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Flood and landslide risk mapping based on a multi-criteria analysis (MCA) in Greater Abidjan (Côte d'Ivoire)

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Abstract. This study presents a multi-hazard risk assessment of flood and landslide hazards in the Greater Abidjan metropolitan area of Côte d'Ivoire, aimed at enhancing disaster risk reduction strategies in data-poor contexts. Using a semi-quantitative approach within a multi-criteria decision-making framework, specifically the Analytic Hierarchy Process (AHP), we assess both hazard and vulnerability factors contributing to flood and landslide risks, incorporating climatic, environmental, and social aspects. An innovative validation method is introduced, leveraging a multi-source database of past disaster events in the region, combining information from well-established disaster loss databases and results from field surveys, thereby enhancing the robustness and reliability of the results. The findings identify risk-prone areas within Greater Abidjan and provide actionable insights for improving disaster risk management. This approach, which builds on previous research by incorporating both flood and landslide risks, advances a multi-hazard perspective and contributes to a deeper understanding of hazard dynamics in Greater Abidjan. It also offers a model that can be applied to similar urban settings across sub-Saharan Africa.

1 Introduction

In 2022, many tropical areas of sub-Saharan Africa experienced heavy rainfall during the rainy season, leading to significant flooding and landslides. According to IFRC (2022), these events have caused human losses and material damage and exacerbated the precariousness of a significant proportion of the population's economic activities. In West Africa, these environmental hazards have significantly impacted communities and their livelihoods, as well as infrastructure, disrupting access to services and humanitarian aid. A year later, in September

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and October 2023, approximately 299,000 people were affected by flooding in 10 countries in the region (OCHA, 2023). These events have boosted the scientific research aimed at assessing natural hazard risks in the region as well as supporting the implementation of successful disaster risk reduction strategies.

In Côte d'Ivoire, much of the existing research on natural hazard risk focuses on the Autonomous District of Abidjan (DAA), the administrative and political centre of the country, and one of the largest French-speaking cities in the world after Paris (OECD, 2015). The Greater Abidjan metropolitan area, located along the Gulf of Guinea in West Africa in the south of the country, covers approximately 4,000 km² and includes the DAA along with its surrounding peripheral areas. As part of a strategic project endorsed by local authorities, this region has undergone rapid expansion, cementing its position as the economic capital of Côte d'Ivoire. Hosting a significant proportion of the nation's urban population, Greater Abidjan's coastal geography and dense population make it highly susceptible to various hazards, particularly flooding and landslides (Kangah and Della, 2015). The frequency and severity of flooding and landslides in the region have escalated in recent years, highlighting an urgent need to develop more effective multi-hazard risk management strategies.

Despite the growing body of research (see, for example, Dewan, 2013; Shah and Shah, 2023), risk assessments in Côte d'Ivoire, as in other data-poor contexts, often focus on single hazards, are spatially fragmented, or address only very small hotspots. Furthermore, many studies fail to incorporate the multiple criteria that contribute to risk and frequently rely on limited datasets, resulting in a significant gap with regard to comprehensive, multi-hazard assessments (Kappes et al., 2012; Mahato et al., 2025; White et al., 2024). This study aims to fill this gap by providing a thorough assessment of flood and landslide risks across the entire Greater Abidjan metropolitan area, including climatic, environmental, and social factors. The objective is to enhance our understanding of these risks and lay the groundwork for effective multi-hazard disaster risk management and mitigation strategies.

According to the United Nations Office for Disaster Risk Reduction (UNDRR, 2022), risk assessment methods can be divided into three main approaches. The quantitative approach uses mathematical models to quantify risks based on hazard, exposure, vulnerability, and adaptive capacity data. The semi-quantitative approach combines quantitative models, semi-quantitative indicators, and qualitative information. The qualitative approach is based on expert judgment and stakeholder input. In a data-poor context, as is the case in the Greater Abidjan region, our methodology is oriented towards a semi-quantitative and parametric approach (Balica et al., 2013; Shah and Shah, 2023), using available data and indicators validated by the scientific literature. Our methodology is supported by a Multi-Criteria Decision-Making (MCDM) framework, in particular the AHP (Analytic Hierarchy Process) developed by Saaty (1987). The AHP is a mathematical decision-making tool used to solve complex problems. It

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helps prioritise chosen criteria by assigning user-defined weights to a hierarchical structure of criteria and sub-criteria.

This method identifies the most relevant components based on the specific needs and understanding of the problem, offering valuable insights into the system under investigation. Widely used in the analysis of risks related to natural hazards (see, for example, Majeed et al., 2023; Morales and de Vries, 2021), the Analytic Hierarchy Process (AHP) facilitates the identification, weighting, and prioritisation of key risk factors using available data and insights from the scientific literature. AHP is particularly well suited for data-scarce regions such as Greater Abidjan, where conventional quantitative risk assessment methods are often impractical due to the lack of consistent, high-resolution datasets. The method offers a transparent and reproducible decision-making framework, allowing experts to integrate qualitative knowledge and local context into the analysis. The results of this study will not only deepen the understanding of risk dynamics in Greater Abidjan but also support broader disaster risk reduction (DRR) strategies applicable to similar rapidly urbanising coastal areas in West Africa.

In the Ivorian context, the study by Danumah et al., 2016 was among the first to apply the Analytic Hierarchy Process (AHP) to assess flood risk in the District of Abidjan, focusing on a single-hazard perspective and emphasizing the role of physical-environmental criteria in determining flood susceptibility. Building on their methodological foundation, our research goes further by adopting a multi-hazard assessment framework that integrates both flood and landslide risks: two interrelated hazards increasingly prevalent in the Greater Abidjan region due to rapid urban expansion and land use changes.

Recent advances in disaster risk science highlight the necessity of transitioning from single-hazard analyses to multi-hazard and systemic approaches that account for cascading effects, spatial interdependencies, and the compounding nature of environmental risks (Gallina et al., 2016; Hürlimann et al., 2024). In this regard, our approach responds to the call for more comprehensive, spatially explicit risk assessments that integrate diverse hazard processes and their socioecological drivers (Tuo et al., 2025). Unlike traditional models that focus on urban cores (Danumah et al., 2016), our study also shifts the analytical scale by extending the spatial coverage beyond the central urban district (2,119 km²) to encompass the entire Greater Abidjan planning zone (4,311 km²), in accordance with the 2016 administrative reform. This broader lens enables us to capture the increasing exposure of peri-urban and even rural fringe zones where planning regulations are weaker and vulnerability is often greater due to informal settlements and lack of basic infrastructure (UNDRR, 2015).

Furthermore, this expansion reflects a growing consensus in climate risk research that stresses the importance of territorialised and inclusive risk governance frameworks, particularly in regions undergoing intense demographic and spatial transformations (Coulibaly et al., 2024; Kouamé and Kouassi, 2023). By means of an AHP-based multi-risk assessment examining the dynamics of uneven urban expansion, our study offers a more realistic and policy-relevant understanding of hazard exposure and vulnerability across the metropolitan continuum of Abidjan. AHP has also proven effective in structuring complex risk assessments, a critical limitation lies in the validation of its outputs. Many prior applications do not compare risk maps to real-world disaster records, which weakens the evaluation of predictive accuracy (Munier and Hontoria, 2021; Phakonkham et al., 2021). To overcome this gap, our approach introduces an innovative validation component: a geo-referenced database of observed past events, compiled from multiple sources including national reports, humanitarian data platforms, and remote sensing-based event detection.

By cross-referencing AHP-derived risk zones with the historical spatial distribution of actual disasters, we are able to assess the model's reliability and robustness in the specific context of Greater Abidjan. This methodological enhancement not only strengthens the credibility of the results but also situates our study at the intersection of expert-based assessment and empirical verification - an essential step toward in terms of operational risk mapping in West African cities experiencing rapid, unplanned urbanisation. AHP is widely used in hazard assessment, its results are often difficult to validate against real-world observations. Comparing risk maps with actual disaster occurrences is rarely performed, thus making the assessment of the model's predictive accuracy challenging. To address this, our approach incorporates an innovative validation method, leveraging a comprehensive, multi-source database of past events in the region. This integration enhances the robustness and reliability of our findings, ensuring a more accurate representation of hazard-prone areas.

The paper is organised as follows: in Section 1, we discuss the hazard and vulnerability factors that contribute to flood and landslide risks for human populations in Greater Abidjan. Section 2 presents the AHP methodology used to identify and assess these risks in our case study area, along with a description of the innovative multi-source validation approach we have developed. In Section 4, the results obtained are presented. Our conclusions and final remarks concerning future research perspectives are provided in Section 5.

2 Understanding hazards and vulnerabilities in Greater Abidjan

Due to its geographical location and rapid urbanisation, Greater Abidjan is highly vulnerable to natural hazard risks, particularly flooding and landslides. These risks are further exacerbated by climate change and human activity. This section analyses both the hazard and vulnerability factors that contribute to these risks, focusing on the climatic, geological, and societal aspects that make Greater Abidjan particularly susceptible to the adverse impacts of flooding and landslides.

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2.1 Climatic factors contributing to flood and landslide hazards

As a result of the global rise in temperatures, the sixth IPCC report highlights an intensification of rainy episodes during monsoon periods in many regions (IPCC, 2023). In Greater Abidjan, heavy rainfall has been identified as a primary natural hazard, often triggering floods and landslides that result in significant loss of life, extensive infrastructure damage, and displacement of communities (Danumah et al., 2016). Understanding heavy rainfall trends is therefore essential in order to anticipate and mitigate hydrological risks such as floods and landslides (see, for example, Kpanou et al., 2021).

However, this task remains challenging due to the high spatial variability of precipitation and the limited availability of high-quality data, whether from direct observations or model outputs (Gbode et al., 2019). The study recently conducted by Yao et al. (2024) helps to fill this gap: their results, based on an academic raingauge network mainly located in the urbanised area of Abidjan district, indicate the key role of the long rainy season and in particular the highest cumulative rainfall periods (HCRPs) over 60 days with regard to the risk of flooding. Rainfall is heavier during the HCRPs of the long rainy season, especially the extremes, with 100% of total floods occurring between the end of April and the beginning of July. According to Yao et al. (2024), it seems that the increase in flooding in Abidjan District is not due to an intensification of daily rainfall but rather to soil sealing linked to urbanisation and the weaknesses of drainage infrastructures.

Kpanou et al. (2021) also demonstrated the particularity of the coastal belt marked by extreme rainfall especially in the May-July period, with the month of June recording the highest rainfall intensity characterised by a strong spatial gradient from the coast to the interior of the continent (see Figure 1). A better appraisal of the atmospheric disturbances associated with these extreme rainfall events and their interaction with sea breezes is crucial in order to elucidate this particularity (Kpanou et al., 2021).

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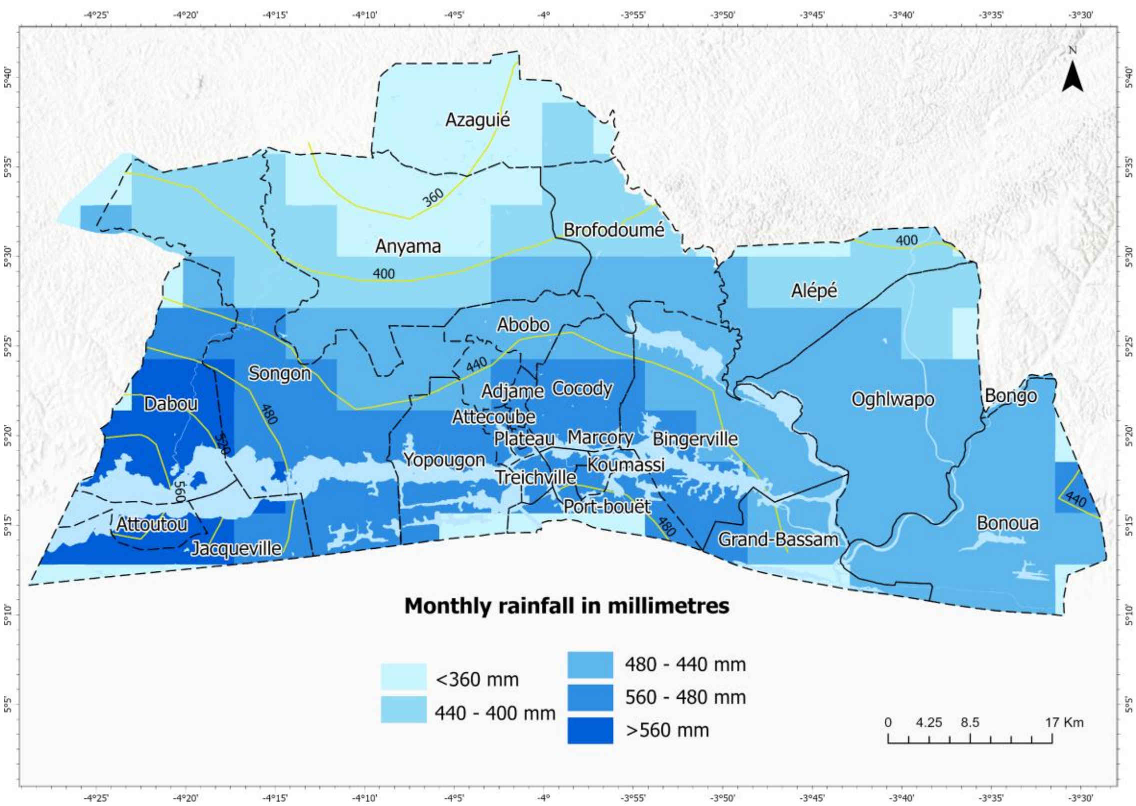

Figure 1: Spatial distribution of rainfall in the month of June, over the period 1991-2020 (data source: https://www.chc.ucsb.edu/data/chirps).

2.2 Geological conditions conducive to landslides

The study area is characterised by a variety of geomorphological features. Among these, the deep depressions located upstream of the Ébrié Lagoon contribute to the increased risk of landslides. The Ébrié Lagoon (named after the Ébrié people, an ethnic group indigenous to the area) is a large, shallow inland water body in Côte d'Ivoire, separated from the Atlantic Ocean by a narrow land strip. The lagoon is influenced by tidal movements and river inflows, playing a key role in the region's hydrological system. The depressions located in its upstream part, often composed of loose and water-saturated soils, provide ideal conditions for the triggering of mass movements. In addition, the presence of steep slopes associated with a complex stratigraphy, primarily consisting of clays and shales, aggravates the instability of the hillsides (Blache, 1941; Tastet and Guiral, 1997).

The abundant monthly rainfall in this region during the month of June (the year's most intense period of rainfall) (see Figure 1) further exacerbates the susceptibility of these areas to landslides. These geological and climatic

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phenomena, combined with human activities such as deforestation or unregulated construction, make the environment particularly vulnerable to landslides.

2.3 Socioeconomic vulnerability factors

Greater Abidjan, which hosts a large part of the country's economic, administrative, and residential activities, is highly vulnerable to natural hazards. The region's vulnerability is exacerbated by rapid urbanisation, inadequate infrastructure, and the impacts of climate change. Assessments of social vulnerability in urban Côte d'Ivoire have identified factors such as population density, settlement patterns, and socioeconomic conditions as key contributors to the region's susceptibility to flooding (Kablan et al., 2017).

Among these factors, population density plays a major role. The high population density resulting from overcrowding can lead to numerous problems. Specifically, in the area under study, urban areas are densely populated according to the latest population census conducted in 2021 by the National Institute of Statistics of Côte d'Ivoire (INS-CI, 2021). The most densely populated communities identified were Abobo, Attécoubé, Koumassi, Marcory, with respective population densities of 28.408; 24.087; 19.421; 11.005; and 6.137 inhabitants per square kilometre. These areas experience a high mortality rate due to hazards during the rainy season (Kangah and Della, 2015).

3 Methodology

The mapping of flood and landslide risks for populations in Greater Abidjan is performed by applying the AHP technique, integrating flood, landslide, and vulnerability indicators, and is validated through a multi-source approach that combines field data with records from available disaster loss databases. The implementation of the AHP modelling proceeds via the processing chain depicted in Figure 2, tailored to the context and objectives of this study.

The AHP, developed by Saaty (1987), is a decision-making framework widely used in various fields such as finance, political science, and engineering. Its flexibility enables the integration of both quantitative and qualitative criteria into a hierarchical structure. The AHP employs a pairwise comparison matrix, assigning weights to the criteria based on their relative importance using a scale of 1 to 9, where 9 denotes the highest significance. The final results are computed through weighted aggregation, expressed mathematically as:

$$OI = \sum_1^n W_i X_i \quad (1)$$

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Where OI is the option index, n is the total number of criteria, W_i is the weight assigned to each criterion, and X_i is the individual assessment of each criterion.

To ensure the reliability of the results, it is essential to evaluate the consistency of the judgments made in the pairwise comparisons. This is achieved by calculating the Consistency Index (CI), which measures the degree of inconsistency in the judgments. Inconsistencies may arise if a criterion is evaluated inconsistently with respect to others. The CI helps identify any flaws in the calculations and evaluations, thereby ensuring the robustness and reliability of the decision-making process. The Consistency Ratio (CR) is used to quantify the consistency of the matrix and is expressed as:

$$CR = CI / RI \tag{2}$$

Where RI represents the Random Index, a value defined by Saaty (1987), and CI is the Consistency Index.

For a matrix to be considered consistent, the largest eigenvalue λ_{max} should equal the number of comparisons n. The CI is calculated as:

$$CI = (\lambda_{max} - n) / (n - 1) \tag{3}$$

This generic multi-criteria analysis framework provides a systematic approach to assessing complex scenarios involving multiple, interrelated factors.

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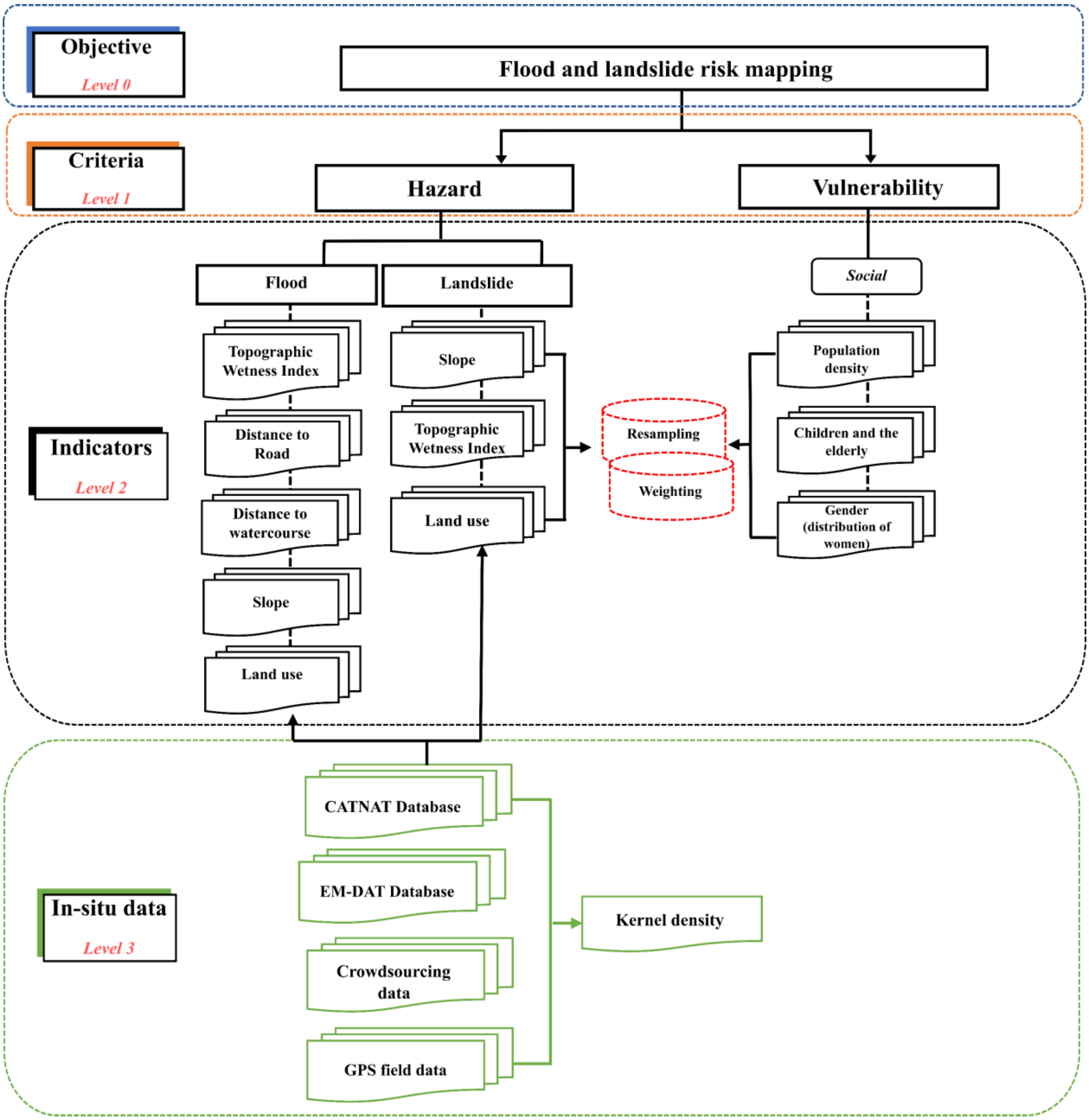

Figure 2: Hierarchical chart of the applied AHP approach.

205 For this study, the AHP framework was customised to address the specific needs of mapping flood and landslide risks in the Greater Abidjan metropolitan area. As illustrated in Figure 2, the methodology was hierarchically organised into four levels to systematically capture both hazard and vulnerability indicators. The objective of the

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AHP (Level 0) was to produce flood and landslide risk maps for Greater Abidjan. To do this, it was necessary to characterise both hazard and vulnerability risk criteria (Level 1). Each criterion was then characterised by a series of specific indicators (Level 2). Finally, all the results obtained were compared with the historical records of hazards that occurred in the region obtained by combining a diverse range of available datasets (Level 3).

Data collection, preparation, and processing to produce both hazard and vulnerability indicators was carried out using GIS software, including the use of the "suitability modeller" tool available in ArcGIS Pro. The selection of the indicators was based on the scientific literature, which helped identify the key factors influencing flooding, landslides, and vulnerability of the population in the Greater Abidjan region. The indicators were chosen for their relevance and impact, as described in previous studies. The weighting coefficients of the indicators were theoretically determined from the pairwise comparison matrix. These weights were derived through a combination of theoretical principles, insights from local knowledge, and field-specific literature, ensuring the methodology's relevance to the regional context. Once the weights for the Level 1 criteria were determined, it was essential to verify the reliability of the results. To achieve this, a consistency index was calculated to assess the consistency of the judgments made for each criterion.

Detailed descriptions of the indicators selected for flood, landslide, and vulnerability maps are discussed hereafter.

3.1 AHP for flood hazard mapping

Flooding is a complex phenomenon influenced by a combination of natural and anthropic factors. In Greater Abidjan, the topography of the region, seasonal rainfall, rapid and often poorly planned urbanisation, as well as other human activities such as the construction of dams and insufficient rainwater drainage, can all contribute to flooding. A series of key indicators contributing to the flood hazard have been identified, based on a review of the scientific literature. Table 1 presents the complete list of indicators chosen for flood hazard mapping, including their assigned weights and data sources. Additionally, the table specifies the initial and resampled spatial resolutions of the datasets used. For each indicator, the table also categorises different value classes and their corresponding scores, which contribute to the overall flood hazard assessment. A detailed description of each indicator, along with the supporting literature that guided its selection, is provided in Section 3.3.

Table 1 : Overview of indicators and metrics used for AHP for flood hazard mapping

Indicator	Classes	Score	Initial spatial resolution (metres	Resample spatial resolution (metres)	Weight	Intensity	Data source

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			and degrees)				
Topographic Wetness Index (TWI)	2.318 - 7.109	1	12.50	12.50	39.7%	Very Low	MNT ALOS PALSAR - *Japan Aerospace Exploration Agency (JAXA) "Hi-Res Terrain Corrected"*
	7.11 - 10.151	2				Low	
	10.152 - 12.823	3				Medium	
	12.824 - 15.588	4				High	
	15.589 - 25.818	5				Very high	
Slope (degrees)	<1°	1	12.50	12.50	34.7%	Very Low	MNT ALOS PALSAR - *Japan Aerospace Exploration Agency (JAXA) "Hi-Res Terrain Corrected"*
	1-5°	2				Low	
	5-9°	3				Medium	
	9-14°	4				High	
	>14°	5				Very high	
Land use	Artificial surfaces	1	10	12.50 (Nearest Neighbour method)	12.6%	Very Low	USGS - Sentinel Level - 2A *S2A-MSIL2A-20200105T103421*
	Agricultural areas	2				Low	
	Forest and semi natural areas	3				Medium	
	Wetlands	4				High	
	Water bodies	5				Very high	
Distance to stream (metres)	2,396 – 4,304 metres	1	0.0021	12.50 (Nearest Neighbour method)	6.7%	Very Low	HydroRIVERS *Delineation of the global river network*
	1,704 – 2,396 metres	2				Low	
	1,046 – 1,704 metres	3				Medium	

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	523 - 1 046 metres	4				High	*derived from HydroSHEDS data at a resolution of 15 arcseconds*
	0 - 523 metres	5				Very high	
Distance to Road (metres)	7,132 – 11,511 metres	1	0.0021	12.50 (Nearest Neighbour method)	6.3%	Very Low	Open Street Maps-*Major Roads*
	4 784 - 7 132 metres	2				Low	
	2,889 – 4,784 metres	3				Medium	
	1,218 – 2,889 metres	4				High	
	0 – 1,218 metres	5				Very high	

In the case of the flood hazard, the CR is 1.3%, which is less than 10%, indicating that the pairwise comparison matrix reported in Table 2 is consistent.

Table 2 : Pairwise comparison matrix for flood hazard mapping

	Distance to watercourse	TWI	Slope	Land use	Distance to Road
Distance to watercourse	1	1.00	5.00	5.00	5.00
TWI	1.00	1	3.00	5.00	5.00
Slope	0.20	0.33	1	2.00	3.00
Land use	0.20	0.20	0.50	1	1.00
Distance to Road	0.20	0.20	0.33	1.00	1
Sum	2.60	2.73	9.83	14.00	15.00

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3.2 AHP for landslide hazard mapping

In the specific case of Greater Abidjan, the choice of criteria for the development of the AHP with regard to landslide hazard mapping focused on internal factors such as the value of the slopes, which can influence the stability of the ground. For example, steep slopes are more likely to experience landslides, especially in combination with loose soils or unstable geological formations. On the other hand, external factors such as water infiltration and overloading due to dense infrastructure were chosen, which can also aggravate the risk of landslides. Rapid urbanisation and unplanned construction can compromise soil stability by disrupting natural rainwater runoff and adding additional loads on slopes. Table 2 presents the complete list of indicators chosen for landslide hazard mapping, including their assigned weights and data sources. Additionally, the table specifies the initial and resampled spatial resolutions of the datasets used. For each indicator, the table also categorises different value classes and their corresponding scores, which contribute to the overall landslide hazard assessment. A detailed description of the indicators, along with the supporting literature that guided its selection, is provided in Section 3.3.

Table 3 : Overview of indicators and parameters used for AHP for landslide hazard mapping

Indicator	Classes	Score	Initial spatial resolution (metres)	Resample spatial resolution (metres)	Weight	Intensity	Data source
Topographic Wetness Index (TWI)	2.318 - 7.109	1	12.50		43.5%	Very Low	MNT ALOS PALSAR - *Japan Aerospace Exploration Agency (JAXA) "Hi-Res Terrain Corrected"*
	7.11 - 10.151	2				Low	
	10.152 - 12.823	3				Medium	
	12.824 - 15.588	4				High	
	2.318 - 7.109	5				Very high	

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Slope (degrees)	<1°	1	12.50		48.7%	Very Low	MNT ALOS PALSAR - *Japan Aerospace Exploration Agency (JAXA) "Hi-Res Terrain Corrected"*
	1-5	2				Low	
	5-9	3				Medium	
	9-14	4				High	
	>14°	5				Very high	
Land use	Artificial surfaces	1	10	12.50 (Nearest Neighbour method)	7.8%	Very Low	USGS - Sentinel Level - 2A *S2A_MSIL2A_20200105T103421*
	Agricultural areas	2				Low	
	Forest and semi natural areas	3				Medium	
	Wetlands	4				High	
	Water bodies	5				Very high	

In the case of landslide hazard, similarly to the figure obtained for flood, the CR is 1.3%, which is less than 10%, indicating that the pairwise comparison matrix reported in Table 4 is consistent.

Table 4 : Pairwise comparison matrix for landslide hazard mapping

	Slope	Topographic Wetness Index	Land use
Slope	1	1.00	5.00
Topographic Wetness Index	1.00	1	7.00
Land use	0.20	0.14	1
Sum	2.20	2.14	13.00

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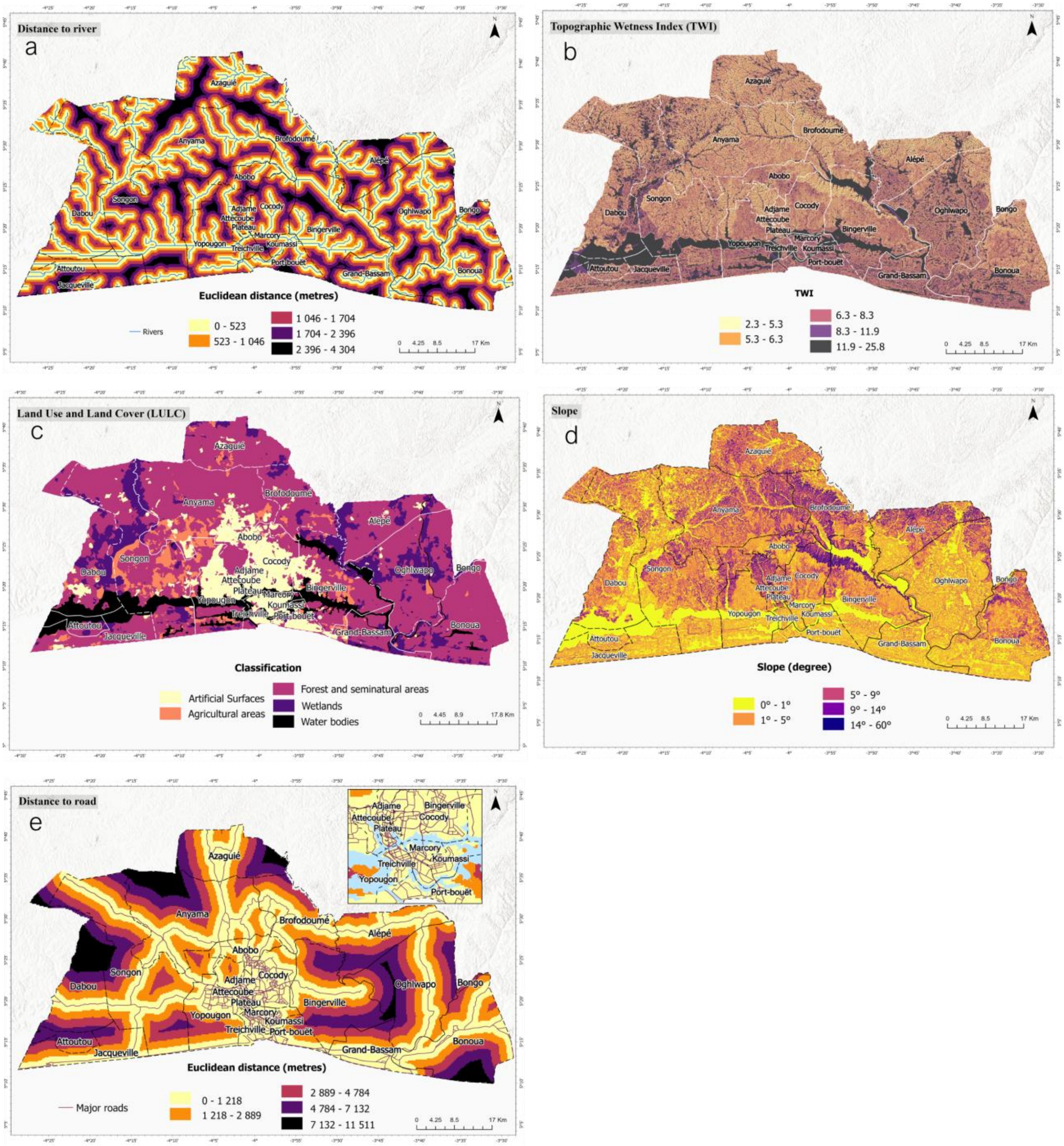

Figure 3: Hazard indicators: (a) Distance to river; (b) Topographic Wetness Index; (c) Land Use and Land Cover; (d) Slope; (e) Distance to road.

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3.3 Flood and landslide hazard indicators

The spatial distribution of the hazard indicators used to assess flood and landslide susceptibility in Greater Abidjan is shown in Figure 3. A detailed description of each indicator is provided in Section 3.3.1 to 3.3.5.

The selection of hazard indicators and their relative importance was based on key parameters derived from a comprehensive review of the literature, field observations, and expert consultations. These parameters include topographic characteristics (e.g. slope gradient, elevation, and curvature), hydrological factors (e.g. rainfall intensity, drainage density, and proximity to water bodies), geological conditions (e.g. soil type and lithology), and land use patterns (e.g. urbanisation, vegetation cover, and human activities). Furthermore, the weighting of each indicator was determined using a multi-criteria decision analysis (MCDA) approach, ensuring a robust and scientifically sound evaluation (Malczewski, 2000).

3.3.1 Distance to river

The proximity of watercourses is a key factor in the assessment of flood risk. Research by Waseem et al., 2023 points out that areas near rivers are more likely to be affected by flooding, due to their increased exposure to flash floods and overflows (Shah and Shah, 2023). The use of Euclidean distance was used to represent this criterion (Figure 3a). This measurement makes it possible to quantify the distance between a given point and the nearest watercourse, which facilitates the assessment of the degree of proximity and therefore the level of risk. The flood threshold can vary depending on a variety of factors, such as local topography, surrounding vegetation, rainfall and human activities. The criterion was ranked in fourth place with a weight of 6.7%. This choice is justified because there is a positive correlation between the proximity of watercourses and the risk of flooding.

3.3.2 The topographic wetness index

The topographic wetness index measures the capacity to evacuate water (Beven and Kirkby, 1979). Assuming these areas are in their natural state (without anthropogenic influence), the areas located south of Greater Abidjan (lowland areas) that have a high congestion index are highly likely to experience flooding (Figure 3b). In contrast, areas to the north (dominated by plateau relief) tend to have a better natural drainage capacity due to their steeper slopes, which reduces the risk of waterlogging and flooding. With a weighting of 43.5 % for landslides and 39.7% for floods in the AHP matrix, this index represents the main criterion in the AHP ranking scale. The importance of this index lies in the fact that its construction is based on multiple geographic parameters, most notably slope,

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which also plays a central role in the spatial analysis process. By integrating slope into its calculation, the index not only reflects terrain wetness potential but also captures key aspects relevant to both flood and landslide risk assessments.

3.3.3 Land use

As with the other criteria, we classified land use and land cover data into five distinct categories. This classification follows the Corine Land Cover (CLC Level 1) scheme and was carried out using our Deep Learning model applied to a Sentinel-2 (Level 2A) image (Figure 3c). The resulting categories include artificial surfaces, agricultural areas, forests and semi-natural areas, wetlands, and water bodies. Due to their contribution to soil sealing and the extensive area they occupy (422 km²), artificial spaces were assigned the highest weightings (12.6% in the case of floods and 7.8% for landslides). Agricultural areas, covering 221 km², were ranked second in terms of their economic importance and their crucial role in the economic activities of local populations (Olahan, 2010). In Greater Abidjan, despite the high level of urbanisation, peri-urban agriculture remains evident in some municipalities on the fringes of the District of Abidjan, such as Anyama, Songon, Dabou, Brofodoumé.

As for forests and natural areas, which represent 2,383 km², they were considered for their essential role in regulating water flows, preventing soil erosion, and protecting watersheds. They also help mitigate the effects of flooding by absorbing some of the excess water and reducing the velocity of flow. Finally, wetlands (495 km²) and water bodies were assigned lower weightings, given their role as water retention areas (339 km² during flood periods), making them beneficial elements for risk management.

3.3.4 Slope

"*Topography influences shallow landslide initiation through both concentration of subsurface flow and the effect of gradient on slope stability*" (Montgomery and Dietrich, 1994). Weighted at 48.7% (landslides) and 34.7% (floods), slope was identified as an important factor in the modelling (Figure 3d). Regions characterised by a steep slope, such as the one extending from the north of the commune of Abobo to Bingerville (inclination of 9° to 14°), and certain slopes in the commune of Cocody (inclination of 5° to 9°) tend to accelerate the flow of rainwater, thus increasing the risk of flooding downstream. This configuration results in Cocody becoming a rainwater receptacle area. Therefore, in the assessment, slope was ranked second. Areas with steep slopes were considered to be at increased risk.

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3.3.5 Distance to the road

Areas with a high density of roads may be more vulnerable to flooding due to certain factors. In this case, the accumulation of runoff water from impermeable surfaces. Anthropogenic factors, as a result of the dilapidated infrastructure of the wastewater and rainwater network, contribute to poor flow (Ouattara et al., 2021) and greatly increase the occurrence of hazards, particularly flooding. With floods weighted at 6.3 %, the high density of the road network within the District of Abidjan (Figure 3e), if the above-mentioned factors are to be considered, would represent a risk element.

3.4 AHP for assessing social vulnerability

According to risk assessment conventions, vulnerability is a crucial element in the assessment of areas at risk (Villagrán de León, 2006). In our methodology, we focused on the social vulnerability of Greater Abidjan, described using a series of demographic criteria. This analysis was made possible using high spatial resolution spatial data provided by META in collaboration with the Centre for International Earth Science Information Network (CIESIN). These data, widely used in scientific research (see, for example, Acosta et al., 2020; Eyre et al., 2020; Portalés-Julià et al., 2023), help address the demographic data deficit present in many countries, especially developing countries. Generated through a combination of deep learning techniques and census data, the data have a low error rate (Tiecke et al., 2017). In this study, these data enabled us to incorporate relevant social vulnerability criteria into our assessment.

Table 5 presents the list of indicators chosen for social vulnerability mapping, including their assigned weights and data sources. Additionally, the table specifies the initial and resampled spatial resolutions of the datasets used. For each indicator, the table also categorises different value classes and their corresponding scores, which contribute to the overall flood and landslide hazard assessment. A detailed description of the indicators, along with the supporting literature that guided its selection, is provided in Sect. 3.5.

Table 5 : Overview of indicators and parameters used in AHP for vulnerability mapping.

Parameters	Classes	Score	Spatial resolution (degrees)	Weight	Intensity	Data source
Population density	0.001-0.802	1	0.00083	57%	Very Low	"Data for Good at Meta"
	0.803-1.418	2			Low	

	1.419-2.035	3			Medium	High-resolution population density
	2.036-5.673	4			High	
	5.674-15.725	5			Very high	
Children and the elderly	0.001-0.802	1	0.00083	9.7%	Very Low	"Data for Good at Meta" High-resolution population density
	0.803-1.418	2			Low	
	1.19-2.035	3			Medium	
	2.036-5.673	4			High	
	5.674-15.725	5			Very high	
Gender (distribution of women)	0.001-0.802	1	0.00083	33.3%	Very Low	"Data for Good at Meta" High-resolution population density
	0.803-1.418	2			Low	
	1.419-2.035	3			Medium	
	2.036-5.673	4			High	
	5.674-15.725	5			Very high	

Table 6 : Pairwise comparison matrix for vulnerability mapping

	Population density	Children and the elderly	Gender
Population density	1	5.00	2.00
Children and the elderly	0.20	1	0.25
Gender	0.50	4.00	1
Sum	1.70	10.00	3.25

In the case of vulnerability mapping, the obtained CR is equal to 2%. Since it is less than 10%, this indicates that the pairwise comparison matrix reported in Table 6 is consistent.

3.5 Vulnerability indicators

The spatial distribution of the different indicators used to assess social vulnerability to floods and landslides in Greater Abidjan is shown in Figure 4. A detailed description of each indicator is provided in Sections 3.5.1 to 3.5.3.

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Similar to the process described for the hazard indicators (see Section 3.3), the selection of these indicators and their relative importance was based on the available literature, field observations, and expert consultations. The weighting of each indicator was determined using a multi-criteria decision analysis (MCDA) approach.

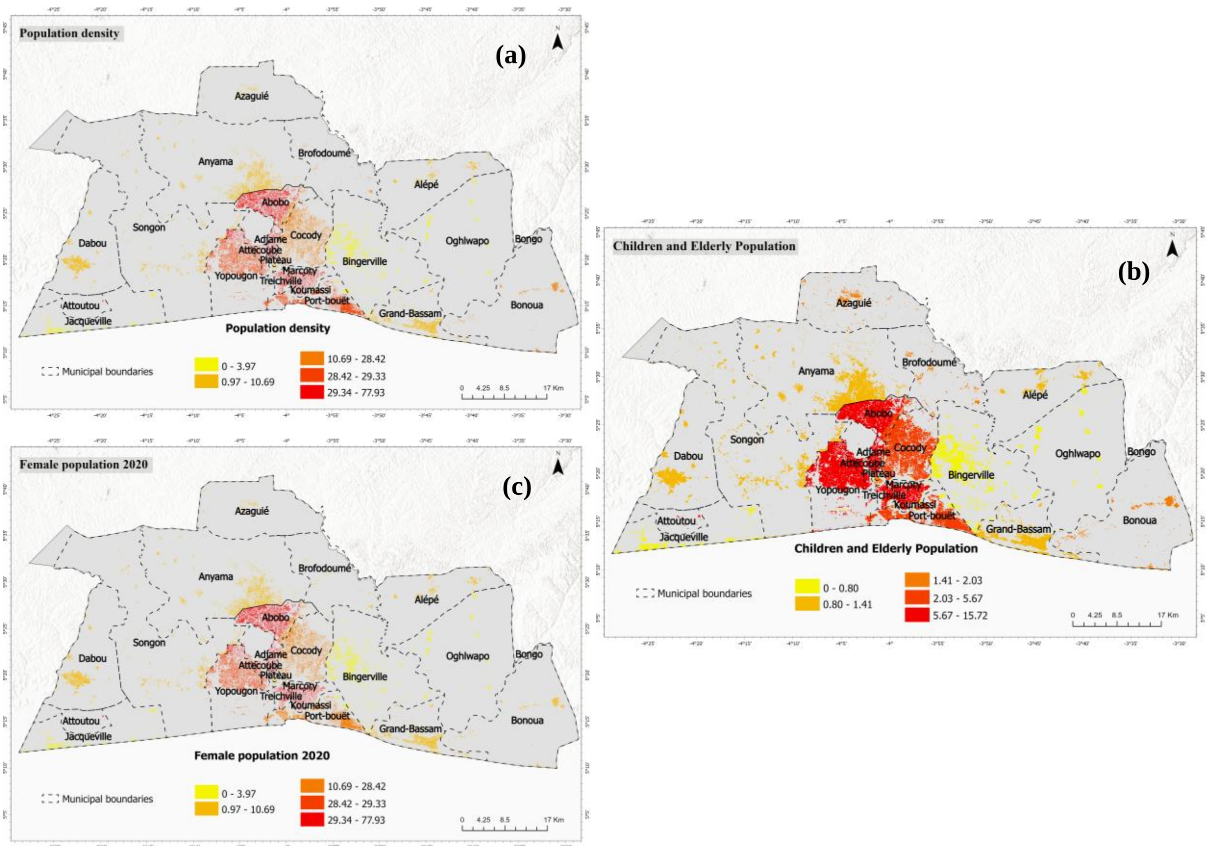

Figure 4: Gridded vulnerability indicators: (a) Population density; (b) Children and the elderly; (c) Gender - distribution of women. Mesh size: 30 m x 30 m.

3.5.1 Population density

Population density is one of the key indicators for assessing social vulnerability (Dewan, 2013). The population density indicator was chosen insofar as it allows us to identify the distribution of populations within the agglomeration (Fig. 4a). In our classification, a higher population density was assigned a greater weighting, while a lower density equated to a lower weighting figure.

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3.5.2 Children and the elderly

Older adults are highly vulnerable to natural hazards due to their limited mobility and the difficulties with regard to evacuation in an emergency (Morisaki et al., 2023). To reflect this aspect of vulnerability, we calculated the ratio of children under 5 years old to adults over 60. This ratio was then mapped across Greater Abidjan, providing a spatial distribution of age-related vulnerability, as shown in the social vulnerability maps (Figure 4b).

3.5.3 Gender

Gender is a key factor in terms of explaining vulnerability to natural hazards, especially in developing countries where sociocultural and religious constraints limit women's freedom of movement (Dewan, 2013). In Côte d'Ivoire, the low literacy rate of women increases their vulnerability. Compared to men, they are assigned to domestic tasks from an early age and have fewer opportunities to access basic education (Côte d'Ivoire, Gender Data Portal, 2025). To capture this dimension of social vulnerability, we included the distribution of women across the region as one of the three key social vulnerability parameters (Figure 4c).

3.6 Corroborating the results obtained from hazard observation

To validate the results of our risk mapping against past occurrences of floods and landslides in Greater Abidjan, we developed an innovative, multi-source database of historical events in the region. The availability of databases reporting the occurrence of natural hazards is still very limited in Côte d'Ivoire. Therefore, it was crucial to consult and integrate various sources of information to reconstruct a reliable dataset of historical floods and landslide events in the region. Our approach integrates data from various institutions: Office for the Coordination of Humanitarian Affairs, 2023; IFRC, 2022; specialised organisations (EM-DAT - The international disaster database, 2024), local and international press articles, in addition to private providers (CATNAT database, 2024), and the results of a field survey we conducted in the Greater Abidjan in October 2023.
Methodologically, all events extracted from these various sources were georeferenced and integrated into a unique database. In cases where precise georeferencing information was unavailable, cross-referencing between different sources was conducted (see Section 3.6.1). Furthermore, a data cleaning process was implemented to eliminate any potential double counting, particularly for events recorded by multiple sources. The resulting database of georeferenced flood and landslide events spanned 53 years, from 1970 to 2023, and included a total of 761 events. The occurrence of these events by municipality is reported in Fig. 5.

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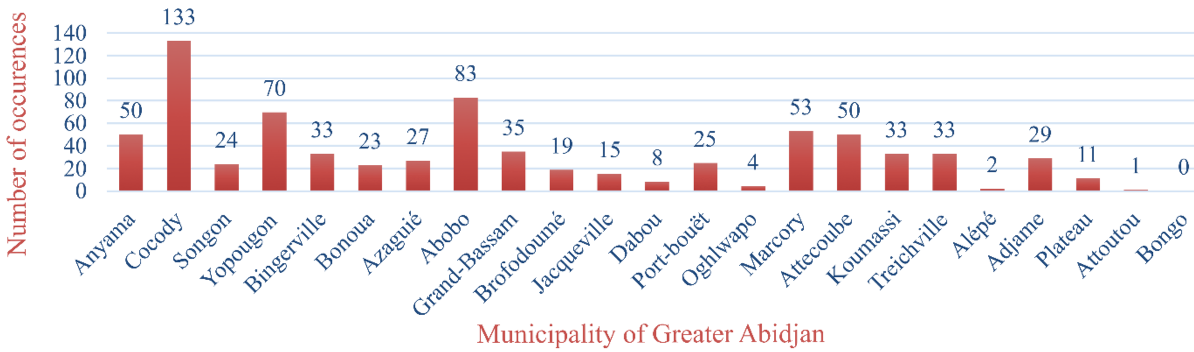

Figure 5: Occurrence of flood and landslide hazards by municipality in Greater Abidjan, based on data observations (1970-2023).

Detailed information on the methodology applied for georeferencing the EM-DAT data using crowdsourced data and the development of the field survey is provided in Sections 3.6.1 and 3.6.2, respectively. The point events from the database were analysed using the Kernel Density Estimation (KDE), a statistical method commonly applied to hazard events for identifying regions with a high concentration of occurrences (see, for example, Walczykiewicz and Skonieczna, 2020; Licata et al., 2023; Notti et al. 2023). In our case, we applied KDE using the extent of the municipalities as a parameter. This was done to ensure that events taking place in small-scale municipalities did not all get merged into a single point. By incorporating the municipal boundaries, we were able to more accurately capture the density of events within each municipality. The result is a density surface that highlights hotspots (areas with a high concentration of events) as illustrated in Figure 6. This graphical representation facilitates easier validation when compared with the outcomes of the AHP mapping.

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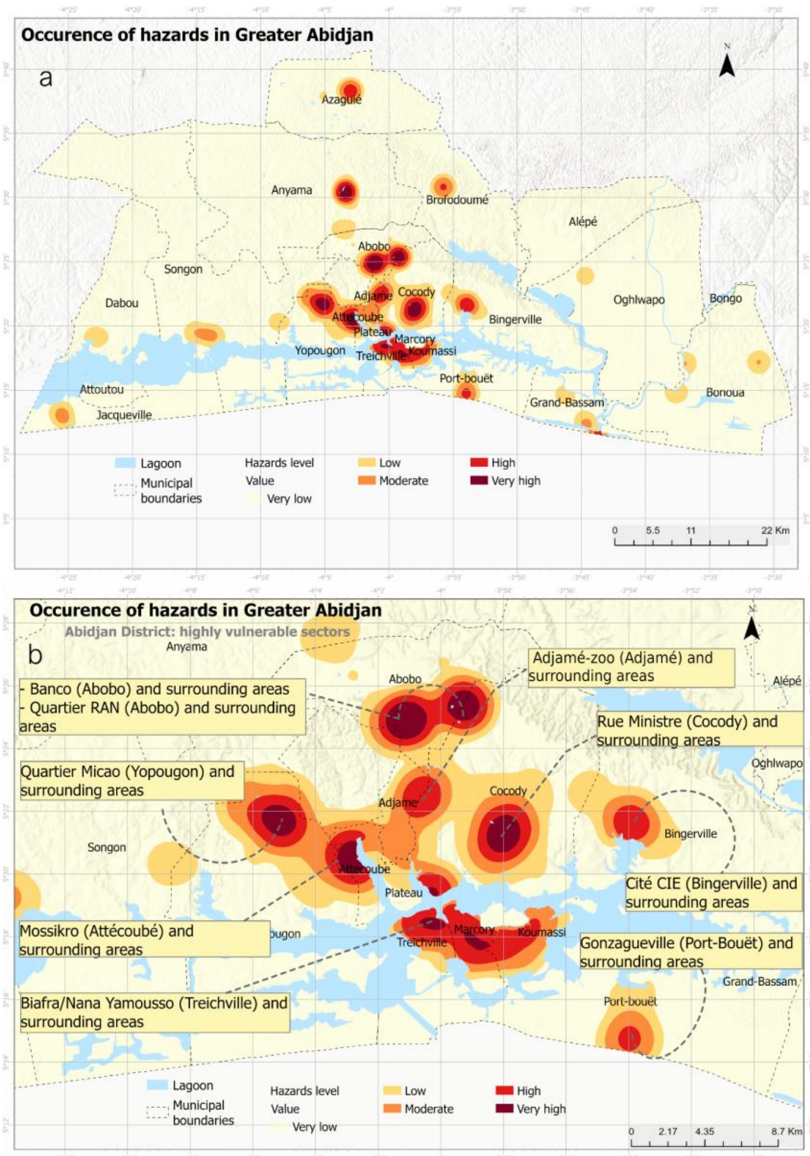

Figure 6: Occurrence of flood and landslide events from 1970 to 2023, obtained combining multiple sources of information (including disaster loss records from official databases and field survey data), at the scale of Greater Abidjan (a), and with a focus on the Abidjan district (b), where most events are concentrated.

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3.6.1 Georeferencing the EM-DAT database events using crowdsourcing data

Provided by the Centre for Research on the Epidemiology of Disasters (CRED), the EM-DAT database is an open-source resource. It gathers information on more than 26,000 mass disasters that have occurred around the world between 1900 and today. The sources of this data are diverse and include United Nations agencies, non-governmental organisations, insurance companies, research institutes, and news agencies (EM-DAT - The international disaster database, 2024).

The use of this database required a filtering process necessary as part of the methodological approach. The initial database (31 records, dating from 1970 to 2023 for Côte d'Ivoire) did not include a geographic coordinate system. Consequently, it was necessary to identify the precise locations of the recordings, based on exogenous research, from press articles; social networks such as X (formerly Twitter), using the hashtags #InondationAbidjan; #civinondation; #civ_inondations and posted by key actors in Ivorian civil society ; and various web pages of official government agencies : the Côte d'Ivoire government; the National Office of Civil Protection (ONPC); Police Secours. This also made it possible to extend our research to certain municipalities aggregated in the initial database, in order to obtain a complete database. At the end of this phase, 51 georeferenced records were identified.

3.6.2 Field survey data

To integrate local knowledge of flood and landslide occurrences in the study area, we conducted a field survey targeting local communities.

To ensure a comprehensive and representative dataset, a stratified random sampling approach was employed for the field survey. This method involves dividing the study area into distinct strata based on specific criteria (in this case, the municipalities) and then randomly selecting samples from each stratum. This technique enhances the accuracy and reliability of the survey results by ensuring that each municipality is proportionally represented according to its geographical area.

During the survey phase, we questioned residents on various aspects related to risks. One key question "Have you ever been directly impacted by natural hazards?" helped identify additional event hotspots in the study area. Out of the 512 responses collected, 129 people answered yes, 127 answered no, and 49 stated that they did not know. The 129 positive responses were integrated into other databases, allowing us to enrich our analyses and refine our observations. As a result of the field survey, we identified 129 additional events to include in the database.

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4 Results and discussion

4.1 Flood hazard mapping

In the Greater Abidjan region, flooding generally occurs as a result of the concentration of runoff water in low-lying areas. The topographical configuration of the sites and the land use make it possible to determine the areas which are most likely to be flooded. The flood susceptibility map obtained by applying the AHP approach described in Section 3 is illustrated in Figure 7. The map analysis reveals that the entire territory is affected by the risk of flooding. However, densely built-up areas, elongated depressions (valley bottoms) or closed depressions (basins), as well as the coastal plain have high rates of occurrence of these hazards. In the Greater Abidjan region, the municipalities most affected are Cocody, Attécoubé, Yopougon, and Adjamé (very high occurrence) (Traoré, 2023). In addition, the outlying areas are not spared from these risks. Areas located in the Comoé River valley to the south-east of Greater Abidjan, in particular Oghlwapo, Bonoua, and Grand Bassam to the south-east (near the estuary), are highly vulnerable to flooding.

A wide range of maps have been drawn up on the basis of hazard occurrences recorded between 1989 and 2022, making it possible to confirm the mapping results. The data added to the risk map is fairly consistent with the results obtained from the modelling.

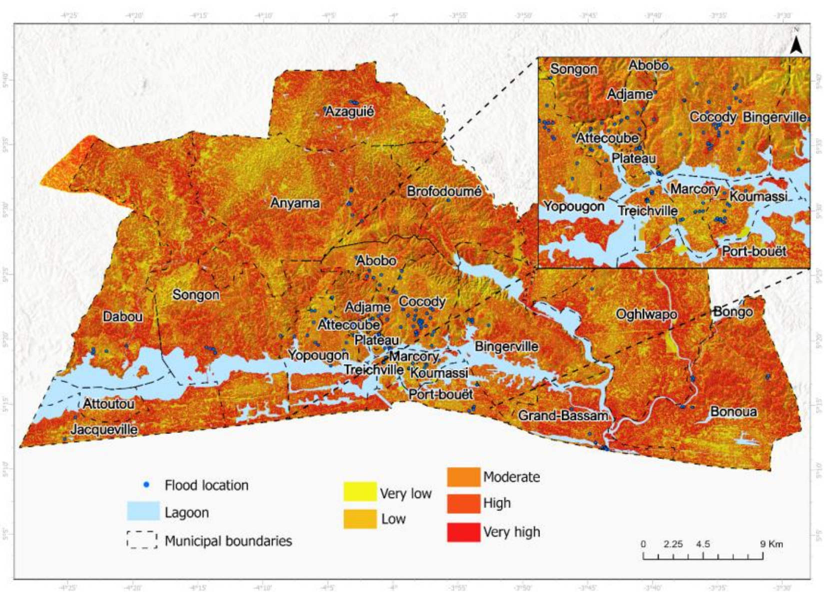

Figure 7. Flood hazard susceptibility map for Greater Abidjan.

4.2 Landslide hazard mapping

The landslide susceptibility map, obtained by applying the AHP approach described in Section 3, is illustrated in Figure 8. Areas with a landslide hazard level ranging from "moderate" to "very high" are primarily located in zones characterised by steep slopes, particularly in the northern sectors of the Bingerville municipality. The correlation between slope gradient and landslide risk is well-documented in the scientific literature, as steep slopes promote soil instability, especially during heavy rainfall (Brabb, 1985; Guzzetti et al., 1999). Similarly, areas at the bottom of valleys also emerge as high-risk zones in the mapping results. These areas are often prone to water accumulation and increased erosion, which enhances their susceptibility to ground movements (van Westen et al., 2008).

In contrast, the plains located in the southern part of Greater Abidjan, particularly in the municipalities of Marcory, Koumassi, and Port-Bouet, appear to be less vulnerable to these hazards. These areas, characterised by flat topography and gentle slopes, offer more stable conditions and are less prone to landslides (Dai et al., 2002).

We can nevertheless observe on the map that, in the centre of the study area, landslides (illustrated by red dots) occur in sectors classified as having a "low" to "moderate" level of occurrence according to our classification. This situation is mainly explained by the high level of urbanisation in these areas, which increases pressure on unstable terrain. Due to urban densification, populations settle on slopes, thereby increasing the risks of soil destabilisation and erosion, which can, in turn, amplify the frequency and intensity of landslides. These observations were highlighted in the research conducted by Andre (2013).

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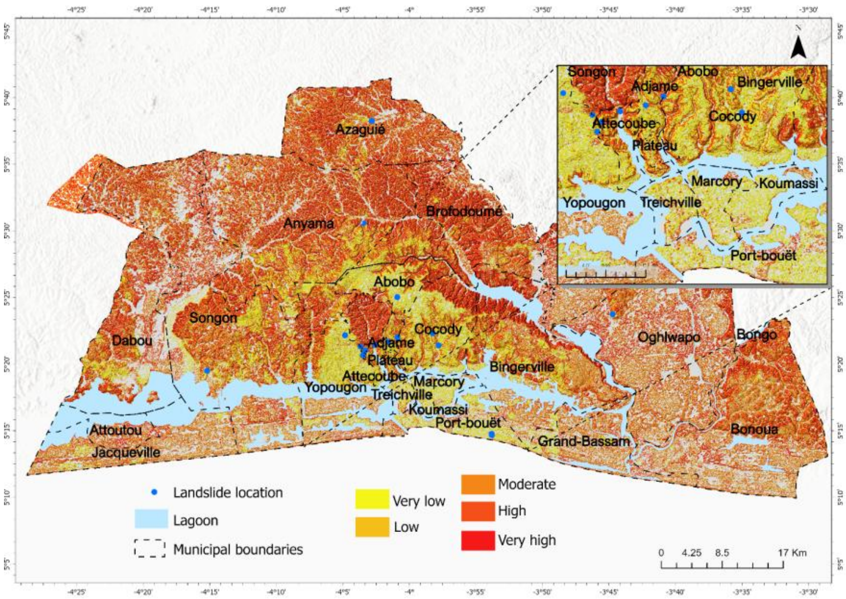

Figure 8. Landslide hazard susceptibility map for Greater Abidjan.

490 ## 4.3 Vulnerability mapping

The vulnerability map, obtained by applying the AHP approach described in Section 3, is illustrated in Figure 9. A joint assessment of the criteria selected throughout the process (population density, proportion of children and elderly people, as well as the distribution of women) reveals a striking observation: certain regions, particularly the centre of the study area, show a particularly "low" and "very low" level of vulnerability. Conversely, areas further away from the very centre exhibit a moderate to very low level of vulnerability. This observation can be explained by the spatial distribution of socioeconomic factors, access to essential services, and the differing levels of urban development across the territory.

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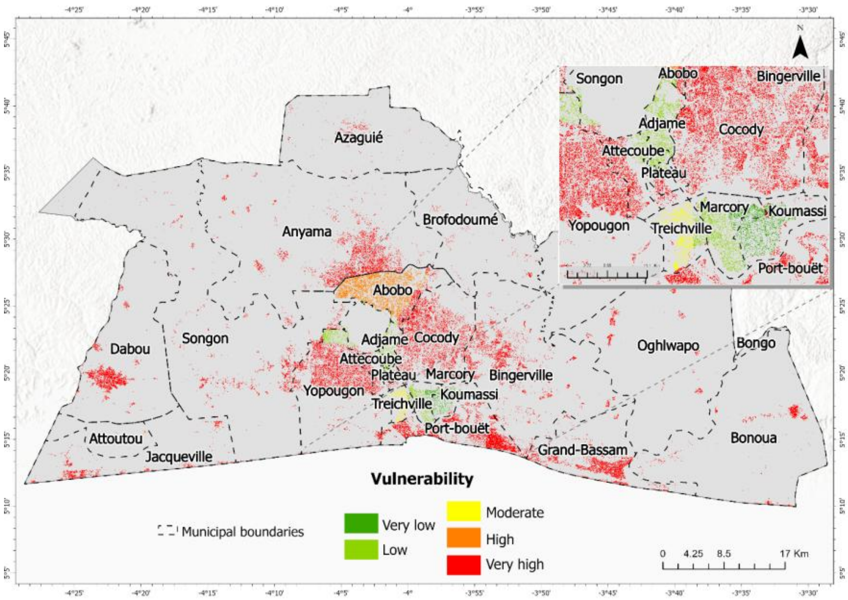

Figure 9: Vulnerability map for Greater Abidjan.

500 **4.4 Flood and landslide risk mapping**

The final result of the AHP is the generation of a flood and landslide risk map, which integrates indicators related to environmental and socioeconomic conditions (Figure 10). First of all, The analysis of the map reveals that the entire Greater Abidjan area is exposed to risks, although the degree of risk varies. In addition to identifying the risk zones, this map highlights a stark contrast between the eastern and western areas of Greater Abidjan. The areas predominantly located in the west, notably the communes of Yopougon and Abobo, are classified as being at "very high risk". These residential zones are mainly inhabited by the middle and lower classes. In contrast, the eastern part of the territory shows vulnerability ranging from "high to very low".

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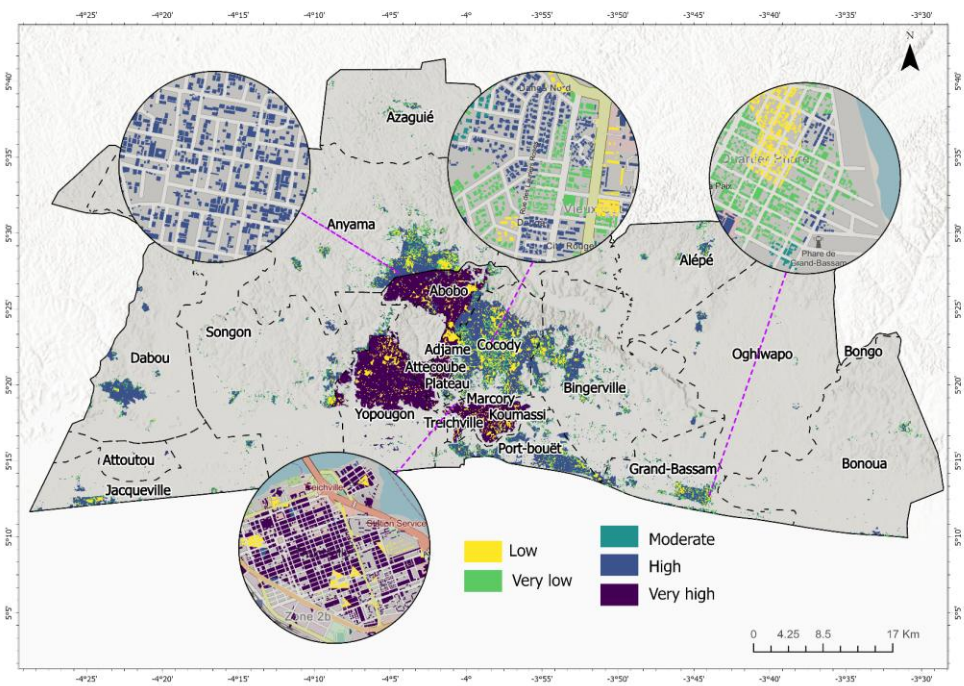

Figure 10: Risk of flood and landslide for the people of Greater Abidjan.

4.5 AHP validation

The validation of the AHP-based risk mapping was conducted through a cross-comparison with our multi-source database of georeferenced flood and landslide events (see Section 3.3). This comparison confirms the overall consistency between the generated risk map and the historical hazard occurrence map.

However, the analysis also highlights spatial variations in risk levels across different areas. Densely populated zones, particularly in the city centre and highly urbanised districts such as Cocody, Bingerville, Attécoubé, and Yopougon, exhibit a higher probability of hazard occurrence. This spatial variability highlights the role of local factors in shaping risk distribution, suggesting that urban characteristics (such as land use patterns and infrastructure density) may significantly influence exposure.

By integrating modelled data with field observations, this validation approach strengthens the reliability of the AHP-based assessment while also identifying potential discrepancies or limitations that warrant further investigation.

4.6 Current limitations and future developments

The multi-criteria approach remains relatively simple to implement, but it is essential to allow for certain parameters before applying it. Among the criticisms noted in the literature, we can mention that the method facilitates compensation between the criteria. As a result, if the weights assigned to each criterion are identical, a positive evaluation on one criterion could compensate for a negative evaluation on another. In addition, as highlighted by Liu et al. (2020), a number of studies agrees to mean a certain subjectivity (Vaidya and Kumar, 2006; Yang et al., 2023) in the calculation of weights from the criteria, which can influence the results in a non-objective way.

On a practical level, although the method can theoretically handle an unlimited number of criteria, it is generally accepted that the human mind can only validly compare up to seven criteria when reasoning in pairs (Piton et al., 2018). Beyond this threshold, it becomes difficult to compare the criteria coherently without the risk of inconsistencies.

On the data side, research has been hampered by the acquisition of a particular types of data related to hazard or vulnerability. In terms of social vulnerability, Dewan's research uses a broader selection of criteria, including literacy, type of housing, health resources, among others (Dewan, 2013). Regarding hazards (flooding/landslide), a number of studies considered the rainfall criterion to be relevant in an AHP matrix.

Another key concern is data availability and uncertainty. Several criteria used in the AHP process, such as land use, population density, or infrastructure quality, are subject to measurement errors and data gaps, which can propagate through the model and impact the reliability of the final risk assessment. In this study, research was hindered by difficulties in acquiring key datasets related to hazard and vulnerability. While Dewan (2013) incorporates additional social vulnerability indicators such as literacy rates, housing conditions, and access to healthcare, these factors were not included here due to data limitations. Similarly, for hazard assessment, certain studies have highlighted the importance of rainfall data as a relevant factor in AHP models, but access to detailed meteorological records can be restricted, limiting its integration.

Another important limitation concerns how multiple hazards are addressed. This study considers both flood and landslide hazards, but it does so independently, without accounting for their possible interactions and cascading effects. In reality, extreme rainfall can trigger both floods and landslides, or floods can weaken slopes, increasing landslide susceptibility. The absence of a fully developed multi-hazard perspective may lead to a partial risk representation. Additionally, the vulnerability assessment focuses solely on social factors - such as population density, gender, and age - without considering other critical aspects, such as the resilience of the built environment, infrastructure quality, and economic capacity. This limitation is closely linked to the aforementioned data

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availability issue. Including these additional factors in future research would enhance the ability to assess vulnerability more comprehensively.

Moreover, expert judgment dependence remains a challenge. The weighting process in AHP relies on expert opinions, which can introduce bias and inconsistencies depending on the experience and perspective of the experts consulted. The availability of experts and the subjectivity involved in assigning weights can significantly influence results.

To overcome these limitations, future research should focus on integrating multi-hazard analysis to account for interactions between different types of hazards, ensuring a more comprehensive risk assessment. It will also be necessary to expand vulnerability indicators to include other aspects that play a significant role in disaster impact. The use of more advanced statistical and machine learning techniques could help reduce subjectivity in weight assignment and improve predictive capabilities. As a major future improvement, it is envisaged to enhance data collection strategies, including the use of remote sensing, GIS technologies, and community-based surveys, as a key requirement to enhance the accuracy and applicability of risk models in data-poor contexts.

5 Conclusion

The primary objective of this research was to identify areas in Greater Abidjan exposed to the risks of flooding and landslides, with the ultimate goal of better supporting disaster risk reduction efforts in the area. To achieve this, the research methodology was oriented towards a multi-criteria analysis fed by geographic data from various sources, mainly open data. The choice of this methodology enabled the integration of both hazard and vulnerability dimensions in the risk assessment and better capturing of the risk dynamics in our study area.

However, beyond these analyses, it is important to highlight that effective flood risk management requires thoughtful urban planning. While structural resistance measures have traditionally been the primary focus of flood prevention efforts, their effectiveness is now being questioned. Recent eviction measures taken by Abidjan's urban authorities in March 2024 reflect the growing commitment to addressing these risks through better urban management. Although natural hazards cannot be eliminated, accurate and anticipated hydrometeorological forecasting helps both the public and governments to prepare for, mitigate, and reduce the damage often caused by these extreme events.

In the absence of an official risk prevention plan specific to the study area, this research could play a crucial role in filling this gap. By aligning with the recommendations of the Sendai Framework for Disaster Risk Reduction (2015-2030), this study provides valuable data and analyses that can serve as a foundation for developing effective

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risk management strategies. However, it is important to acknowledge the limitations of this research, particularly regarding data availability and the ability to capture the interactions between hazards. Future research can build on this foundation by addressing these gaps, refining vulnerability assessments, and improving data sources for more precise risk mapping.

By identifying and mapping risk hotspots, this research offers local authorities and decision-makers a clearer understanding of where preventive measures should be focused to reduce the impacts of flooding and landslides. In this way, this research not only addresses an institutional void but also strengthens the resilience of local communities to natural hazards.

Data availability. All raw data can be provided by the corresponding authors upon request.

Author contributions. H.K.T.: Conceptualisation, Methodology, Investigation, Visualisation, Writing - original draft preparation; S.L: Conceptualisation, Supervision, Writing - review & editing; G.D.: Conceptualisation, Supervision, Writing - review & editing, Funding acquisition; E.K.K: Conceptualisation, Supervision, Writing - review & editing; S.D.A.: Conceptualisation, Supervision, Writing - review & editing, Funding acquisition.

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Competing interests. The authors declare that they have no conflict of interest.

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