etc.

In this vein, the study by Orellana Valdez (2023) shows that environmental problems in urban areas differ from those in rural areas. Phenomena such as runoff, floods, and heat storage originate in built-up areas. At the same time, the loss of agricultural soil or the fragmentation of ecosystems are inherent problems in peri-urban rural areas. Another study, conducted by Hermida et al. (2019), outlines four dimensions that, undoubtedly, are inherent to the characterization of the phenomenon of floods in urban and rural areas: spatial and visual accessibility, the continuity of the green corridor, the conditions of the public space, and those of the first built line. Similarly, the research carried out by Zamora Saenz, Mazari Hiriart, and Almeida Leñero (2018) proposes 11 indicators to recover urban rivers, key elements for mitigating the consequences of floods. Some of these are: protection of areas for the conservation of priority species, potential surface area for soil restoration, reforestation quality index, basic river expenditure on rains and on dry land, surveillance and monitoring actions, among others.

It should be noted that, as far as we know, in the urban and rural areas studied in the province of Cotopaxi-Ecuador (Latacunga and Tanicuchí), located in the central part of the country, specific research has not been carried out that integrates the factors that influence rain and river floods, i.e., floods caused by rivers overflowing, and those caused when the terrain is saturated by water due to the accumulation of rain over a long period of time. Therefore, analyzing these cases is relevant, since the results can be extrapolated to other urban and rural areas with similar characteristics.

This research identifies the factors that can influence floods and links them to three scales of analysis: territorial, urban/rural, and local. In this sense, the objective is to develop a multiscale methodology on floods in urban and rural areas through three steps: first, documentary collection and review, second, mapping and characterization of the territorial scope and selection of specific study areas, and third, analysis of regulations and technical instruments related to territorial planning. These processes have been conducted via a qualitative method and spatial analysis techniques using Geographic Information Systems (ArcGIS software). The following hypothesis has been proposed: The Territorial Planning Plan of the Latacunga Canton integrates disaster risk management into territorial planning and identifies the main factors potentially related to floods in its urban and rural areas. Finally, this study outlines proposals or measures to address the problems related to these factors and to the three scales, showing that changes in land use and land cover are the most relevant factors and mainly affect the urban/rural scale, being key in flood risk management, since the actions should be specific and executed from this level outwards, to implement a comprehensive risk management.

II.THEORETICALFRAMEWORK

As a starting point, key concepts in disaster risk management are mentioned, including threat, exposure, vulnerability, and risk. Threat is "*a phenomenon of natural, biological or anthropogenic origin, which may cause loss,*

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damage or disruption to people, infrastructure, services, ways of life or the environment" (National Emergency Office of the Ministry of the Interior and Public Security [ONEMI], 2021, p.10).

Meanwhile, exposure "*is defined by the location of the population, infrastructure, services, livelihoods, environment, or other elements in an impact area as a result of the manifestation of one or more threats*" (ONEMI, 2021, p.19). Similarly, "*vulnerability is the conditions determined by physical, social, economic, and environmental factors or processes that increase the susceptibility of a person, a community, a property, or systems to the effects of threats*" (SNGRE, 2018b, p.10). Thus, in the current context, it can be considered that:

> "Territorial vulnerability to climate change is multidimensional and is related to a combination of factors associated with the location and degree of fragility of human settlements, as well as related productive activities, in areas prone to natural threats" (ECLAC, 2019, p.39).

Finally, risk is the "*probable loss of life or damage in a society or community in a specific time period, which is determined by the threat, vulnerability, and responsiveness*" (SNGRE, 2018b, p.10). In this sense, for the risk to exist, there must be a threat and a population vulnerable to its impact (Rotger, 2018).

It should be noted that, in the analyzed case, the threat is potential flooding, which will only become a risk when its effects affect areas occupied by exposed populations, namely, the urban and rural areas of the province of Cotopaxi that are vulnerable to this phenomenon.

In the same vein, the review of the state of the art has allowed identifying four macro factors that contribute to floods: increased probability of occurrence and intensity of hydrometeorological phenomena, changes in land use and cover, issues in flood control hydraulic works, and failures in the storm drain and sewer system. Below, several approaches or concepts that have served as the basis for this methodology are described.

Thus, the concept of flooding is developed further, which "[...] *is water overflowing the normal confines of a river or any body of water*" (World Meteorological Organization [WMO] and United Nations Educational, Scientific and Cultural Organization [UNESCO], 2012, p.127). It is also considered a flood "[...] *when the rainfall has exceeded the maximum water retention and soil infiltration capacity (flooding due to soil saturation), or the water flow exceeds the maximum transport capacity of rivers, streams or estuaries*" (SNGRE, 2018a, p.29).

In this context, several factors cause flooding: *"[...] however, the most frequent cause is due to torrential rains and thaws that cause inland rivers and reservoirs to overflow"* (Walker & Saunders, 1995, p.6).

Next, each flood-related factor involved in the proposed multiscale analysis is explored, starting with the highest probability of occurrence and the strength of hydrometeorological phenomena. Intrinsic to this factor are several aspects that are closely related, among them: variations in the frequency of intense rains due to winter or the El Niño Phenomenon, an increase in intense rains in unusual periods caused by climate change (IPCC, 2013), rapid melting of snow or ice from volcanoes or mountains (Walker & Saunders, 1995), and soil saturation. In Ecuador, the National Institute of Meteorology and Hydrology (INAMHI) is responsible for providing meteorological and hydrological statistical information to the public and academic sectors for decision-making across different areas of society (Iza Wong, 2024).

On the other hand, changes in land use and land cover are among the main factors driving floods in urban and rural areas. This is evidenced by the analysis of the following aspects: changes in the vegetation cover of the watershed or urban or rural area, leading to runoff (Francés Gracia, 1997), the advance of the agricultural and livestock frontier, the lack of connectivity of natural and semi-natural green spaces, public spaces without urban green infrastructure, degradation of rivers in urban areas, inadequate safety strips, the increase of urbanized areas (Valladares Ros, Gil Hernández, & Forner Sales, 2017) or informal settlements in flood zones, among others.

Another factor is the failure of hydraulic flood control works, such as levees, containment dams, regulating reservoirs, channeling, and canalization. These systems generate a false sense of security, along with many limitations and operational problems, environmental impacts, and high costs (Rossel, Cadier & Gómez, 1996).

Finally, the failure of the storm sewer system, or hydraulic insufficiency, is another of the most common causes of flooding in urban areas (Hernández Rodríguez, 2012). The role of storm drains is to remove rainwater from streets and other areas to prevent issues such as traffic interruptions, property damage, and basement flooding, among others. When infrastructure of this type is planned, it is not designed for torrential rains, since it is considered more economical to assume damage and specific problems than to design and size for such extreme events (Hardenbergh & Rodie, 1966).

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Flooding also has immediate consequences. For example, the accumulation of waste in certain areas, the breakage of water channels that can lead to contamination of drinking water, and therefore the appearance of diseases and epidemics.

Over time, many countries have been improving flood response strategies to reduce the population's vulnerability to adverse hydrometeorological events. In this sense, emphasis is placed on proper flood risk management. "*An integrated approach to flood risk management is a combination of risk management measures that, taken as a whole, can successfully reduce flood risks in cities*" (Jha, Bloch & Lamond, 2012, p.28). These management measures can be divided into two types: structural and non-structural.

"*The structural measures aim to reduce the risk of flooding by controlling the flow of water, both outside and inside urban settlements*" (Jha, Bloch & Lamond, 2012, p.28). Among them, drainage channels and flood defenses stand out and can be effective when adequately maintained, as in the case of the Thames Barrier, the defenses along the coast of the Netherlands in the North Sea, or the systems in Japanese rivers. However, structural measures can fail for various reasons, including events whose magnitude exceeds design specifications. Some measures can also transfer the risk of flooding, reducing it in one place and increasing it in another.

On the other hand, non-structural measures include risk management through the development of capacities to address flood threats in the environments where people work and live. The most sustainable and natural solutions are among the non-structural measures, including wetlands, natural buffers, or early warning systems, which do not require significant initial investments, but do require an adequate understanding of the flood threat (Jha, Bloch & Lamond, 2012).

III. METHODOLOGY AND DATA

This research has been based on a case study, supported by a qualitative method and spatial analysis techniques. Hence, characteristics and guidelines have been established to create a "Multiscale analysis methodology regarding floods in urban and rural areas", which contains the following items: problems and factors involved in floods, ways of action, and competencies. For this, the following scales have been considered: territorial scale (watersheds), urban/rural scale (urban and rural areas), and local scale (neighborhoods, specific sectors, stretches of rivers, streets, urban facilities, etc.). The methodological phases that have been followed are:

1. Documentary review and compilation: literature, cartography, previous works, academic articles, etc.
2. Analysis of regulations and technical instruments: Territorial Planning Plan of the Latacunga Canton, references, and other minimum technical standards on risk prevention and mitigation in the context of floods. These documents have been analyzed to demonstrate the comprehensive incorporation of disaster risk management into territorial planning and to identify possible flood mitigation strategies in urban and rural areas.
3. Search for geographical information to produce maps and multiscale analysis of the territorial scope, and to identify specific cases to analyze the affectation: Identification of the hydrographic watersheds in Cotopaxi (Figure 1) and their relationship with specific urban and rural areas. For this, the following tasks have been carried out:

   Steps to characterize the threat:
   - Calculation of watersheds at the national level based on Ecuador's Digital Terrain Model, cell size 50x50m (Military Geographical Institute [IGM], 2020).
   - Watersheds and their relationship with Ecuador's provinces.
   - Hydrographic analysis to identify the water network of existing or potential watercourses, and other water bodies at a territorial scale.
   - Watersheds that affect Cotopaxi (Pastaza, Esmeraldas, and Guayas). This mapping includes analyses of the three basins, hydrography, and urban and rural areas.

   Steps to characterize the exposure:
   - Identification and cartographic representation of Cotopaxi's urban and rural areas in locations susceptible to flooding.
   - Areas susceptible to flooding on a territorial scale (IGM, 2020).

   Steps to characterize the vulnerability:
   - Vegetation cover at a territorial scale, and its relationship with the watersheds that affect Cotopaxi.
   - Analysis of the effects of possible floods in Cotopaxi's urban and rural areas (Latacunga and Tanicuchí).

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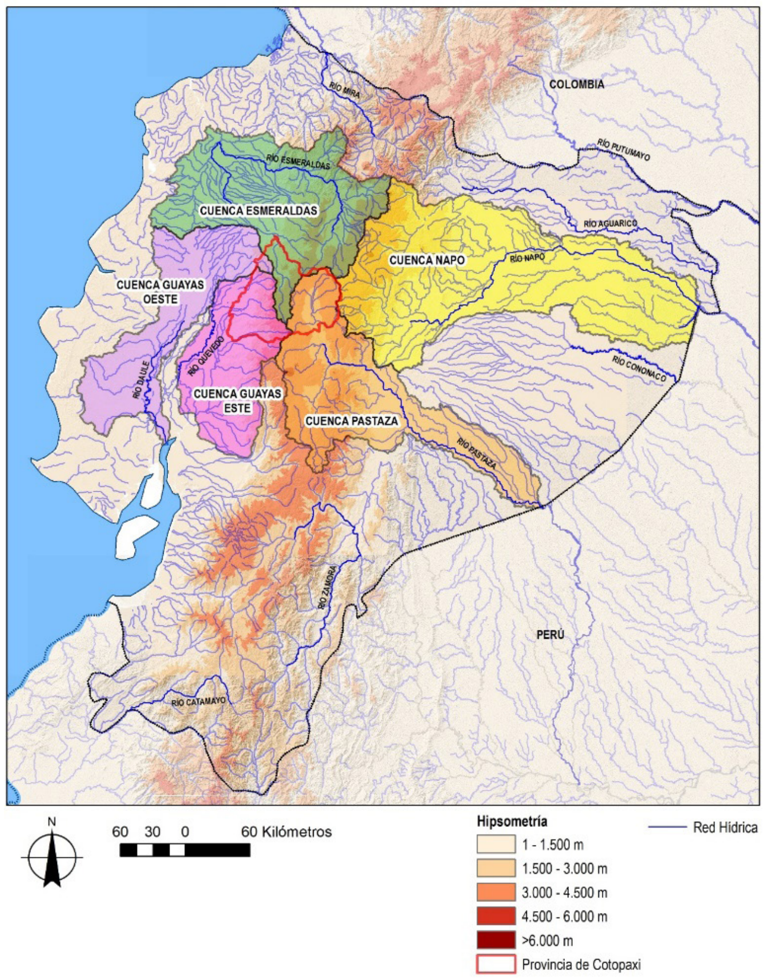

Figure 1. Watersheds in Cotopaxi. Source: Prepared by the authors using the NSI (National Secretariat of Information) (2020) and IGM (2020).

IV. RESULTS

According to the methodology described (phases 1 and 2), an extensive collection and analysis of information has been conducted to develop the "Multiscale analysis methodology regarding floods in urban and rural areas." This includes the factors involved in floods, problems, strategies or courses of action, and related administrative competencies (Contreras Velarde et al., 2021; Granda, 2023; Zevenbergen, Gersonius, & Radhakrishan, 2020; Libertun, 2023; Vega Aguilar, Malla Ceferino, & Bejarano Copo, 2020).

This methodology has allowed establishing interrelationships between scales and factors that influence floods in urban and rural inland areas. In this sense, four macro factors related to rainfall and river-related floods have been identified, which are further broken down into specific factors and problems. Similarly, strategies have been identified to counteract the adverse effects of potential floods and, finally, the administrative bodies responsible for the different scenarios. The results are detailed below:

Increased probability of occurrence and strength of hydrometeorological phenomena

As for the relationship between the scales and the specific factors that may contribute to floods (Figure 2), three of them exhibit a multiscale character. The factor "rapid melting of snow or ice in volcanoes and mountains" is an exception. This is related to the territorial scale (Figure 3) and the urban/rural scale (Figure 4) due to the magnitude and scope of the topographic elevations, whose climatic and meteorological data will be the same.

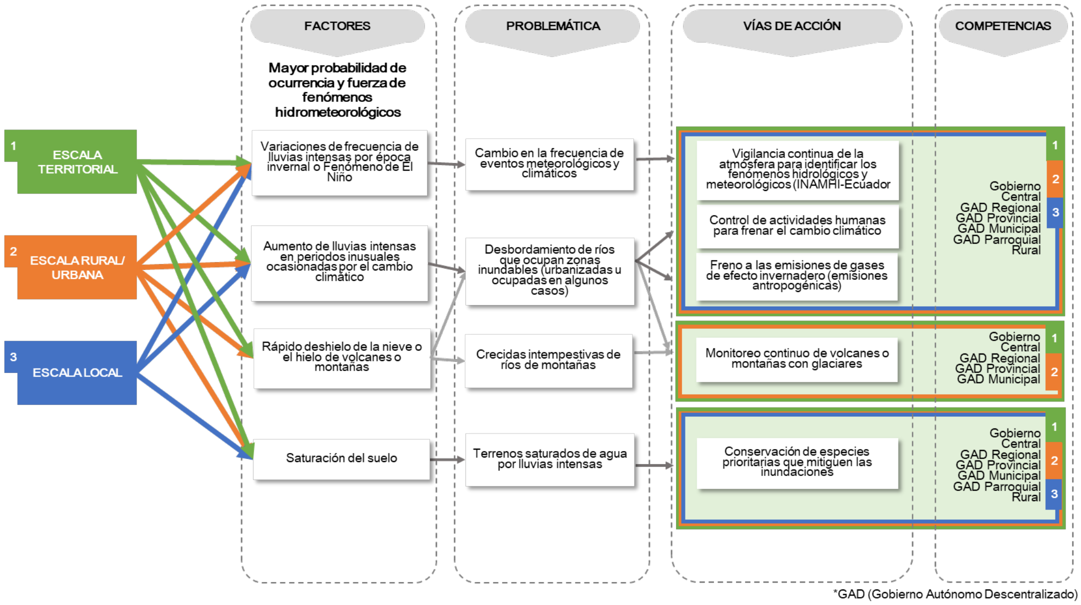

Figure 2. Multiscale factor-macro interrelation 1. Source: Prepared by the authors.

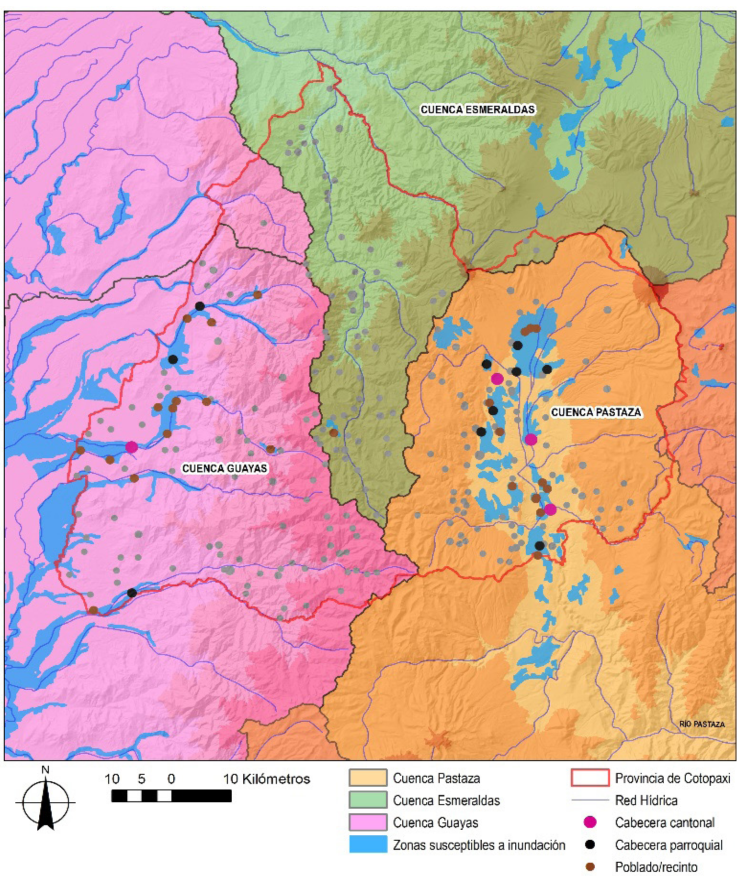

Figure 3. Urban and rural areas of Cotopaxi in areas susceptible to flooding (3 basins). Source: Prepared by the authors based on SNI (2020) and IGM (2020).

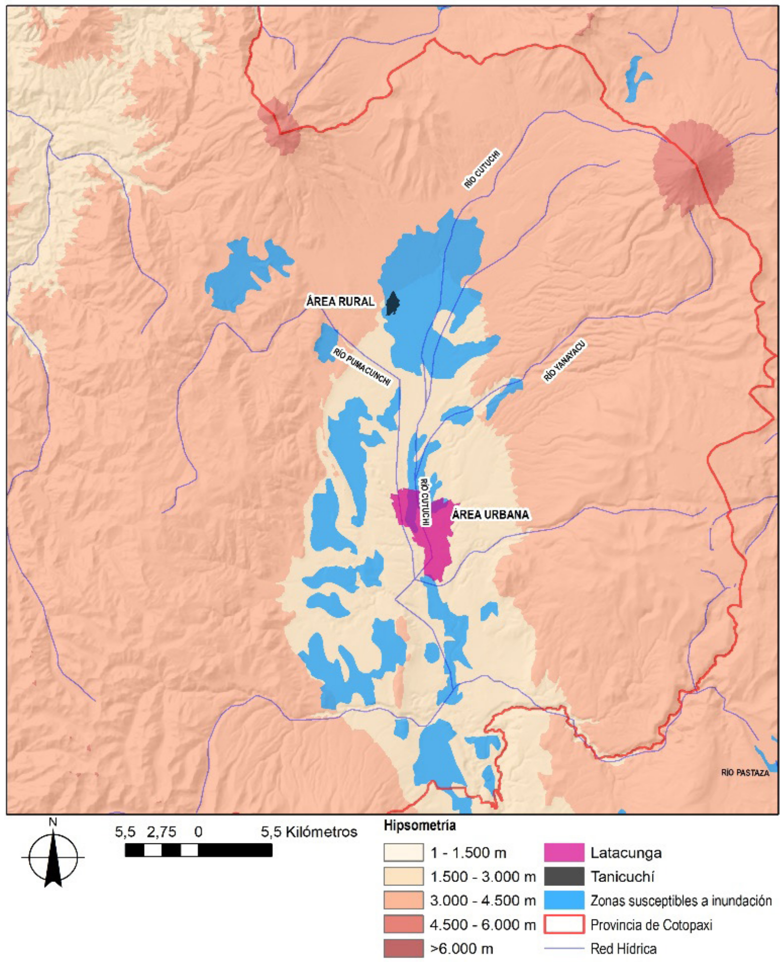

Figure 4. Latacunga and Tanicuchí. Source: Prepared by the authors based on SNI (2020) and IGM (2020).

Similarly, there are specific factors that share problems and, therefore, ways of action and competencies. For example, "rapid melting of snow or ice in volcanoes and mountains" has its own problem that refers to the "flash floods of mountain rivers", and another shared one, "overflow of rivers occupying flood zones". In this sense, relationships are dynamic and allow feedback between variables or characteristics. That is, the aforementioned factor has significant implications at the territorial and urban/rural scales, given the extent of topographic features such as volcanoes and mountains. Therefore, the consequences derived from the problems should be addressed jointly.

Change in land use and land cover

This factor, which affects floods, is the most representative of all the factors. Considering the specific flood factors, the urban/rural scale covers 7 of the 8 factors (Figure 5). Therefore, this scale is key to flood disaster risk management in urban and rural areas, indicating that actions to mitigate and reduce the vulnerability of affected areas should be timely, specific, and implemented from this level down to other related levels. Some specific factors also cover two scales, but in no case all three scales together. In any case, the actions of competent bodies to reduce flood risk should be coordinated and integrated. At the territorial scale, there are three specific flood factors, one of which is river degradation in the watersheds. Similarly, local-scale factors can be measured or observed in specific areas or delimited spaces, such as informal settlements, urbanized areas, urban river stretches, and specific public spaces. Finally, another important factor in the established relationship is the series of problems that arise from each flooding factor, highlighting management deficiencies in territorial planning and land occupation.

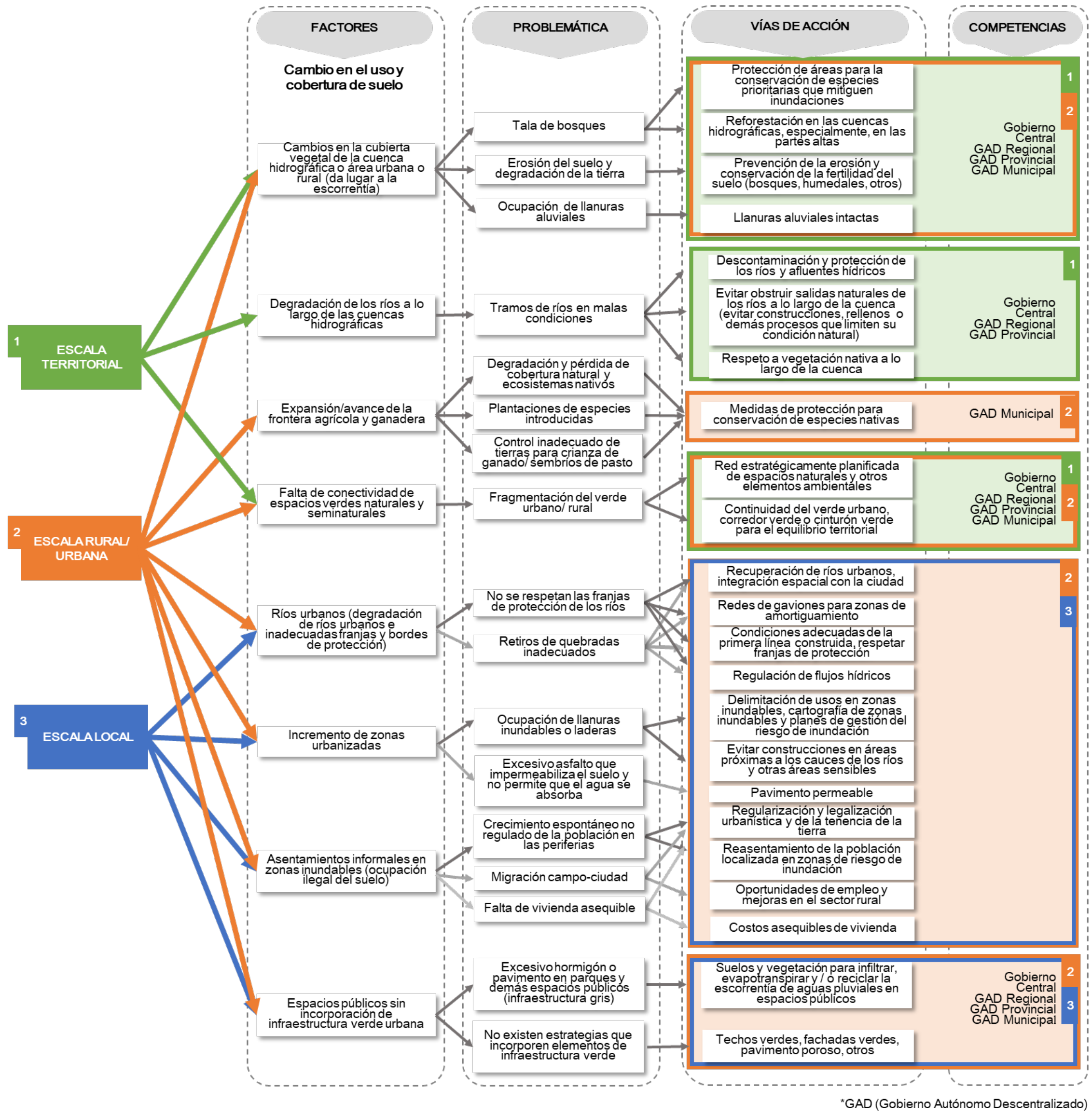

Figure 5. Multiscale factor-macro interrelation 2. Source: Prepared by the authors.

Failure in flood control hydraulic works

The specific factors equally relate to all three scales. The limitations and operational problems of the structures and hydraulic works would affect large expanses of land and specific local areas. Likewise, it has been demonstrated that there are multiple ways to address the problems posed by hydraulic structures in the short, medium, and long term, such as using non-structural measures to reduce the risk of flooding in urban and rural areas. These solutions represent a more economical and dynamic alternative to minimize the impact of this threat. Among them, emergency plans, risk mapping, territorial planning, and the implementation of early warning systems stand out. However, there is also a need for structural solutions that demonstrate their effectiveness and long-term sustainability.

Failure in the storm drain and sewer system

This macro factor is among the most common, especially in urban areas. It reflects the hydraulic insufficiency and structural failure of the sewer system. It also has particular problems and, at first glance, is easy to solve. However, in

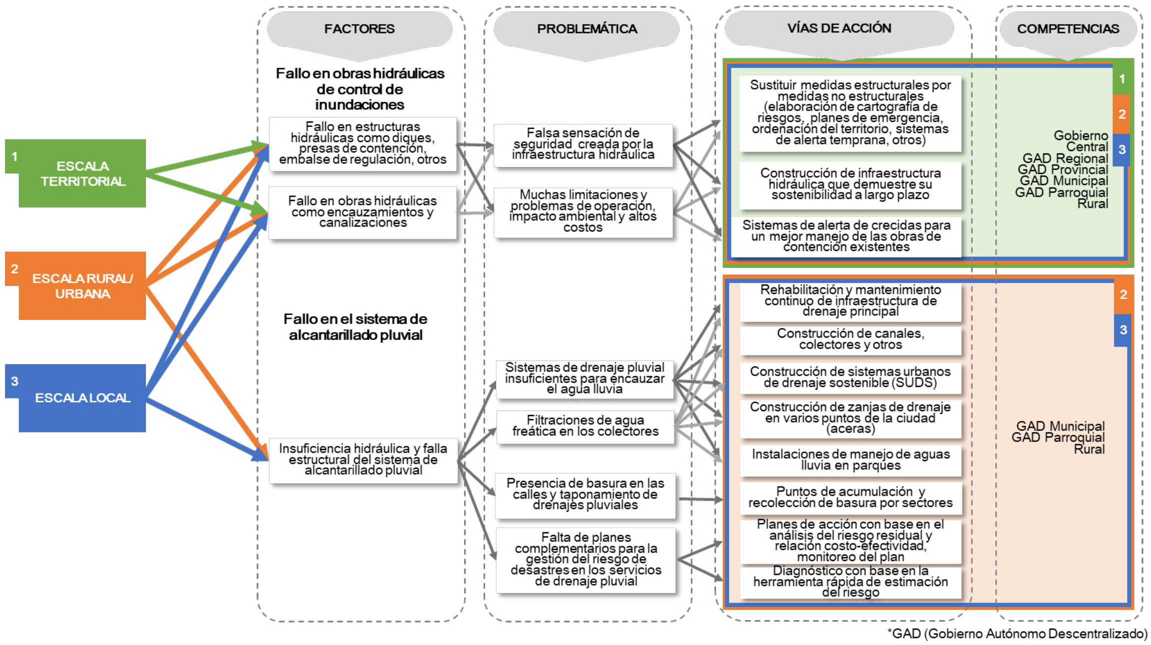

Figure 6. Interrelation of multiscale factors-macro 3 and 4. Source: Prepared by the authors.

most cities in Ecuador, there is inadequate planning and construction of storm drainage systems that are not adapted to sudden meteorological changes. Also, the use of nature-based solutions to support these conventional drainage systems is an emerging issue in the country.

Similarly, phase 3 of the methodology has allowed obtaining a multiscale characterization that covers both the territorial scope of Cotopaxi and the specific areas of Latacunga and Tanicuchí. In this sense, in Latacunga, the area affected by possible floods covers 4.23 km^2, resulting from the overlap between the urban area and areas susceptible to flooding. Damage from possible flooding occurs in the northern part of the urban area, where consolidated neighborhoods, facilities, and additional services are located. Latacunga has around 98,355 inhabitants, and the approximate population that would be affected is 22,272. Meanwhile, in Tanicuchi, the affected area is 1.15 km^2, and the areas susceptible to flooding cover 100% of the parish boundaries. Tanicuchí has 12,831 inhabitants, and the entire population would be affected.

Finally, in addition to serving as the basis for the multiscale methodology, when applying phase 2, regarding the analysis of regulations and technical instruments, five components of the Latacunga Development and Territorial Planning Plan have been reviewed to respond to the hypothesis raised. In this sense, what has been evidenced is that there is no comprehensive incorporation of disaster risk management in territorial planning instruments, and the different issues inherent to floods are not directly linked, such as green infrastructure, informal settlements, urban rivers, green public spaces, storm drains, non-structural solutions, etc. Hence, the bases for understanding floods in urban and rural areas of Cotopaxi are developed in isolation from one another. This is the case: floods are treated only to contextualize the threat; they are even relegated below volcanic threats.

V. DISCUSSION

Aragón-Durand (2014) notes that although floods also affect rural areas, the damage and losses can be greater in urban areas due to the high concentration of people, services, infrastructure, etc. These negative consequences can impact regional and even national development. In this study, the Latacunga urban area is affected by floods in the northern area, where consolidated neighborhoods, services, and important facilities are located, unlike the Tanicuchi rural area, which has different characteristics.

Similarly, the disappearance of wetlands, the rise in built-up areas, inadequate drainage, and other factors have caused major floods in urban areas during episodes of torrential rain. This phenomenon is embedded in the

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factor "Greater probability of occurrence and strength of hydrometeorological phenomena" and is one of the leading causes of floods, affecting all three scales. On the other hand, the factor "Change in land use and land cover" is decisive in floods and includes specific factors such as the advance of the agricultural frontier, changes in native vegetation cover in watersheds, and river degradation. The failure of hydraulic flood control works and the sewer system is also a structural issue with specific solutions. The latter is not planned for severe storms, since it is understood that it is more economical to assume and repair damage after a flood than to prevent it, an approach that has greater impacts and consequences.

In this sense, determining the origin of floods in urban and rural areas is essential to implement effective strategies, where structural and non-structural solutions are developed in a balanced way, fulfilling the premise that an integrated approach to flood management is a combination of measures that, taken as a whole, can be successful (Jha, Bloch & Lamond, 2012).

Hence, there is a need to perform a multiscale analysis to determine the consequences, implications, and actions in case of flooding. Some studies apply methodologies based on the evaluation of resilience indicators, to have a quantitative approach for the analysis of sustainability in urban space, that is, they are specific studies that do not contemplate several scales and evaluate issues such as public spaces and green areas, unlike this study that analyzes several factors involved in floods (Tumini, Arriagada Sickinger & Baeriswyl Rada, 2017).

VI. CONCLUSIONS

This research develops its own approach, the multiscale analysis methodology, for floods in urban and rural areas, which interrelates the factors involved across three scales: territorial, urban/rural, and local. The methodology has allowed identifying the origin of floods at different scales and, in turn, establishing specific problems, possible courses of action, and administrative competencies. It has also highlighted the direct relationship among all the scales and the importance of considering them holistically. It is essential to emphasize that the different problems, approaches, and competences result from an exhaustive analysis of the literature, regulations, existing studies, and related issues in urban and rural areas in the context of floods.

In this sense, four macro flood factors have been identified in urban and rural inland areas: 1. the highest probability of occurrence and strength of hydrometeorological phenomena, 2. the change in land use and land cover, 3. the failure of hydraulic flood control works, and 4. the failure of the storm drain and sewer system. Among the four macro factors, the one with the greatest impact across all three scales is land-use and land-cover change. This factor highlights several issues to be analyzed in the context of floods, including the expansion of the agricultural frontier, connectivity between natural and semi-natural spaces, informal settlements, urban rivers, and green public spaces. Likewise, the remaining three macro factors encompass a set of fundamental conditions for studying floods in urban and rural areas in an integrated way, thereby establishing responsibilities and attributions at each scale.

Finally, the territorial and multiscale vision is key to the effectiveness of the response to any emergency or disaster. This article questions the urgency of integrating disaster risk management and the study of the flood threat into territorial planning and land-use management through different scalar approaches to minimize risk and reduce the impact of floods in urban and rural areas, prioritizing, for this purpose, the use of nature-based solutions to mitigate floods.

VII. CONTRIBUTION OF AUTHORS CRediT:

Conceptualization, P. C.; Data curation; Formal analysis, P. C.; Acquisition of financing; Research, P. C., E. R., G. R.; Methodology, P. C., E. R., G. A.; Project management; Resources; Software; Supervision; Validation; Visualization; Writing – original draft, P. C.; Writing - proofreading and editing.

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