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Flood risk method for scarce-data catchments and municipalities

Método de evaluación del riesgo de inundaciones para cuencas y municipios con datos escasos

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ABSTRACT: Floods pose significant challenges in regions with limited resources and data, requiring simplified methodologies for effective risk assessment. This study presents a flexible framework for analyzing flood hazard, exposure, and vulnerability at the municipal level in data-scarce or developing countries. By integrating diverse data sources and employing statistical validation, the methodology ensures reliable results, even with minimal baseline information. It supports regional planning by facilitating flood risk calculations and extrapolations to watershed scales. While based on experiences in Central America, this approach is applicable globally, offering a systematic tool for flood risk assessments and environmental zoning in resource-constrained settings.
Keywords: flood risk assessment; developing countries; data scarcity; municipal-level analysis; catchment-scale extrapolation.

RESUMEN: Las inundaciones representan desafíos significativos en regiones con recursos y datos limitados, lo que requiere metodologías simplificadas para una evaluación efectiva del riesgo. Este estudio presenta un marco flexible para analizar el peligro, la exposición y la vulnerabilidad a inundaciones a nivel municipal en países en desarrollo o con escasez de datos. Al integrar diversas fuentes de datos y emplear validación estadística, la metodología garantiza resultados confiables, incluso con información de

base mínima. Apoya la planificación regional al facilitar cálculos de riesgo de inundaciones y su extrapolación a escalas de cuenca. Aunque se basa en experiencias de América Central, este enfoque es aplicable globalmente, ofreciendo una herramienta sistemática para la evaluación del riesgo de inundaciones y la zonificación ambiental en contextos con recursos limitados.
Palabras clave: evaluación del riesgo de inundaciones; países en desarrollo; escasez de datos; análisis a nivel municipal; extrapolación a escala de cuenca.

Introduction

Floods stand as one of the most pervasive and devastating natural-origin disasters worldwide, inflicting significant socio-economic and environmental repercussions. However, the ability to effectively assess and manage flood risk remains a formidable challenge, particularly in regions grappling with limited resources and data scarcity (Al-Awadhi et al., 2024). Across the globe, floods exact a heavy toll on communities, disrupting livelihoods, displacing populations, and causing extensive damage to infrastructure and ecosystems (Sejati et al., 2024). This universal hazard underscores the urgent need for robust but replicable methodologies to evaluate and mitigate flood risk.

Data scarcity poses a significant challenge in addressing flood risk worldwide (Diniz Oliveira et al., 2024). Limited access to reliable data on hydrological parameters, land use patterns, and socio-economic factors complicates the development of accurate risk assessment models and decision-making processes (Quesada-Román et al., 2024a). Inadequate hydrological monitoring, gaps in historical data, and outdated land registries hinder model calibration and vulnerability assessment (Ley et al., 2023). Socio-economic data collection is constrained by logistical challenges, resulting in incomplete datasets and uncertainties in risk assessments (Alcántara, 2019). Overcoming data scarcity requires improved data collection mechanisms and partnerships to develop more effective flood risk management strategies globally (Hidalgo et al., 2013).

Amidst these challenges, diverse approaches have emerged for calculating flood risk, ranging from complex hydrological models to simplistic methodologies tailored to data-constrained environments (Chinedu et al., 2024). These methods leverage available data sources, statistical techniques, and risk indices to estimate flood hazard, exposure, and vulnerability, enabling stakeholders to identify high-risk areas and prioritize mitigation efforts (Acosta-Quesada and Quesada-Román, 2024; Hidalgo, 2021). Importantly, simplistic methods have shown promise in facilitating flood risk assessments in regions with limited data availability, demonstrating adaptability across various latitudes and contexts (Tariq et al., 2020). By employing straightforward algorithms and readily accessible data inputs, these approaches offer pragmatic solutions for assessing and managing flood risk in resource-constrained settings (Mai et al., 2020).

The Regional Assessment Report on Disaster Risk in Latin America and the Caribbean (GAR Synthesis, 2021) identifies new risk patterns concentrating in medium and small urban areas. Over half of the cities with 500,000+ inhabitants are highly vulnerable to at least one natural hazard, affecting approximately 340 million people in Latin America and the Caribbean. The Centre for Research on the

Epidemiology of Disasters (CRED, 2024) reports that floods were the most recurrent disaster globally from 2001 to 2020 and in 2021, causing significant economic losses, particularly in the Americas.

Central America a natural laboratory to test new flood risk assessment techniques due that is the result of tectonic and climatological dynamics that have built suitable conditions for natural floods in areas such as intermontane floodplains and extensive lowlands that connect to the sea. These areas have been historically used for human settlements and agriculture due to their easy access to water and other natural resources such as wood, fertile soils, and minerals. Since pre-Columbian times flood impacts and adaptations have been recorded in multiple archaeological sites of the region (Barrios and Batres, 2019). Since the Colonial times there are several records of extraordinary flood events related to cold fronts, tropical cyclones, and intensive rainy season (Guevara-Munua et al., 2018). In the last decades, both exposure and vulnerability have increased due to the lack of territorial planning and a disorganized urban growth, resulting in optimal flood risk conditions in urban areas and rural flatlands where the number of annual flood events have increased tremendously in the last decades (Figure 1).

Central America serves as a compelling case study, where the application of simplistic flood risk assessment methods has yielded valuable insights into hazard exposure and vulnerability. Floods are by far the disaster with more casualties, affected people, and economic damages historically in the region (CRED, 2024). Despite facing data scarcity challenges and enduring the impacts of recurrent floods, the region has made strides in developing tailored approaches to assess and mitigate flood risk, underscoring the potential for simplistic methodologies to be successfully implemented in diverse geographical settings. In this paper, we explore the global significance of flood impacts, the implications of data scarcity for flood risk assessment, the diverse methods available for calculating flood risk, and the successful implementation of simplistic approaches in mitigating flood risk, with Central America serving as a pertinent illustration of these principles. Through this analysis, we aim to provide insights that can inform more effective flood risk management strategies worldwide.

Materials and methods

For flood hazard assessment, historical flood records were extracted from the DesInventar database (https://db.desinventar.org/) and linked with spatial layers using a unique municipality identifier. The Geographic Information System (ArcMap, QGIS, or ArcGIS Pro) facilitated data processing, employing clipping operations to delineate flooded areas within municipalities and calculate corresponding polygonal areas at the municipal level across the four countries under study (El Salvador, Honduras, Costa Rica, and Panama, see Figure 2). The resulting data were exported to Excel and further analyzed using the R programming language and RStudio software. The percentage of each municipality's area within official flood zones was calculated, representing the extent of flood hazard. This involved summing the total number of recorded floods and determining the percentage of municipal area within the designated flood zones.

Exposure assessment involved the calculation of population and road density averages for each municipality. Population density was obtained for 400 m H3 hexagons (Kontur, 2022). Road network data was obtained from OpenStreetMap (OSM, 2024) and summarized using the "Summarize Within" tool. Both population and road density averages were normalized on a scale from 0 to 1, representing exposure

Fig. 1: Flood common events in Central America. Tropical cyclones such as Hurricane Eta in 2020 affect normally large flatlands in Honduras (a). Urban floods have become usual in the last decades as in San Salvador (b) or Turrialba in Costa Rica (c). Most Panamanian floods are in Panama city but some particular rural catchments such as La Villa River in Azuero Peninsula are commonly affected (d).

levels. Vulnerability assessment considered the Human Development Index (HDI) as a proxy for vulnerability. The HDI, comprising variables such as education, income, and life expectancy, was inverted to reflect higher vulnerability in less developed municipalities. Each component of the HDI was considered in assessing vulnerability, focusing on the socio-economic factors contributing to vulnerability.

Flood risk was calculated by integrating normalized hazard, exposure, and vulnerability values. Each variable was assigned a weight of 0.3 to balance their contribution, and the resulting risk score was multiplied by 100 for consistency. This weighted formula ensured that the hazard, exposure, and vulnerability were equally important in determining flood risk.

$$RISK=(Hazard\times0.3)\times(Exposure\times0.3)\times(Vulnerability\times0.3)\times100$$

Natural breaks classification was applied to categorize risk levels into low, medium, and high, providing a comprehensive assessment of flood risk across the study area. This methodological process, summarized in Figure 3, enables systematic evaluation of flood hazard, exposure, vulnerability, and risk, utilizing available data sources and widely used GIS techniques. By delineating each step into distinct

Fig. 2: Honduras, El Salvador, Costa Rica, and Panama were the selected countries of Central America for this study.

subsections, the methodology provides clarity and transparency in the assessment process, facilitating reproducibility and comparability in future studies.

Results

Flood hazard by country

Eight catchments with high flood hazard values were identified in Honduras: Chamelecón, Ulúa, Aguán, Nacaome, Choluteca, Coco (bordering Nicaragua), Cruta, and Warunta. The municipalities at high risk within these catchments include El Progreso, El Negrito, San Manuel, Pimienta, Potrerillos, Santiago de Puringla, Jano, Marcovia, San Lorenzo, Apacilagua, La Soledad, and Puerto Lempira. In the Chamelecón catchment, municipalities with medium hazard values are Veracruz, Florida, Santa Bárbara, San Marcos, Choloma, La Lima, and Puerto Cortes. The highest hazard catchments are in the central, southern, and western regions, while lower hazard areas are towards the east.

In El Salvador, high hazard values were identified in the Estero de Jaltepeque and Bahía de Jiquilisco catchments. High-risk municipalities include Santiago Nonualco, San Luis La Herradura, Zacatecoluca,

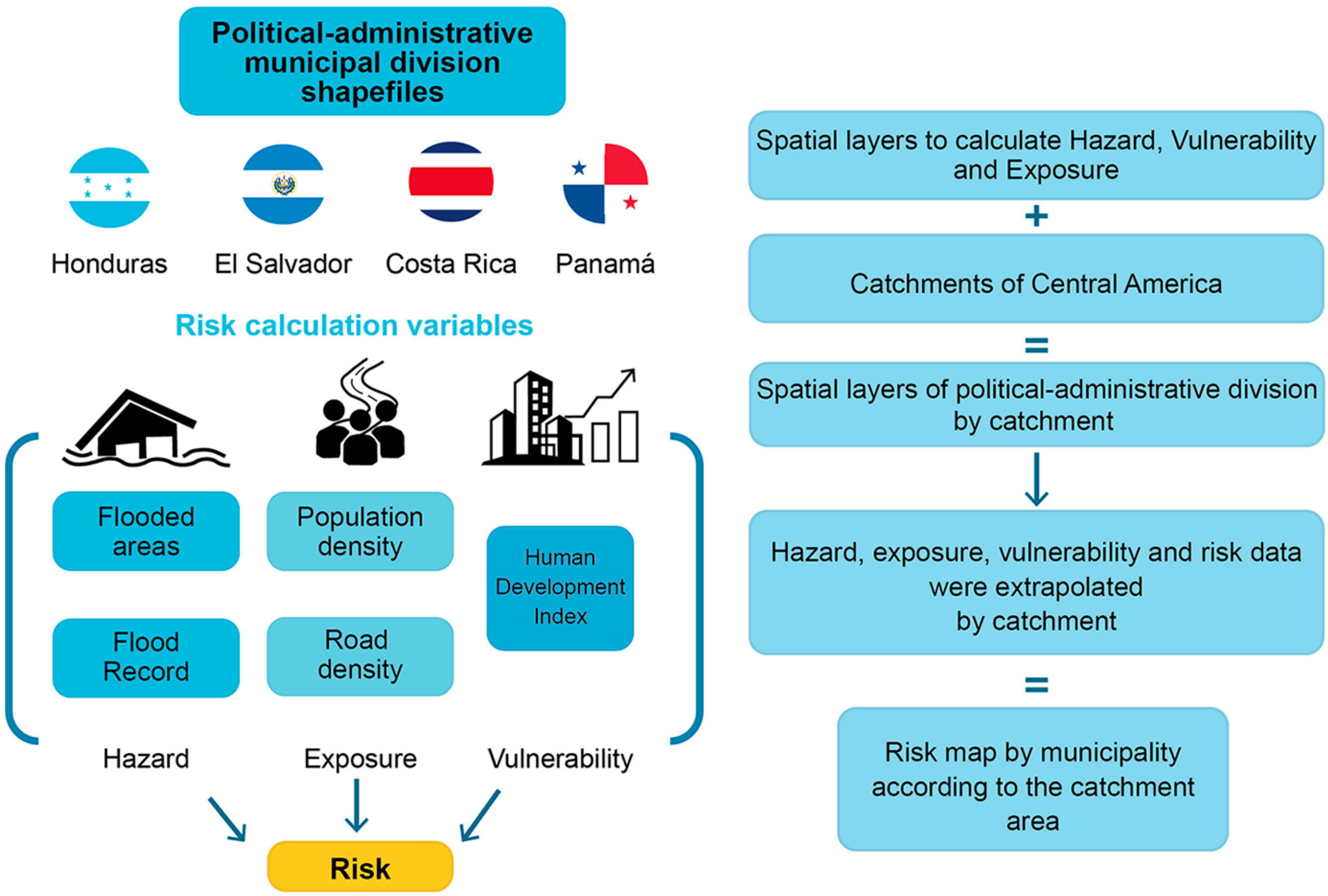

Fig. 3: Schematic plot to determine flood risk at catchment level using municipal data. A study case of four countries of Central America.

Jiquilisco, Puerto El Triunfo, and San Dionisio. Additionally, San Miguel, Ciudad Arce, Sacacoyo, San Salvador, and San Francisco Menéndez were categorized as high risk, though they are part of catchments with medium hazard. High hazard catchments are located on the Pacific coast in the south, while medium hazard catchments are in the north and center.

In Costa Rica, the Tempisque, Nicoya Peninsula, Northern Coast, Tortuguero, La Estrella, Sixaola, and Osa Peninsula catchments have high hazard values. High-risk municipalities include Liberia, Carrillo, Santa Cruz, Nicoya, Puntarenas, Pococí, and Talamanca. Upala, San Carlos, Sarapiquí, and Bagaces have high hazard values, despite their catchments being classified with medium hazard. Osa and Golfito municipalities have medium hazard values within high hazard catchments. High hazard areas are primarily around the Gulf of Nicoya, northern, and eastern regions on the Caribbean slope, while low hazard areas are in the central and Central Pacific regions.

In Panama, high hazard catchments are located in the western region (Rio Coto, Rio Chico, Rio Chiriquí), the Azuero Peninsula, the central part of the country (Rivers between El Tonosí and La Villa, Rio La Villa, Rio Parita, Rio Santa María), and the metropolitan region (Rio Chagres, Rivers between Caimito and Juan Díaz, Rio Juan Díaz, and Rio Pacora). High-risk municipalities include Barú, Boquerón, Alanje, David, Dolega, San Félix, Remedios, Guararé, Los Santos, Santa María, Aguadulce, Antón, Colón, and Panama. Catchments with low hazard are found in the northern slope (Caribbean Sea) and the eastern region of the country.

Flood exposure by country

Municipalities with high flood exposure include San Pedro Sula, La Lima, Choloma, Nueva Arcadia, Dulce Nombre, El Progreso, San Manuel, Villa Nueva, Pimienta, Potrerillos, San Francisco de Yojoa, Las Lajas, Siguatepeque, Ajuterique, Lejamaní, La Paz, Mapulaca, San Lorenzo, Distrito Central, Santa Lucía, Valle de Ángeles, and Santa Ana de Yusguare. The high-exposure catchments corresponding to these municipalities are Motagua, Chamelecón, Ulúa, Lempa, Nacaome, Choluteca, and Río Negro, mainly in the eastern part of the country, bordering Guatemala and El Salvador. Municipalities like Choloma, Omoa, El Paraíso, Santa Rita, Copán Ruinas, Cabañas, San Fernando, La Encarnación, San Jorge, Concepción de María, and El Triunfo fall within the Río Negro and Motagua catchments and have medium exposure values, despite being in high-exposure catchments. The far eastern part of the country has catchments with medium and low exposure.

In El Salvador, catchments with high exposure are concentrated in the northern and central regions, including the Paz River, Grande de Sonsonate, Lempa, El Jute, Bocana Toluca, and Jiboa. Municipalities with high exposure include Sonzacate, San Salvador, Mejicanos, Ayutuxtepeque, Cuscatancingo, Delgado, and Soyapango. Municipalities with medium exposure in these catchments are Ahuachapán, Turín, San Lorenzo, Atiquizaya, El Refugio, Chalchuapa, San Sebastián Salitrillo, Zaragoza, Nuevo Cuscatlán, San Marcos, and Santo Tomás. For the Jiboa catchment, municipalities with medium exposure include Ilopango, El Carmen, Cojutepeque, San Cristóbal, and San Ramón.

In Costa Rica, the Grande de Tárcoles catchment has high exposure, affecting the municipalities of Alajuelita, San José, Flores, San Pablo, Tibás, Goicoechea, Montes de Oca, and Curridabat, all located in the Greater Metropolitan Area (GAM) in the central part of the country, with high population density. Medium exposure catchments are found in the north, center, and east, while low exposure catchments are in the southeast.

In Panama, two catchments are classified with high exposure: the rivers between El Caimito and El Juan Díaz, and the rivers between El Juan Díaz and Pacora, which flow into the Bay of Panama. The municipality of San Miguelito is categorized with high exposure. Medium exposure catchments are in the southern part of the country, flowing into the Gulf of Parita, including the Parita River, Santa María River, and rivers between Tonosí and La Villa. Additionally, catchments flowing into the Charco Azul Bay, such as the Coto and Neighbors River, Old Chiriquí River, and Chiriquí River, have medium exposure.

Flood vulnerability by country

In Honduras, four catchments with high vulnerability were identified: Motagua and Lempa in the westernmost part, and Warunta and Cruta in the far east along the Caribbean coast. Municipalities with high vulnerability include Nueva Frontera, Florida, El Paraíso, Copán Ruinas, San Antonio, San Jerónimo, Concepción, Santa Rita, Cabañas, La Unión, San Jorge, San Fernando, Lucerna, Fraternidad, Dolores Merendón, Puerto Lempira, Wampusirpi, Mercedes, Guarita, Cololaca, San Sebastián, San Manuel, Belén Gualcho, Tambla, San Juan Guarita, Valladolid, Tomalá, San Manuel Colohete, San Marcos de Caiquin, San Andrés, La Virtud, Gualcince, Mapulaca, Santa Cruz, Candelaria, Virginia, Piraera, San Antonio, Erandique, San Juan, San Miguelito, Dolores, San Francisco, Concepción, Santa Lucia, Magdalena, Colomoncagua, Yamaranguila, San Marcos de Sierra, Santa Elena, and Yaruna. Northern catchments are categorized with low vulnerability. Some municipalities like San Antonio, Nueva Frontera, Florida, La Jigua, San Jerónimo, Dolores, Concepción, Trinidad de Copán, Naranjito, Protección, and San Luís have high vulnerability within catchments with medium values.

In El Salvador, high vulnerability is found in border and coastal areas, with central areas having lower values. High vulnerability catchments include Barra de Santiago, the group of catchments of Sihuapilapa, Mizata, Aguacayo, La Perla, Irayol, Taquillo, Shuza, El Zonte, El Palmar, and Rio Turco in the southwest, as well as Lempa, Grande de San Miguel, Goascorán, Siramá, Río Las Conchas or El Jocote, Laguna los Chorros or Maquique, Guarrapuca, San Román, Conchagüita, El Envoque, and Piedra de Agua catchments. Municipalities with high vulnerability are found mainly in peripheral areas and near the coasts.

In Costa Rica, high vulnerability is distributed in coastal and border areas. High exposure catchments include Changuinola, Sixaola, Estrella, Banano, Moín, and Madre de Dios River in the east. Municipalities with high vulnerability include Talamanca, Limón, Matina, Puntarenas, Nandayure, Hojancha, Nicoya, Santa Cruz, Carrillo, La Cruz, Bagaces, Cañas, Tilarán, Montes de Oro, Garabito, Parrita, Tarrazú, Quepos, Dota, Coto Brus, Buenos Aires, Pococí, Corredores, Upala, Los Chiles, Sarapiquí, Guácimo, San Mateo, and León Cortes.

In Panama, high vulnerability catchments are identified in the western region (northern slope) including Changuinola River, rivers between Changuinola and Cricamola, Calovébora River, Cricamola River, and between Cricamola and Calovébora; southern slope including Fonseca River and between Chiriquí and San Juan Rivers, Tabasará River, and San Pablo River. In the central region (northern slope), catchments include Belén River and between Belén and Coclé del Norte River. In the eastern region, high vulnerability catchments include Bayano River, rivers between Bayano and Santa Bárbara, Santa Bárbara River, rivers between Mandinga and Armila, and Chucunaque River. Municipalities with high vulnerability include Almirante, Jirondai, Santa Catalina or Calovébora, Omar Torrijos Herrera, Kuna Yala Region, and Santa Fé de Darién.

Flood risk by country

Six catchments in Honduras are classified with high flood risk: Motagua, Chamalecón, Ulúa, Nacaome, Choluteca, and Río Negro. Seven catchments are classified with medium risk: Lempa, Goascorán, Lean, Aguán, Patuca, Warunta, and Cruta. High and medium flood risk catchments are located in the central, western, and southern parts of the country, with the municipalities detailed in Figure 3.

For the Motagua catchment, the municipalities of Omoa, Santa Rita, Cabañas, and La Encarnación are classified with high risk, while San Jorge, San Fernando, Copán Ruinas, El Paraíso, Florida, and Nueva Frontera are classified with medium risk. In the Chamalecón catchment, high-risk municipalities include Veracruz, San Nicolas, San Antonio, Florida, Macuelizo, Choloma, Puerto Cortés, and La Lima. Medium-risk municipalities are Dolores, San Jerónimo, Concepción, Nueva Arcadia, Santa Bárbara, San Luis, San José de Colinas, San Marcos, and Petoa.

In the Ulúa catchment, high-risk municipalities are San Agustín, San Marcos, Gracias, San Rafael, Santiago de Puringla, Lejamaní, Siguatepeque, San Jerónimo, La Libertad, Las Lajas, Potrerillos, Pimienta, El Progreso, El Negrito, San Manuel, and La Lima, with additional medium-risk municipalities throughout the catchment. The Nacaome catchment has three high-risk municipalities: Nacaome, San Lorenzo, and Marcovia, located in the lower part of the catchment. Municipalities with medium risk are found in the middle part, while Lepaterique in the upper part is categorized as low risk.

High-risk municipalities for the Choluteca catchment are El Paraíso, Apacilagua, Santa Ana de Yusguare, and Namasigüe. For the Río Negro catchment, El Triunfo is the only municipality with high risk, while municipalities with medium risk values are distributed throughout the catchment. Among catchments with medium risk, some municipalities have high flood risk values. These include Lempa, Aguán, and Warunta catchments, with Santa Lucía in Lempa, Jano, Sabá, Sonaguera, and Tacoa in Aguán, and Puerto Lempira in Warunta. Table 1 shows the catchments in Honduras and the municipalities with high risk.

In El Salvador, thirteen catchments are classified with high flood risk: Río Paz, Las Marías, Mandinga, Lempa, Estero de San Diego, Bocana Toluca, Comalapa, Jiboa, Estero de Jaltepeque, Bahía de Jiquilisco, Río Managuara or Bananera, Maderas, and Volcán Conchagua, as shown in Table 2. The high-risk municipalities are illustrated in Figure 4. For the Paz catchment, San Francisco Menéndez and Ahuachapán are classified with high risk, while San Sebastián Salitrillo, Chalchuapa, Atiquizaya, and Turín are medium risk. Las Marías and Mandinga catchments have municipalities with medium risk, including Acajutla for Las Marías, and Sonsonate, Cuisnahuat, and Santa Isabel Ishuatán for Mandinga.

The Lempa catchment has fourteen high-risk municipalities: Santa Ana, Ciudad Arce, Sacacoyo, Colón, Aguilares, Apopa, Mejicanos, San Salvador, Cuscatancingo, Delgado, Soyapango, Tonacatepeque, El Carmen, and Berlín. These are located mainly in the central part of the country and in the upper catchment, except Berlín in the middle-lower catchment. Many municipalities with medium flood risk are spread throughout the catchment, while low flood risk is found in the north and northeast.

In the Estero San Diego catchment, La Libertad is classified with high flood risk. In the Bocana Toluca catchment, San Marcos, Santo Tomás, Panchimalco, Huizúcar, Rosario de Mora, and a section of La Libertad are classified with medium risk. For the Comalapa catchment, San Luis Talpa is high risk, while La Libertad, Olocuilta, and San Juan Talpa are medium risk. The Jiboa catchment also has San Luis Talpa (high risk), along with San Pedro Masahuat and Ilopango.

In the Estero de Jaltepeque catchment, five municipalities are high risk: San Luis La Herradura, Santiago Nonualco, San Juan Nonualco, Zacatecoluca, and Tecoluca. San Pedro Masahuat, El Rosario, and San Rafael Obrajuelo are medium risk, and two others are low risk. For the Bahía de Jiquilisco catchment, Jiquilisco and San Dionisio are high risk, while Puerto El Triunfo, Usulután, Ozatlán, and Jucuarán are medium risk. The Managuara or Bananera, Maderas, and Volcán Conchagua catchments, located in the east bordering the Gulf of Fonseca, include La Unión (high risk for Managuara, medium for Maderas and Volcán Conchagua), and Conchagua (medium risk for Maderas and Volcán Conchagua).

Four catchments were categorized with high flood risk for Costa Rica, fourteen with medium flood risk, and ten with low flood risk (Figure 5). The catchments classified with high flood risk are listed in Table

Table 1

Catchments and municipalities classified with high flood risk for Honduras.

Name of the catchment	Municipality
Motagua	Omoa, Santa Rita, Cabañas, La Encarnación
Chamelecón	Veracruz, San Nicolas, San Antonio, Florida, Macuelizo, Choloma, Puerto Cortés, La Lima
Ulúa	San Agustín, San Marcos, Gracias, San Rafael, Santiago de Puringla, Lejamaní, Siguatepeque, San Jerónimo, La Libertad, Las Lajas, Potrerillos, Pimienta, El Progreso, El Negrito, San Manuel, La Lima
Nacaome	Nacaome, San Lorenzo, Marcovia
Choluteca	El Paraíso, Apacilagua, Santa Ana de Yusguare, Namasigüe
Río Negro	El Triunfo

3, and they are the Península de Nicoya y Costa Norte, Tempisque, Grande de Tárcoles, and Península de Osa. The catchments with medium flood risk were San Juan, Bebedero, Abangares, Tortuguero, Reventazón-Parismina, Tusubres, Parrita, Damas, Naranjo, Térraba, Esquinas, Estrella, Moín, and Río Madre de Dios. These catchments are located in the central part of the country, the northern section, and the Pacific coast of Costa Rica, as well as in the Nicoya Peninsula.

The municipalities of Puntarenas, Nandayure, Nicoya, and Santa Cruz for the Nicoya Peninsula catchment were classified with high flood risk, while the municipalities of La Cruz, Carrillo, and Hojancha for the same catchment presented a medium flood risk value. For the Tempisque catchment, the municipalities of Liberia, Carrillo, and Santa Cruz were classified with high risk, while Nicoya and Bagaces were considered to have a medium flood risk.

For the Grande de Tárcoles River catchment, the following municipalities were classified with high flood risk: Goicochea, La Unión, Curridabat, Desamparados, Alajuelita, San José, Tibás, Santo Domingo, San Pablo, Flores, Alajuela, Grecia, and Palmares. All these municipalities are located in the upper catchment. Municipalities like Aserrí, Montes de Oca, Moravia, San Isidro, San Rafael, Barva, Santa Bárbara, Belén, Escazú, Poás, Naranjo, Atenas, Mora, Turrubares, and Puntarenas were classified as medium flood risk. The last catchment classified with high risk was the Península de Osa, which has two municipalities, Puntarenas and Golfito, classified with medium flood risk.

Among the catchments classified with medium risk, it is worth highlighting San Juan, Térraba, Parrita, Tortuguero, and Bebedero. For the San Juan catchment, four municipalities were classified with high flood risk: Sarapiquí, San Carlos, Los Chiles, and Upala. The Bebedero catchment has four municipalities, two of which were classified as high risk and two as medium risk. The ones classified as high risk were Bagaces and Cañas, while those classified with medium risk were Tilarán and Abangares.

For the Parrita catchment, the municipalities classified with high risk were Aserrí and Desamparados. The Térraba River catchment has two municipalities with high flood risk: Pérez Zeledón and Buenos Aires, and one municipality with medium risk, which is Coto Brus. For the Tortuguero catchment, there is one municipality with high risk, which is Pococí. Matina and Talamanca municipalities were classified with high risk, but the Matina and Sixaola catchments were classified with low flood risk. The municipalities and their different classifications can be seen in Figure 4.

Table 2

Catchments and municipalities classified as high flood risk in El Salvador.

Name of the catchment	Municipality
Río Paz	San Francisco Menéndez, Ahuachapán
Las Marías	Acajutla (Riesgo medio)
Mandinga	Sonsonate, Cuisnahuat, Santa Isabel Ishuatán (Riesgo medio)
Lempa	Santa Ana, Ciudad Arce, Sacacoyo, Colón, Aguilares, Apopa, Mejicanos, San Salvador, Cuscatancingo, Delgado, Soyapango, Tonacatepeque, El Carmen, Berlín
Estero de San Diego	La Libertad (Riesgo medio)
Bocana Toluca	San Marcos (Riesgo medio), Santo Tomás (Riesgo medio), Panchimalco (Riesgo medio), Huizúcar (Riesgo medio), Rosario de Mora (Riesgo medio), La Libertad (Riesgo medio)
Comalapa	San Luis Talpa
Jiboa	San Luis Talpa, San Pedro Masahuat, Ilopango,
Estero de Jaltepeque	San Luis La Herradura, Santiago Nonualco, San Juan Nonualco, Zacatecoluca, Tecoluca
Bahía de Jiquilisco	Jiquilisco, San Dionisio
Río Managuara o Bananera	La Unión
Maderas	Conchagua (Riesgo medio), Managuara (Riesgo medio)
Volcán Conchagua	Conchagua (Riesgo medio), Managuara (Riesgo medio)

In Panama, several catchments are classified with high flood risk, including Río Coto y Vecinos, Río Chiriquí Viejo, Río Escárrea, Río Chico, Río Chiriquí, rivers between Tabasará and San Pablo, rivers between Tonosí and La Villa, Río La Villa, Río Parita, Río Santa María, Río Grande, rivers between El Antón and El Caimito, Río Caimito, and between El Indio and El Chagres. Table 4 lists these catchments and their respective high-risk municipalities.

For the Río Coto y Vecinos catchment, Barú is classified with high flood risk. In the Río Chiriquí Viejo catchment, Tierras Altas and Bugaba are high risk, while Renacimiento and Barú sections, and Alanje are medium risk. The Río Escárrea catchment has Alanje at high risk and Bugaba at medium risk.

Table 3

Catchments and municipalities classified with high flood risk for Costa Rica.

Name of the catchment	Municipality
Península de Nicoya y Costa Norte	Puntarenas, Nandayure, Nicoya, Santa Cruz
Tempisque	Liberia, Carrillo, Santa Cruz
Grande de Tárcoles	Goicochea, La Unión, Curridabat, Desamparados, Alajuelita, San José, Tibás, Santo Domingo, San Pablo, Flores, Alajuela, Grecia, Palmares
Península de Osa	Puntarenas, Golfito

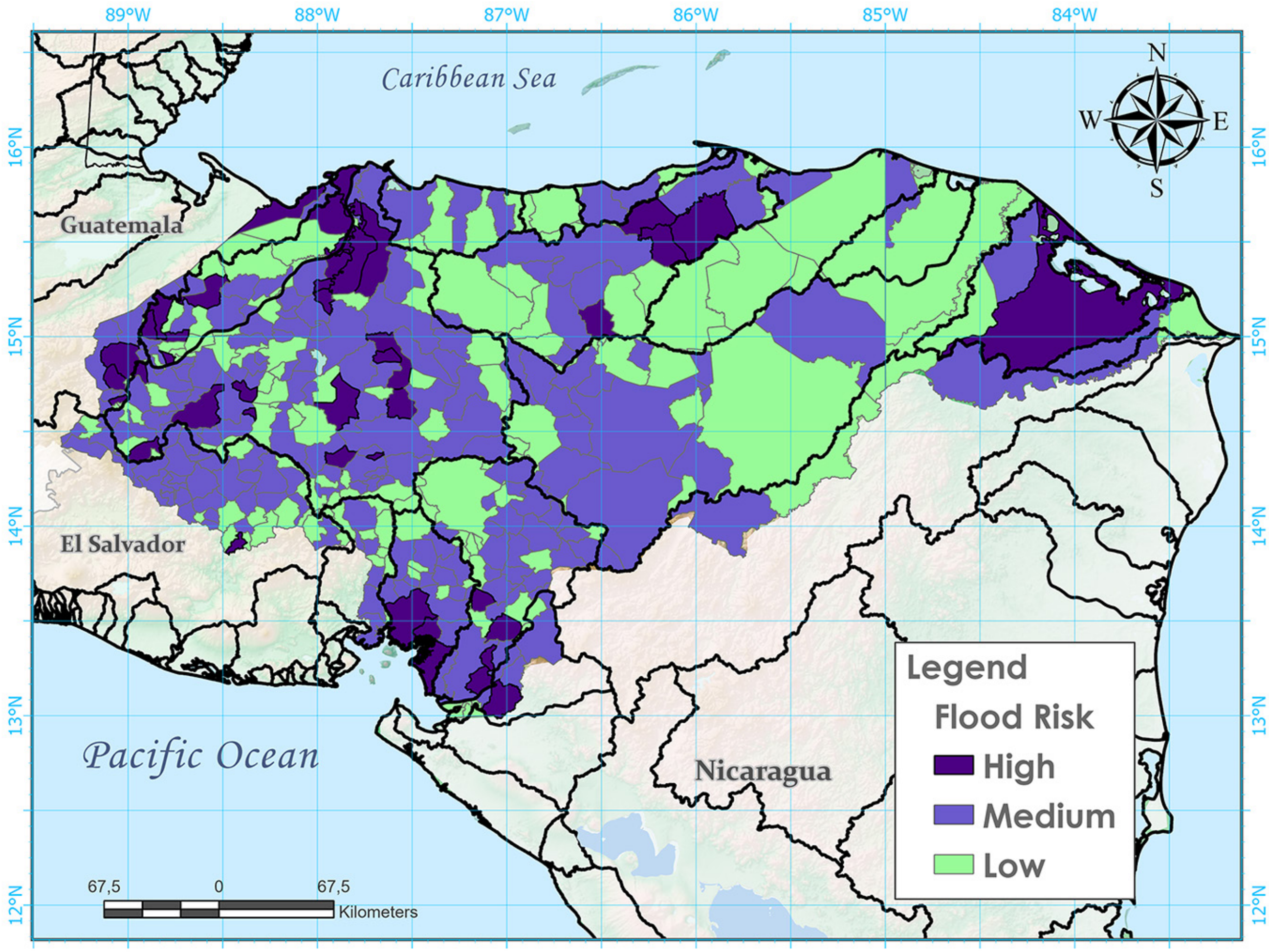

Fig. 4: Spatial distribution of flood risk according to its classification by municipality of Honduras belonging to each catchment.

For Río Chico, Alanje and Boquerón are high risk, while Boquerón and David are medium risk. The Río Chiriquí catchment includes David, Dolega, and Boquete at high risk, and Guala at medium risk.

Municipalities in the rivers between Tonosí and La Villa catchment, including Pedasí, Pocrí, Las Tablas, Guararé, and Los Santos, are high risk, while Tonosí is medium risk. The Río La Villa catchment has Chitré and Los Santos at high risk, and Los Pozos, Macaracas, and Pesé at medium risk. In the Parita catchment, Chitré is high risk, while Ocú, Pesé, and Parita are medium risk.

The Río Santa María catchment includes San Francisco, Calobre, Aguadulce, Santa María, and Parita at high risk, with Santiago at medium risk. The Río Grande catchment lists Agua Dulce as medium risk along with Olá, La Pintada, Penonomé, and Antón, while Natá is high risk. The catchment between El Antón and El Caimito rivers has Antón and Chame at high risk, San Carlos and Capira at medium risk.

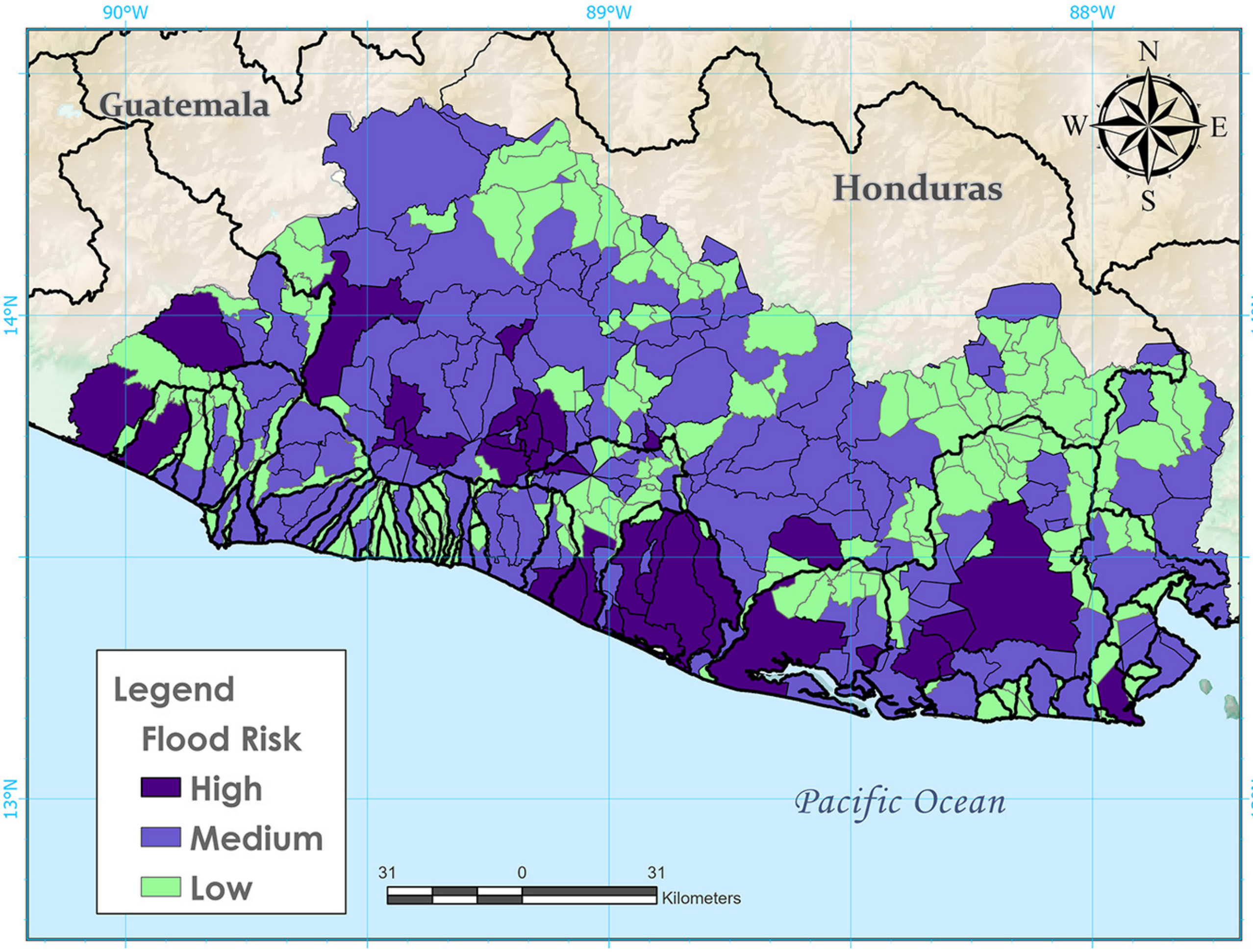

Fig. 5: Spatial distribution of flood risk according to its classification by municipality of El Salvador belonging to each catchment.

La Chorrera and Arraiján are medium risk in the Río Caimito catchment, and Chagres is medium risk in the catchment between El Indio and El Chagres rivers.

Medium flood risk catchments include Río Sixaola, Río San San, rivers between Changuinola and Cricamola, rivers between Fonseca and Tabasará, Río San Pablo, Río San Pedro, rivers between San Pedro and Tonosí, Río Tonosí, Río Antón, Río Coclé del Norte, Río Chagres, rivers between Chagres and Mandinga, rivers between El Caimito and El Juan Díaz, rivers between El Bayano and El Santa Bárbara, and Río Santa Bárbara, and rivers between Santa Bárbara and Chucunaque.

In these medium-risk catchments, the catchment of rivers between Changuinola and Cricamola includes high-risk municipalities Chiriquí Grande and Jirondai. The Río Fonseca catchment, and rivers between Chiriquí and San Juan have San Lorenzo at high risk and David and Besikó at medium risk. The catchment of rivers between Fonseca and Tabasará has high-risk municipalities San Félix and Remedios,

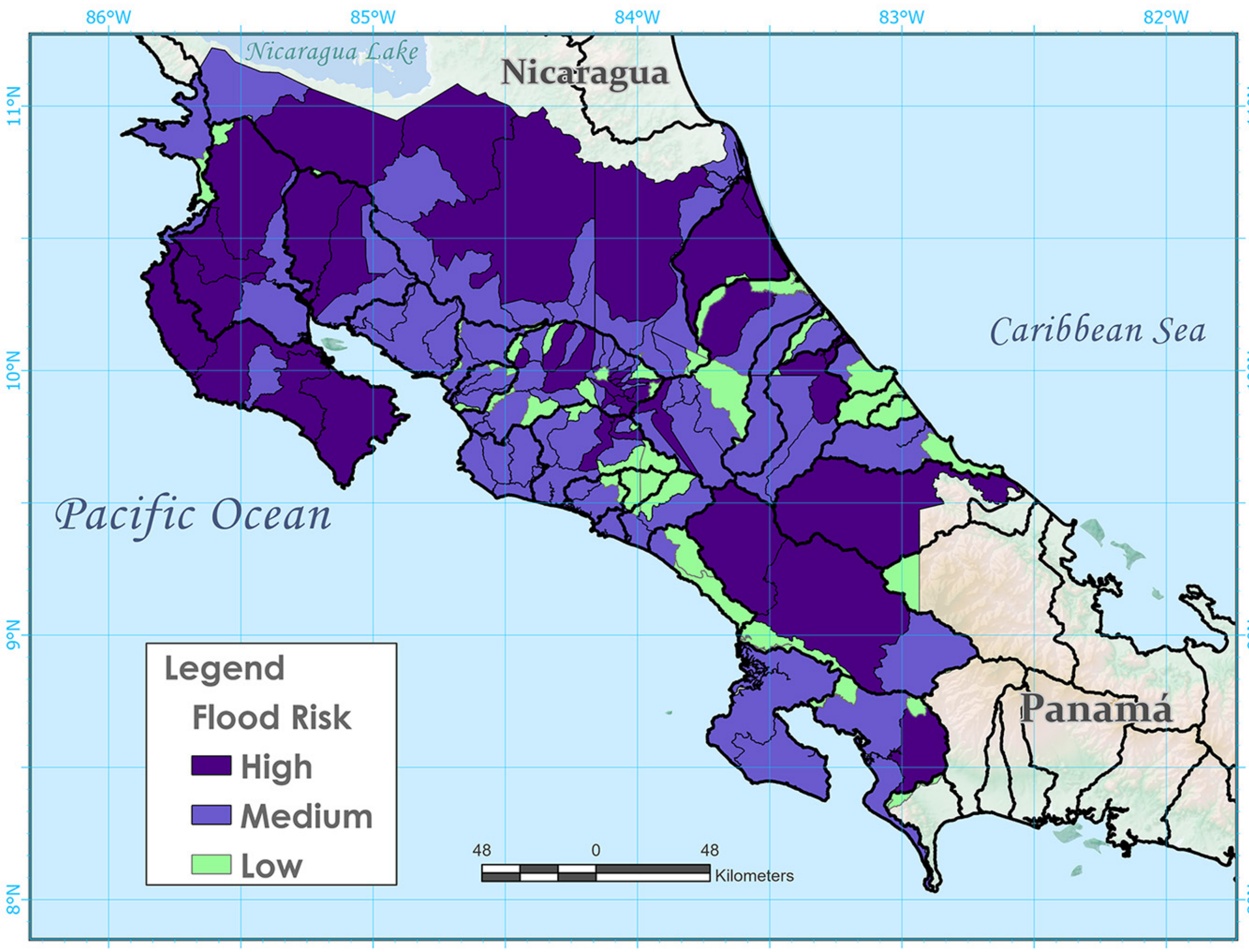

Fig. 6: Spatial distribution of flood risk according to its classification by municipality of Costa Rica belonging to each catchment.

with Tolé at medium risk. For the catchment of rivers between San Pedro and Tonosí, Mariato is high risk, and Santiago is medium risk. The Río Chagres catchment lists La Chorrera and Colón at high risk, and Capira, Arraiján, and Panamá at medium risk. In the Río Bayano catchment, Chepo is categorized with high risk. The distribution of these municipalities and their categories is detailed in Figure 6.

In the Central American region, an analysis of maximum flood risk values identified several catchments classified as high-risk for flooding. The catchments with high flood risk include the Grande de Tárcoles in Costa Rica, and the Grande de San Miguel, Bahía de Jiquilisco, Estero de Jaltepeque, and Jiboa catchments in El Salvador. Additionally, the Paz River catchment, located between Guatemala and El Salvador, and the Lempa River catchment, spanning Guatemala, El Salvador, and Honduras, were also classified as high risk. The Chamelecón catchment, situated between Guatemala and Honduras, is another high-risk area. Within Honduras, the Nacaome River and Choluteca River catchments are categorized as high risk for the region. The municipalities for each of these catchments are listed in Table 5.

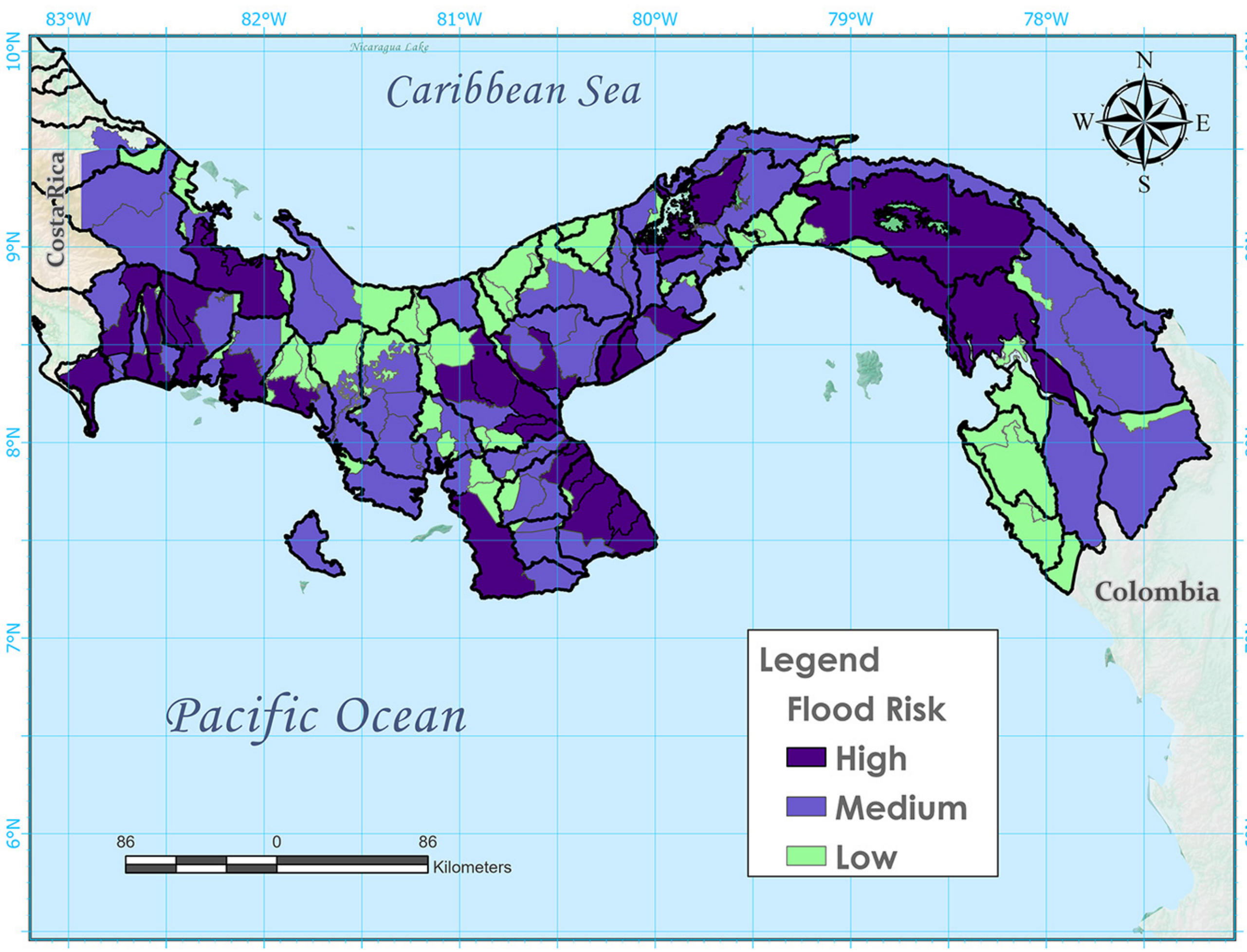

Fig. 7: Spatial distribution of flood risk according to municipality classification for each watershed in Panama.

Discussion

Based on the obtained results, a total of 36 catchments were classified as high-risk for flooding across the Central American countries. These include 6 in Honduras, 13 in El Salvador, 4 in Costa Rica, and 14 in Panama.

Flood risk in Honduras

The study's findings align with the UNDAC Assessment Missions Report for Storms Eta and Iota (December 15, 2020) and the Evaluation of the Effects and Impact of Tropical Storm Eta and Hurricane Iota in Honduras by ECLAC and the Inter-American Development Bank (ECLAC, 2021).

Table 4

Catchments and municipalities classified with high flood risk for Panama.

Name of the catchment	Municipality
Ríos Coto y Vecinos	Barú
Río Chiriquí Viejo	Tierras Altas, Bugaba
Río Escárrea	Alanje
Río Chico	Alanje, Boquerón
Río Chiriquí	David, Dolega, Boquete
Ríos Entre Tabasará y San Pablo	Soná (Riesgo medio)
Ríos Entre Tonosí y La Villa	Pedasí, Pocrí, Las Tablas, Guararé, Los Santos
Río La Villa	Chitré, Los Santos
Río Parita	Chitré
Río Santa María	San Francisco, Calobre, Aguadulce, Santa María, Parita
Río Grande	Agua dulce (Medium risk)
Ríos Entre El Antón y El Caimito	Antón, Chame
Río Caimito	La Chorrera (Medium risk), Arraiján (Medium risk)
Río Caimito y entre El Indio y El Chagres	Chagres (Medium risk)

These reports highlight municipalities affected by floods, many of which are classified as high-risk in this study. Notably, floods have been the most frequent disaster event from 1970 to 2019, with 36 events affecting 1,790,300 people, primarily due to extreme river flows, floods, and excessive rainfall. The Sula Valley, including municipalities like El Progreso, Puerto Cortes, El Negrito, and La Lima, experienced flooding events and is categorized as high-risk in the Chamelecón, Ulua, and Lean catchments (Quesada-Román et al., 2024b).

Suárez and Sánchez (2012) indicate a rising trend in hydrometeorological events, with floods being the most recurrent. These events impact many people due to a lack of risk management strategies, inadequate rural and urban planning, and significant demographic growth in high-risk areas. This study identifies opportunities for preventive measures in these high-risk areas. The Motagua, Chamelecón, Ulua, Nacaome, Choluteca, and Río Negro catchments are notable for their high flood risk, encompassing municipalities with varying risk levels (ECLAC, 2021, 2022; UNDP, 2022; World Bank, 2018). This highlights the need for targeted adaptation and mitigation measures based on the geographical and socio-economic characteristics of each area.

This study's results for Honduras show that flood impacts are concentrated in regions identified as high-risk. Affected municipalities include those in the central-southern corridor, central-western region, northwestern region, northern region, and eastern region in the Department of Gracias a Dios. The departments of Cortes, Santa Barbara, Lempira, Yoro, Colon, Gracias a Dios, Valle, and Choluteca, as well as the central Municipality of Distrito Central, frequently experience flooding. These areas belong to high or medium flood risk catchments, including Ulua, Chamelecón, Lempa, Aguan, Patuca, Coco or Segovia, Kruta, Plátano, Goascorán, Nacaome, and Choluteca.

Table 5

Catchments with high flood risk at the regional level.

Name of the catchment	Municipalities classified as high-risk within the catchment.	Maximum risk value
Río Ulúa	San Agustín, San Marcos, Gracias, San Rafael, Santiago de Puringla, Lejamaní, Siguatepeque, San Jerónimo, La Libertad, Las Lajas, Potrerillos, Pimienta, El Progreso, El Negrito, San Manuel, La Lima.	1
Río Lempa	Santa Ana, Ciudad Arce, Sacacoyo, Colón, Aguilares, Apopa, Mejicanos, San Salvador, Cuscatancingo, Delgado, Soyapango, Tonacatepeque, El Carmen, Berlín y Santa Lucía.	1
Río Grande de Tárcoles	Goicochea, La Unión, Curridabat, Desamparados, Alajuelita, San José, Tibás, Santo Domingo, San Pablo, Flores, Alajuela, Grecia, Palmares.	1
Río Jiboa	Ilopango, San Pedro Masahuat, San Luis Talpa	0.75
Nacaome	Nacaome, San Lorenzo, Marcovia	0.75
Río Paz	San Francisco Menéndez, Ahuachapán.	0.71
Río Grande de San Miguel	San Miguel, El tránsito, Concepción Batres.	0.69
Jaltepeque	San Luis la Herradura, Santiago Nonualco, San juan Nonualco, Zacatecoluca, Tecoluca.	0.67
Bahía de Jiquilisco	San Dionisio, Jiquilisco.	0.58
Río Choluteca	El Paraíso, Apacilagua, Santa Ana de Yusguare, Namasigüe	0.57
Río Chamelecón	Veracruz, San Nicolas, San Antonio, Florida, Macuelizo, Choloma, Puerto Cortés, La Lima	0.55

The vulnerability in these catchments and their municipalities is exacerbated by continuous impacts, low human development levels, and low purchasing power. Ineffective recovery and reconstruction policies and low resilience further weaken local economies, forcing people to settle in exposed areas and increasing the need for reconstruction efforts.

Flood risk in El Salvador

The Flood Risk Analysis in Priority Catchments and Flood Risk Profile presented by the Inter-American Development Bank (IDB) in 2016 uses a methodology similar to this study, focusing on quantifying losses. The IDB document maps flood-prone areas, highlighting high susceptibility along the Pacific Ocean and near major rivers and lakes. The departments of Usulután, San Miguel, La Unión, La Paz, Sonsonate, and Ahuachapán are identified as high-risk by the IDB, aligning with the findings of this study for the San Miguel, Jiquilisco Bay, Jaltepeque Estuary, Jiboa, Comalapa, and Paz River catchments.

Historically, floods have been recurrent in San Salvador, a municipality identified as high-risk in this study. Records from 1915 to 2015 attribute causes to urban expansion, soil impermeabilization, geomorphological accidents, inadequate stormwater drainage, and institutional failures. Marineros and García (2021) report that from 1900 to 2020, El Salvador experienced frequent and impactful earthquakes, floods, and debris flows. Significant flood events have occurred in the lower Lempa catchment, where municipalities like Berlín are high risk, while San Vicente, Mercedes Umaña, and Tecoluca are medium risk.

El Salvador's most flood-susceptible areas are typically in the lower parts of catchments, near coastal zones, river mouths, reservoirs, and lagoons. Examples include southern Ahuachapán and Sonsonate, the coastal zone facing the El Bálsamo mountain range, the lower Jiboa River catchment, Jalponga, Jaltepeque Estuary, the lower Grande de San Miguel River catchment, Jiquilisco Bay, and the main rivers' banks in the Lempa River catchment (MARN, 2010).

Hurricane Julia's passage highlighted municipalities at risk of flooding: Pasaquina, Conchagua, Intipucá, Chirilagua, San Dionisio, Puerto El Triunfo, Jiquilisco, Tecoluca, San Pedro Masahuat, San Luis La Herradura, San Luis Talpa, La Libertad, Tamanique, Teotepeque, Acajutla, San Francisco Menéndez, and Jujutla. These align with those classified as high and medium risk in this study.

Flood risk in Costa Rica

The cartography presented in this report aligns with the findings for Costa Rica, highlighting high hazard values in the municipalities within the San Juan, Tortuguero, Bebedero, and Tempisque catchments, as well as those in the Nicoya Peninsula and Northern Zone catchments. Medium hazard values are observed in the La Estrella, Térraba, and Osa Peninsula catchments. According to Quesada-Román (2022a), municipalities in the San Juan, Tortuguero, Tempisque, Tusubres, Parrita, and Damas catchments are categorized as high flood risk areas. This study also identifies additional high-risk municipalities in the Sixaola River, Térraba, Grande de Tárcoles, and Nicoya Peninsula catchments. Historically, these regions have experienced flooding and have been extensively studied (Quesada-Román, 2017; Villalobos et al., 2024). In urbanized areas, factors such as road and population density, coupled with the proximity of rivers, increase vulnerability and the likelihood of floods (Acosta-Quesada and Quesada-Román, 2025; Garro-Quesada et al., 2023; Quesada-Román, 2022b; Quesada-Román et al., 2021).

Arroyo-González (2011) studied the incidence of hydrometeorological events, and his study shows the number of floods per district for each province. For San José, many records are seen in the Desamparados, Pérez Zeledón, and Santa Ana municipalities (Quesada-Román et al., 2023a). In the Puntarenas province, they are observed in the Puntarenas, Aguirre, and Golfito municipalities; for Alajuela, they are observed in the Alajuela, San Carlos, and Upala municipalities; for Heredia, they are observed in the Heredia, Sarapiquí, and Flores municipalities; for the Cartago province, they are observed in the Cartago, La Unión, and Turrialba municipalities; for the Limón province, they are observed in the Limón, Siquirres, Pococí, and Matina municipalities; and for the Guanacaste province, they are observed in the Carrillo, Liberia, Nicoya, Santa Cruz, Cañas, and Nandayure municipalities. Most of these municipalities are classified as high flood risk using the methodology employed here, with only a few of them assigned a medium flood risk (Orozco-Montoya et al., 2022; Quesada-Román et al., 2023b). According to climate change scenarios for the mid-21st century, greater floods are projected, especially in the Pacific slope (Hidalgo et al., 2024).

Flood risk in Panama

The methodology used in this study aligns with the findings from the Ministry of Environment of the Republic of Panama's 2022 diagnosis of flood-prone areas. Both studies utilize data from the Disaster Inventory System, DesInventar, and identify similar high-risk areas impacted by hydrometeorological events. Key areas include Tierras Altas in Chiriquí (high risk), Bocas del Toro, Panama City (medium risk), West Panama (La Chorrera and Chame, high risk), Darien (Santa Fé, high risk), and Panama (Chimán and Chepo, high risk). Lince (2023) in the Panama Flood Plan also presents a map of flood susceptibility, identifying five major flood areas consistent with this study. These areas include La Chorrera and Colón (both high risk), Tonosí (with Mariato and Tonosí classified as high and medium risk, respectively), and municipalities such as Barú, Bugaba, and Alanje (high risk).

From 1990 to 2013, floods accounted for 57% of natural events in Panama, causing the most deaths and significant losses in housing and infrastructure (Gordon, 2014). Gordon's cartography aligns with the high-risk municipalities identified in this study. An analysis of DesInventar data confirms Panama's high exposure to natural disasters, with over 100,000 homes and 1.5 million people affected in the last four decades (23 years). Quesada-Román et al. (2024c) also describe floods, landslides, and strong winds as the most recurrent natural hazards in Panama.

This research is significant as recent studies on flood risk in Latin America and the Caribbean, indexed in the Web of Science (WoS) database, lack citations for the Republic of Panama (Pinos and Quesada-Román, 2022). Through precise statistical analysis, geotechnologies, and available techniques, this study provides unprecedented and accurate results, effectively identifying and delimiting flood risk areas in Panama (Rivera-Solís, 2022). Risk assessment studies involve analyzing hazards, exposure, and vulnerability, making the resulting risk map an effective tool for land use planning and risk management (DG-SINAPROC, 2022).

Conclusions

The analysis conducted in Central America serves as a pertinent illustration of the methodological challenges and opportunities in flood risk assessment, yet its findings extend far beyond this region. The identified lack of hazard mapping and risk analysis, particularly in the context of floods, underscores a pervasive issue globally. The absence of detailed municipal-level maps highlights a critical knowledge gap in disaster risk management, necessitating urgent action on a broader scale. To address these methodological challenges, decision-makers are encouraged to prioritize the development and implementation of comprehensive flood risk assessment methodologies. This includes improving hazard mapping techniques and conducting regular risk analyses using updated data sources. Allocating resources towards the creation of detailed hazard, vulnerability, and exposure maps at the municipal level is imperative for enhancing risk assessment accuracy and effectiveness.

There are several key recommendations for the future application of this methodology. Firstly, fostering greater collaboration and engagement among stakeholders, including local communities, is essential for refining and validating flood risk assessment methodologies. Empowering communities to participate in flood prevention and response efforts not only strengthens local resilience but also enriches the data available for risk assessment. Secondly, investments in technological advancements, such as resilient infrastructure and early warning systems, are integral to enhancing flood risk management capabilities. By leveraging innovative tools and methodologies, decision-makers can better understand and mitigate the impacts of floods, safeguarding lives, and livelihoods worldwide. Lastly, while the study's focus on Central America offers valuable insights, its methodological implications extend to diverse geographical contexts. Therefore, future applications of this method should consider adapting and refining the approach to suit the specific needs and challenges of different regions. Overall, by addressing methodological challenges and adopting comprehensive flood risk assessment approaches, decision-makers can enhance disaster resilience and protect vulnerable communities globally.

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