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Estudos em Ciências Agrárias e Ambientais

Eduardo Spers
(Organizador)

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PRÓLOGO

Os desafios contemporâneos relacionados ao uso dos recursos naturais, à conservação da biodiversidade, às mudanças ambientais e à sustentabilidade dos sistemas produtivos exigem abordagens cada vez mais integradas. Nas Ciências Agrárias e Ambientais, essa integração se torna especialmente relevante diante da necessidade de conciliar produção, conservação, desenvolvimento territorial e uso responsável dos recursos, considerando tanto os processos ecológicos quanto as dimensões sociais e econômicas envolvidas.

O oitavo volume de ***Estudos em Ciências Agrárias e Ambientais*** reúne quatorze capítulos organizados em quatro eixos temáticos: **Território, mudanças ambientais e conservação; Solo, biodiversidade e agroecossistemas sustentáveis; Produção sustentável, manejo e organização dos sistemas produtivos; e Economia circular, transformações ambientais e história da agricultura.** Em conjunto, os trabalhos propõem um percurso que parte de questões ambientais e territoriais amplas e avança em direção ao funcionamento dos agroecossistemas, às estratégias de produção sustentável e às transformações históricas das relações entre agricultura, recursos e paisagem.

O primeiro eixo reúne estudos voltados às mudanças ambientais, à vulnerabilidade territorial, à soberania alimentar e à conservação de áreas naturais. As análises destacam como clima, uso da terra, planejamento territorial, políticas de desenvolvimento e participação comunitária interferem diretamente na relação entre sociedade e ambiente. A vulnerabilidade de áreas costeiras diante da elevação do nível do mar, por exemplo, envolve não apenas fatores físicos, mas também infraestrutura, uso do solo, planejamento e capacidade adaptativa. Da mesma forma, a soberania alimentar é discutida a partir das disputas pelo território, pela terra e pela água e das diferentes formas de organização da produção rural.

No segundo eixo, o olhar se volta ao solo, à biodiversidade e ao funcionamento dos agroecossistemas. A agricultura regenerativa é apresentada como uma abordagem sistêmica voltada à recuperação da saúde e da funcionalidade do solo, com princípios relacionados à redução da perturbação, à cobertura permanente, à diversidade e à integração planejada entre componentes do sistema produtivo. Os estudos sobre fungos micorrízicos, bactérias rizosféricas e recursos fitogenéticos ampliam essa discussão ao abordar diferentes dimensões da biodiversidade e de sua importância ecológica. As interações entre organismos e solo, a participação de microrganismos nos processos de transformação da matéria orgânica e a conservação da diversidade vegetal evidenciam a relevância dos recursos biológicos para o funcionamento dos ecossistemas e para o desenvolvimento de estratégias de conservação e uso sustentável.

O terceiro eixo aborda diferentes estratégias de aprimoramento dos sistemas produtivos, considerando aspectos técnicos, ecológicos e organizacionais. São discutidas alternativas como a utilização de microrganismos benéficos para reduzir a dependência da fertilização mineral, o emprego de alimentos vivos na aquicultura, o comportamento e o manejo de bovinos autóctones em sistemas extensivos de montanha e formas coletivas de organização e comercialização entre pequenos produtores. Os trabalhos demonstram que a sustentabilidade da produção depende não apenas da eficiência no uso dos recursos, mas também da adequação das práticas de manejo, da conservação da paisagem e das condições de organização econômica e social dos produtores.

Por fim, o quarto eixo estabelece um diálogo entre aproveitamento de recursos, transformação ambiental e história da agricultura. O estudo sobre a utilização da casca de noz para a produção de carvão ativado examina os requisitos técnicos e de investimento associados à valorização de resíduos agroindustriais, em consonância com os princípios da economia circular. Os dois capítulos seguintes ampliam a perspectiva temporal ao investigar as relações entre agricultura, clima, desmatamento e transformações sociopolíticas nas terras baixas maias, bem como os conhecimentos, as tecnologias de manejo da água e as intervenções sobre a paisagem desenvolvidos no contexto da agricultura andina e inca. Em conjunto, esses trabalhos permitem considerar diferentes formas de utilização e transformação dos recursos naturais, desde experiências históricas de organização agrícola até propostas contemporâneas de valorização de materiais e processos produtivos.

A diversidade dos capítulos reunidos neste volume evidencia que os desafios ambientais e agrícolas contemporâneos não podem ser compreendidos de forma isolada. Solo, água, biodiversidade, território, produção, tecnologia e organização social constituem dimensões interdependentes de sistemas em constante transformação.

Ao integrar estudos sobre conservação, sustentabilidade, produção e história da agricultura, este volume contribui para ampliar o debate sobre formas mais equilibradas de relação entre sociedade, sistemas produtivos e ambiente, valorizando tanto a inovação científica quanto o conhecimento acumulado ao longo do tempo.

Boa leitura!

Eduardo Eugênio Spers

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CAPÍTULO 1

VULNERABILITY DUE TO RISING SEA LEVELS IN THE COLOMBIAN CARIBBEAN

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Johan Andrés Avendaño Arias
Instituto Geográfico Agustín Codazzi (IGAC)
Bogotá D.C., 111321
Bogotá D.C., Colombia
https://orcid.org/0000-0002-7193-2070

Leonardo Santana Bohorquez[1]
Instituto Geográfico Agustín Codazzi (IGAC)
Bogotá D.C., 111321
Bogotá D.C., Colombia
https://orcid.org/0009-0007-2070-5971

Ivan Dario Camacho Puerto
Instituto Geográfico Agustín Codazzi (IGAC)
Bogotá D.C., 111321
Bogotá D.C., Colombia
https://orcid.org/0009-0004-7211-4274

Gustavo Enrique Ramírez Gómez
Instituto Geográfico Agustín Codazzi (IGAC)
Bogotá D.C., 111321
Bogotá D.C., Colombia
https://orcid.org/0000-0002-5710-974X

ABSTRACT: The coastal systems of the Colombian Caribbean face various threats from climate change, including sea level rise (SLR), projected at 18 centimeters by 2040. This phenomenon, together with flooding, loss of ecosystems, and damage to infrastructure, increases vulnerability in coastal zones. This study evaluates the physical vulnerability to SLR in Cartagena, Coveñas, Ciénaga and Manaure, from the perspective of sensitivity and adaptive capacity. Factors such as building material, land use, road connection, public services, topography, and elements of adaptive capacity such as land use planning, resource performance, and infrastructure resilience were analyzed. Data on appraisals, cadastre, land use, economic activities and population were used, as well as the Land Management Plans and Municipal Development Plans. The results show that in Cartagena, 17,430 buildings are at risk, of which 2,187 are highly vulnerable. In Ciénaga, 1,892 properties are threatened, with 1,510 in very high vulnerability. In Coveñas, 1,027 buildings are exposed, of which 302 are highly vulnerable. In Manaure, 748 buildings are at risk, with 469 in very high vulnerability. In economic terms, it is estimated that losses associated with SLR would represent 36.5% of the total value of properties in Cartagena, 4.2% in Ciénaga, 37.5% in Coveñas and 31.7% in Manaure. The economic activities with the greatest number of properties exposed to SLR are residential, commercial, tourism, and institutional.

KEYWORDS: vulnerability; coastal flooding; climate change; cadastral; impacts; Colombian Caribbean.

[1] Corresponding author

VULNERABILIDAD ANTE EL AUMENTO DEL NIVEL DEL MAR EN EL CARIBE COLOMBIANO

RESUMEN: Los sistemas costeros del Caribe Colombiano enfrentan diversas amenazas derivadas del cambio climático, entre ellas el ascenso del nivel del mar (SLR), el cual para 2040, está proyectado ascienda 18 centímetros. Este fenómeno desencadenará inundaciones, que afectarán tanto los ecosistemas terrestres como la infraestructura existente incrementando así la vulnerabilidad de las zonas costeras. Este estudio se evaluó la vulnerabilidad física al SLR en los municipios de Cartagena, Coveñas, Ciénaga y Manaure, basado en la perspectiva de la sensibilidad y la capacidad de adaptación. Se analizaron factores como el material constructivo, uso del suelo, conexión vial, servicios públicos, topografía y elementos de la capacidad adaptativa como el ordenamiento territorial, la ejecución de recursos y la resiliencia de la infraestructura. Se utilizaron datos de avalúos, catastro, uso del suelo, actividades económicas y población, así como los Planes de Ordenamiento Territorial con el fin de evidenciar el impacto a nivel económico del SLR. Los resultados muestran que, en Cartagena, 17,430 edificaciones están en riesgo, de las cuales 2,187 presentan alta vulnerabilidad. En Ciénaga, 1,892 predios están amenazados, con 1,510 en muy alta vulnerabilidad. En Coveñas, 1,027 construcciones están expuestas, de las cuales 302 son altamente vulnerables. En Manaure, 748 edificaciones están en peligro, con 469 en muy alta vulnerabilidad. En términos económicos, se estima que las pérdidas asociadas al SLR representarían el 36.5% del valor total de las propiedades en Cartagena, el 4.2% en Ciénaga, el 37.5% en Coveñas y el 31.7% en Manaure. Las actividades económicas con mayor cantidad de predios expuestos al SLR son residencial, comercial, turística e institucional.
PALABRAS CLAVE: vulnerabilidad; inundación costera; cambio climático; catastro; impactos; Caribe Colombiano.

1. INTRODUCTION

Currently, coastal systems are particularly sensitive to phenomena associated with climate change such as sea level rise (SLR[2]), marine acidification, changes in sea surface temperature -SST- and coastal erosion (Hernández-Narváez et al., 2019; Martínez & Zavala, 2011) Among these, SLR is a phenomenon related to global warming produced by two main factors: thermal expansion and melting of glaciers and ice sheets (IDEAM, 2018; Sinha et al., 2023). Among its effects are the loss of urban and beach areas, ecosystem impacts, displacement of communities or changes in the distribution areas of species, impacts on infrastructure and economic activities, exacerbating vulnerability, poverty and local inequalities (IDEAM et al., 2017; Monsalves, Pincheira-Ulbrich, & Rojo 2013).

In the framework of the understanding of risk promoted by the Intergovernmental Panel on Climate Change -IPCC- (2014), sensitivity indicates to what degree and in what

[2] In a broader definition, SLR is the change in global or local sea level height on seasonal, annual, or longer time scales due to changes in ocean volume as a result of changes in the mass or density of ocean water, as well as changes in the shape of ocean basins and changes in the Earth's gravitational and rotational fields IPCC (2019).

way coastal systems, made up of institutions, people, economic activities, infrastructure or ecosystems, are affected by climate change, and particularly SLR. This concept, together with the adaptive capacity to respond, reduce and adjust to the affectations produced (IPCC, 2014), allows understanding the vulnerability of systems. Therefore, vulnerability is the predisposition of the system to be negatively affected due to its exposure[3], given mainly between sensitivity and adaptive capacity (IDEAM, 2017b). However, this concept has been approached from an economic, social, institutional and physical perspective, among others; placing it in a polysemic, multidimensional and multiscale concept as proposed by Michellier et al. (2020).

Considering the socioeconomic and environmental implications of SLR, vulnerability studies are valuable inputs for decision making in terms of adaptation, mitigation and knowledge management of climate change in coastal cities, as well as economic development and planning of these areas (Díaz-García et al., 2020). The Third National Climate Change Communication (Tercera Comunicación Nacional de Cambio Climático, TCNCC) of Colombia considers, based on projections of the Coupled Model Intercomparison Project Phase 5 (CMIP5) and the scenario of maximum greenhouse gas emissions (RCP 8.5), a rise in the average sea level of about 18 cm by 2040, 29 cm by 2070 and 40 cm by 2100. (IDEAM et al., 2017).

In the Colombian Caribbean, this scenario for 2040 implies the most critical flooding due to the rise in areas where strategic ecosystems such as mangroves and swamps are located (IDEAM et al., 2017b); as well as major and intermediate cities of the country's urban system, such as Barranquilla, Cartagena, Santa Marta, Riohacha, San Andrés, Turbo, Manaure, Ciénaga, Coveñas and Puerto Colombia: recognized as important demographic, economic and political-administrative nuclei on a national and regional scale. These coastal cities and communities currently face a wide range of challenges related to disaster events and climate change.

Studies on the impact of the SLR in the Colombian Caribbean are varied, including evaluations from a risk approach (Rangel-Buitrago & Posada-Posada, 2013; Hernández-Narváez et al., 2019); multidimensional analysis of vulnerability, for example, in its coastal dimension (García Echavarría, Alcántara-Carrió, & Jaramillo, 2022), political-administrative (Guardela Contreras, 2023) or in its infrastructure (Hamburguer Cárdenas & Ramírez Molina, 2023); as well as in the estimates of the impacts generated such as erosion (Echeverry & Marriaga, 2018); flooding and extreme waves (Orejarena-Rondón, 2019),

[3] According to IPCC (2014), exposure is the presence of people, livelihoods, species or ecosystems, environmental services and resources, infrastructure, or economic, social or cultural assets in locations that could be adversely affected.

loss of strategic ecosystems such as mangroves (Herrera Carmona et al. , 2024) and its effects on the tourism and hotel industry (Jaramillo Rodríguez, Mejía Ayala & Lamprea Quiroga, 2024).

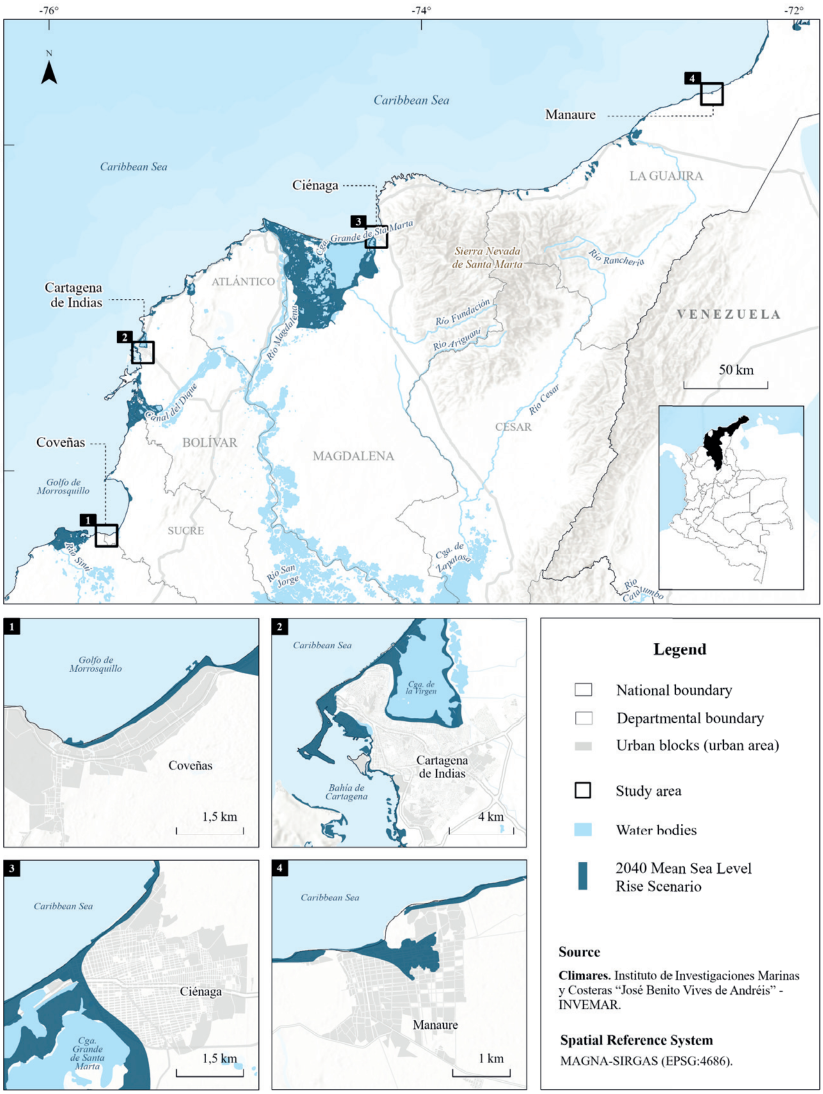
These studies as a whole show a high sensitivity of the Colombian Caribbean to SLR; however, there have been few studies involving the physical vulnerability of coastal areas based on the structural conditions of housing and the state of the environment. This is relevant because this region is exposed to hazards of hydrometeorological and hydroclimatic origin, which, in a combined effect with SLR, amplify their impact, such as storm surges, storms, strong winds and rains, floods and coastal erosion. In recent years, these hazards have brought emergencies with consequences in loss of housing and road infrastructure, displacement of people, effects on economic activities, social mobilization, among others (Mejía, 2024; El Informador, 2024; W Radio, 2023; Caracol Radio, 2020; Vivas, 2019; Torrado, 2018; El Colombiano, 2011; Semana, 2010).

To address physical vulnerability studies, cadastre information on architectural, physical and environmental characteristics and the use of buildings is a reliable, accurate and open source of information for the development of planning and adaptation strategies for SLR and risk scenarios (Van der Molen, 2009; Belmonte et al., 2011). In this sense, this article aims to identify the physical vulnerability caused by SLR in the year 2040 in four cities of the Colombian Caribbean coast: Cartagena de Indias, Coveñas, Ciénaga and Manaure. The article is organized in four parts. The first deals with the study area and the exposure scenario, followed by an explanation of the methodology, based on an understanding of vulnerability, as well as the variables, sources and calculations used. The third part presents the results of physical vulnerability and expected impacts. Finally, the fourth part delves into conclusions, discussions and future areas of research.

2. STUDY AREA

The study area covers four municipalities in the Colombian Caribbean, selected for their heterogeneous social dynamics, which allows different contexts to be addressed in relation to SLR. The following is a map showing the location of the municipalities (see Figure 1) and a presentation of each of them. Cartagena de Indias, located in the Colombian Caribbean, stands out as a tourist and strategic destination thanks to its seaport and the Cartagena refinery (COSALFA, n.d.). With a projected population of 1,059,626 people by 2024, it faces a housing deficit of 95,663 homes, and 43.6% of its inhabitants live in moderate poverty (Cartagena Cómo Vamos, 2023).

Figure 1. Location map of the municipalities.



Ciénaga, located in the department of Magdalena, faces multiple challenges related to its geographic location and socioeconomic conditions. Its exposure to flooding and tropical storms, together with the high incidence of poverty and limitations in basic services, aggravates its vulnerability to SLR. In addition, factors such as violence and internal displacement further aggravate the difficulties in the municipality (REACH Initiative, 2023).

Coveñas is in the Caribbean region and the Gulf of Morrosquillo, with a population of approximately 17,091 people (DANE, 2018), it faces serious limitations in terms of access to basic services, such as sewerage (28.8%) and natural gas (49.9%). Its economy depends mainly on tourism, manufacturing and fishing (Gobernación de Sucre, EPI, & Fondo Mixto para la Promoción de la Cultura y las Artes, 2023).

Finally, Manaure, in the region of Media Guajira, Colombia, has a population of 74,528 inhabitants (DANE, 2018), of which 8,032 reside in its urban area. Its economy is centered on salt production, artisanal fishing and a growing tourism (Alcaldía Municipal de Manaure, 2016).

The analysis of these municipalities is fundamental, as they represent contrasting realities where economic, social, environmental, physical vulnerabilities converge, as well as those related to the institutional capacity for their management. Their exposure to sea level rise (SLR), added to their structural and economic conditions, evidences the urgency of understanding how this phenomenon compromises their local dynamics and threatens their sustainable development strategies.

3. MATERIALS

To delimit the areas potentially exposed to sea advance and establish a baseline to assess the impact of SLR, the SLR projection generated for the Third National Climate Change Communication (TCNCC) was used, based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) projections and the high emissions scenario RCP 8.5 or inactions. This scenario, also known as climate inaction, projects a global sea level rise of approximately 18 cm by 2040 (IDEAM et al., 2017b).

Regarding population data, the spatial information of the blocks of the National Geostatistical Framework of the National Administrative Department of Statistics (Departamento Administrativo Nacional de Estadística, DANE) of the 2018 census was used. To estimate the possible economic losses of the properties, the current threatened uses and the physical sensitivity of vulnerable buildings, we used the cadastral data available from the Agustín Codazzi Geographic Institute (Instituto Geográfico Agustín Codazzi, IGAC), specifically for buildings, properties and physical homogeneous zones for the years 2020 to 2024, since they are an official source and also the most detailed source of real estate in the country.

In addition, data from the Municipal Performance Measurement Index, developed by the National Planning Department (Departamento Nacional de Planeación, DNP) for the year 2021, were used to evaluate the current capacities of the municipalities in the face of SLR. Documents such as Land Management Plans and Municipal Development Plans were also reviewed to construct a Municipal Adaptation Index, which made it possible to evaluate the capacities of the territories in the face of sea level rise.

4. METHODS

Two main approaches to climate change vulnerability assessment can be identified: outcome vulnerability, which focuses on residual impacts following adaptation processes (Kelly & Adger, 2000; O'Brien et al., 2007), and contextual vulnerability, which examines the current capacities of systems to cope with external pressures within contexts of social, economic, and environmental inequality (O'Brien et al., 2007). This study adopts the latter perspective because, as noted by Petrone-Mendoza et al. (2024), it allows the incorporation of structural factors that condition territorial responses to SLR.

The Fifth Assessment Report (AR5) of the IPCC (2014) establishes that climate risk results from the interaction among hazard, exposure, and vulnerability. Within this framework, vulnerability is defined as the *propensity or predisposition to be negatively affected* and includes two components: sensitivity and adaptive capacity (IPCC, 2014, p. 5). Following this conceptualization, the present study focuses exclusively on physical vulnerability, understood as the susceptibility of the built environment and buildings to sustain damage due to SLR.

To identify potentially affected areas, the official projection developed for the Third National Communication on Climate Change (IDEAM et al., 2017b) was used. It is based on CMIP5 projections under the RCP 8.5 scenario and estimates an increase of 18 cm by 2040. This layer constitutes the spatial reference for identifying buildings located in susceptible areas. All spatial procedures were carried out using geographic information systems (GIS).

The vulnerability formula is presented below, followed by a detailed description of each component of physical vulnerability.

$$Vulnerability\ to\ climate\ change = \frac{Sensibility}{Adaptative\ capacity}$$

To assess vulnerability, the values of each component were previously standardized on a common scale from 0 to 1, which ensured comparability between variables. Subsequently, the results were classified on an ordinal scale from 1 to 5, representing increasing levels of impact: very low, low, medium, high and very high. This classification was carried out using the quintile method.

4.1. SENSIBILITY

The IPCC (2014) defines sensitivity as the degree to which a system may be affected, either adversely or beneficially, by climate variability or change. In this study, physical sensitivity was operationalized using the Physical Homogeneous Zones (ZHF) developed by the Instituto Geográfico Agustín Codazzi (IGAC), which were used as an input for the physical and economic characterization of properties. ZHF allow areas with relatively homogeneous characteristics to be grouped and, consequently, differences among properties to be established according to their construction conditions and immediate surroundings (IGAC, 2024).

The estimation of physical sensitivity considered two components: the construction conditions of buildings and the physical and urban conditions of the immediate surroundings. The first was represented by the *Physical Conditions of Construction* (PCC) indicator, derived from the Construction Typification (TC), while the second was represented by the *Physical Conditions of the Environment* (PCE) indicator, derived from the last two digits of the ZHF code.

Physical Conditions of Construction (PCC)

ZHF are identified by a three-digit code. The first digit corresponds to the Construction Typification (TC), an ordinal classification ranging from 1 to 6 that differentiates buildings according to their construction, architectural, and material characteristics. In this study, this classification was used as an approximation of the construction conditions that may contribute to the physical sensitivity of properties to climate change-related effects. This assumption is consistent with the literature indicating that material and construction conditions can influence the susceptibility of buildings to climate and environmental hazards (IPCC, 2014; Rufat et al., 2015; Tate, 2013; Jha et al., 2021).

To incorporate this classification into the sensitivity index, the ordinal TC scale was transformed to an interval between 0 and 1 using min–max normalization. The scale was subsequently inverted to orient the indicator toward physical sensitivity. The expressions used were:

$$TC_{\text{norm}} = \frac{TC - TCmin}{TCmax - TCmin}$$

$$PCC_{\text{norm}} = 1 - TC_{\text{norm}}$$

where (TC) corresponds to the Construction Typification category assigned to the property, while TCmin and TCmax correspond to the lower and upper limits of the classification used. Thus, the transformation can be expressed directly as:

$$TC_{\text{norm}} = \frac{TC - 1}{6 - 1}$$

The first expression transforms the original TC scale to an interval between 0 and 1, while the second reverses its orientation so that higher PCC values represent relatively less favorable construction conditions and, therefore, greater physical sensitivity.

Consequently, a category of TC=1 obtains a PCC value of 1, whereas a category of TC=6 obtains a PCC norm value of 0. Thus, the transformation preserves the order of the original classification while reversing its orientation so that higher values represent higher relative levels of sensitivity.

This transformation does not imply that differences between TC categories represent linear differences in physical sensitivity. Its purpose is to standardize and orient the classification for incorporation into the composite index. Therefore, PCC is interpreted in relative terms within the construction-condition classification used by the ZHF.

Physical Conditions of the Environment (PCE)

The second component corresponds to the physical and urban conditions of the property's immediate surroundings. This component was derived from the second and third digits of the ZHF code, which represent the classification assigned to the conditions of the surrounding environment.

Based on this coding, the Physical Conditions of the Environment (PCE) indicator was constructed. Since the values of this classification are coded from 00 to 99, min–max normalization was applied over the complete range:

$$\boldsymbol{PCE_{\text{norm}} = \frac{PCE - 0}{99 - 0}}$$

where (PCE) corresponds to the value formed by the last two digits of the ZHF code. The transformation allows the values of this classification to be expressed on a common scale between 0 and 1 while preserving their relative position within the range used. Thus, the lowest and highest classification values are located at the lower and upper ends of the normalized scale, respectively.

The transformation does not seek to assign an absolute physical meaning to the numerical difference between categories, but rather to rescale the existing coding so that it can be compared with the construction-condition indicator. Therefore, PCE norm is interpreted in relative terms and according to the environmental classification established in the ZHF.

Finally, the construction-condition and environmental indicators were integrated to obtain the physical sensitivity index (S). An equal weight was assigned to each component, considering that construction conditions and environmental conditions represent complementary dimensions of physical sensitivity:

$$S = 0.5 \cdot PCC_{\text{norm}} + 0.5 \cdot PCE_{\text{norm}}$$

Thus, the (S) index ranges from 0 to 1, where higher values represent higher relative levels of physical sensitivity, derived from the combination of the construction and environmental conditions characterized through the ZHF.

This procedure simultaneously integrates construction conditions and immediate environmental conditions, allowing relative differences in physical sensitivity associated with the material and urban conditions of properties and their surrounding areas to be identified. Given the absence of a standardized methodology for establishing differentiated weights between these two components, an equal weighting of 0.5 was adopted for each component, without assigning greater influence to either dimension in the absence of a specific empirical basis.

4.2. CAPACITY ADAPTATIVE

Adaptive capacity is defined as “the ability of systems, institutions, humans and other organisms to adjust to potential damages, take advantage of opportunities or respond to consequences” (IPCC, 2014, p. 1758). In this study, adaptive capacity was characterized using the Municipal Development Measurement Index (MDM), prepared by the National Planning Department. The MDM provides standardized information on municipal management and institutional performance, allowing differences in the capacities available at the municipal level to be incorporated into the vulnerability assessment.

The analysis focused on the Management component of the MDM, which includes aspects related to the mobilization of own resources, budget execution, open government and transparency, and the use of land-use planning tools (Table I). These aspects provide a general characterization of the institutional and management conditions that may support the capacity of municipalities to respond to external pressures.

Because the MDM reflects conditions observed during the reference period, it was used as a baseline of municipal adaptive capacity rather than as a projection of future institutional conditions. The study therefore does not attempt to predict the decisions, investments, or adaptation measures that municipalities may implement by 2040, as these cannot be established from the projected SLR scenario. Instead, the analysis combines the projected 2040 SLR scenario with the best available characterization of current municipal capacities.

Municipal Development Measurement Index

The MDM, prepared by the National Planning Department, measures municipal performance in terms of management and development. In this analysis, priority was given to the Management component, whose specific characteristics are detailed in Table I.

Table I. Aspects Evaluated in the MDM.

Aspect Evaluated	Description
Mobilization of own resources	Assessment of resources generated at the municipal level through taxes such as property tax or valuation and their investment.
Execution of budgeted resources	Measures the efficiency in executing the budget allocated to municipal projects.
Open government and transparency	Evaluates activities related to citizen services, transparency, and participatory accountability.
Use of land-use planning tools	Analyzes how the administration uses planning instruments to generate revenue, such as urban planning.

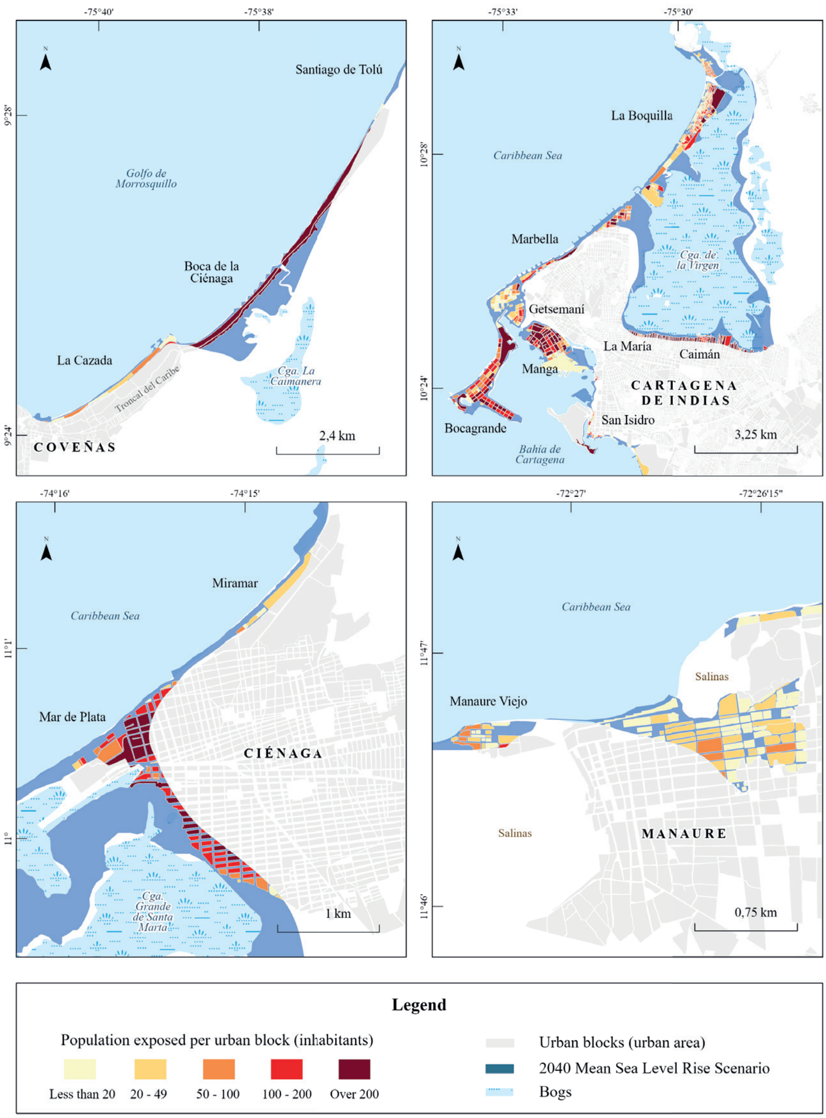
Accordingly, the MDM was used to characterize municipal adaptive capacity from an institutional and management perspective. The resulting assessment should be interpreted as a representation of the capacities available during the reference period under the projected 2040 SLR scenario, rather than as a prediction of future municipal capacity.

5. RESULTS

5.1. SOCIOECONOMIC AND PHYSICAL EXPOSURE TO SLR

5.1.1. Population exposed to SLR

Figure 2. Population per block exposed to SLR 2040.



Note. Own elaboration with data from DANE, National Population and Housing Census 2018.

Figure 2 shows the distribution of population density in each city. In Cartagena, the neighborhoods south of the Ciénaga de la Virgen, as well as Bocagrande and Manga, have high densities, reaching up to 860 people per block. In Ciénaga, density is higher in the central core, particularly in commercial areas, and decreases towards the peripheries. In Coveñas, the peripheral areas along the tourist axis show higher density, while the municipal core has a lower density. Manaure, on the other hand, has a moderate and dispersed density without significant population concentrations.

According to Table II, the proportion of population exposed to SLR projected for 2040 varies among the municipalities analyzed. Manaure has the highest percentage of exposed population with 21.6%. It is followed by Coveñas, with 19.8% of its population exposed. In Ciénaga, the percentage is lower, reaching 13.8%. Cartagena, despite having the largest total population, has the lowest percentage, with 9.1% of its population at risk.

Table II. Exposed urban population in relation to the total.

Municipality	Exposed population	Total urban population	Percentage of exposed people
Coveñas	2,377	11,993	19.8%
Ciénaga	15,057	109,106	13.8%
Manaure	2,448	11,334	21.6%
Cartagena	78.844	868.657	9.1%

Note. Prepared by the authors with data from DANE, National Population and Housing Census 2018.

5.1.2. Exposure of Constructions to SLR

According to the analysis of buildings exposed to SLR projected for 2040, presented in Table V, Coveñas stands out with the highest percentage of exposed buildings, reaching 34.5% of its infrastructure at risk. It is followed by Manaure with 26.0%, while Ciénaga and Cartagena present lower percentages, with 7.9% and 7.8%, respectively. These data underscore the variability in the structural vulnerability of the municipalities with respect to the projected SLR. In addition, in terms of building density, a pattern of concentration toward urban centers is observed, while the peripheries show a more dispersed distribution.

Table III. Number of urban buildings exposed in relation to the municipal total.

Municipality	Exposed buildings	Total buildings	Percentage of exposed buildings
Coveñas	2,033	5,891	34.5%
Ciénaga	1,892	24,037	7.9%

Municipality	Exposed buildings	Total buildings	Percentage of exposed buildings
Manaure	695	2,677	26.0%
Cartagena	17.430	223.237	7.8%

Note. Prepared by the authors with cadastral information from IGAC (2020-2023).

Table VI shows the number of buildings exposed to SLR projected for 2040 by neighborhood in Cartagena de Indias. It is observed that the neighborhoods with the most exposed buildings are Manga (3,957), La Boquilla (3,024) and Bocagrande (2,544), while those with the least number of exposed buildings are La María (4) and San Isidro (1). Although complete information was not available for other municipalities, it was decided to present this analysis at the neighborhood level for Cartagena to demonstrate how the available data allows for a detailed spatial analysis.

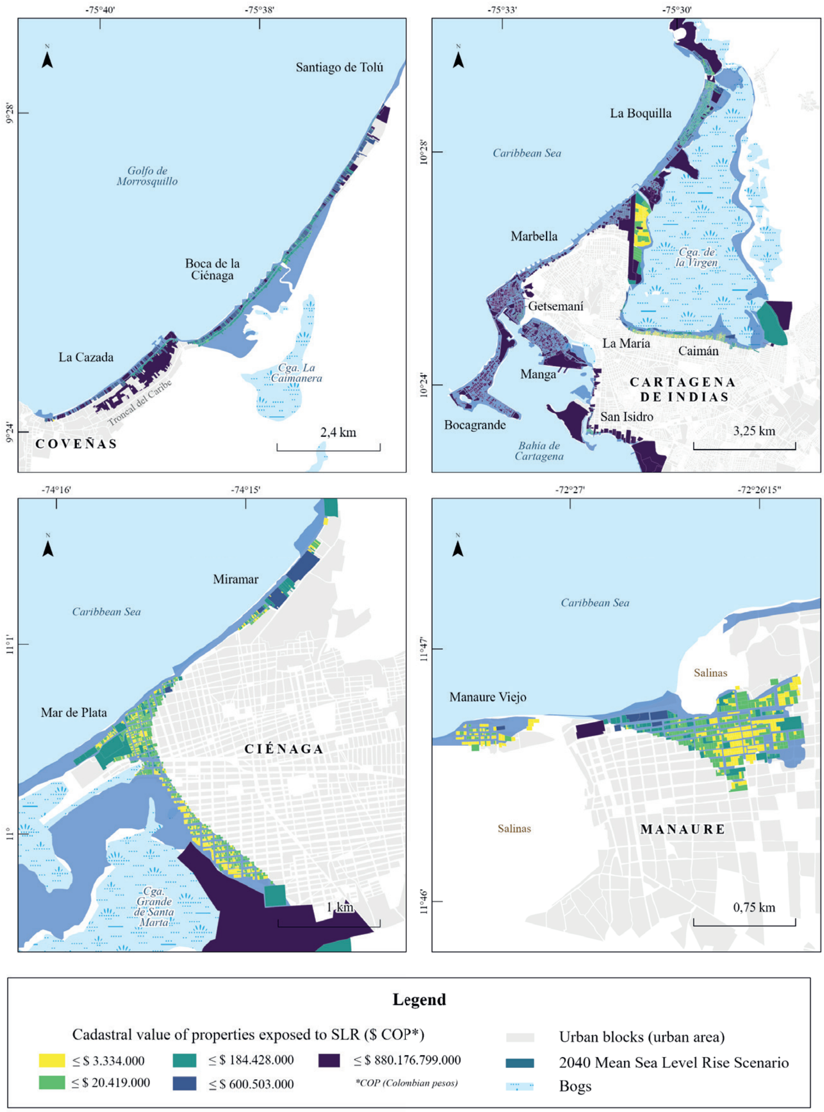
Table IV. Number of buildings exposed by neighborhood in Cartagena de Indias.

Neighborhood	**Number of Buildings**	**Neighborhood**	**Number of Buildings**
Manga	3,957	Olaya St. Central	208
La Boquilla	3,024	El Laguito	207
Bocagrande	2,544	El Cabrero	145
Centro	924	Pasacaballos	81
Getsemaní	915	Punta Arenas	73
Castillogrande	852	Leticia	69
Crespo	671	Olaya St. Progreso	56
San Diego	650	Zona Industrial	54
Olaya St. Rafael Núñez	435	Punta Canoa	41
República del Líbano	404	Albornoz	31
Arroyo de Piedra	304	Olaya St. Playa Blanca	23
La Matuna	277	Olaya St. La Puntilla	11
El Bosque	263	Fredonia	10
Marbella	254	La Esperanza	4
Boston	245	La María	4
Olaya St. Ricaurte	243	Olaya St. Zarabanda	1
Olaya St. 11 de Noviembre	214	San Isidro	1
La Candelaria	212		

Note. Prepared by the authors with cadastral information from IGAC (2020-2023) and MIDAS data from the Mayor's Office of Cartagena.

5.1.3. Economic estimation of losses of properties exposed to SLR

Figure 3. Cadastral value of properties exposed to SLR.



Note. Own elaboration with cadastral information from IGAC (2020-2023).

Figure 3 shows the distribution of cadastral values in the four study cities. In Cartagena de Indias, the properties with the highest cadastral values are located mainly along the coast, which is explained by the interaction of human activities with the sea. In these areas, tourism, hotel, recreational, institutional and port activities, among others, are developed. In contrast, in the southern zone of the Ciénaga de La Virgen, human settlements have lower cadastral values compared to the areas previously analyzed, and residential uses predominate.

In Ciénaga, the distribution of cadastral values varies among the lower property value classes, showing a slight downward trend towards recently developed urban areas. For Coveñas, cadastral values are distributed along the coastline, which can be attributed to the attractiveness of its tourist zones and the boost that the sector has had in this area. Finally, in Manaure, there is a concentration of the highest cadastral values in the center of the municipality, corresponding to the most consolidated area, while values decrease towards the peripheries in the process of growth.

Table V is key in showing the economic value of areas potentially threatened by SLR in the cities analyzed. This information provides an estimate of the possible economic losses, both of land and buildings. It is important to note that the cadastral appraisals provided by the IGAC, based on its methodology, do not exceed 60% of the commercial value of the properties, which indicates that the real economic impact could be greater than that estimated in this analysis.

Table V. Cadastral value of land potentially exposed to SLR by 2040.

City	Total Appraisal (COP)	Appraisal of Land Exposed to SLR (COP)	Percentage (%)
Cartagena de Indias	28.35 trillion	10.36 trillion	36.5
Coveñas	536.91 billion	201.50 billion	37.5
Ciénaga	296.24 billion	12.38 billion	4.2
Manaure	28.33 billion	8.98 billion	31.7

Note: Prepared by the authors with cadastral information from IGAC (2020-2023).

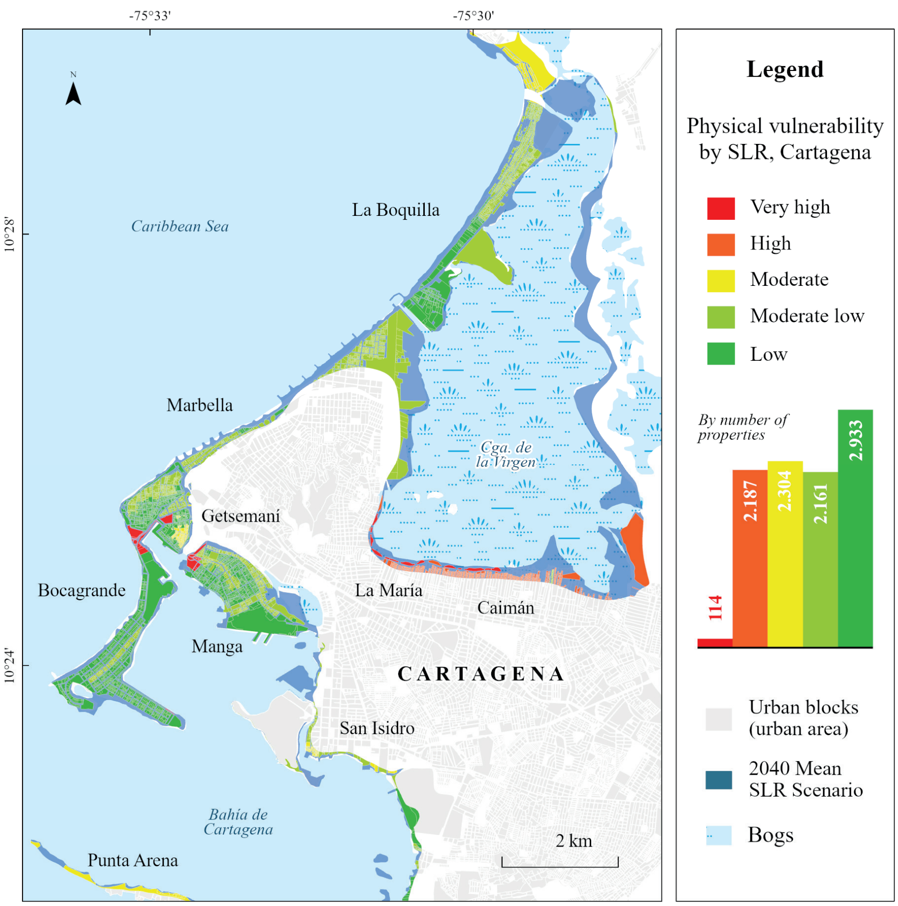
5.2. PHYSICAL VULNERABILITY DUE TO RISING SEA LEVELS

5.2.1. Cartagena de Indias

The analysis of physical vulnerability to SLR in the municipality reveals that 9,699 properties (6.1%) are at risk. As shown in Figure 4, most of the settlements near the coastline have low or moderate-low vulnerability. This is attributed to their older urban consolidation, which gives them better coverage of public services, road infrastructure and an important economic activity linked to tourism and the seaport. However, isolated cases of high vulnerability were identified in sectors such as La Boquilla and Manga, possibly linked to inconsistencies in cadastral assignments.

In contrast, the southern zone of the Ciénaga de La Virgen is highly vulnerable due to precarious construction conditions, the absence of land use regulations, limited access to basic services, and poor road infrastructure. In addition, a significant number of highly vulnerable properties are concentrated in Punta Arena, on the island of Tierra Bomba. In terms of Cartagena's SLR capacities, the city shows a relatively high level, especially in the area of open government and environmental transparency, with 88.76 out of 100 points. However, the weakest aspect is land use planning, where the city scores 53.74 points.

Figure 4. Map of physical vulnerability to SLR in Cartagena de Indias.



In relation to the impact of sea level rise (SLR) on the different economic destinations, Table VI indicates that residential properties will be the most affected in Cartagena, they also represent the largest number of properties in very high vulnerability (61 properties), in addition to constituting a significant proportion of the areas of low and moderate vulnerability on the coastline. Undeveloped urban lots represent the second most affected economic destination, concentrating the largest number of properties with a high degree of vulnerability. Commercial activity occupies third place in terms of impact, with the majority of properties classified at low to moderate vulnerability levels.

Table VI. Vulnerable buildings according to their economic destination [4] – Cartagena de Indias.

Economic Purpose	Vulnerability					General total
	Low	Moderately Low	Moderate	High	Very High	
Residential	1137	1053	1903	889	61	5043
Industrial	43	6	1			50
Commercial	583	314	45		6	948
Agricultural	3	13	27	9		52
Cultural	1		2			3
Recreational	3	3		2	1	9
Health	1	5				6
Institutional	26	16	6		2	50
Educational	37	26	9	1	1	74
Religious	245	328	113	82	23	791
Livestock	1					1
Forestry		2	1			3
Public Use	21	7	2	3	5	38
Special Services:	1		1			2
Developable Lot Not Urbanized	66	22	108	1188	10	1394
Urbanized Lot Not Built	7	3	8	8		26
Non-Developable Lot	1	2	1		1	5
General Total	2176	1800	2227	2182	110	8495

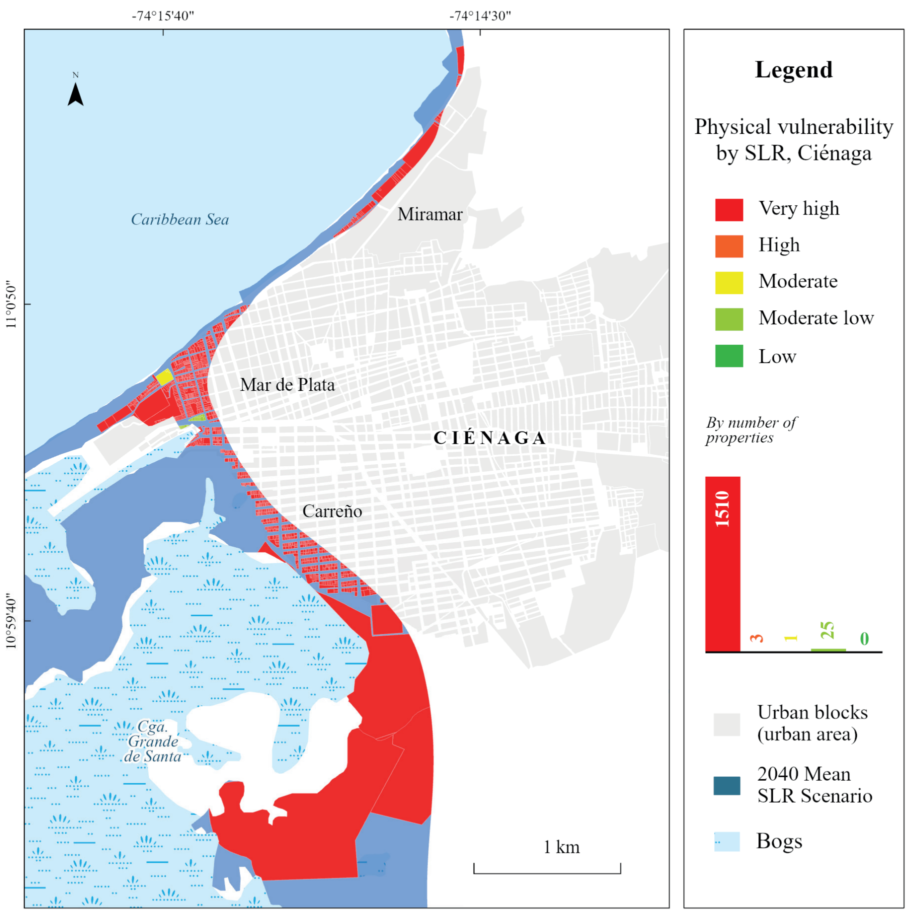
5.2.2. Ciénaga

Figure 5 shows a marked predominance of areas with very high physical vulnerability. This territory is characterized by buildings with low structural quality, which translates into limited resistance to environmental and climatic factors, such as flooding. In addition, these areas face insufficient coverage of basic public services, particularly

[4] The economic destination is the classification for statistical purposes given to each property as a whole -land, constructions or buildings-, at the time of property identification in accordance with the predominant activity carried out therein (IGAC, 2021).

sanitation, together with an absence of urban planning and a deteriorated and poorly functional road infrastructure. These conditions are aggravated by a low adaptive capacity (35.06). This score reflects significant limitations in key areas: the mobilization of own resources (16.27) reflects low fiscal autonomy, restricting investment in adaptation; in open government and transparency (10.84), deficiencies in management and participation affect response capacity; and in territorial planning (38.63), the limited use of planning tools hinders risk mitigation.

Figure 5. Map of physical vulnerability to SLR in Ciénaga.



La Table VII reveals that the use most affected by SLR vulnerability is residential, with 1,446 properties classified in the highest impact category. In second place are undeveloped urbanized lots, with 29 properties showing high vulnerability. This distribution reflects a low economic diversity in the area, since vulnerable plots associated with other uses, such as commercial, recreational or industrial, represent a significantly lower proportion.

Table VII. Vulnerable buildings by economic destination - Ciénaga.

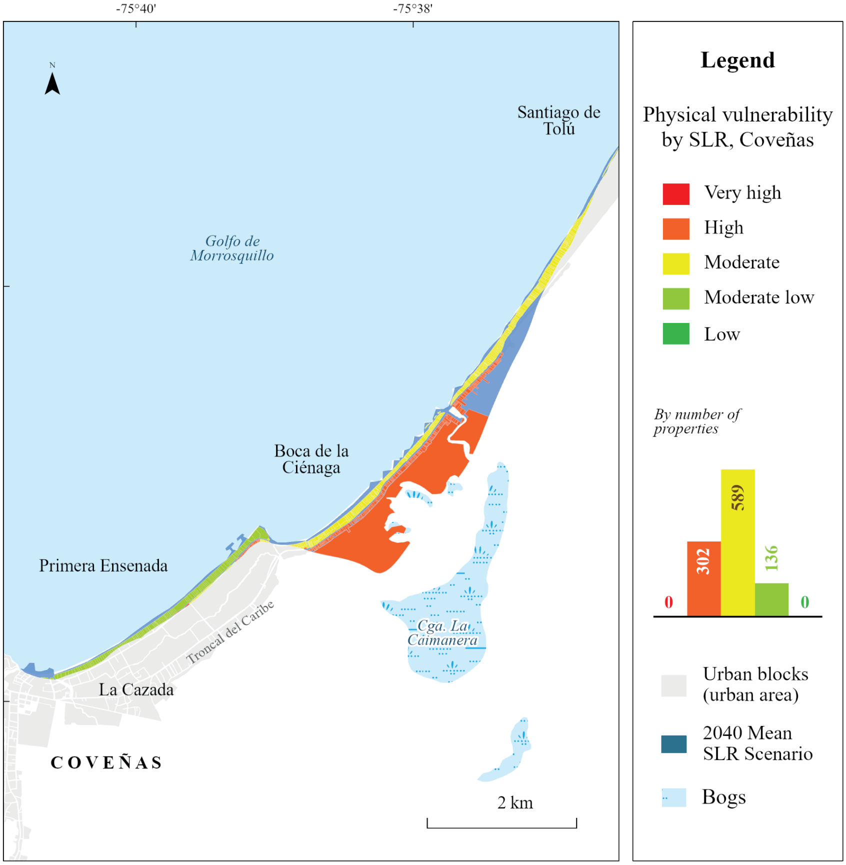
Economic Purpose	Vulnerability					General total
	Low	Moderately Low	Moderate	High	Very High	
Residential		22	1	2	1446	1471
Commercial		3			9	12
Agricultural					13	13
Recreational					9	9
Health					1	1
Educational					2	2
Developable Lot Not Urbanized					17	17
Urbanized Lot Not Built				1	29	30
General Total		25	1	3	1526	1555

5.2.3. Coveñas

In Coveñas, of a total of 1,027 vulnerable properties, 589 have a moderate degree of vulnerability, 302 have a high degree of vulnerability, and 136 have a low moderate degree of vulnerability. The greatest vulnerability is identified in the peripheral areas, where public service coverage is incomplete and the road infrastructure is characterized by unpaved or narrow roads of less than 4 meters. Houses in these areas are usually built with basic materials such as wood, brick or prefabricated, with zinc or tile roofs, and their finishes are simple. Unexpectedly, the properties adjacent to the coastal strip exhibit less vulnerability compared to those located further inland, attributable to the boost in tourism development, which has favored better infrastructure and service conditions, thus strengthening their capacity to adapt to SLR.

In the central core of the municipality, vulnerability is moderately low, associated with a more robust infrastructure, better established basic and complementary services, and greater economic diversity due to the presence of mixed uses.

Figure 6. Map of physical vulnerability to SLR in Coveñas.



According to economic activity, Table VIII shows residential use as the most impacted, with 456 properties classified in a moderate degree of vulnerability and 265 in a high degree, evidencing the risks faced by households in Coveñas. Recreational activity, with 107 properties in moderate vulnerability and 21 in high vulnerability, reflects the exposure associated with tourism development in coastal areas. For its part, the institutional activity registers 21 properties in high vulnerability, highlighting the threat to critical infrastructure.

Table VIII. Vulnerable buildings according to their economic destination - Coveñas.

Economic Purpose	Vulnerability					General total
	Low	Moderately Low	Moderate	High	Very High	
Residential		103	456	265		824
Commercial		1	2	1		4

Economic Purpose	Vulnerability					General total
	Low	Moderately Low	Moderate	High	Very High	
Agricultural				1		1
Recreational		4	107	21		132
Institutional			2	21		23
Forestry			1			1
Public Use		1				1
Urbanized Lot Not Built			8	1		9
No Information		27	16	1		44
General Total		136	592	311		1039

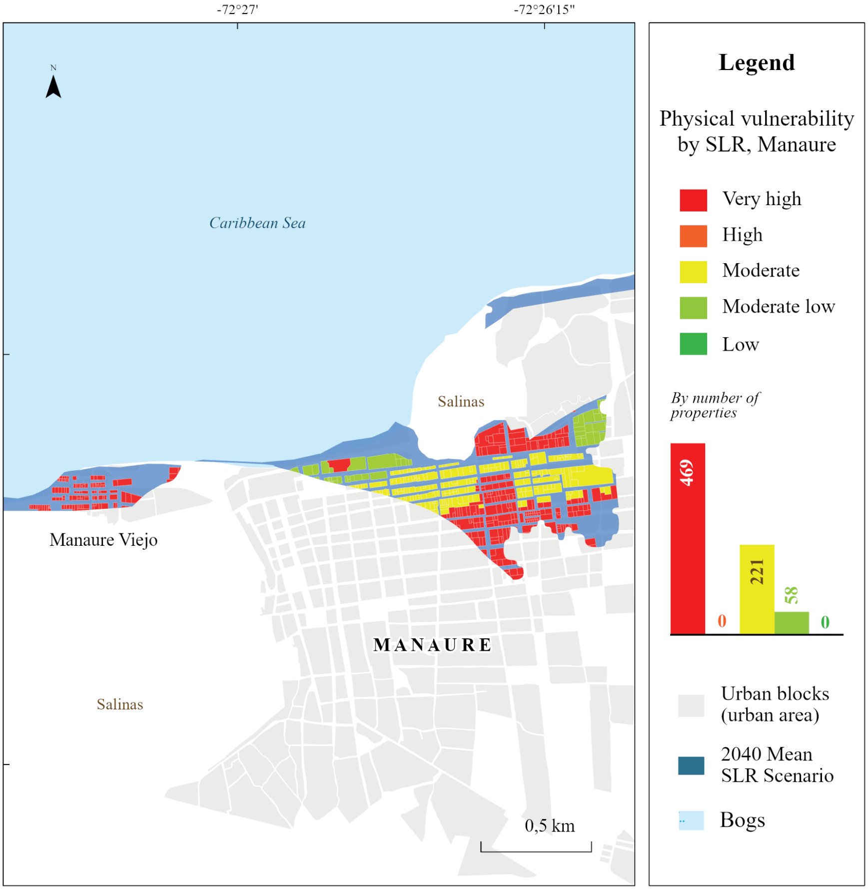
5.2.4. Manaure

Vulnerability in this municipality reflects that 469 properties present a very high vulnerability, mostly concentrated in the periphery of the municipal core. These properties are characterized by their unplanned construction, the use of precarious materials, their location in marginal areas with incomplete basic services and unpaved roads. On the other hand, 221 properties show moderate vulnerability, corresponding to brick or block buildings with simple finishes, which have basic and complementary services, as well as paved roads. In the central core, there are more consolidated areas, with better infrastructure conditions, basic and complementary services, paved roads, and buildings with facades classified as regular, built with brick or block walls and concrete slab or asbestos cement tile roofs. These properties have a low moderate vulnerability, with a total of 58 cases.

In terms of adaptive capacity, the municipality's performance can be considered moderate, standing out in aspects such as transparency (66.67) and resource execution (62.31). However, its main weakness lies in the mobilization of resources, both tax and non-tax, with a significantly low value of 2.65.

Minor inconsistencies were identified in the assignment of scores in the eastern peripheral zone of the municipality, where some cases classified as moderate-low and moderate-moderate vulnerability should correspond to high or very high. In a future phase, it is intended to improve the calculation method to automatically detect and correct these discrepancies, ensuring that the information can be used as a reliable and accurate planning. tool.

Figure 7. Map of physical vulnerability to SLR in Manaure.



La Table IX reveals that residential properties show the highest concentration of vulnerability, with 479 properties in high vulnerability, 150 in moderate and 32 in moderate low, suggesting deficiencies in construction quality and urban infrastructure. Undeveloped developable lots also show significant vulnerability, with 78 properties in very high and 66 in moderate, reflecting the absence of urbanization evidenced by the lack of access to basic services such as potable water, sewerage and paving. On the other hand, industrial, commercial, recreational, educational, religious and public uses present low vulnerability, with few cases in each grade, indicating less exposure to risks.

Table IX. Vulnerable buildings according to their economic destination - Coveñas.

Economic Purpose	Vulnerability					General total
	Low	Moderately Low	Moderate	High	Very High	
Residential		32	150		479	661
Industrial		1				1
Commercial		2	2		1	5
Agricultural			1			1
Recreational			1			1
Health		5	1			6
Educational		1			1	2
Religious		1				1
Public Use					1	1
Developable Lot Not Urbanized		16	66		78	160
Urbanized Lot Not Built					1	1
No Information					7	7
General Total		58	221		568	847

6. DISCUSSION

In Colombia, several studies have addressed vulnerability to SLR. Gallego and Selvaraj (2019) analyzed the vulnerability of the coastline in Buenaventura, considering factors such as sea level rise, coastal morphology, and land use. Hernández-Narváez et al. (2019) examined the impacts of sea level rise and coastal erosion in the coastal region, focusing on food security, human habitat, and infrastructure, under the IPCC framework. Restrepo-Ángel et al. (2021) highlighted that geological subsidence in Cartagena intensifies the effects of sea level rise. This research contributes significantly to the field by conducting a prospective assessment of the physical vulnerability of real estate and urban structures to SLR.

Regarding the results, it was estimated that in Cartagena 78,844 people and 17,430 urban buildings are exposed to SLR, figures that differ from those reported by Invemar et al. (2014), which identify 117,624 vulnerable people. This variation may be due to the fact that the Invemar study includes, in addition to SLR, flooding due to heavy rainfall, which expands the areas analyzed. While Invemar highlights neighborhoods such as Olaya Herrera, Nuevo Paraíso, El Pozón, Bocagrande and República del Líbano, this study highlights Manga, La Boquilla, Bocagrande, Centro and Getsemaní (see Table VI). These differences could be explained by the use of different SLR projections, since Invemar considers an increase of between 15 and 20 centimeters for 2040 and includes the effect of heavy rains in its analysis.

In the framework of the TCNCC, IDEAM et al. (2017b) developed the Vulnerability and Risk Analysis for Climate Change in Colombia, with a comprehensive and multisectoral approach. Although the TCNCC provides a broad view of vulnerability to climate risks, the results of this research evidence greater vulnerability in the municipalities studied, underscoring the need for detailed analyses at local scales to better understand the specific dynamics of adaptation to SLR. It is important to recognize that, although social, economic and administrative transformations between studies may generate uncertainty in the projections, these analyses remain fundamental for administrations and communities to make informed decisions and react in a timely manner to possible emergencies.

The analysis reveals how vulnerability associated with SLR is strongly conditioned by structural inequalities in the municipalities studied. In Cartagena, a clear duality is observed: while consolidated areas such as Bocagrande and the historic center have infrastructure that largely mitigates their vulnerability, sectors such as the Ciénaga de La Virgen are critically exposed due to lack of regulation, precarious construction and limited basic services. This contrast shows that urban consolidation does not necessarily promote equity, but can perpetuate exclusion dynamics, particularly in the peripheries, where social and physical vulnerability is higher.

In municipalities such as Ciénaga, Coveñas and Manaure, the results differ due to their contexts Ciénaga faces a high risk derived from its precarious construction and the scarce institutional capacity to manage land use, which aggravates exposure in peripheral areas. In Coveñas, although some sectors are physically more exposed, tourist activity and economic investment have strengthened the adaptive capacity of certain properties, showing that vulnerability does not depend exclusively on physical factors. For its part, Manaure, with its territorial marginality, reflects the need to articulate institutional and community efforts to overcome exclusion and promote contextually appropriate solutions. These cases underscore that solutions must transcend physical infrastructure, also considering the economic and social dynamics that perpetuate exclusion and risk.

In terms of vulnerability and commercial activities to SLR, residential uses are the most vulnerable in all cities, highlighting the direct impact on households and the need to ensure safe habitability in a context of climate change. These uses present a greater predisposition to a high degree of vulnerability. On the other hand, although commercial, recreational and institutional activities are less representative in numerical terms, they present significant risks due to their concentration in areas with greater direct exposure.

However, their lower vulnerability compared to residential uses can be attributed to economic and infrastructure factors, which give them a greater capacity to adapt to the impacts of SLR and other oceanic phenomena.

We also assessed the potential economic losses to the city's real estate assets, as well as the impact of sea level rise on the various economic activities of the municipalities. This integrated approach allows us not only to understand the direct implications of SLR, but also to provide a solid basis for local authorities to make informed decisions. This information is essential for local administrations to anticipate, prioritize strategic sectors and act effectively in mitigating and adapting to SLR risks.

These results underscore the urgency of implementing differentiated actions to mitigate vulnerability to SLR. While consolidated coastal areas require mitigation and adaptation strategies to protect their critical and economic infrastructure, marginal areas require urgent structural and social interventions to improve living conditions, regularize settlements and guarantee equitable access to basic services, preventing exclusion and precariousness from continuing to grow.

The multipurpose cadastre is a key input for analyzing territorial vulnerability to climate change, as it offers a unique geographical detail at the property level. Its information on physical characteristics, land use and infrastructure, together with its constant updating and public access, allows for the assessment of vulnerability conditions and informed decision making. This study shows that the impact of SLR varies among properties, highlighting the need for more precise analyses, which are still limited in the country. Thus, the multipurpose cadastre complements and amplifies the effectiveness of other approaches, providing a more accurate and nuanced view of territorial risks and inequalities.

Although this research provides a detailed view of municipal vulnerability to SLR, it is necessary to recognize certain aspects that may influence its scope and interpretation. Cadastral data were key to assessing economic losses and territorial vulnerability, but the comparison between properties showed some discrepancies in the scores assigned to the physical homogeneous zones. Although these inconsistencies did not significantly affect the results, they do highlight the need to optimize data collection and validation procedures. Implementing additional methodologies to correct for variations could improve the accuracy of the analyses.

On the other hand, the analysis of municipal capacity considered both tax and non-tax revenues; however, municipalities with greater economic dynamism, such as those with a high presence of commerce, industry or tourism, have higher collection levels. In municipalities with a high proportion of informal housing, additional challenges are evident, since this condition not only limits resources, but also increases the attention to the vulnerable population. Therefore, future studies could include informality as a key variable to analyze its impact on the local response capacity to SLR.

Finally, this research opted to assign equal weights to the variables, allowing for a balanced and transparent analysis. However, future studies could explore methodologies such as assigning differentiated weights through expert criteria or multi-criteria approaches, to further adjust the analyses to the dynamics of each municipality. These strategies would provide additional perspectives without underestimating the usefulness and robustness of the implemented approach.

Spatial inequalities in the distribution of infrastructure, basic services and land-use regulation are evidence of a structural imbalance in the development of the municipalities studied. In the central urban centers, comprehensive planning favors the concentration of critical infrastructure, such as transportation networks and service systems, which improves the quality of life and fosters economic development. However, in peripheral areas, lack of planning and insufficient road infrastructure and essential services generate marginalization, increasing territorial disconnection and the vulnerability of the inhabitants. This analysis shows spatial segregation, a product of the historical disconnection of these areas from urban planning processes, perpetuating their vulnerability and exclusion within the territory.

Sea level rise requires a research approach that considers both its immediate effects and long-term transformations in coastal cities. It is essential to delve deeper into the dynamics of climate migrations and their impact on the receiving territories, analyzing how they redistribute risks, widen inequalities and limit access to essential resources. Likewise, identifying areas of potential displacement and designing inclusive and resilient urban strategies will make it possible to anticipate future scenarios. This field must move towards interdisciplinary approaches that integrate the social, economic and environmental dimensions, promoting solutions that reduce structural vulnerabilities and guide planning towards effective responses to emerging climate challenges.

7. CONCLUSION

The analysis reveals that vulnerability to sea level rise (SLR) is not only a matter of geographic exposure, but also of deep structural inequalities in the urban areas studied. Poor infrastructure conditions, lack of planning and low adaptive capacity are concentrated in the most vulnerable sectors, indicating that the impacts of climate change are not evenly distributed. These findings suggest that, in addition to the traditional mitigation approach, it is essential to implement strategies that address structural inequalities and strengthen local adaptive capacities, setting a precedent for public policies that integrate sustainable and contextualized solutions to SLR in Colombia.

Real estate assets directly exposed to sea level rise must be considered along with adjacent areas, as these will also be subject to the collateral effects of phenomena such as coastal erosion, beach retreat, flooding, and increased frequency and intensity of storms and high tides. These surrounding areas, although not directly under the immediate threat of SLR, will experience significant impacts due to coastal dynamics and the interaction of these phenomena, which increases the vulnerability of communities. This set of risks increases the complexity of vulnerability scenarios, underscoring the urgency of anticipating future impacts and adopting preventive measures that protect communities as a whole.

Projected sea level rise by 2040 threatens to aggravate territorial inequalities, especially in the most vulnerable areas. The lack of adaptive capacity and the fragility of these areas require urgent action. It is necessary to implement urban policies that integrate climate risk management, prioritizing prevention and infrastructure improvement in critical areas. Only through differentiated interventions that address both infrastructure protection and equitable access to services will it be possible to mitigate vulnerability to SLR, promoting spatial justice and reducing social and territorial exclusion.

The multipurpose cadastre emerges as a key tool for understanding the distribution of risk and accounting for exposed assets, making it possible to assess the impacts of phenomena such as sea level rise at a precise scale, such as the property unit. This tool can guide informed decision making, promoting resilient and equitable urban development. In this context, SLR is not only an environmental challenge, but also a challenge for spatial and social justice, as well as for long-term sustainable urban planning.

Sea level rise triggers massive relocation processes to less exposed areas, intensifying the demand for space in already overburdened areas. This phenomenon can lead to gentrification, displacing the most vulnerable residents and deepening urban segregation, relegating the affected populations to peripheries marked by precarious conditions in terms of services, infrastructure and quality of life. These processes exacerbate social inequalities and generate territorial, economic and social tensions that jeopardize urban cohesion and the resilience of cities. Faced with these challenges, it is urgent to implement inclusive and resilient urban planning strategies that integrate vulnerable communities in climate change adaptation processes.

8. AUTHORS' CONTRIBUTIONS

LSB: conceptualization, methodology, formal analysis, writing (original draft).

GERG: conceptualization, writing, cartographic design.

IDCP: methodology, writing (review and editing).

JAAA: project administration, methodology.

All authors have read and approved the published version of the manuscript.

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SOBRE O ORGANIZADOR

Eduardo Eugênio Spers realizou pós-doutorado na Wageningen University (WUR), Holanda, e especialização no IGIA, França. Possui doutorado em Administração pela Universidade de São Paulo (USP). Foi Professor do Programa de Mestrado e Doutorado em Administração e do Mestrado Profissional em Comportamento do Consumidor da ESPM. Líder do tema Teoria, Epistemologia e Métodos de Pesquisa em Marketing na Associação Nacional de Pós-Graduação e Pesquisa em Administração (ANPAD). Participou de diversos projetos de consultoria e pesquisa coordenados pelo PENSA e Markestrat. É Professor Titular no Departamento de Economia, Administração e Sociologia, docente do Mestrado em Administração e Coordenador do Grupo de Extensão MarkEsalq no campus da USP/Esalq. Proferiu palestras em diversos eventos acadêmicos e profissionais, com diversos artigos publicados em periódicos nacionais e internacionais, livros e capítulos de livros sobre agronegócios, com foco no marketing e no comportamento do produtor rural e do consumidor de alimentos.

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