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The Contribution of Flood Risk Assessments to Risk Management in Low- and Middle-Income Countries / Tiepolo, M., Ganora, D., Giulio Tonolo, F., Vesipa, R.. - In: ENVIRONMENTS. - ISSN 2076-3298. - ELETTRONICO. - 13:(2026). [10.3390/environments13110624]

Availability:
This version is available at: 11583/3017947 since: 2026-11-15T12:38:09Z

Publisher:
MDPI

Published
DOI:10.3390/environments13110624

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16 November 2026

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Review

The Contribution of Flood Risk Assessments to Risk Management in Low- and Middle-Income Countries

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Abstract

Floods account for a substantial share of disaster damage, particularly in low- and middle-income countries (LMICs). Despite the Official Development Aid mobilised between 2000 and 2024 to address flooding in LMICs, damage has not decreased significantly. During this period, the number of flood risk assessments (FRAs) increased exponentially, particularly after 2018. However, literature reviews have paid little attention to this proliferation and the contribution of FRAs to risk management. This study examines the usability of FRAs for risk treatment in LMICs. We analysed 164 FRAs covering rural areas in 38 LMICs, published over the past 20 years, assessing data and information quality and the knowledge-building process. Only 7% of FRAs publicly share information through a repository, 15% identify populations at risk, 22% map inundation depth, and 56% recommend risk-treatment measures. In 86% of cases, knowledge production is based primarily on desk work rather than involving flood-prone communities. We recommend that FRAs be supported by data meeting the ISO 25024 standard. FRAs developed with public funds should make all underlying data publicly available, in accordance with FAIR principles. Moreover, FRAs should support risk treatment, while knowledge should be transdisciplinary and co-produced with communities at risk of flooding.

Keywords: co-development; disaster risk reduction; data quality; information quality; knowledge building; participation; risk management

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Academic Editor: Joaquim Esteves Da Silva

Received: 4 October 2026
Revised: 28 October 2026
Accepted: 11 November 2026
Published: 13 November 2026

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1. Introduction

Between 2000 and 2018, floods accounted for 23% of disaster-related damage [1], while low- and middle-income countries (LMICs) accounted for 89% of the population exposed to floods [2]. During this period, the Official Development Assistance (ODA) supported substantial efforts to reduce flood risk. Member countries of the Organisation for Economic Co-operation and Development provided USD 251 billion to address disasters in LMICs [3]. In December 2010, Google launched Google Earth Engine, a cloud-based platform providing free access to satellite imagery and Earth Observation (EO) data processing. Global Flood Awareness Systems became operational in 2011, enabling early flood warnings [4]. Since the mid-2000s, the commercialisation of LiDAR systems for topographic mapping [5], new versions of hydraulic simulation software, and free, open-source geographic information systems have enabled more refined hydraulic modelling. These developments in data, technology and software supported the first flood risk assessments (FRAs) of the Benoué River

in Cameroon [6] and the Pak Phanang River in Thailand [7], followed by 30 assessments by 2018. This surge in research was facilitated by dozens of new scientific journals that offered new publication channels, often with low costs and shorter publication processes.

Although data and FRAs have advanced, losses and damage from river flooding in LMICs have not decreased [1]. One possible explanation is the allocation of ODA for disasters: between 2000 and 2018, 87% was allocated to emergency response and 7% to reconstruction, relief, and rehabilitation, compared with only 6% for prevention and preparedness (Table S1). We hypothesise that the risk management process provides an additional explanation. According to IEC 31010 Risk management—Risk assessment techniques [8], FRAs should estimate risk levels, identify options for reducing them, and determine whether risk treatment is warranted. These steps inform decisions on reducing the probability or impacts of flooding and implementing appropriate risk-treatment measures. However, the 30 FRAs published up to 2018 identified few measures without detailing prioritisation and feasibility, thereby impeding their integration into development planning, as recommended by the United Nations Sendai Framework for Disaster Risk Reduction 2015–2030 [9]. Moreover, FRAs provided less knowledge on exposure than on hazard [10,11]. FRAs were more frequently conducted in urban areas, where poverty is highly concentrated, than in rural areas [12]. This imbalance is notable given the effects of floods on global rice yields [13], food security [14] and rural livelihoods [15]. Furthermore, emergency flood–diversion infrastructure protecting urban settlements was located primarily in rural areas [16,17].

Between 2018 and 2024, the share of ODA allocated to prevention and preparedness increased more than twofold. Larger LMICs also began investing in this sector, while risk-assessment expertise expanded and access to flood data improved. The Copernicus Sentinel missions provide free and openly accessible Earth observation data suitable for operational flood assessment. Multispectral optical imagery from Sentinel-2, available since 2015, supports the delineation of inundated areas under cloud-free conditions, whereas C-band synthetic aperture radar imagery from Sentinel-1, available since 2014, enables day-and-night flood mapping even in the presence of cloud cover. [18]. Sensors mounted on remotely piloted aircraft systems enabled timely, very-high-resolution mapping of flood areas and assets [19–22]. Consequently, FRAs in LMICs steadily increased, particularly after 2018. However, existing literature reviews have not adequately examined this surge in research [23–29] (Tables 1 and S2).

Table 1. Literature reviews of FRAs, 2016–2026.

Review Focus	Period	Articles	Articles on LMICs	Reference
Systematic	2010–2024	750	175	[23]
Geospatial	2010–2024	89	44	[24]
Hydrological	2005–2025	78		[25]
Geospatial	1985–2023	1,872		[11]
Methods	2000–2023	126	20	[26]
Methods	1979–2020	1,326	555	[27]
Uncertainty	1996–2019			[10]
Flash floods	1995–2015	60	unknown	[28]

Literature reviews focus on the methods used in FRAs [24–28], the contributions of hazard, exposure, and vulnerability to the determination of risk [10,11,23,24], and specific parameters such as flood depth and uncertainty [10,23,26]. Researchers have not yet considered the contribution of FRAs to the risk management process. Integrating FRAs into risk management requires data, information, and risk knowledge compatible with risk policy formulation and risk treatment.

The research question is thus as follows: to what extent do FRAs for rural areas contribute to risk management in LMICs? Failing to address this question marginalises rural livelihoods and the sustainable use of rivers in favour of urban issues.

This semi-structured review [29] aims to assess the applicability of FRAs for risk management and their main bottlenecks. Its novelty lies in assessing the usability of FRA outputs in the flood-management process.

The analysis focuses on peer-reviewed articles published over the past 20 years. We used a historical approach to reconstruct the contributions of various disciplines to FRAs that shaped this tool's current limitations. We examined consistency between FRAs and planning tools that coordinate risk treatment, focusing on data quality, fitness for purpose of information, and risk-knowledge development. The comparison between FRAs and planning tools informs recommendations for improving future assessments.

2. Materials and Methods

This review examines data, information and knowledge. Following Weichselgartner et al. [30], we define data as structured facts, information as processed data that enables an understanding of relationships, and knowledge as organised information. FRAs use data on precipitation, river discharge, topography, soil, inundation depth, assets (including buildings, infrastructure, and crops), population and risk-reduction measures. The information primarily concerns hazard, exposure, vulnerability, and risk maps; depth-damage functions; priority risk reduction measures; and the cost–benefit of risk treatment. The knowledge process concerns how information is derived and how decisions on risk reduction are made.

As FRA is a standardised component of risk management, we have limited our search to studies that explicitly mention it in the title, abstract or keywords. We searched Scopus for published articles in the previous 20 years using the search term 'river flood risk assessment' and in Google Scholar with 'évaluation risques inondation', 'evaluacion riesgo inundacion' and 'avaliação risco inundações'. We then restricted results to the 141 countries classified by the World Bank as LMICs. Using the same keywords, we repeated the search across journals classified by SCImago as first quartile (Q1) journals in the Environmental Science and Earth and Planetary Sciences subject areas. We also identified additional FRAs using a snowball method from the references of the identified FRAs and reviews. FRAs in rural regions support risk management by mapping risk-reduction measures and making information accessible. We excluded almost half of the identified FRAs because they lacked risk maps, were conducted at country scale, focused predominantly on urban contexts, or were not openly accessible. The final search identified 164 FRAs published between January 2007 and September 2026, addressing predominantly rural contexts in 38 countries (Figure 1 and Table S3).

We divided the FRAs into three equal groups, based on the micro-, meso-, and macro-scales of the territory under consideration. The first group may include rural towns, the second secondary towns, and the third cities, provided the rural part of the territory is predominant by area.

We collected 20 local development, risk management, integrated river basin management, and emergency/contingency plans for 16 countries with FRAs (Tables S4 and S5). The plans are available on the websites of the respective local authorities or the ministries promoting their adoption. For each plan, we identified the information that the corresponding FRAs could provide.

IEC 31010, Risk management—risk assessment techniques [8] provides the basis for defining the expected content of an FRA and its relationship with risk management. Consequently, we compared FRA outputs with the plan inputs used to organise risk treatment. We assessed the accessibility, availability, completeness, precision, and accuracy of

the data included in or accompanying the FRAs, following ISO 25024, Measurement of data quality [31] (Table 2), and considered recommendations concerning publicly funded data [32,33].

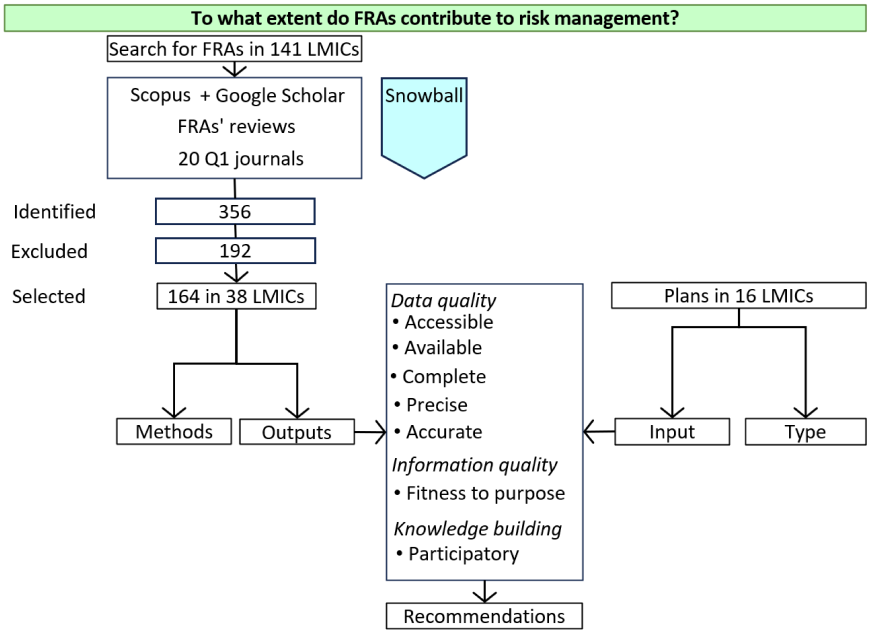


Figure 1. Flow chart of the literature review.

Table 2. A selection of data quality characteristics in accordance with ISO 25024.

Characteristics	Definition
Accessibility	Data can be accessed through appropriate interfaces and mechanisms
Availability	Data is accessible and retrievable when required by authorised users or systems
Completeness	All required data is present, and no essential information is missing
Precision	Data values are exact and have appropriate granularity for their intended use
Accuracy	Data correctly represents the real world they are intended to model

The first indicator of completeness is the presence of metadata. The minimum content of metadata includes a description of the reference period, the reference area, the units of measurement, the methods, the classification, the data provider, the source, the symbols and abbreviations, and a list of the codes used [34,35].

We then assessed information quality in terms of fitness for purpose using three indicators: the risk map scale and details, the prioritisation of risk-treatment measures and the cost–benefit analysis. Finally, we addressed the risk-knowledge development process, focusing on the participation of flood-prone communities in providing information, in decision-making and in contributing to decisions on risk reduction.

The comparison between FRA outputs and plan inputs focused on data, information quality, and knowledge-building dimensions, using seven output characteristics and 20 indicators. Nine indicators correspond to the input required for the four types of plans under consideration. Their frequency indicates how often the FRAs are compatible with the plans.

3. Results

3.1. Types of FRAs and Their Outputs

FRAs conducted in rural contexts in LMICs lack a single, unambiguous definition of risk and a standardised structure, despite established definitions and frameworks [8,36].

In many cases, risk assessment is treated as equivalent to flood susceptibility assessment. Most FRAs consist solely of analysis and end with an estimation of risk level. Only a small proportion extend to risk evaluation and assess whether measures are warranted. The study area spans scales ranging from micro-scale studies, such as river basins or small administrative jurisdictions of less than 800 km^2, to macro-scale studies [37], including regions exceeding 16,400 km^2 and extending to 1.8 million km^2 (Table S6). Consequently, the methods used vary considerably. Regarding the methods used by FRAs, 73% use indicators, 20% use hydrological, hydraulic and damage modelling, 3% use satellite imagery, and 3% use other methods (Table S7). Depending on the method, risk is conceptualised as a function of hazard and vulnerability [38] or of hazard and expected damage, with vulnerability expressed in terms of damage [39]. The number of FRAs increased steadily since 2019 (Figure 2).

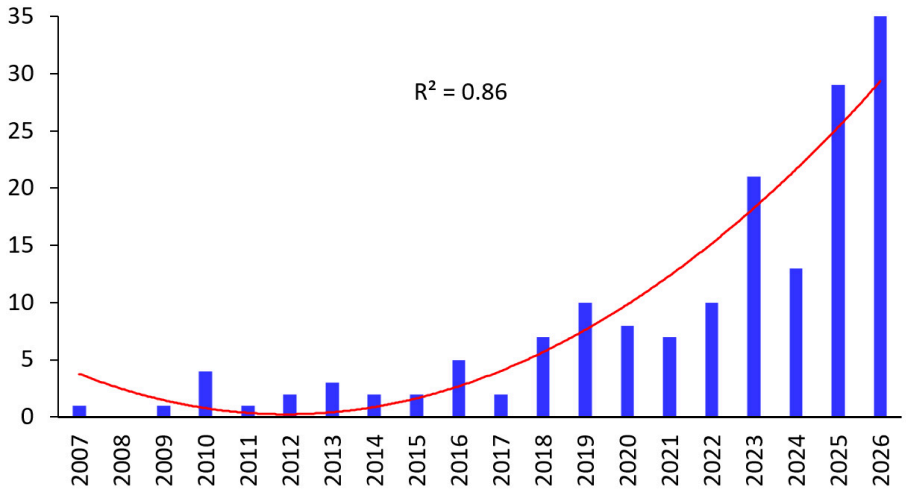


Figure 2. Number of FRAs on prevailing rural areas of LMICs published between January 2007 and September 2026.

China, India, Bangladesh, Ethiopia, Indonesia, and Pakistan account for 56% of all FRAs published during the study period (Figure 3). The studies are clearly skewed by income. Upper-middle-income countries account for 43% of studies and make up 45% of LMICs, while low-income countries account for only 10% of studies despite making up 19 per cent of LMICs.

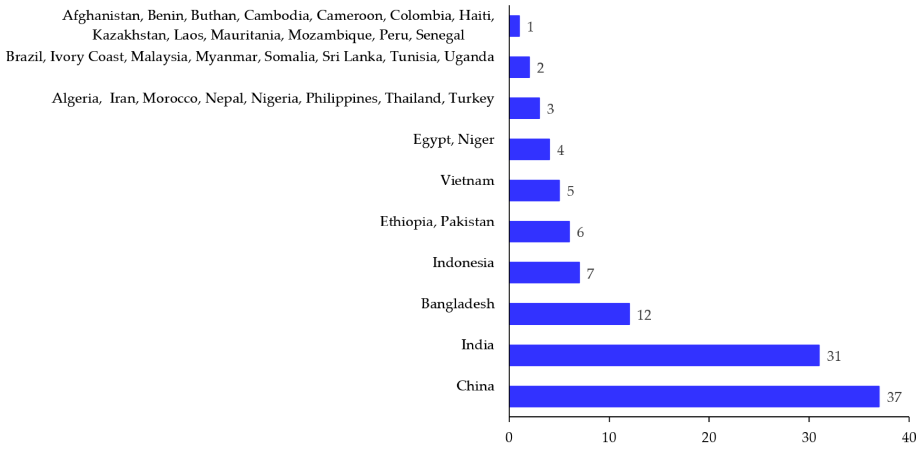


Figure 3. LMICs per number of FRAs published between January 2007 and September 2026.

3.1.1. Indicators

The earliest indicator-based FRAs combined hazard, exposure and vulnerability layers within a GIS. At meso- and macro-scales, local administrative jurisdictions served as the smallest units of analysis. The 2009 FRA for Thailand's Pak Phanang basin [7] is among the earliest applications in LMICs. Researchers subsequently weighted the indicators using Saaty's analytic hierarchy process [40]. Early applications also included the Huaihe River basin (2010) [41], Liaoning Province, China (2014) [42], and the district of Abidjan (2016) [43]. The map resolution depends on the spatial resolution of the input indicators. These FRAs typically use EO data from Landsat sensors, with a maximum spatial resolution of 30 m × 30 m. Consequently, they generally classify assets exposed to flooding into macro-classes of land cover such as arable land, forest, urban fabric, bare soil, and water bodies, rather than identifying individual assets.

A second indicator-based approach maps factors influencing flooding using existing datasets on rainfall, land slope, cover, and soil type. Applied at meso-scale, this method involves experts assigning weights to these factors, followed by multi-criteria analysis. Researchers use various techniques to manage spatial information layers in a GIS environment [44]. The 2012 FRA for China's Dongjiang River basin [45] is among the earliest examples of this approach in LMICs. These risk index maps do identify individual assets.

Morphometric analysis has a long history, dating to Strahler's [46] geomorphological analysis of catchments. It classifies catchments within a river basin according to their flood susceptibility using linear parameters (e.g., stream order, number, length, sinuosity and bifurcation), areal parameters (e.g., area and perimeter circularity) and topographic parameters (e.g., elevation and gradient). Catchments are ranked by summing their scores across these parameters to identify priority areas for water and soil conservation during flash floods. Early applications include studies in southern Sinai, Egypt (2011) [47], and Wadi Wuheida and Rajil, Jordan (2017) [48]. In FRA research, morphometric analysis has been used since the 2014 assessment of the Tahaddart watershed in Morocco [49].

Machine Learning (ML) and GeoAI are the more recent additions to indicator-based methods. ML applications commonly use random forests, an ensemble method that trains multiple decision trees, to improve predictive performance and reduce overfitting. ML overcomes the subjectivity involved in assigning weights to the flood-related explanatory factors. One of the earliest applications was conducted in Yunnan Province (2019) [50].

Indicator-based methods have several limitations: they cannot reliably estimate unobserved flood scenarios or flood propagation time, evaluate the effects of risk-reduction measures, or incorporate local knowledge. Consequently, they remain confined to analysis. Other limitations include reliance on weights assigned by unspecified or a very small number of experts [51], which ML seeks to address, and the limited use of ground-truth data beyond map validation.

3.1.2. Hydrological, Hydraulic and Damage Modelling

Frequency-based flood damage modelling in LMICs relies on a chain of three model types. The river basin hydrological model supplies the discharge inputs for flood analysis. In gauged basins with sufficiently long flood records, researchers can estimate a flood frequency curve directly from observations [52]. In ungauged basins, they use either direct regional models or indirect rainfall-runoff models. Regional models 'transfer' flood observations from hydrologically similar basins to the ungauged site [52], whereas rainfall-runoff models use frequency analysis of extreme precipitation and model its conversion into runoff [53,54]. Researchers usually model several return periods to generate flood scenarios (e.g., 5, 10, 30, 50, 100 and 200), estimating the corresponding discharge for each. For gauged rivers, these discharges can be derived from observed flow records. The models

draw on the work of Horritt and Bates [55] and Horton [56]. In LMICs, it was first applied to the Kalu Ganga River in Sri Lanka (2010) [57] and the Yom River in Thailand (2011) [58].

The hydraulic model uses discharges for the selected return periods to simulate flow through the river channel and across the floodplain, using a DEM, embankments, and other relevant topographic features. Software such as MIKE, HEC-RAS and BASEMENT can simulate flood extent, depth, velocity, and propagation time. Simulation may be one- or two-dimensional (1D or 2D) [55], depending on river dynamics and computational requirements. Previous events with known (or estimable) flood extent and inflows can help calibrate parameters such as the roughness coefficient and validate model results [57].

The damage model complements hydrological and hydraulic modelling by estimating expected damage from flood depth and duration, typically using depth-damage relationships. When the model also accounts for flood probability (the inverse of the return period), it estimates monetary flood risk. Since the early 2000s, this method has been developed primarily at meso- and micro-scales, including through tools such as HAZUS in urban contexts across North America and Europe. In LMICs, early application was in the Muda River basin, Malaysia (2010), followed by applications in Latin America [58,59]. For risk management, damage modelling can support residual-risk assessment and cost–benefit analysis of risk-reduction measures. Other applications include insurance, estimating the expected impacts of individual flood-defence works, and impact-based early warning systems (EWS) [60,61]. The resulting maps can provide high spatial resolution and be used directly in planning [62,63]. Recently, models have simulated how climate change affects the extent of flood-prone areas. The simulation begins by selecting the radiative concentration pathway (RCP) scenario of interest as defined by the Intergovernmental Panel on Climate Change. The moderate RCP4 scenario is usually used as a reference. Subsequently, regional climate models provide peak rainfall for each gauge station within the river basin, and a rainfall-runoff model estimates the discharge required for hydraulic modelling to determine flood-prone areas [64–66]. A key limitation of modelling is the need for ground-level data. For example, in LMICs, floodplains are often delineated using low-resolution DEMs (SRTM and ALOS PALSAR), which may not accurately capture multi-channel or relatively narrow watercourses. This can cause overestimation of flood impacts [67]. Moreover, updated bathymetric surveys are required, while assets identified from high-resolution satellite imagery or updated maps require ground verification. Consequently, production times are lengthy.

3.1.3. Rapid Mapping

Flood extent can be mapped from optical or radar EO data. Freely accessible EO data with a few-day frequency at medium resolution make this method useful for emergency response during severe floods and for validating flood-prone areas identified by other methods. Optical imagery can be used to extract flood edges using indices such as the Modified Normalised Difference Water Index. Radar imagery is useful when flooding occurs under cloudy conditions or during the night. In LMICs, rapid mapping is used at meso- and macro-scales. An early application mapped flooding in the northern Bihar plains of the eastern Indo-Gangetic Plain using Landsat-ETM and Landsat-MSS imagery [68]. The analysis by Brivio et al. of the 2000 flood in Piedmont, Italy, using SAR imagery is also cited as a landmark study [69]. The first reported use of EO for flood risk assessment was in Nigeria in 2013 [70]. Production time depends on image availability [71]. However, the method is poorly suited to flash floods, whose dynamics last only a few hours and whose dynamics EO can capture only in areas of standing water, not in those affected by the flood wave. Operational since 2012, the Copernicus Emergency Management Service has delivered ready-to-use geospatial products through its Rapid Mapping and Risk and

Recovery Mapping components for more than a decade and, since 2024, has systematically included floodwater-depth estimates derived from EO imagery and digital elevation models in its rapid-mapping products for flood emergencies [72].

3.2. Flood Management Plans

LMICs use various plans to prevent and manage floods, with each addressing specific stages of flood management: prevention, preparedness, response, rescue and recovery. Local development and risk management plans primarily support prevention. Integrated river basin management (IRBM) plans also focus on prevention, but at a macro scale, encompassing multiple local authorities and, in some cases, several countries. Emergency/contingency plans are used locally for preparedness, response, rescue and recovery.

3.2.1. Local Development Plans

Local development plans are widely used medium-term municipal planning tools, drawing on the long-standing experience of US General or Comprehensive Plans. They cover the main areas within a local authority's remit (agriculture and livestock, environment, communications and transport, culture, education, housing, health, and land use). These plans should identify areas unsuitable for development because of flood exposure, designate safe areas for settlement expansion, and identify priority sites for water, sanitation and hygiene (WASH) interventions.

3.2.2. Risk Management Plans

Many local governments in Cameroon, Colombia, the Philippines, South Africa, and Togo have adopted risk management plans. These plans identify flood-exposed areas and localities for zoning and inventories of exposed assets. They also specify the measures to be implemented, their costs and implementation schedules. Common measures include early warning, raising awareness among the exposed population, training community leaders, shelter construction, food storage, emergency kits, and resettlement.

3.2.3. Integrated River Basin Management Plan

In LMICs, IRBM drew on the experience of the Tennessee River Authority and gained momentum in the first half of the 1970s with plans for the Mekong, Senegal and Tana rivers. This was followed by numerous plans in the early 2010s for the Ganges and for smaller rivers including the Awash and Omo in Ethiopia, the Cagayan and Ranao in the Philippines and the Selangor in Malaysia. These plans aim to manage river use sustainably, ensure the continuous flow of water and sediments, support ecological restoration, agriculture, geological safeguarding, disaster protection and hazard management. IRBM plans also require a modelling-based flood forecasting system.

3.2.4. Emergency and Contingency Plans

Emergency plans address preparedness, response, rescue and recovery following a flood alert. They primarily require information on areas and locations at risk (including those affected by past events), categorised by degree of vulnerability (with a map and description). They also require information on the exposed population, school buildings to be evacuated or requisitioned as relief centres, and evacuation routes. For flood management, additional information includes flood propagation time, river level and warning time (Table S5).

3.3. FRA Outputs and Plan Inputs

FRAs can provide input such as flood models to RBM plans; buildings, population at risk, and propagation time to E plans; measures and identification of flood-prone areas to LD plans; and flood depth, the number and location of measures to RM plans (Table 3).

Table 3. FRA outputs and Emergency (E), Local Development (LD), River Basin Management (RBM), and Risk Management (RM) plan inputs.

Flood Risk Assessment Outputs				Plan Inputs
Dimensions	**Characteristics**	**Indicator Name**	**%**	
Data quality	Accessible	Link to a repository	10	
	Available	Data retrievable	7	
	Complete	Metadata	8	
		Flood model	20	RBM
		Buildings at risk	9	E
		Population at risk	15	E
		Inundation depth	22	RM
		Propagation time	0	E
		Measures	53	LD
	Precise	Asset resolution	3	
		DEM high resolution	3	
		Measure's quantity	3	RM
		Measure's location	9	RM
	Accurate	Floodable area	42	LD
		Ground truth	37	
Information quality	Fitting to purpose	Map scale, landmarks	14, 46	
		Priority measures	1	
		Cost–benefit	1	
Knowledge-building	Participation	Information provision	17	
		Measures decision	3	

3.3.1. Accessibility

Of the 164 FRAs, 50% were publicly funded, 31% did not declare their funding source and the remaining 19% were privately funded or funded by the authors (Table S7). Recommendations for free access to publicly funded research outputs and the principles proposed by Mons et al. [33] thus apply to 50% of the FRAs. However, only 10% of the data from publicly funded FRAs are accessible via a repository, 20% are available from the authors on 'reasonable request', 2% declared available in a repository were not found, and 68% are inaccessible (Table S7). Of the 16 FRAs that provide accessible data, only 4 include vector datasets of risk maps, 2 include hazard maps and 1 includes flood depth data. Five provide general information on the questionnaires used and indicator weighting, which is of limited value for operational data reuse.

3.3.2. Availability

Availability was 75% because, in mid-2026, of the 16 FRAs that declared their data accessible via a repository, four were not accessible through the provided link (Tables S7 and S8).

3.3.3. Completeness

Data are complete when accompanied by metadata specifying how and why they were collected, the process used, the software that generated them, and the format in which

they were released. Only 1 in 12 datasets includes such metadata. Completeness also applies to the FRA contents in accordance with IEC 31010. For example, buildings and populations at risk are identified in only 9% and 15% of FRAs, respectively. For emergency planning, knowing how many residents live in the flood-prone area is crucial for alerting exposed populations and organising evacuation and rescue operations. It also supports the identification and preparation of nearby flood shelters, including their capacity and catering requirements. Flood propagation time matters when FRA is linked to an EWS. Unfortunately, no FRAs estimate it. Inundation depth is reported by 22% of FRAs, despite being important for identifying specific risk-reduction measures (Table S12).

With 56% of FRAs recommending risk-reduction measures, the average was three measures each (Table S10). No significant differences were found between FRA types, except in the average number of measures recommended by indicator-based FRAs (Table 4).

Table 4. Average number of recommended measures by type of FRA.

Type of FRA	Recommended Measures	
	Number	Average Measures per FRA
Indicators	45	4
Modelling	51	3
Rapid mapping	20	2

The most frequently recommended non-structural measures are FEWs, land-use planning, community awareness, restrictions on developing flood zones, and emergency planning. Common structural measures include constructing, reinforcing, and maintaining embankments; afforestation and greening in general; maintaining and extending drainage systems; storing stormwater or floodwater; and resettlement (Table 5).

Table 5. Measures in 92 FRAs on LMICs.

Measure		Number	Frequency %
Non-structural	Early warning system	39	12
	Land-use planning	32	10
	Community awareness	26	8
	Development ban in flood zone	9	3
	Emergency plan	8	3
	Other	64	20
Structural	Embankments, dykes	24	7
	Afforestation and greening	21	7
	Drainage improvement	15	5
	Stormwater storage	12	4
	Resettlement	7	2
	Other	62	19
Total		319	100

Measures can also be classified by purpose: prevention, which reduces exposure; defence, which reduces hazard magnitude; mitigation, which reduces the impacts on assets; preparedness, which addresses an imminent or ongoing disaster; and recovery, which restores living conditions and assets following a disaster [73]. Of the measures proposed 319 times by the 92 FRAs considered, fewer than one-third relate to prevention, approximately one-third to defence and mitigation, and one-third to preparedness and recovery (Tables 6 and S11).

Table 6. Classification of measures proposed by 92 FRAs in LMICs between 2009 and 2016.

Measure Class	Aim	Number	Frequency
Prevention	Exposure reduction	103	32
Defence	Hazard reduction	43	13
Mitigation	Asset protection	72	23
Preparation	Crisis response	88	28
Recovery	Restoring life	13	4
Total		319	100

3.3.4. Precision

Object-based asset identification is used in 7% of FRAs. Only 3% use a DEM with a spatial resolution finer than 5 m and a vertical accuracy of 5 m [62]. For risk-reduction measures, 9% of FRAs localise recommended measures, 2% quantify them, and 2% evaluate their feasibility only (Table S12).

3.3.5. Accuracy

Only 46% of FRAs assess result accuracy. In half of these cases, accuracy assessment is limited to maps, water extent, and land cover, with verification through comparison with previous studies or maps (31%). Consequently, the accuracy of most FRA maps remains unknown (Table S13).

3.3.6. Fitting to Purpose

Information quality considers maps, measures prioritisation, and cost–benefit analysis. Map scales range from 1:40 million to 1:14,000. However, only 5 of 164 FRAs provide maps suitable for operational use, defined here as a scale larger than 1:50,000. Furthermore, 48% of the maps lack useful landmarks for locating the risk factors shown (Table S13). Local development plans should identify safe zones for settlement expansion or resettlement and agricultural investment, but only 2% of the FRAs address these requirements. Administrative boundaries appear in 32% of FRAs, while settlement locations appear only in 10% (Table S14). Maps are accompanied by data on risk assets in three out of ten cases. Measures are prioritised and evaluated in only 2 of 100 cases [62,64].

3.3.7. Participation

A total of 62% of FRAs result from desk work only. Communities at risk of flooding participate in the FRA process in only 10% of cases (Table S15). When they participate, their involvement remains at the lowest levels of the participation ladder [74], primarily as providers of data or information collected via questionnaires or focus groups on exposure, vulnerability and potential damage. Participation extends to decisions on prevention measures in only 4 of 164 FRAs [62,64,75,76] (Table S16).

4. Discussion

The limited reduction in flood damage mentioned in the introduction may be due to several factors, in addition to limited mitigation funding. This study considers only the coherence between the FRA and the plans as one possible contributing factor. In upper-middle-income countries, planning does not typically rely on academically produced FRAs, instead drawing on information systems developed to meet the standards of public authorities or ODA consultants [77,78]. However, published FRAs can demonstrate innovative methodologies, identify emerging issues, train practitioners in flood-risk reduction and, in low-income countries with understaffed water departments, support decision-making. In both contexts, FRAs should thus be better coordinated with planning systems.

Our analysis of 20 years of assessments reveals the proliferation of FRAs since 2019, particularly in South and South-East Asia, the regions most affected by flooding [2]. However, the SFDRR's call, made over 10 years ago, to work at the local level and with communities appears to be struggling to gain traction. We identified important misalignments between FRA outputs and the operational requirements of flood risk treatment. Three dimensions of this discrepancy are particularly relevant across geographical scales and may help bridge this gap: (i) data quality, (ii) information quality and (iii) knowledge-building.

4.1. Data Quality

Data quality is standardised [31], and recommendations exist for publicly funded data [32,33]. Of the quality characteristics defined in ISO 25024, we assessed accessibility, availability, completeness, precision and accuracy.

Only 10% of FRAs' data was found accessible, although half of the FRAs were publicly funded (Table S6). This finding is consistent with the systematic review of the disaster literature [79]. Publishing data and information is particularly important where data availability is limited [80].

Completeness refers to the inclusion of all necessary information, with metadata forming an integral part of the data. In the few cases where data meet the accessibility criteria, the metadata are insufficiently described. Information on buildings and populations at risk is also incomplete, despite the long-standing availability of global datasets that can support their estimation across LMICs [81,82]. Inundation depth is reported in 22% of FRAs, although it is particularly relevant to risk treatment. Completeness also applies to risk-reduction measures. These are absent from the majority of FRAs, while those that are recommended average only three per FRA. Flood risk reduction policies should draw on a range of measures to reflect territorial complexity and reduce dependence on any individual measure [83]. Moreover, measures are generally described superficially, and no FRA addressed their equitable distribution among exposed populations [84]. These figures are compounded by the fact that only 9% of the measures are geographically located, 2% are quantified, and their feasibility is rarely assessed. Furthermore, the measures focus only marginally on prevention. Therefore, the limited ODA allocation to prevention identified earlier also applies to FRAs, which focus on defence, mitigation, preparedness, and recovery. Where FRAs omit these steps of risk assessment, they provide limited information for selecting and implementing risk-treatment measures.

Precision concerns whether data granularity is appropriate for its intended use. Although FRA authors state that their assessments are intended for planners and decision-makers, the geospatial information is often coarse and outdated. This is notable because the majority of FRAs were published after 2020, by which time high-resolution datasets, including DEMs and assets [85], were freely accessible. This finding is consistent with previous observations concerning hydrological data, DEMs [86,87], and inundation depth derived from Earth observation data [87]. DEM resolution affects estimated flood depth, which in turn influences damage estimates and, consequently, risk [88]. Precision also concerns the quantity and location of proposed measures, which are rarely specified in FRAs, limiting their usefulness for risk treatment.

Accuracy, which measures the discrepancy between modelled and observed data, is assessed in only 46% of FRAs. Of these, only 31% verify flood and risk maps in the field or against historical maps.

4.2. Information Quality

Hazard, vulnerability, and risk maps are rarely drawn at scales sufficient for operational use. In half of cases, maps lack identifiable landmarks that could help locate the spatial

extent of flooding [89] and exposure dynamics [90]. FRAs thus also show limited spatial risk analysis, a shortcoming previously identified in climate risk assessments [91]. Measures depend on inundation depth and the spatial concentration of assets. For example, flood defences prove ineffective when water depth exceeds 2 m, while polder systems may require significant investment to protect relatively few homes. Unfortunately, only a minority of FRAs provide information on this aspect. Measures, which at best are only briefly listed, should be prioritised, and residual risk should be calculated and assessed (IEC 31010) by a cost–benefit analysis with few exceptions [62–64]. The reviewed FRAs overlook this phase.

4.3. Developing Knowledge of Risk

Most FRAs were developed entirely as desk-based studies, disregarding local knowledge [92,93] and with little involvement of at-risk communities [94], particularly in decisions on risk treatment [95]. Reduced preparation time is the most frequently cited justification for this approach [50]. However, it contrasts with the legal requirements for public participation in disaster risk reduction in India (e.g., Gram Panchayat), Bangladesh [96], the Philippines [97], South Africa [98], and most sub-Saharan countries in preparing local development plans [99]. Conversely, involving flood-exposed communities in FRA preparation can improve understanding of hazard dynamics and risk perception [100] and minimise community opposition to top-down measures [101]. Although insecurity can restrict fieldwork in some regions, collaboration with local governments may help overcome these constraints [102]. Moreover, without field data, the reliability of risk components such as asset vulnerability decreases. The infrequent involvement in the FRA process does not allow for further consideration of the use of local knowledge and local ownership of the FRA.

In rural LMICs FRAs, siloed knowledge [103] remains prevalent, whereas transdisciplinary knowledge co-production can support understanding of hazards and risk reduction. In urban contexts [104–106], for example, co-production has been used to link FRAs with EWS to develop impact-based EWSs [60,61].

4.4. Limitations

This review has three main limitations. First, it focuses on fluvial floods and excludes coastal and pluvial flooding. Second, it is limited to open-access literature. Therefore, the quality of FRAs may be overestimated. Third, it excludes publications in languages other than English, French, Spanish and Portuguese. Consequently, countries such as China, India, Turkey and Egypt are likely to be under-represented.

4.5. Implications and Recommendations

The findings have implications for future FRAs, SFDRR monitoring, and associated reporting. FRAs should align more closely with the requirements of flood-risk treatment, particularly the assessment, prioritisation, and evaluation of measures. Authors should also follow recommendations and standards for disseminating data from publicly funded research and improve the quality and usability of geospatial information. Monitoring of FRAs should be extended beyond a narrow insurance perspective [107] to include risk evaluation and treatment.

Finally, three recommendations follow for future FRA practice: (i) adopt a planning, policy and institutional perspective [108]; (ii) work in transdisciplinary teams [109] and (iii) use FRA preparation as an opportunity to build local-government capacity, raise awareness among exposed communities [110] and strengthen their participation in decision-making.

5. Conclusions

This study was prompted by the limited critical reflection on the contribution of FRAs to flood management. We examined 164 FRAs from 38 LMICs published in French, English, Spanish, and Portuguese over 20 years. Risk analysis predominated over risk evaluation. Our findings support the hypothesis that FRAs' weaknesses contributed to limited progress in flood management in LMICs. The data and information produced by FRAs were rarely suitable for flood-risk treatment because of insufficient quality and a frequent monodisciplinary, desk-based approach that conflicts with the principles of public participation established in several countries. However, the review identified examples of high-quality FRAs carried out in collaboration with flood-exposed communities that may provide useful models for future assessments. Data and maps should be openly accessible and systematically accompanied by metadata. Data precision should be significantly improved and accuracy assessed. Risk knowledge should be developed transdisciplinarily and be co-produced with flood-exposed communities, with greater attention to risk evaluation. Without accessible and usable datasets, sufficiently precise information and co-produced risk knowledge, the contribution of FRAs to flood management will remain limited, ultimately rendering disaster risk reduction less effective.

Supplementary Materials: Tables S1–S16 can be downloaded at https://data.mendeley.com/datasets/t77ywzrp6b/2 (accessed on 27 October 2026), Table S1: ODA 1995–2024; Table S2: FRAs reviews; Table S3: FRAs in LMICs 2007–26; Table S4: Plans in 28 LMICs; Table S5: Plans input; Table S6: Extension of studied region; Table S7: FRA type & data access; Table S8: FRAs supplementary material; Table S9: FRAs output; Table S10: FRAs measures; Table S11: FRAs treatment strategies; Table S12: FRAs completeness, precision; Table S13: FRAs accuracy; Table S14: Info quality; Table S15: Ground truth; Table S16: FRAs process.

Author Contributions: Conceptualisation, M.T.; methodology, M.T.; investigation, D.G., F.G.T., M.T. and R.V.; resources, M.T.; data curation, M.T.; writing—original draft preparation, review and editing, D.G., F.G.T., M.T. and R.V.; visualization, M.T.; supervision, M.T.; project administration, M.T.; funding acquisition, M.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Italian Agency for Development Cooperation, grant number AID 012487.

Data Availability Statement: The original data presented in the study are openly available in Mendeley Data, Flood Risk Assessments for Rural Areas of Low- and Middle-income Countries 2007–2026, at https://doi.org/10.17632/t77ywzrp6b.2.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AVHRR	Advanced Very-High Resolution Radiometer
DEM	Digital Elevation Model
E	Emergency
EWS	Early Warning System
EO	Earth Observation
FAIR	Findability Accessibility Interoperability Reusability
FRA	Flood Risk Assessment
GIS	Geographic Information System
GloFAS	Global Flood Awareness Systems
HEC-RAS	Hydrological Engineering Center-River Analysis Software
IEC	International Electrotechnical Commission
IRBM	Integrated River Basin Management

ISO	International Standardisation Organisation
LD	Local Development
LiDAR	Light Detection and Ranging
LMICs	Low- and Middle-Income Countries
MCA	Multi-Criteria Analysis
ML	Machine Learning
NOAA	National Oceanic and Atmospheric Administration
ODA	Official Development Assistance
OECD	Organisation for Economic Co-operation and Development
RBM	River Basin Management
RCP	Radiative Concentration Pathway
RM	Risk Management
SAR	Synthetic Aperture Radar
SFDRR	Sendai Framework for Disaster Risk Reduction
SRTM	Shuttle Radar Topographic Mission
UNDRR	United Nations Office for Disaster Risk Reduction
US	United States
WASH	Water Sanitation and Hygiene

References

1. Sauer, I.J.; Mester, B.; Frieler, K.; Zimmermann, S.; Schewe, J.; Otto, C. Limited progress in global reduction of vulnerability to flood impacts over the past two decades. *Commun. Earth Environ.* **2024**, *5*, 239. [CrossRef]
2. Rentschler, J.; Salhab, M.; Jafino, B.A. Flood exposure and poverty in 188 countries. *Nat. Commun.* **2022**, *13*, 3527. [CrossRef] [PubMed]
3. OECD. Data Explorer, DAC5: Aid (ODA) by Sector and Provider. Available online: https://data-explorer.oecd.org/ (accessed on 17 September 2026).
4. Alfieri, L.; Burek, P.; Dutra, E.; Krzeminski, B.; Muraro, D.; Thielen, J.; Pappenberger, F. GloFAS–global ensemble streamflow forecasting and flood early warning. *Hydrol. Earth Syst. Sci. Discuss.* **2012**, *9*, 12293–12332. [CrossRef]
5. Muhadi, N.A.; Abdullah, A.F.; Bejo, S.K.; Mahadi, M.R.; Mijic, A. The use of LiDAR-derived DEM in flood applications: A review. *Remote Sens.* **2020**, *12*, 2308. [CrossRef]
6. Tchotsoua, M.; Fotsing, J.-M.; Moussa, A. Evaluation des risques d'inondation dans la vallée de la Bénoué en aval du barrage de Lagdo (Cameroun). In Proceedings of the Journées scientifiques inter-réseaux de l'Agence universitaire de la Francophonie, Hanoi, Vietnam, 6–9 November 2007.
7. Wipulanusat, W.; Nakrod, S.; Prabnarong, P. Multi-hazard Risk Assessment Using GIS and RS Applications: A Case Study of Pak Phanang Basin. *Walailak J. Sci. Technol.* **2009**, *6*, 109–125.
8. *IEC 31010*; Risk Management—Risk Assessment Techniques. Edition 2 (2019). ISO-International Organization for Standardization: Geneva, Switzerland, 2009. Available online: https://www.iso.org/standard/72140.html (accessed on 26 September 2026).
9. UNSDR. *Sendai Framework for Disaster Risk Reduction 2015–2030*; UNISDR: Geneva, Switzerland, 2015. Available online: https://www.undrr.org/media/16176/download?startDownload=20260528 (accessed on 26 September 2026).
10. Díez-Herrero, A.; Garrote, J. Flood risk analysis and assessment, applications and uncertainties: A bibliometric review. *Water* **2020**, *12*, 2050. [CrossRef]
11. Sibandze, P.; Kalumba, A.M.; Aljaddani, A.H.; Zhou, L.; Afuye, G.A. Geospatial mapping and meteorological flood risk assessment: A global research trend analysis. *Environ. Manag.* **2025**, *75*, 137–154. [CrossRef] [PubMed]
12. Guo, X.; Zhu, A.L.; Chen, R.; Li, Q.; Li, Y.; Luo, Y.; Yin, C.; Cai, Y.; Xia, Z. Flood disaster management neglects rural areas. *Nat. Food* **2025**, *6*, 413–414. [CrossRef] [PubMed]
13. Li, Z.; Rosa, L.; Gorelick, S. Severe floods significantly reduce global rice yields. *Sci. Adv.* **2025**, *11*, eadx7799. [CrossRef] [PubMed]
14. Reed, C.; Anderson, W.; Kruczkiewicz, A.; Nakamura, J.; Gallo, D.; Seager, R.; McDermid, S.S. The impact of flooding on food security across Africa. *Proc. Natl. Acad. Sci. USA* **2022**, *119*, e2119399119. [CrossRef] [PubMed]
15. Chowdhury, J.R.; Parida, Y.; Agarwal, P. How flood affects rural employment in India: A gender analysis. *Int. J. Disaster Risk Reduct.* **2022**, *73*, 102881. [CrossRef]
16. Morris, J.; Beedell, J.; Hess, T.M. Mobilising flood risk management services from rural land: Principles and practice. *J. Flood Risk Manag.* **2016**, *9*, 50–68. [CrossRef]

17. Kuang, D.; Liao, K.-L. When the rural is deliberately flooded to protect the urban: Examining the social costs in emergency flood diversion to inform more sustainable spatial flood risk management. *Environ. Sci. Policy* **2025**, *170*, 104116. [CrossRef]
18. Geudtner, D.; Gebert, N.; Tossaint, M.; Davidson, M.; Heliere, F.; Navas Traver, I.; Furnell, R.; Torres, R. Copernicus and ESA SAR Missions. In *Proceedings of the 2021 IEEE Radar Conference (RadarConf21)*; IEEE: Piscataway, NJ, USA, 2021. [CrossRef]
19. Thuyet Minh, D. A comprehensive overview on UAV-based applications for flood management. *Meas. Sci. Technol.* **2025**, *36*, 086006. [CrossRef]
20. Belcore, E.; Piras, M.; Pezzoli, A.; Massazza, G.; Rosso, M. Raspberry PI3 multispectral low-cost sensor for UAV based remote sensing, Case study in South-West Niger. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *XLII-2/W13*, 207–214. [CrossRef]
21. Lou, H.; Wang, P.; Yang, S.; Hao, F.; Ren, X.; Wang, Y.; Shi, L.; Wang, J.; Gong, T. Combining and Comparing an Unmanned Aerial Vehicle and Multiple Remote Sensing Satellites to Calculate Long-Term River Discharge in an Ungauged Water Source Region on the Tibetan Plateau. *Remote Sens.* **2020**, *12*, 2155. [CrossRef]
22. Hidayah, E.; Halik, G.; Indarto, I.; Khaulan, D.W. Flood hazard mapping of the Welang river, Pasuruan, East Java, Indonesia. *J. Appl. Water Eng. Res.* **2022**, *11*, 333–344. [CrossRef]
23. Mia, M.S.J.; Guasselli, L.A.; de Oliveira, G. Avaliação de Risco a Inundações: Análise Bibliométrica entre 2010 e 2024. *Rev. Bras. Geogr. Física* **2026**, *19*, 1568–1587. [CrossRef]
24. Gasmi, F.; Aly, M.H. A Comprehensive Systematic Review of Contemporary Geospatial Approaches to Flood Hazard and Risk Assessment. *Urban Sci.* **2026**, *10*, 271. [CrossRef]
25. Oo, T.Z.; Humphries, U.W. Hydrological modeling of flood impacts under land use and land cover change: A systematic review of tools, trends, and challenges. *MethodsX* **2026**, *16*, 103724. [CrossRef] [PubMed]
26. Tabasi, N.; Fereshtehpour, M.; Roghani, B. A review of flood risk assessment frameworks and the development of hierarchical structures for risk components. *Discov. Water* **2025**, *5*, 10. [CrossRef]
27. Diaconu, D.C.; Costache, R.; Popa, M.C. An Overview of Flood Risk Analysis Methods. *Water* **2021**, *13*, 474. [CrossRef]
28. Ali, K.; Bajracharyar, R.M.; Raut, N. Advances and Challenges in Flash Flood Risk Assessment: A Review. *J. Geogr. Nat. Disast.* **2017**, *7*, 2. [CrossRef]
29. Snyder, H. Literature review as a research methodology: An overview and guidelines. *J. Bus. Res.* **2019**, *104*, 333–339. [CrossRef]
30. Weichselgartner, J.; Pigeon, P. The role of knowledge in disaster risk reduction. *Int. J. Disaster Risk Sci.* **2015**, *6*, 107–116. [CrossRef]
31. *ISO/IEC 25024*; Measurement of Data Quality. ISO-International Organisation for Standardisation: Geneva, Switzerland, 2015. Available online: https://www.iso.org/standard/35749.html (accessed on 26 September 2026).
32. OECD-Organisation for Economic Co-Operation and Development. *OECD Principles and Guidelines for Access to Research Data from Public Funding*; OECD: Paris, France, 2007. Available online: https://www.oecd.org/content/dam/oecd/en/publications/reports/2007/04/oecd-principles-and-guidelines-for-access-to-research-data-from-public-funding_g1gh7fe5/9789264034020-en-fr.pdf (accessed on 6 June 2026).
33. Mons, B.; Schultes, E.; Liu, F.; Jacobsen, A. The FAIR principles: First generation implementation choices and challenges. *Data Intell.* **2020**, *2*, 1–9. [CrossRef]
34. United Nations Economic Commission for Europe. *Getting the Facts Right: A Guide to Presenting Metadata with Examples on the Millennium Development Goals Indicators*; United Nations: New York, NY, USA, 2013. Available online: https://unece.org/statistics/publications/getting-facts-right (accessed on 26 September 2026).
35. Eurostat. Metadata Overview. 2026. Available online: https://ec.europa.eu/eurostat/web/metadata (accessed on 26 September 2026).
36. United Nations General Assembly. Report of the Open-Ended Intergovernmental Expert Working Group on Indicators and Terminology Relating to Disaster Risk Reduction, 2016, 71st Session, Agenda Item 19 c Sustainable Development. *Disaster Risk Reduction*. Available online: https://www.undrr.org/publication/report-open-ended-intergovernmental-expert-working-group-indicators-and-terminology (accessed on 26 September 2026).
37. de Moel, H.; Jongman, B.; Kreibich, H.; Merz, B.; Penning-Roswell, E.; Ward, P.J. Flood risk assessment at different spatial scales. *Mitig. Adapt. Strateg. Glob. Change* **2015**, *20*, 865–890. [CrossRef] [PubMed]
38. UNDRO-Office of the United Nations Disaster Relief Co-Ordinator. *Natural Disasters and Vulnerability Analysis*; Report of Experts Group Meeting (9–12 July 1979); UNDRO: Geneva, Switzerland, 1980; 49p. Available online: https://archive.org/details/naturaldisasters00offi/page/n5/mode/2up (accessed on 26 September 2026).
39. Wisner, B.; Blaikie, P.; Cannon, T.; Davis, I. *At risk. Natural Hazards People's Vulnerability and Disasters*; Routledge: New York, NY, USA, 1994.
40. Saaty, T.L. How to make a decision. The analytical hierarchical process. *Inf. J. Appl. Anal.* **1994**, *24*, 19–43. [CrossRef]
41. Tian, Y.; Wu, Y.; Liao, X. Flood Risk Assessment Based on Entropy Weight and Cloud Model: A Case Study in Huaihe River Basin of China. In *Proceedings of the 2010 The 2nd Conference on Environment Science and Information Application Technology, Wuhan*; IEEE: Piscataway, NJ, USA, 2010; pp. 80–83. [CrossRef]
42. Guo, E.; Zhang, J.; Ren, X.; Zhang, Q.; Sun, Z. Integrated risk assessment of flood disaster based on improved set pair analysis and the variable fuzzy set theory in central Liaoning Province, China. *Nat. Hazards* **2014**, *74*, 947–965. [CrossRef]

43. Danumah, J.H.; Odai, S.N.; Saley, B.M.; Szarzynski, J.; Thiel, M.; Kwaku, A.; Kouame, F.K.; Akpa, L.Y. Flood risk assessment and mapping in Abidjan district using multi-criteria analysis (AHP) model and geoinformation techniques, (cote d'ivoire). *Geoenviron. Disasters* **2016**, *3*, 10. [CrossRef]
44. Kurniawan, A.A.; Sunardi, S.; Hendarmawan, H.; Ridwansyah, I. A systematic literature review on GIS and MCDA based flood risk management determinants in developing countries. *Discov. Appl. Sci.* **2026**, *8*, 1161. [CrossRef]
45. Zeng, F.; Lai, C.; Wang, Z. Flood Risk Assessment Based on Principal Component Analysis for Dongjiang River Basin. In *Proceedings of the 2012 2nd International Conference on Remote Sensing, Environment and Transportation Engineering, Nanjing, China*; IEEE: Piscataway, NJ, USA, 2012; pp. 1–4. [CrossRef]
46. Strahler, A.N. Quantitative analysis of watershed geomorphology. *Trans. Am. Geophys. Union* **1957**, *38*, 913–920. [CrossRef]
47. Youssef, A.M.; Pradhan, B.; Hassan, A.M. Flash flood risk estimation along the St. Katherine road, southern Sinai, Egypt using GIS based morphometry and satellite imagery. *Environ. Earth Sci.* **2011**, *62*, 611–623. [CrossRef]
48. Farhan, Y.; Ayed, A. Assessment of flash flood hazard in arid watershed of Jordan. *J. Geogr. Inf. Syst.* **2017**, *9*, 717–751. [CrossRef]
49. Rifai, N.; Khattabi, A.; Rhazi, L. River flood modeling for integrated flood risk management: Case of Tahaddart watershed (Northwestern Morocco). *J. Water Sci.* **2014**, *27*, 57–69. [CrossRef]
50. Ma, M.; Liu, C.; Zhao, G.; Xie, H.; Jia, P.; Wang, D.; Wang, H.; Hong, Y. Flash flood risk analysis based on machine learning techniques in the Yunnan province, China. *Remote Sens.* **2019**, *11*, 170. [CrossRef]
51. Membele, G.M.; Naidu, M.; Mutanga, O. Examining flood vulnerability mapping approaches in developing countries: A scoping review. *Int. J. Disaster Risk Reduct.* **2025**, *69*, 102766. [CrossRef]
52. Grimaldi, S. Statistical hydrology. In *Treatise on Water Science, Four-Volume Set*, 1st ed.; Elsevier: Amsterdam, The Netherlands, 2011; pp. 479–517. [CrossRef]
53. Solomatine, D.P.; Wagener, T. Hydrological modeling. In *Treatise on Water Science, Four-Volume Set*, 1st ed.; Elsevier: Amsterdam, The Netherlands, 2011. [CrossRef]
54. Tingsanchali, T.; Karim, F. Flood-hazard assessment and risk-based zoning of a tropical flood plain: Case study of the Yom River, Thailand. *Hydrol. Sci. J.* **2010**, *55*, 145–161. [CrossRef]
55. Horrit, M.S.; Bates, P.D. Evaluation of 1D and 2D numerical models for predicting river flood inundation. *J. Hydrol.* **2002**, *268*, 87–99. [CrossRef]
56. Horton, R.E. Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. *Bul. Geol. Soc. Am.* **1945**, *56*, 275–370. [CrossRef]
57. Samarasinghe, S.M.J.S.; Nandalal, H.K.; Weliwitiyac, D.P.; Fowzed, J.S.M.; Hazarikad, M.K.; Samarakoond, L. Application of remote sensing and GIS for flood analysis: A case study at Kalu-Ganaga River, Sri Lanka. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2010**, *XXXVIII*, 110–115. Available online: https://www.isprs.org/proceedings/xxxviii/part8/pdf/JTS61_20100608150800.pdf (accessed on 26 September 2026).
58. Redondo-Tilano, S.A.; Boucher, M.A.; Lacey, J. Emerging strategies for addressing flood-damage modeling issues: A review. *Int. J. Disaster Risk Reduct.* **2025**, *116*, 105058. [CrossRef]
59. Julien, P.Y.; Ghani, A.A.; Zakaria, N.A.; Abdullah, R.; Chang, C.K. Case study: Flood mitigation of the Muda River, Malaysia. *J. Hydraul. Eng.* **2010**, *136*, 251–261. [CrossRef]
60. Tarchiani, V.; Massazza, G.; Rosso, M.; Tiepolo, M.; Pezzoli, A.; Housseini, M.I.; Katiellou, G.L.; Tamagnone, P.; De Filippis, T.; Rocchi, L.; et al. Community and impact based early warning system for flood risk preparedness: The experience of the Sirba River in Niger. *Sustainability* **2020**, *12*, 1802. [CrossRef]
61. Kiptum, A.; Mwangi, E.; Otieno, G.; Njogu, A.; Kilavi, M.; Mwai, Z.; MacLeod, D.; Neal, J.; Hawker, L.; O'Shea, T.; et al. Advancing operational flood forecasting, early warning and risk management with new emerging science: Gaps, opportunities and barriers in Kenya. *J. Flood Risk Manag.* **2022**, *18*, e12884. [CrossRef]
62. Tiepolo, M.; Abraiz, M.; Housseini, M.I.; Baoua, O.; Belcore, E.; Cannella, G.; Ganora, D.; Marmolejo Gutiérrez, A.; Piras, M.; Saretto, F.; et al. Integrating high-resolution geoinformation with local knowledge enhances flood risk assessment: A case study from rural Niger. *Nat. Hazards Res.* **2026**, *in press*. [CrossRef]
63. Rrokai, S.; Molinari, S.; Paz Idarraga, C.D.; Rotaru, A.M.; Ergun, Z.; Porzio, M.; Costa, A.; Radice, A. Flood risk assessment and participative process in the data-scarce Metuge district of Mozambique: An exportable approach. *Int. J. Disaster Risk Reduct.* **2025**, *116*, 105163. [CrossRef]
64. Edamo, M.L.; Hatiye, S.D.; Minda, T.T.; Ukumo, T.Y. Flood inundation and risk mapping under climate change scenarios in the lower Bilate catchment, Ethiopia. *Nat. Hazards* **2023**, *118*, 2199–2226. [CrossRef]
65. Chowdhury, N.; Choudhary, M. Flood risk assessment of the Narmada Basin, India, under climate change scenarios. *Aqua. Water Infrastruct. Ecosys. Soc.* **2024**, *73*, 2150. [CrossRef]
66. Putriasri, A.E.; Eliasta, L.; Amatullah, S.I.; Sandi, C.; Pahlevi, A.R.; Hikmat, S.N.; Jaya, I.; Kosasih, B.; Rahmawati, A.; Hermawan, Y. Ciujung river basin flood risk assessment due to climate change and its countermeasure. *IOP Conf. Ser. Earth Environ. Sci.* **2024**, *1343*, 012037. [CrossRef]

67. Tiepolo, M.; Housseini, M.I.; Cannella, G.; Katiellou, G.L.; Ganora, D.; Marmolejo Gutiérrez, A.; Saretto, F.; Tarchiani, V.; Vesipa, R. The contribution of fine-grained exposure data to flood risk assessment along the Niger River. *Nat. Hazards* **2026**, *122*, 554. [CrossRef]
68. Pandey, A.C.; Singh, S.K.; Nathawat, M.S. Waterlogging and flood hazards vulnerability and risk assessment in Indo Gangetic plain. *Nat. Hazards* **2010**, *55*, 273–289. [CrossRef]
69. Brivio, P.A.; Colombo, R.; Maggi, M.; Tomasoni, R. Integration of remote sensing data and GIS for accurate mapping of flooded areas. *Int. J. Remote Sens.* **2002**, *23*, 429–441. [CrossRef]
70. Nkeki, F.N.; Henah, P.J.; Ojeh, V.N. Geospatial techniques for the assessment and analysis of flood risk along the Niger-Benue basin in Nigeria. *J. Geogr. Inf. Syst.* **2013**, *5*, 123–135. [CrossRef]
71. Voigt, S.; Giulio-Tonolo, F.; Kucera, J.; Jones, B.; Schneiderhan, T.; Platzeck, G.; Kaku, K.; Hazarika, M.K.; Czaran, L.; Li, S.; et al. Global trends in satellite-based emergency mapping. *Science* **2016**, *353*, 247–252. [CrossRef] [PubMed]
72. Poterek, Q.; Caretto, A.; Braun, R.; Clandillon, S.; Huber, C.; Ceccato, P. INterpolated FLOod Surface (INFLOS), a rapid and operational tool to estimate flood depths from Earth observation data for emergency management. *Remote Sens.* **2025**, *17*, 329. [CrossRef]
73. Hegger, D.L.T.; Driessen, P.P.J.; Wiering, M.; Van Rijswick, H.F.M.W.; Kundzewicz, Z.W.; Matczak, P.; Crabbé, A.; Raadgever, G.T.; Bakker, M.H.N.; Priest, S.J.; et al. Toward more flood resilience: Is a diversification of flood risk management strategies the way forward? *Ecol. Soc.* **2016**, *21*, 52. [CrossRef]
74. Arnstein, S. A ladder of citizen participation. *J. Am. Plan. Assoc.* **1967**, *35*, 216–224. [CrossRef]
75. Tiepolo, M.; Bacci, M.; Braccio, S.; Bechis, S. Multi-Hazard Risk Assessment at Community Level Integrating Local and Scientific Knowledge in the Hodh Chargui, Mauritania. *Sustainability* **2019**, *11*, 5063. [CrossRef]
76. Dao, N.X.; Hang, N.T.M.; Hole, L.R.; Khang, N.T. Flood risk assessment and mitigation strategies for areas downstream of the Vuc Tron reservoir, Vietnam. *KSCE J. Civ. Eng.* **2026**, *30*, 100601. [CrossRef]
77. Benouar, D.; Benmokhtar, A. Risk governance for the implementation of the Sendai Framework for Disaster Risk Reduction in Algeria. *Int. J. Disaster Risk Sci.* **2025**, *16*, 58–70, Correction in *Int. J. Disaster Risk Sci.* **2025**, *16*, 71. [CrossRef]
78. Bonasia, R.; Lucatello, S. Linking flood susceptibility mapping and governance in Mexico for flood mitigation: A participatory approach model. *Atmosphere* **2019**, *10*, 424. [CrossRef]
79. Mazimwe, A.; Hammouda, I.; Gidudu, A. Implementation of FAIR principles for ontologies in the disaster domain: A systematic literature review. *Int. J. Geo-Inf.* **2021**, *10*, 324. [CrossRef]
80. Shrestha, A.; Láng-Ritter, J.; Taka, M.; Sundman, J.; Kallio, M.; Zhao, D.; Juvakoski, A.; Niu, Q.; Le, M.; Caggiano, M.F.; et al. Navigating Data Scarcity in Flood Risk Assessment. *Wiley Interdiscip. Rev. Water* **2026**, *13*, e70085. [CrossRef]
81. Wojciech, S.; Kashubin, S.; Ritter, M.; Annkah, A.; Bouchareb, Y.S.E.; Dauphin, Y.; Keysers, D.; Neumann, M.; Cisse, M.; Quinn, J. Continental-scale building detection from high resolution satellite imagery. *arXiv* **2021**. [CrossRef]
82. Smith, A.; Bates, P.D.; Wing, O.; Sampson, C.; Quinn, N.; Neal, J. New estimates of flood exposure in developing countries using high-resolution population data. *Nat. Commun.* **2019**, *10*, 1814. [CrossRef] [PubMed]
83. de Goër de Herve, M. Fair strategies to tackle unfair risks? Justice considerations within flood risk management. *Int. J. Disaster Risk Reduct.* **2022**, *69*, 102745. [CrossRef]
84. Ghaffarian, S.; Ghaffarian, S. Automatic building detection based on supervised classification using high resolution Google Earth images. *Int. Arch. Photogram. Remote Sens. Spat. Inf. Sci.* **2014**, *XL-3*, 101–106. [CrossRef]
85. Jacobsen, K. Digital elevation models—From satellite images to free available DEMs. *Int. Arch. Photogram. Remote Sens. Spat. Inf. Sci.* **2025**, *XLVIII-M-6–2025*, 147–152. [CrossRef]
86. McClean, F.; Dawson, R.; Kilsby, C. Implications of using global digital elevation models for flood risk analysis in cities. *Water Resour. Res.* **2020**, *56*, e2020WR028241. [CrossRef]
87. Destefanis, T.; Guliyeva, S.; Boccardo, P.; Fissore, V. Advancing Flood Detection and Mapping: A Review of Earth Observation Services, 3D Data Integration, and AI-Based Techniques. *Remote Sens.* **2025**, *17*, 2943. [CrossRef]
88. de Moel, H.; Aerts, J.C.J.H. Effect of uncertainty in land use, damage models and inundation depth on flood damage estimates. *Nat. Hazards* **2011**, *58*, 407–425. [CrossRef]
89. Henstra, D.; Minano, A.; Thistlethwaite, J. Communicating disaster risk? *Nat. Hazards Earth Syst. Sci.* **2019**, *19*, 313–323. [CrossRef]
90. Rindsfuser, N.; Zischg, A.P.; Keiler, M. Monitoring flood risk evolution: A systematic review. *iScience* **2024**, *27*, 110653. [CrossRef] [PubMed]
91. Anderson, M.J.; Logan, T. Risk without place: Why most climate risk assessments fail to support place-based adaptation. *Clim. Risk Manag.* **2026**, *52*, 100816. [CrossRef]
92. Danladi, A.; Ling, G.H.T.; Dan'arewa, A.D.; Lawl, Y.Z.; Akoka, P.; Zango, M.S.; Dyachia, S.Z. Acquisition of flood disaster risk reduction indigenous knowledge in Kaduna floodplain, Kaduna town, Nigeria. *Tex. J. Multidiscip. Stud.* **2021**, *3*, 44–52.
93. Bennett, M.M.; Gleason, C.J.; Tellman, B.; Alvarez Leon, L.F.; Friedrich, H.K.; Ovienmhada, U.; Mathews, A.J. Bringing satellites down to Earth: Six steps to more ethical remote sensing. *Glob. Environ. Change Adv.* **2024**, *2*, 100003. [CrossRef]

94. Madushani, J.A.T.; Withanage, N.C.; Mishra, P.K.; Meraj, G.; Kibebe, C.G.; Kumar, P. Thematic and bibliometric review of remote sensing and geographic information system-based flood disaster studies in South Asia during 2004–2024. *Sustainability* **2025**, *17*, 217. [CrossRef]
95. Darmi, T.; Mujtahid, I.M.; Indarti, S.; Agussalim, M. Community based institutional governance in Rindu Hati village for building a sustainable and disaster-resilient tourism destination. *IOP Conf. Ser. Earth Environ. Sci.* **2025**, *1556*, 012089. [CrossRef]
96. Azad, M.A.K.; Uddin, M.S.; Zaman, S.; Ashraf, M.A. Community-based disaster management and its salient features: A policy approach to people-centred risk reduction in Bangladesh. *Asia-Pac. J. Rural Dev.* **2020**, *29*, 135–160. [CrossRef]
97. Pasamonte, R.C. Strengthening community engagement in local disaster management: The Northern Mindanao, Philippines experience. *J. Public Pol.* **2025**, *11*, 1–7. [CrossRef]
98. Agyemang, F. Legal and policy perspectives on public participation and disaster risk management in South African cities. *J. Local Gov. Res. Innov.* **2025**, *6*, a259. [CrossRef]
99. Tiepolo, M.; Braccio, S. Mainstreaming disaster risk reduction into local development plans for rural Tropical Africa: A systematic assessment. *Sustainability* **2020**, *12*, 2196. [CrossRef]
100. Fekete, A.; Aslan, A.B.; Madruga de Brito, M.; Dominguez, I.; Fernando, N.; Illing, C.J.; Apil, K.K.C.; Mahdavian, F.; Norf, C.; Platt, S.; et al. Increasing flood risk awareness and warning readiness by participation—But who understands what under 'participation'? *Int. J. Disaster Risk Reduct.* **2021**, *57*, 102157. [CrossRef]
101. Vasileiou, K. Integrating local and scientific knowledge in disaster risk reduction: A systematic review of motivations, processes, and outcomes. *Int. J. Disaster Risk Reduct.* **2022**, *81*, 103255. [CrossRef]
102. Tiepolo, M.; Abraiz, M.; Bacci, M.; Baoua, O.; Cannella, G.; Fiorillo, E.; Ganora, D.; Ibrahim, M.I.; Katiellou, G.L.; Piras, M.; et al. Flood damage risk mapping along the River Niger: Ten benefits of a participated approach. *Climate* **2025**, *13*, 80. [CrossRef]
103. Morrison, A.; Westbrook, C.J.; Noble, B.F. A review of the flood risk management governance and resilience literature. *J. Flood Risk Manag.* **2017**, *11*, 291–304. [CrossRef]
104. Vedeld, T.; Coly, A.; Ndour, N.M.; Hellevik, S. Climate adaptation at what scale? Multi-level governance, resilience, and coproduction in Saint Louis, Senegal. *Nat. Hazards* **2016**, *82*, S173–S199. [CrossRef]
105. Schaer, C.; Hanounou, E.K. The real governance of disaster risk management in peri-urban Senegal: Delivering flood response services through co-production. *Prog. Dev. Stud.* **2017**, *17*, 38–53. [CrossRef]
106. Williams, D.S.; Máñez Costa, M.; Celliers, L.; Sutherland, C. Informal settlements and flooding: Identifying strengths and weaknesses in local governance for water management. *Water* **2018**, *10*, 871. [CrossRef]
107. UNDRR. *Global Assessment Report on Disaster Risk Reduction*; United Nations Office for Disaster Risk Reduction: Geneva, Switzerland, 2022. Available online: www.undrr.org/GAR2022 (accessed on 1 June 2026).
108. Waseem, H.B.; Rana, A. Floods in Pakistan: A state-of-the-art review. *Nat. Hazards Res.* **2023**, *3*, 359–373. [CrossRef]
109. Krueger, T.; Maynard, C.; Carr, G.; Bruns, A.; Mueller, E.N.; Lane, S. A transdisciplinary account of water research. *WIREs* **2016**, *3*, 369–389. [CrossRef] [PubMed]
110. Rosmaldi, H.S.; Ahmed, M.F.; Mokhtar, M.B.; Lim, C.K. Reviewing challenges of flood risk management in Malaysia. *Water* **2023**, *15*, 2390. [CrossRef]

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