

IPCC-Aligned Framework for Flood Vulnerability Indices: A Scoping Review of Geospatial Indicators for Adaptation Planning

Franklin Gaspar

up202204098@up.pt

University of Porto

Fernando B. Alves

University of Porto

Ana Monteiro

University of Porto

Cecília Rocha

University of Porto

Research Article

Keywords: Climate Vulnerability, Vulnerability Assessment, Flood Risk Assessment, Urban Flood Resilience, Climate Adaptation, Green–Blue Infrastructure

Posted Date: September 1st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10342533/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

IPCC-Aligned Framework for Flood Vulnerability Indices: A Scoping Review of Geospatial Indicators for Adaptation Planning

Franklin Gaspar; Fernando B. Alves; Ana Monteiro; Cecília Rocha.

F. Gaspar (Corresponding author)

CITTA—Research Centre for Territory, Transport and Environment, Faculty of Engineering, University of Porto, 4200-465 Porto, Portugal.

Orcid: 0009-0009-1013-3767; e-mail: up202204098@up.pt

F. B. Alves

CITTA—Research Centre for Territory, Transport and Environment, Faculty of Engineering, University of Porto, 4200-465 Porto, Portugal.

Faculty of Architecture and Arts, Lusíada University of Porto, Rua de Moçambique 21 e 71, 4100-348 Porto, Portugal.

Orcid: 0000-0001-5993-528X; e-mail: alves@fe.up.pt

A. Monteiro

Faculty of Arts and Humanities, University of Porto, Via Panorâmica, s/n, 4150-564 Porto, Portugal.

CITTA—Research Centre for Territory, Transport and Environment, Faculty of Engineering, University of Porto, 4200-465 Porto, Portugal.

Orcid: 0000-0002-3392-2664; e-mail: anamt@letras.up.pt

C. Rocha

CITTA—Research Centre for Territory, Transport and Environment, Faculty of Engineering, University of Porto, 4200-465 Porto, Portugal.

Orcid: 0000-0002-9736-434X; e-mail: carocha@fe.up.pt

Abstract

Operationalising urban flood resilience requires robust flood-vulnerability assessments capable of identifying vulnerable areas and populations to support evidence-based adaptation planning and risk-reduction strategies. Flood Vulnerability Indices (FVIs) integrate geospatial indicators to characterise Exposure, Sensitivity, Adaptive Capacity and, in risk-oriented frameworks, Hazard. However, current FVIs exhibit substantial conceptual and methodological inconsistencies limiting cross-study comparability and transferability. To address this gap, we conducted a PRISMA-guided scoping review aligned with the IPCC AR6 framework, harmonising 2,437 geospatial indicators extracted from 131 English-language peer-reviewed studies indexed in Scopus and Web of Science. Indicators were classified into the four IPCC climate dimensions: Hazard (710), Exposure (699), Sensitivity (588) and Adaptive Capacity (440). Despite widespread use of the term vulnerability, 48% of FVIs omitted either Sensitivity or Adaptive Capacity, revealing substantial inconsistencies in vulnerability operationalisation. Within Sensitivity, the most frequently represented indicators captured disability, household composition, employment status and income, whereas composite measures of social vulnerability remained comparatively uncommon. Green–blue infrastructure accounted for over 10% of all indicators, highlighting the increasing incorporation of nature-based solutions into contemporary FVIs. Following FAIR principles, this review provides a transparent, replicable catalogue of IPCC-aligned indicators and data sources, supporting future evidence-based assessment for urban flood resilience and adaptation planning.

Keywords: Climate Vulnerability; Vulnerability Assessment; Flood Risk Assessment; Urban Flood Resilience; Climate Adaptation; Green–Blue Infrastructure

Introduction

As climate change intensifies and urban populations continue to grow, urban flooding triggers multiple disruptions and cascading risks to public health and critical infrastructure (World Economic Forum, 2026; World Health Organization, 2025), creating an urgent need for urban planners and policymakers to develop robust and accurate tools to evaluate climate-related vulnerability (Hidalgo et al., 2019; Monteiro et al., 2022). In climate adaptation planning, Flood Vulnerability Indices (FVI) has emerged as a map-based composite tool that integrates meteorological, environmental and socioeconomic geospatial indicators to identify spatial clusters and estimate potential flood impacts (Dhawale et al., 2024; Rehman et al., 2019), supporting decision-making in public health, disaster risk and climate adaptation (Reinwald et al., 2024). However, this indicator based approach relies on constructing complex indices that overlay environmental, climatic, socio-economic and institutional factors, facing significant challenges regarding data collection, normalisation, weighting and aggregation (Al-Hashimi & Seenath, 2026; Nguyen et al., 2025). Although current practice increasingly demands better integration of scientific and data-driven outputs into practical planning tools (Arana-Ruedas et al., 2026; Shirmohammadi et al., 2026), the field still lacks a theoretical foundation to validate indicator selection and index composition (Al-Rawas et al., 2024; Smith et al., 2026), as well as transparency in selecting and evaluating exposure and vulnerability indicators (Aboagye & Sharifi, 2026; Rahimi et al., 2026).

Regarding this, since the publication of its Third Assessment Report (TAR) (IPCC, 2001), the Intergovernmental Panel on Climate Change (IPCC) conceptualisation of climate vulnerability - initially defined as a function of exposure, sensitivity and adaptive capacity - has been widely adopted across scientific, professional and policy communities (Asayama, 2024; Monteiro et al., 2022). However, from the Fifth (AR5) and Sixth (AR6) IPCC Assessment Reports (IPCC, 2014; 2023) onwards, vulnerability was reframed within a broader climate risk framework: vulnerability now encompasses only sensitivity and adaptive capacity, distinguished from the territorial factors of Exposure and from the climatic drivers that constitute Hazard. This evolution established a risk-based conceptualisation in which risk arises from the interaction of Hazard, Exposure and Vulnerability, providing a foundation for contemporary climate risk assessments, policies and adaptation programmes (World Health Organization, 2025), while also adding complexity to the operationalisation of former vulnerability dimensions (Estoque et al., 2023; Ishtiaque et al., 2022; Monteiro et al., 2022). **Figure 1** illustrates this conceptual transition from the TAR/AR4 vulnerability framing the AR6 risk-based harmonisation adopted in this review.

Although the IPCC climate framework provides a widely recognised reference for scientists and policymakers (Asayama, 2024; Sharifi et al., 2026), its operational adoption in FVI remains uneven. Indicators are frequently selected, grouped, and labelled differently across studies, sometimes combining pre-AR5 vulnerability structures with post-AR5 risk terminology, revealing considerable heterogeneity in conceptual framing and operational structure of indicator-based assessments (Prashar et al., 2024). This results in conceptual ambiguity regarding thematic dimensions, reduces cross-study comparability, and limits the transferability of findings to policy contexts (Reinwald et al., 2024). In response to this gap, this study adopts a PRISMA-Scoping Review design with explicit alignment to the IPCC AR6 framework, to examine how geospatial indicators are conceptualised and structured within FVI across the peer-reviewed literature, supporting a more transparent, systematic and replicable approach of geospatial indicators to urban Flood vulnerability assessment.

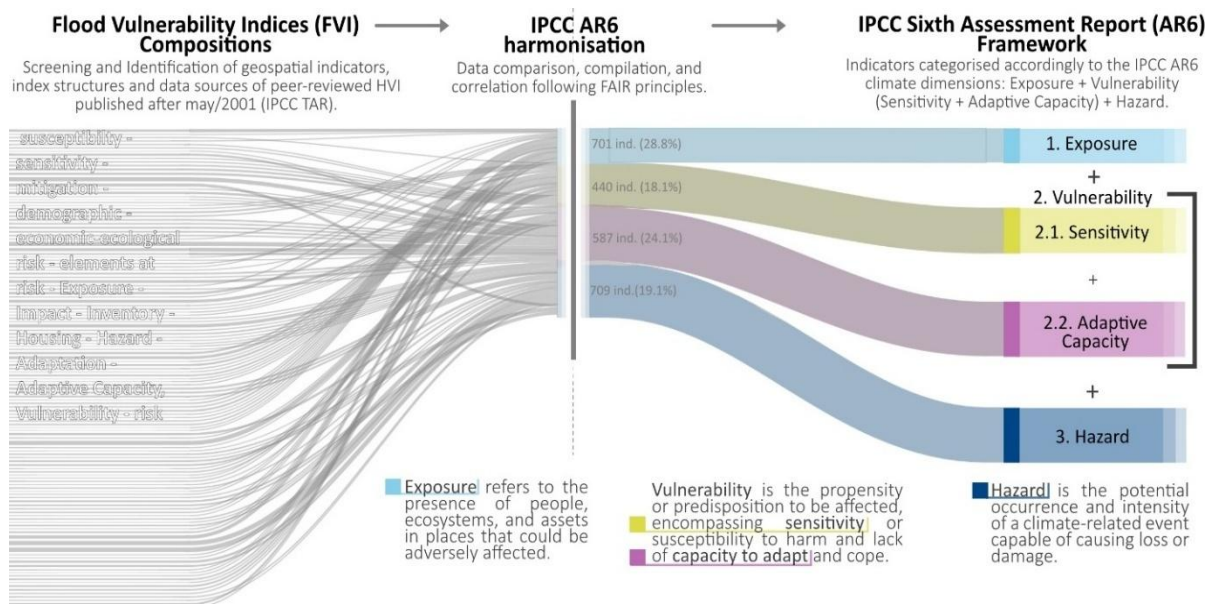


Fig. 1. Harmonisation process of FVI geospatial indicators within the IPCC-AR6 framework. The Sankey diagram classifies peer-reviewed indicators into climate dimensions, with flow widths highlighting the predominance of hazard and exposure.

98

99 Study Aims and Research Questions

100 Building on the evolution of IPCC vulnerability and risk frameworks, this study examines how
 101 geospatial indicators are conceptualised and operationalised within peer-reviewed FVI. Its aim
 102 is to support more consistent and evidence-based applications of FVI for urban Flood risk
 103 assessment and climate adaptation planning. The study addresses the following research
 104 questions: (RQ1) How are geospatial indicators selected, conceptualised and structured within
 105 current FVI when harmonised under the IPCC AR6 framework? (RQ2) Which geospatial
 106 indicators and data sources are most frequently used across the four IPCC dimensions (Hazard,
 107 Exposure, Sensitivity, Adaptive Capacity)? (RQ3) How is green-blue infrastructure (GBI)
 108 represented in current FVI, and what are the main gaps in its operationalisation?

109 Methods

110 Protocol and registration

111 This scoping review was based on the Arksey and O'Malley (Arksey & O'Malley, 2005)
 112 framework. We also followed the Preferred Reporting Items for Scoping Reviews (PRISMA-ScR)
 113 guidelines (Tricco et al., 2018) (see **Additional file 1**). This systematic approach was applied to
 114 identify and summarise existing geospatial indicators of FVI from peer-reviewed research
 115 articles published in open-access scientific journals. Conference papers, editorials, and grey
 116 literature were excluded. An overview of all studies included in the scoping review is provided
 117 in **Additional file 2**. The screening process involved an independent dual review of titles and
 118 abstracts, followed by full-text analysis, with disagreements resolved through consensus. The
 119 review was guided by FAIR principles (Findable, Accessible, Interoperable and Reusable;
 120 Wilkinson et al., 2016) to ensure transparency, reproducibility, and reuse of geospatial indicators
 121 in future research and professional practice. Detailed FAIR-oriented documentation of the
 122 structured database is provided in **Additional file 3**.

Information Sources

A systematic literature search was conducted on December 9, 2025, to identify peer-reviewed articles indexed in the Scopus and Web of Science (WoS) databases, with publication identifiers (DOI or ISBN). The search strategy incorporated the following terms and Boolean operators: "urban*" AND "climat*" AND "vulnerab*" AND "flood*" AND ("index*" OR "indice*" OR "map*"). Clarivate EndNote™ was employed as the primary tool for screening the identified literature.

Eligibility criteria

(i) Only papers published in English were included to avoid translation-related bias; (ii) To ensure FAIR's Findability and Accessibility, only freely available online (open-access) articles were considered; (iii) To support FAIR's Interoperability and Reusability of the geospatial data, only studies that explicitly reported the geospatial data used for climate mapping were included, with articles lacking data-source information excluded. Finally, (iv) to align the conceptual framework for climate vulnerability with international standards, this review only includes literature published after May 2001. This date corresponds with the release of the IPCC's TAR, which first established criteria for evaluating exposure, sensitivity and adaptive capacity, as well as standardising key concepts related to climate vulnerability, within the scientific and professional communities on a global scale.

Study Selection

Articles identified through Scopus and WoS were imported into EndNote™ for screening and duplicate removal, following three steps: (i) Initial screening: Titles and abstracts were independently reviewed by two researchers to assess relevance based on the predefined eligibility criteria (Section 2.2). After title and abstract screening, records that were not written in English, constituted grey literature, or failed to meet the FAIR open-access requirements were excluded; (ii) Full-text assessment: Potentially relevant papers were then examined in full. Discrepancies between reviewers were resolved through discussion and, when necessary, adjudicated by a third reviewer; (iii) Exclusion criteria: Records were excluded if they did not incorporate an FVI-based assessment, or if geospatial data information was not explicitly reported. This procedure ensured that only scientifically validated FVI were included for subsequent data charting and analysis.

Data charting and harmonisation process

Indicators were extracted from the 131 eligible studies using a standardised charting form developed in Microsoft Excel. Data charting was conducted independently by two reviewers to ensure consistency and accuracy. The harmonisation process comprised four sequential stages aligned with the FAIR principles: (i) Data comparison – Indicators were first recorded in their original terminology to preserve traceability to source studies, then recategorised into IPCC AR6 dimensions to establish cross-study comparability; (ii) Data compilation – structuring indicators hierarchically into standardised thematic categories to ensure interoperability; (iii) Data correlation – identifying recurrent approaches used for standardisation, aggregation and spatialisation to enhance reusability; and (iv) Data source identification – documenting data provenance and prioritising open-access datasets to support findability and accessibility. Together, these stages ensured methodological transparency, traceability, and the systematic application of FAIR principles across all reviewed FVIs.

Collating, summarising and reporting the results

The structured database (**Additional file 4**) was designed to facilitate cross-study comparison of geospatial indicators used in FVI. Variables were organised into five conceptual blocks: (i) Study and framework context, including Indicator_ID, Study_ID, and Conceptual_Framework, identifying each indicator and its vulnerability-based or risk-based approach. Each study was assigned a unique identifier (ART.ID) to ensure traceability across the structured database and throughout the analysis; (ii) Conceptual classification, comprising the original terminology used by authors (Original_Dimension), its harmonised classification under the IPCC framework (Reviewed_Dimension_IPCC), and the assigned thematic domain (Thematic_Domain); (iii) Indicator attributes, including original and harmonised indicator names (Original_Indicator, Reviewed_Indicator), and a brief definition (Indicator_Description), (iv) Methods and spatialisation, documenting analytical procedures (Method) and spatial data types (Spatial_Data_Type). Finally, (v) data source attributes, describing data provenance (Data_Source) and source typology (Data_Source_Category).

Results

Summary of search

A total of 1398 articles were identified and exported into Endnote, of which 575 were from Scopus and 823 from WoS databases. Of these, 310 were excluded due to duplication, resulting in 1088 records for screening. From these, 678 records were excluded for not being open access, 75 were excluded for being conference presentations outputs, 37 were excluded after reading the titles and abstracts and 32 articles were excluded for not being in English. Subsequently, 266 documents were eligible for full-text reading. Of these, 135 were excluded for not incorporating an FVI or for lacking geospatial data information, resulting in a total of 131 selected studies (see **Figure 2**).

Characteristics of the included studies

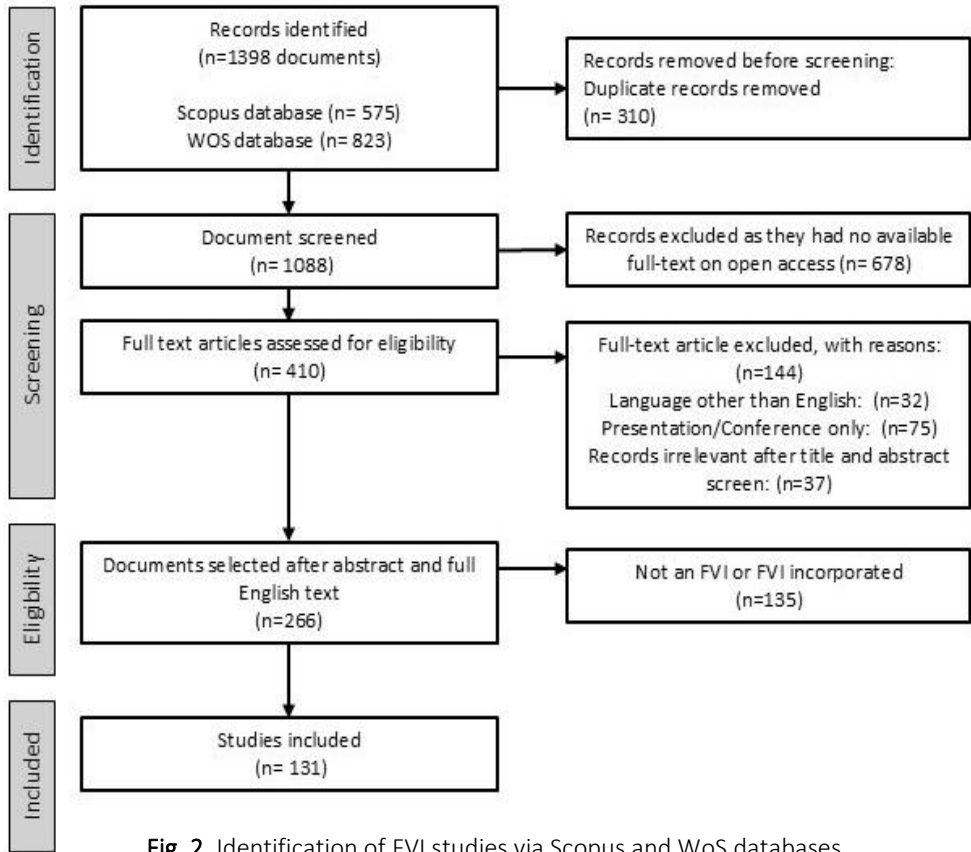


Fig. 2. Identification of FVI studies via Scopus and WoS databases.

The 131 studies included in this review are summarised with full details of each FVI in **Additional file 4**. Overall, the reviewed literature is relatively recent: nearly 70% of the studies were published after 2021, 24% between 2016 and 2020, and 6% from 2011 to 2015. From the 131 publications, 43 (32,8%) were international collaborations, with the highest numbers of collaborations attributed to China (13 collaborations), followed by India (6), Pakistan (6), Germany (5) and USA (5). In total numbers, Indian and Chinese institutions had the greatest number of contributions for our work, with 26 and 23 papers respectively, followed by Germany with 9, Pakistan with 7 and USA with 6. Study cases are distributed across multiple continents, with the highest concentration in Asia (57%), followed by Africa (16%), Europe (15%), North America (5%), South America (5%), Oceania (1%) and Central America (1%).

To address the research questions, we extracted key findings from the reviewed papers in three steps. First, we examined how geospatial indicators are selected, conceptualised and structured within current FVI when harmonised under the IPCC AR6 framework, documenting inconsistencies between stated conceptual frameworks and actual operationalisation of IPCC dimensions (Hazard, Exposure, Sensitivity, Adaptive Capacity). Second, we identified the most frequently used geospatial indicators across the four IPCC dimensions, along with their primary data sources, and flagged those available as open-access alternatives. Third, we examined how GBI is represented in current FVI, including indicator types (vegetation, water bodies, drainage networks) and operationalisation gaps. All findings were compiled into a structured, replicable catalogue of IPCC-harmonised indicators to support climate adaptation planning and design.

Data Comparison

Across the 131 FVIs included in this review, 2,437 geospatial indicators were collected and, following IPCC-aligned standardisation, compiled into a single repository, distributed across the four IPCC-AR6 climate dimensions: Hazard (29.1%, n = 710), Exposure (28.7%, n = 699), Adaptive Capacity (24.1%, n = 588), and Sensitivity (18.1%, n = 440). as **Figure 3**.

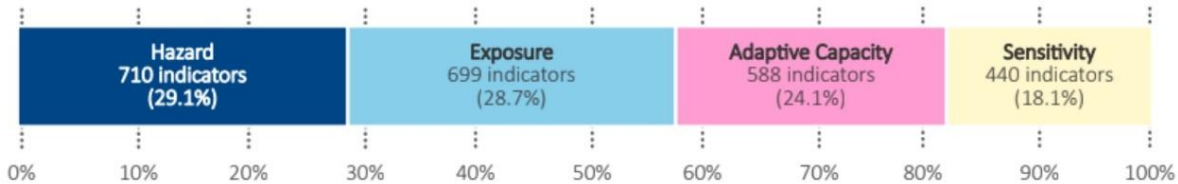


Fig. 3. Total distribution of geospatial indicators identified in the review (n = 2,437), proportionally classified according to the IPCC climate dimensions.

On average, each FVI comprised a medium of 16 geospatial indicators, with the number per index ranging from 5 to 59. The highest counts were observed in Art.115 (59 indicators), Art.114 (57 indicators), and Art.86 (55 indicators) and Art.31 included 54 indicators. In contrast, Art.19 and Art.83 included 5 indicators, and Art.58 and Art.121 each included 6 indicators, as shown in **Figure 4**.

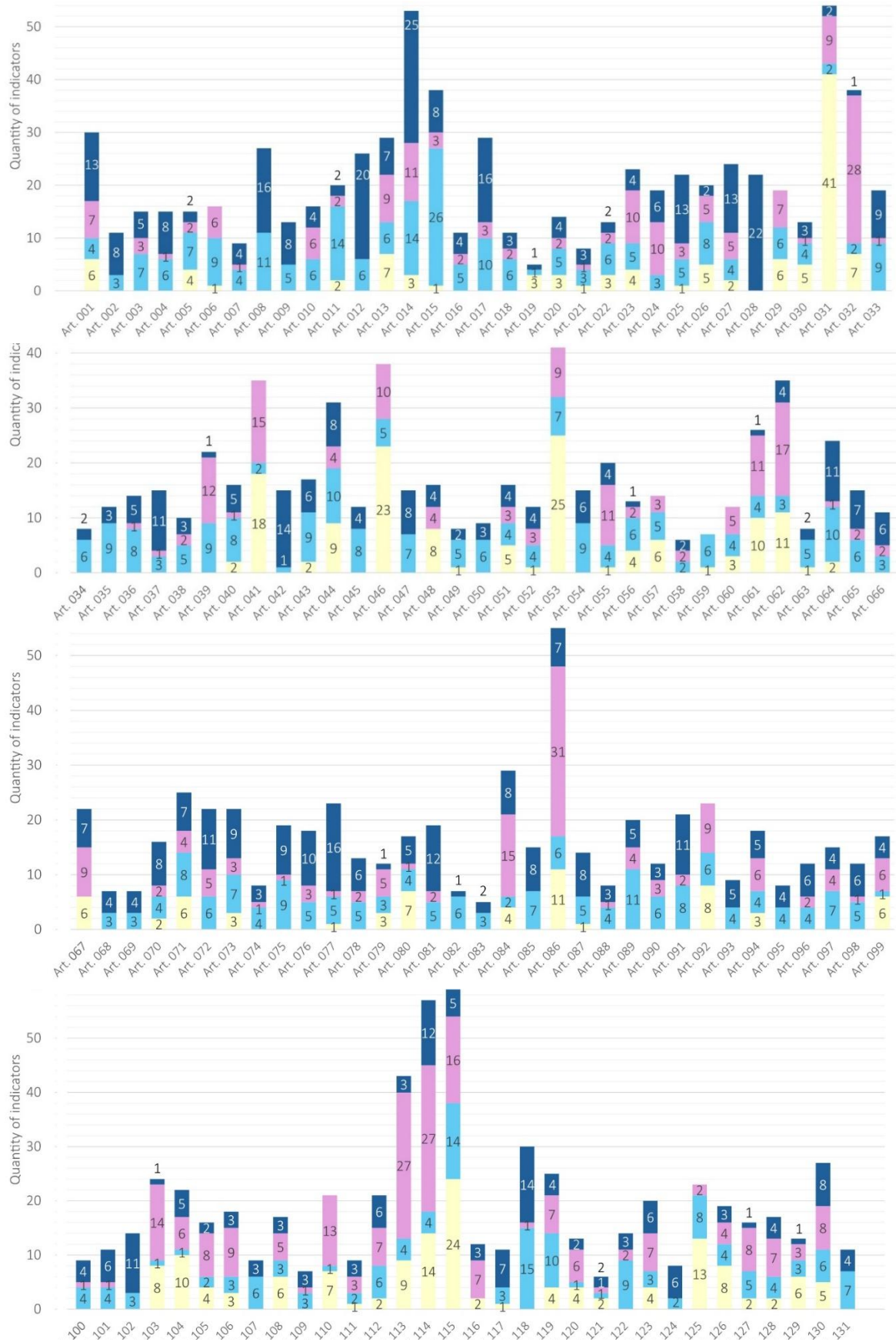


Fig. 4. Distribution of geospatial indicators across the 131 reviewed FVI and their classification within IPCC risk dimensions. Bar height represents the total number of indicators per index (5–59), with colours distinguishing Exposure, Sensitivity, Adaptive Capacity, and Hazard components.

Although all 131 reviewed studies described their approaches as Flood Vulnerability assessments, harmonisation under the IPCC AR6 framework revealed important discrepancies between conceptual framing and index composition. Overall, 63 studies (48%) did not fully operationalise vulnerability, omitting either Sensitivity or Adaptive Capacity, while 23 studies (17.6%) omitted both vulnerability dimensions altogether. Separately, 11 studies (8.4%) excluded the Hazard dimension despite adopting a risk-oriented framework. Across all reviewed studies, Exposure was the most consistently represented climate dimension, appearing in 127 studies (97%), followed by Hazard (120/131; 92%), Adaptive Capacity (101/131; 77%), and Sensitivity (74/131; 56%). Finally, regarding conceptual framework, over half of the studies (52%, or 68 out of 131) do not mention IPCC at all. For the remaining, 42% (55/131) explicitly cite the IPCC framework in their main text while 6% of the studies (08/131) reference it only in the bibliography, without direct citations in the full text. A complete overview of the climate dimensions and indicators included in each study is provided in **Additional file 4, Section AF4.1**.

Data Compilation

To ensure interoperability, the resulting datalist organises all gathered indicators, harmonised into three hierarchical levels: (i) the IPCC-AR6 climate dimension, (ii) the thematic category, and (iii) the indicator nomenclature. In total, the reviewed indicators were organised into 24 thematic categories distributed across the four IPCC-AR6 climate dimensions (**Figure 5**).



Fig. 5. IPCC-aligned categorisation of reviewed indicators across climate risk dimensions. The inner ring represents the proportional distribution of indicators [n = 2,437] among Sensitivity, Exposure, Adaptive Capacity, and Hazard; the outer ring illustrates their thematic categories.

Within each thematic domain, indicators were ranked according to their frequency of occurrence across the reviewed studies to identify the primary drivers of FVI composition, as summarised in **Table 1**.

Hazard comprised four thematic domains: Flood Extreme Events (12%), Meteorological Variables (7%), Hydrological Variables (7%), and Flood Damage (3%). Among the 709 Hazard indicators, the most frequent were Flood Extent Area [110], Distance to Water Bodies [52], Annual Mean Precipitation [47], Historical Flood Areas [36], Heavy Precipitation Frequency [25], and Topographical Wetness Index [22]. Together, these indicators characterise the spatial extent and recurrence of flood-prone areas, represent proximity to flood sources, and describe the atmospheric, topographic and hydrological processes influencing flood magnitude, timing and spatial distribution.

Exposure included six thematic domains: Topography and Terrain (10%), Land Cover and Imperviousness (8%), Green and Blue Surfaces (4%), Built Characteristics (4%), Population Distribution (3%), and Environmental Pollution (0.2%). Across 701 indicators, Land Use and Land Cover Classification (LULC) [158], Terrain Elevation [97], Population Density [72], Terrain Slope [65], Soil Type [43], and Building Typology [40] were the most recurrent. Collectively, these indicators describe land-surface characteristics regulating infiltration and runoff, the spatial distribution of exposed populations and assets, and built-environment features influencing flood exposure.

Sensitivity was organised into six thematic domains: Economic and Educational Status (9%), Population Age (3%), Social Equity (2%), Household (2%), Health (2%), and Sensitivity Composites (1%), the latter integrating multiple demographic and socioeconomic variables into composite measures of social vulnerability. Among the 441 Sensitivity indicators, the most frequently reported were Population with Disability [30], Household Composition [27], Employment Status [26], Income per Capita [22], Unemployed People [22], and Low-Income People [22], indicating the predominance of demographic and socioeconomic variables within this dimension. Sensitivity Composites accounted for 32 indicators (1.3%), with the most frequent combinations being Gender and Education [4], Household Composition and Social Network [4], and the Index of Multiple Deprivation (IMD) [3], a multidimensional indicator integrating income, employment, education, health, crime, housing accessibility and living-environment conditions.

Adaptive Capacity encompassed eight thematic domains: Social Capital and Awareness (6%), Grey and Green–Blue Infrastructure for Flood Mitigation (4%), Transportation and Mobility Networks (4%), Governance and Institutional Capacity (3%), Emergency Response Infrastructure (3%), Essential Utility Coverage (2%), Access to Community Amenities and Shelters (2%), and Housing Tenure and Shelter Capacity (1%). Among the 586 indicators, Flood Event Awareness and Perception [63], Road Infrastructure [51], Proximity to Healthcare Facilities [40], Social Networks [25], Healthcare Capacity [22], and Ability to Organise and Coordinate [22] were the most recurrent. These indicators characterise the institutional, infrastructural and community resources that support preparedness, response and recovery during flood events.

Table 1. Classification of geospatial indicators by climate dimensions and thematic domains in reviewed FVI.

HAZARD 29.1%	
Thematic Domains	Indicators [n]
Flood Extreme Events 11.8% [288]	• Flood Extent area [108] • Proximity to Water Bodies [52] • Historical Flood areas [36] • 100-year flood / 1% AEP flood [15] • Sea level rise (SLR) [11] • 050-year flood / 2% AEP flood [10] • Flood susceptibility - Future scenario [9] • Flood frequency (Return period) [9] • Multi-risk-prone area [9] • Distance to flood-prone areas [5] • 010-year flood / 10% AEP flood [4] • Coastal erosion [3] • Intersection: Road X River [3] • 200-year flood / 0.5% AEP flood [3] • 500-year flood / 0.2% AEP flood [3] • 005-year flood / 20% AEP flood [4] • 002-year flood / 50% AEP flood [2] • Lower Layer Super Output Area [2] • Social media users in risk areas [1].
Meteorological Variables 7.1% [174]	Annual mean Precipitation (PP) [47] • Heavy frequency PP [25] • Daily PP [13] • Future annual mean PP [9] • Annual max. PP [6] • Monthly PP [5] • Rate of Change in Annual mean Temperature (Tp) [5] • Annual mean Tp [5] • Daily Max. PP [5] • Future daily mean PP [4] • Annual very heavy days PP [4] • 5-day continuous max. PP [4] • Continuous duration PP (h) [3] • Continuous intensity PP [3] • Cyclone frequency p/year [3] • Warm days p/year [3] • Annual max. daytime Tp [2] • Warm nights p/year [2] • PP Hourly Max. [2] • Global Climate Models (GCMs) [2] • Low freq. PP p/year [2] • Cold spell frequency [2] • Annual min. nighttime Tp [2] • Max. consecutive days PP p/year [2] • Cold days p/year [2] • Future scenario Tp [1] • Annual max. nighttime Tp [1] • Cold nights p/year [1] • Consecutive dry days (CDD) [1] • Diurnal Tp range (DTR) [1] • Annual min. daytime Tp [1] • Potential Evapotranspiration (PET) [1] • Water balance: PP minus PET [1] • PP Historical intensity [1] • PP intensity [1] • PP Daily difference (Future - Historic) [1] • PP Future intensity [1].
Hydrological Variables 6.6% [159]	• Topographical Wetness Index (TWI) [22] • Runoff [20] • Flood Inundation depth [18] • Water depth [15] • Discharge [13] • Storm surge level [12] • Flow Accumulation [11] • Stream power index (SPI) [10] • Flow velocity [5] • Groundwater Depth [5] • River / Stream order [4] • Temporal Flood Intensity Ratio (STFIR) [3] • Runoff - Sediment Transport Index (STI) [2] • River channel width [2] • Flow Direction [2] • Topographic Position Index (TPI) [2] • Index of Turbid Waters (ITW) [2] • Short Lag Time (SLT) [1] • River Bifurcation ratio [1] • Root Mean Square Error (RMSE) [1] • Short Inundation Time (SIT) [1] • Discharge for 200-year / 0.5% AEP [1] • Coastal wave height [1] • Runoff - time of concentration (Tc) [1] • River channel migration rate [1] • Discharge for 050-year / 2% AEP [1] • Discharge for 100-year / 1% AEP [1] • Nash–Sutcliffe Efficiency (NSE) Model [1].
Flood Damage 3.7% [89]	Affected Population [21] • Flood Economic Damage (\$) [16] • Affected Buildings [15] • Affected Community amenities and services [9] • Affected Essential Utility Services [6] • Affected transportation and mobility [5] • Affected Agricultural Area [4] • Population routines disruption [6] • Affected Heritage [2] • Presence of debris/ floating material [2] • Affected Green areas [2] • City recovery time (days) [1].
EXPOSURE (28.7%)	
Thematic Domains	Indicators [n]
Topography and Terrain 10% [244]	Terrain elevation (m) [97] • Terrain Slope (%) [65] • Soil/ Rock Type [43] • Surface Curvature [13] • Watershed Area [10] • Aspect/ Direction [6] • Manning roughness coefficient [5] • Bathymetry (m) [3] • Soil erosion [2].
Land Cover and Imperviousness 7.6% [184]	Land use/land cover classification (LULC) [158] • Surface Permeability Class [17] • LULC - Future scenario [5] • Points of interest (POIs) [4].
Green and Blue Surface 4.1% [99]	Vegetation Type [32] • Vegetation Coverage [26] • Water Body Type [19] • Water Body Surface [17] • Wetland Surface [3] • Wetland type [2].
Built Characteristics 3.7% [90]	Build. typology [40] • Build. material [25] • Build. Conservation age [21] • Build. height [2] • Build. roof [2].
Population Distribution 3.2% [78]	• Population Density (PD) [72] • Pop. Growth [6].
Environmental Pollution 0.2% [4]	• Soil and water pollution [3] • Air pollution [1].

ADAPTIVE CAPACITY (24.1%)	
Thematic Domains	Indicators [n]
Social Capital and Awareness 5.5% [135]	Flood Event Awareness and Perception [63] • Social Networks (SN) [25] • Ability to Organize and Coordinate (AOC) [22] • Access to communication technologies [17] • Traditional and minorities Knowledge [4] • Ability to Swim [2] • SN: loneliness [2].
Green-Blue Infrastructure (GBI) for Flood Mitigation 3.9% [94]	Blue drainage network [21] • Mixed drainage network [13] • Green urban areas [11] • Grey drainage network [10] • Grey mitigation units [10] • Mixed mitigation units [10] • Blue mitigation units [8] • Drainage condition and maintenance [4] • Drainage obstructions locations [3] • Mitigation performance [3] • BGI's Benefit-to-Cost [1].
Transportation and Mobility Networks 3.6% [87]	Road Infrastructure [51] • Access to public Transport [19] • Vehicle Access and Ownership [9] • Public mobility [5] • Traffic dynamics/ speed [2] • Access to public Transport (electric) [1].
Governance and Institutional capacity 3.2% [78]	Multi-agency collaboration [21] • Insurance and social support [19] • Climate plans [15] • Access to credit facilities [11] • Climate budgeting [9] • Real Estate and Land value (%) [3].
Emergency Response Infrastructure 3.2% [77]	Proximity to Healthcare Facilities [40] • Healthcare Capacity [22] • Emergency Rescue Accessibility [11] • Evacuation routes [4].
Essential Utility Service 2.3% [55]	Basic utilities coverage [16] • Water supply cover. [10] • Energy supply cover. [9] • Sewage network cover. [7] • Drinking water cover. [7] • Waste collection cover. [3] • Clean Fuel cover. [2] • Alternative energy cover. [1].
Access to Community Amenities and Shelter 1.5% [37]	Access to flood shelters [12] • Access to educational facilities [9] • Access to Public service facility [7] • Access to Retail and food services [6] • Access to Recreational and sports facilities [3].
Housing Tenure and Quality 1% [23]	Housing Tenure (HT) rented [11] • HT owned [8] • HT 2nd home [2] • HT Communal Residence [2] • HT Houseless [2].
SENSITIVITY (18.1%)	
Thematic Domains	Indicators [n]
Economic and Educational Status 8.5% [208]	Employment status [26] • Low-income Pop. [22] • Unemployed Pop. [22] • Income per capita [22] • Local Economic Activity and Output [21] • Education: Illiteracy [20] • Gross Domestic Product (GDP) [17] • Educ. level [17] • Educ.: High educ. Pop. [9] • Debt: high-rate areas (%) [7] • Income per household [7] • Educ.: low educ. Pop. [4] • Fixed Asset Investment (FAI) [3] • High-income Pop. [3] • Savings status [3] • Energy consume [2] • Real Estate/ Land Value [2] • Med-income Pop. [1].
Population Age 3.2% [77]	Population 65+ years [19] • Pop. 05 yrs [12] • Pop. 05 and 65+ yrs [9] • Pop. Age structure [7] • Working age Pop. 15 to 64 yrs [4] • Pop. 15 and 65+ yrs [2] • Pop. 10 and 60+ yrs [2] • Pop. 14 yrs [2] • Pop. 05 to 14 yrs [2] • Pop. 10 and 65+ yrs [2] • Pop.:15 yrs [2] • Pop.:06 yrs [2] • Pop. 75+ yrs [2] • Pop.:19 and 55+ yrs [1] • Pop. 16 yrs [1] • Pop.:15 and 60+ yrs [1] • Working age Pop. 15 to 60 yrs [1] • Pop. 16 and 65+ yrs [1] • Pop. 07 to 12 yrs [1] • Pop.:07 and 65+ yrs [1] • Pop. 12 and 65+ yrs [1] • Pop. 09 yrs [1] • Pop. Age structure - Future scenario [1].
Social Equity 1.7% [42]	Gender [21] • Ethnicity minorities [16] • Language barrier [4] • Crime rate [1].
Household 1.7% [42]	Household (HH) composition (n° Pop.) [27] • HH quality conditions [15].
Health 1.6% [39]	Pop. with disability [30] • Flood-Related Illness [5] • Flood-Related Incidents and Mortality [4].
Sensitivity Composites 1.3% [32]	Gender + Education [4] • Household (HH) + Social Network [4] • Index of Multiple Deprivation (IMD) [3] • Age + Health [2] • Employment + Education + HH [2] • Employment + Gender [2] • Employment + Gender + Social Network [2] • HH + gender + age [2] • Gender + Health [2] • HH + income + age [2] • HH + Employment + Pop.:5 yrs [1] • HH + Pop. 65+ yrs: Retirement homes [1] • Health + Electricity dependence [1] • HH + Gender + Ethnicity [1] • HH + Employment + Gender [1] • Pop. – 5 yrs.+ disability [1] • Employment + education [1].

A total of 250 indicators were directly related to GBI across the Hazard, Exposure, and Adaptive Capacity dimensions, accounting for 10.5% of all indicators. Within Hazard, Distance to Water Bodies [52] reflected the dual role of water bodies as both flood sources and mitigation assets. Within Exposure, the most recurrent GBI indicators were Vegetation Type [32], Vegetation Coverage [26], Water Body Type [19], and Water Body Surface [17], describing the spatial distribution and composition of vegetation and water bodies as biophysical components of flood exposure. Within Adaptive Capacity, the most frequent indicators were Blue Drainage Network [21], Mixed (Grey and GBI) Drainage Network [13], and Green Urban Areas [11], reflecting the growing adoption of hybrid grey–green infrastructure approaches for flood mitigation. However, the economic performance of GBI was represented only once (Benefit-to-Cost [1]), indicating that cost-effectiveness is rarely incorporated into current FVI frameworks. The complete dataset of gathered indicators is listed in **Additional file 4, Section AF4.2**.

Data Correlation

Spatial integration of indicators within Geographic Information Systems (GIS) is a common analytical component across FVI studies, with procedures varying according to the climatic dimension. Sensitivity indicators were predominantly aggregated at areal-unit levels, such as census blocks, wards, or civil parishes. Exposure indicators relied more frequently on raster-based GIS modelling, remote sensing classification, and object-oriented image analysis. Hazard indicators were commonly derived from hydrodynamic models (e.g., LISFLOOD-FP, HEC-RAS, MIKE), buffer, density analysis, and spatial interpolation of meteorological and hydrological data. Adaptive Capacity indicators were more frequently analysed using buffer, network analysis (e.g., travel time, service area coverage), and proximity-based techniques. **Table 2** summarises the identified approaches to indicator normalisation, weighting and mapping.

Table 2. Recurrent approaches used for standardisation, aggregation and spatialisation of FVI indicators.

Dimension	Standardisation	Aggregation	Spatialisation
Sensitivity	min-max scaling; z-score; quantile / percentile classification	principal component analysis (PCA); analytic hierarchy process (AHP); entropy weighting	GIS overlay; zonal statistics; spatial interpolation through Inverse Distance Weighting (IDW) and/or kriging.
Exposure	min-max scaling; z-score; percentile / quantile classification	AHP; multi-criteria decision analysis (MCDA) / weighted overlay; entropy weighting	GIS overlay; line density analysis; buffer/ proximity analysis.
Adaptive Capacity	min-max scaling; z-score; quantile / percentile classification	AHP; PCA; entropy weighting	GIS overlay; buffer analysis; network analysis (travel time, service area, fastest route); line density analysis.
Hazard	min-max scaling; z-score; percentile / quantile classification	AHP; machine learning; entropy weighting	GIS: overlay; buffer/ proximity analysis; line density analysis.

Min-max scaling and z-score standardisation were the most frequently applied normalisation techniques for Sensitivity, Exposure, and Adaptive Capacity indicators, while Hazard indicators additionally relied on percentile-based or quantile classifications. Principal Component Analysis (PCA) was the dominant weighting and combining method for Sensitivity, whereas Analytic Hierarchy Process (AHP) appeared consistently across all dimensions. Entropy weighting was also widely employed, particularly for Exposure and Adaptive Capacity. For Hazard, machine learning algorithms (Random Forest, XGBoost, CatBoost, ANN) emerged as a recurrent alternative to traditional multi-criteria approaches. In terms of mapping, GIS overlay and raster modelling were common across Exposure and Hazard, while Sensitivity relied more on zonal

statistics and spatial interpolation. Adaptive Capacity was predominantly mapped using buffer, network, and line density analyses. The detailed overview of correlation approaches adopted per studies in the review is provided in **Additional file 4, Section AF4.2**.

Data Sources supporting FVI indicators

Data sources used to derive FVI indicators originated from a wide range of institutional, environmental and technological datasets. Governmental agency datasets represented the most frequently reported source, accounting for 24.1% of all identified inputs, followed by satellite imagery (15.6%), software simulations (13.7%), census data (12.7%) and questionnaires (11.9%). Scientific literature (6.6%) and meteorological datasets (5.5%) also contributed substantially, whereas on-site surveys (4.4%), open urban data (3.6%), GPS-derived data (1.3%) and health records (0.5%) were less frequently reported, as illustrated in **Figure 6**.

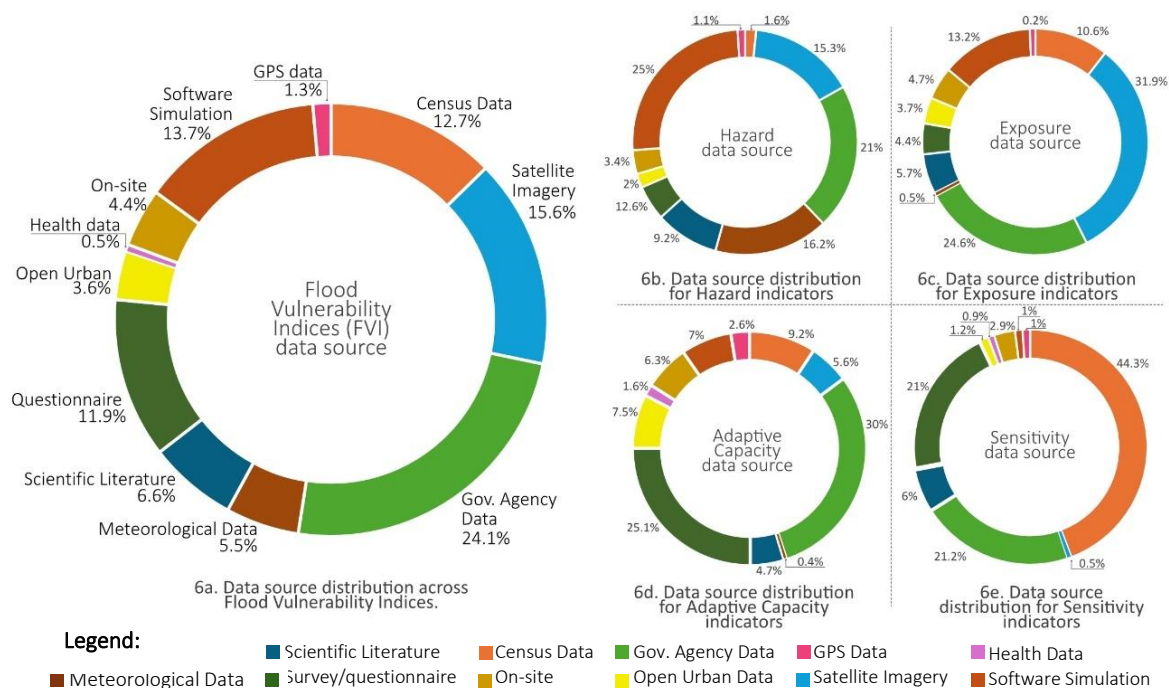
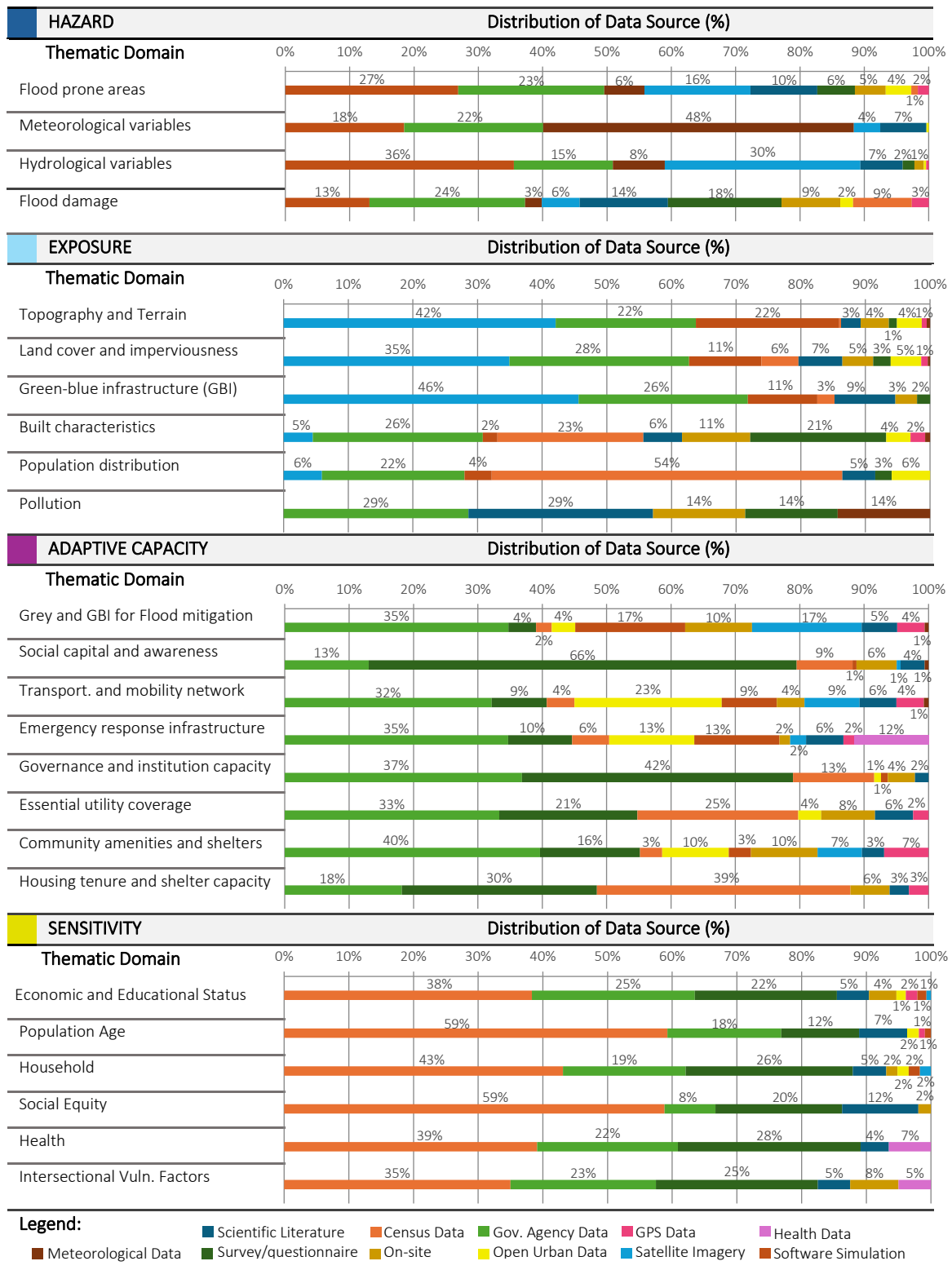


Fig. 6. Contribution of data source types to reviewed FVI and distribution across IPCC-AR6 dimensions (Sensitivity, Exposure, Adaptive Capacity, and Hazard).

When analysed across the four IPCC-AR6 climate dimensions, distinct data-source patterns emerged. Hazard indicators relied primarily on software simulations supported by meteorological observations and satellite imagery, Exposure on satellite imagery and governmental datasets, Adaptive Capacity on governmental, survey and census data, and Sensitivity predominantly on census and demographic datasets. The distribution of data sources across thematic domains is summarised in **Table 3**.

Hazard indicators were mainly derived from software simulations (25%), governmental records (21%), meteorological datasets (16.4%), and satellite imagery (15.3%), with smaller contributions from scientific literature, questionnaires, on-site surveys, census data, open urban data and GPS records. Software simulations were the principal source for Flood-Prone Areas and Hydrological Variables, governmental records predominated in Flood Damage and historical flood events, meteorological datasets supported Meteorological Variables, and satellite imagery complemented Hydrological Variables and flood mapping.

Table 3. Data Source distribution per Thematic Domains.



343 Exposure indicators relied primarily on satellite imagery (31.9%) and governmental datasets
 344 (24.6%), followed by software simulations (13.2%) and census data (10.6%). Additional
 345 contributions originated from scientific literature, on-site surveys, questionnaires, open urban
 346 data, GPS records and meteorological datasets. Satellite imagery was the principal source for
 347 Topography and Terrain, Land Cover and Imperviousness, and Green and Blue Surfaces, whereas

governmental datasets predominated in Built Characteristics and Pollution. Census data was the principal source for Population Distribution.

Adaptive Capacity showed the greatest diversity of data sources. Governmental datasets represented the largest contribution (30%), followed by survey and questionnaire data (25.1%), census data (9.2%), open urban data (7.5%), software simulations (7%), on-site surveys (6.3%), satellite imagery (5.6%) and scientific literature (4.7%). Governmental datasets predominated in infrastructure-related thematic domains, whereas survey data was the principal source for Social Capital and Awareness and Governance and Institutional Capacity. Census data mainly supported Housing Tenure and Shelter Capacity.

Sensitivity indicators were predominantly derived from census datasets, representing 44.3% of all identified sources and underpinning every thematic domain. Governmental datasets (21.2%) and survey data (21%) were the next most frequent sources, particularly for Population Age, Economic Status, Educational Status, Household Characteristics, Health and Social Equity. Scientific literature, on-site surveys, open urban data, software simulations, GPS records and health administrative datasets together accounted for the remaining sources.

Open-access datasets, combining free satellite imagery and open urban data, represented 19.2% of all identified data sources. Their contribution was highest in Exposure (35.6%), followed by Hazard (17.3%), Adaptive Capacity (13.1%) and Sensitivity (1.7%).

Within Exposure, free satellite imagery represented the primary data source for Topography and Terrain [165], Land Cover and Imperviousness [102], and Green and Blue Surfaces [67], while also contributing to Population Distribution [7] and Built Characteristics [6]. Open urban datasets complemented these domains, particularly Topography and Terrain [12], Population Distribution [6], Land Cover and Imperviousness [4], Built Characteristics [3] and Soil Type [1]. High-resolution Digital Elevation Models (DEMs) were primarily derived from Japan Aerospace Exploration Agency (JAXA) ALOS AW3D30 and United States Geological Survey (USGS)/National Aeronautics and Space Administration (NASA) SRTM datasets. Land-cover, imperviousness and green–blue surface indicators were mainly derived from USGS/NASA Landsat 8 OLI/TIRS and European Space Agency (ESA) Sentinel-2 MSI, while historical land-cover analyses frequently relied on Landsat 5 TM. Complementary open datasets included Google Street View and Amap/Gaode Maps for validation of land cover and extraction of built characteristics, the WorldPop Gridded Population Dataset (WorldPop) and World Bank Open Data for population distribution, the FAO/UNESCO Soil Map for soil type, and the Open Development Initiative (ODI) for terrain information in Southeast Asian contexts.

For Hazard, free satellite imagery primarily supported Hydrological Variables [81] and Flood Extreme Events [81], while also contributing to Meteorological Variables [12] and Flood Damage [9]. Frequently reported datasets included USGS/NASA SRTM, JAXA ALOS AW3D30 and USGS/NASA ASTER GDEM for topographic and hydrological modelling, together with JAXA ALOS PALSAR DEM for hydrological applications. Flood extent mapping commonly relied on ESA Sentinel-1 SAR, ESA Sentinel-2 MSI, ESA CORINE Land Cover and USGS/NASA Landsat 8 OLI/TIRS. Open urban datasets complemented Flood Extreme Events [16], Flood Damage [6], Meteorological Variables [1] and Hydrological Variables [1], including OpenStreetMap (OSM) for mapping affected buildings and infrastructure, Twitter for geolocating affected populations and services, WorldClim and Weather Underground for meteorological information, and HydroSHEDS for hydrological datasets.

In Adaptive Capacity, free satellite imagery mainly supported Grey and Green–Blue Infrastructure for Flood Mitigation [29], while also contributing to Transportation and Mobility Networks [12], Access to Community Amenities and Shelters [4], Emergency Response Infrastructure [3], and Social Capital and Awareness [1]. Open urban datasets were the principal source for Transportation and Mobility Networks [32] and complemented Emergency Response Infrastructure [16], Access to Community Amenities and Shelters [6], Grey and Green–Blue Infrastructure for Flood Mitigation [6], Essential Utility Coverage [3], and Governance and Institutional Capacity [1]. Frequently used datasets included USGS/NASA SRTM DEM, Indian Space Research Organisation (ISRO) IRS P6 LISS III and ESA CORINE Land Cover for mapping green–blue infrastructure, transport networks and local amenities. OSM was widely used to derive transportation and infrastructure networks, while Google Earth Engine, Google Maps and Amap/Gaode Maps (China) provided Points of Interest (POIs) representing community facilities and shelters. Online real-estate databases were additionally used to derive average land and property values for governance-related indicators.

For Sensitivity, open-access datasets were used only occasionally, serving as complementary sources for Economic and Educational Status [2] and Household [1]. Satellite-derived datasets included USGS/NASA–NOAA VIIRS Nighttime Lights, used as a proxy for low-income conditions based on artificial illumination intensity, and USGS/NASA Landsat 5 TM and Landsat 8 OLI/TIRS, used to identify informal settlement expansion in data-scarce regions. WorldPop and ArcGIS demographic data extraction tools provided complementary information on population distribution and household characteristics. A comprehensive catalogue of all identified data sources is provided in **Additional File 4, Section AF4.2**.

Discussion

By harmonising 2,437 geospatial indicators within the IPCC AR6 framework, this review provides a standardised reference for FVI development, improving methodological transparency and comparability across studies. The synthesis shows that the field is expanding rapidly but remains marked by five key challenges: (i) conceptual inconsistency, (ii) limited representation of socio-demographic vulnerability, (iii) uneven assessment of Adaptive Capacity to prepare for, respond to and recover from flood events, (iv) fragmented integration of green-blue infrastructure, and (v) the underutilisation of open-access geospatial datasets to support Adaptive Capacity and Sensitivity assessments. Together, these findings highlight the need for greater methodological consistency to improve the comparability, transferability and operational application of FVI assessments for flood adaptation planning.

First, conceptual inconsistency remains one of the principal barriers to methodological standardisation. Harmonisation under the IPCC AR6 framework showed that 48% of reviewed studies omitted either Sensitivity or Adaptive Capacity, despite describing their approaches as vulnerability assessments. Likewise, a smaller proportion of studies adopted risk-based terminology while excluding Hazard altogether. Such inconsistencies reduce methodological comparability, hinder cumulative knowledge development and limit the transferability of FVIs across cities and regions (Nguyen et al., 2025; Rahimi et al., 2026; Sharifi et al., 2026). Greater alignment between vulnerability concepts, climate dimensions and indicator selection would strengthen reproducibility while facilitating interoperable assessment frameworks for urban planning and climate adaptation.

Second, socio-demographic sensitivity remains comparatively underrepresented despite its central role in shaping flood impacts. Urban flood resilience ultimately depends on the

characteristics of affected populations, including age, health, socioeconomic status and demographic dependency. Notably, older-adult indicators represented only 2,2% of all identified indicators, suggesting that current FVIs may underestimate neighbourhoods where demographic vulnerability amplifies flood impacts. Consequently, spatial prioritisation currently favour areas of greater physical exposure while overlooking locations where moderate hazards coincide with socially vulnerable populations (Kaur et al., 2025; Mester et al., 2025; Nguyen et al., 2025).

Third, adaptive capacity emerged as the most methodologically diverse climate dimension, because it integrates infrastructure, governance, accessibility and community preparedness (Lyngdoh et al., 2025). Nevertheless, most studies measure the presence of infrastructure and services rather than their effectiveness during flood events. Future assessments would benefit from performance-oriented indicators capable of capturing institutional response, service continuity and community preparedness under real emergency conditions (Kaur et al., 2025; Mester et al., 2025; Rahimi et al., 2026).

Fourth, green-blue infrastructure (GBI) related indicators accounted for 10,7% of all identified indicators and were incorporated across Hazard, Exposure and Adaptive Capacity, reflecting the growing recognition of nature-based solutions within flood-risk management. However, vegetation, water bodies and drainage systems were generally represented as isolated variables rather than as interconnected socio-ecological systems. This fragmented representation limits the assessment of ecosystem services, interactions with conventional grey infrastructure and the broader co-benefits of integrated adaptation strategies (Akhter et al., 2025; Alves et al., 2019; Osheen et al., 2024). More integrated indicator frameworks would better represent how GBI simultaneously contributes to hazard reduction, exposure mitigation and adaptive capacity.

Fifth, open-access geospatial data remain underused in Sensitivity and Adaptive Capacity. Although freely available datasets account for 19.2% of all identified data sources, their contribution was considerably lower in Adaptive Capacity (13.1%) and Sensitivity (1.7%), where indicators still rely mainly on governmental and census records. While open datasets cannot yet fully replace the detailed official information needed to characterise social vulnerability, combining them with local survey data offers a practical alternative for flood-assessment workflows and decision-support platforms (Cerri et al., 2021; Radoszynski & Numada, 2023). Such limited use represents an important opportunity for methodological development, as it can help address two major limitations identified in this review: the underrepresentation of socio-demographic vulnerability and the inconsistent assessment of adaptive capacity.

Study limitations

This study has limitations related to its eligibility criteria and analytical scope. First, the review included only English-language, peer-reviewed studies that explicitly reported FVI together with their geospatial indicators and data sources. Consequently, relevant studies published in other languages, grey literature, or indices with insufficient methodological reporting may have been excluded. Second, although harmonisation under the IPCC AR6 framework improved conceptual comparability across studies, the reclassification of indicators occasionally required interpretative judgement where original terminology was ambiguous or inconsistent with IPCC definitions. Finally, this review did not evaluate the predictive performance, weighting schemes, or validation of individual FVI. Instead, the analysis focused on their conceptual structure, indicator composition and alignment with the IPCC AR6 framework, rather than on the performance of specific case studies or post-implementation outcomes.

Future research

For future research, the findings of this review highlight several priorities for advancing the development of Flood Vulnerability Indices. First, greater conceptual standardisation is needed to improve consistency between vulnerability definitions, climate dimensions and indicator selection. Future FVIs should strengthen the representation of socio-demographic sensitivity, particularly through indicators capturing ageing populations, health conditions and socially vulnerable groups. Adaptive capacity assessments should also move beyond inventories of infrastructure and public services by integrating physical assets with measures of institutional effectiveness, governance, community preparedness and social capital that influence the ability to anticipate, respond to and recover from flood events. Likewise, more integrated Green–blue–grey infrastructure frameworks are needed to evaluate ecosystem services, hybrid infrastructure performance, implementation constraints and the cost-effectiveness of nature-based solutions. Finally, the adoption of standardised open-data workflows combining remote sensing, open geospatial databases and socioeconomic information would improve the reproducibility, interoperability and transferability of FVIs, supporting evidence-based urban flood adaptation planning across diverse geographic and data-scarce contexts.

Conclusion

This scoping review provides the first IPCC AR6-aligned harmonisation of geospatial indicators used in Flood Vulnerability Indices, synthesising 2,437 indicators extracted from 131 peer-reviewed studies into a transparent and interoperable framework. By systematically organising indicators, methodological approaches and geospatial data sources across the Hazard, Exposure, Sensitivity and Adaptive Capacity dimensions, the review revealed substantial conceptual inconsistencies in the operationalisation of vulnerability, particularly the frequent omission of Sensitivity and Adaptive Capacity despite widespread use of the term Flood Vulnerability. It also identified the most frequently adopted indicators and highlighted the growing, yet still fragmented, representation of green–blue infrastructure within current FVIs. Beyond identifying these gaps, this study delivers a Findable, Accessible, Interoperable and Reusable (FAIR) oriented catalogue of harmonised indicators, methodological variables and geospatial data sources that supports reproducibility, cross-study comparison and evidence-based FVI development. The resulting database provides a practical resource for researchers, planners and decision-makers seeking to design more transparent, comparable and policy-relevant flood vulnerability assessments. As cities face increasing flood risks under climate change, harmonised and openly accessible geospatial indicators can contribute to more consistent urban flood adaptation planning and strengthen the translation of climate risk assessments into urban flood resilience and adaptation policies.

Author contribution Conceptualisation, F.G, F.A., A.M. and C.R.; methodology, F.G, F.A., A.M. and C.R.; investigation, F.G., F.A. and A.M.; writing—original draft preparation, F.G and F.A.; writing—review and editing A.M and C.R.; supervision, F.A., funding acquisition, F.G. All authors have read and agreed to the published version of the manuscript.

Funding This work was supported by Fundação para a Ciência e a Tecnologia (FCT), Portugal, through doctoral grant 2024.00538.BD. Institutional support was provided to CITTA – Research Centre for Territory, Transports and Environment, under the funding UID/04427, financed by FCT, I.P./MECI through national funds.

Data Availability The structured database of geospatial indicators, methods, and data sources used in this study is publicly available through Zenodo Repository under a Creative

527 Commons Attribution 4.0 International (CC BY 4.0) license. It includes a structured Excel
528 database of geospatial indicators used in Flood Vulnerability Indices (n = 131), together with
529 accompanying FAIR-oriented documentation. The dataset can be accessed at [Zenodo DOI to
530 be added upon article acceptance].

531 **Supplementary Information** The online version contains supplementary material available
532 at the journal website.

Additional file 1: Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist.

Additional file 2: FAIR-oriented workflow for harmonising geospatial indicators in Flood Vulnerability Indices.

Additional file 3: Overview of FVI studies included in the scoping review (n=131).

Additional file 4: Structured dataset of included studies, geospatial indicators, methods, and data sources.

533

534 Declarations

535 **Ethical approval** All authors have read, understood, and have complied as applicable
536 with the statement on “Ethical responsibilities of Authors” as found in the Instructions for
537 Authors.

538 **Competing Interests** The authors declare no competing interests.

539 References

- 540 Aboagye, P. D., & Sharifi, A. (2026). Urban climate action planning case studies: A review of
541 trends, approaches, and reported barriers and drivers. *Journal of Environmental*
542 *Management*, 397. <https://doi.org/10.1016/j.jenvman.2025.128269>
- 543 Akhter, F., Bastola, S., Penn, J., & Douthat, T. (2025). A review of flood mitigation benefit-cost
544 analyses' inclusiveness of environmental watershed effects and environmental
545 vulnerability: gaps in progress towards more resilient flood hazard decision-making.
546 *Frontiers in Built Environment*, 11. <https://doi.org/10.3389/fbuil.2025.1531265>
- 547 Al-Hashimi, X. M., & Seenath, A. (2026). On the need for a hazardous flood vulnerability index:
548 A critical review and conceptual framework for health, environment, and equity.
549 *Anthropocene*, 53. <https://doi.org/10.1016/j.ancene.2026.100539>
- 550 Al-Rawas, G., Nikoo, M. R., & Al-Wardy, M. (2024). A review on the prevention and control of
551 flash flood hazards on a global scale: Early warning systems, vulnerability assessment,
552 environmental, and public health burden. *International Journal of Disaster Risk*
553 *Reduction*, 115. <https://doi.org/10.1016/j.ijdr.2024.105024>
- 554 Alves, A., Gersonius, B., Kapelan, Z., Vojinovic, Z., & Sanchez, A. (2019). Assessing the Co-
555 Benefits of green-blue-grey infrastructure for sustainable urban flood risk
556 management. *Journal of Environmental Management*, 239, 244–254.
557 <https://doi.org/10.1016/j.jenvman.2019.03.036>
- 558 Arana-Ruedas, D. R., Pino-Vargas, E., del Aguila-Ríos, S., & Ramos-Fernández, L. (2026). Digital
559 transformation in climate change management: Tools for managing droughts, floods,
560 and frost in South America: A systematic review. *Frontiers in Climate*, 8.
561 <https://doi.org/10.3389/fclim.2026.1765251>
- 562

- Arksey, H., & O'Malley, L. (2005). Scoping studies: towards a methodological framework. *International Journal of Social Research Methodology*, 8(1), 19–32. <https://doi.org/10.1080/1364557032000119616>
- Asayama, S. (2024). The history and future of IPCC special reports: A dual role of politicisation and normalisation. *Climatic Change*, 177(9). <https://doi.org/10.1007/s10584-024-03788-1>
- Cerri, M., Steinhausen, M., Kreibich, H., & Schröter, K. (2021). Are OpenStreetMap building data useful for flood vulnerability modelling? *Natural Hazards and Earth System Sciences*, 21(2), 643–662. <https://doi.org/10.5194/nhess-21-643-2021>
- Dhawale, R., Schuster-Wallace, C. J., & Pietroniro, A. (2024). Assessing the multidimensional nature of flood and drought vulnerability index: A systematic review of literature. *International Journal of Disaster Risk Reduction*, 112. <https://doi.org/10.1016/j.ijdrr.2024.104764>
- Estoque, R. C., Ishtiaque, A., Parajuli, J., Athukorala, D., Rabby, Y. W., & Ooba, M. (2023). Has the IPCC's revised vulnerability concept been well adopted? *Ambio*, 52(2), 376–389. <https://doi.org/10.1007/s13280-022-01806-z>
- Hidalgo, J., Lemonsu, A., & Masson, V. (2019). Between progress and obstacles in urban climate interdisciplinary studies and knowledge transfer to society. *Annals of the New York Academy of Sciences*, 1436(1), 5–18. <https://doi.org/10.1111/nyas.13986>
- Intergovernmental Panel on Climate Change (2001). *Climate change 2001: Synthesis report*. Cambridge University Press. <https://www.ipcc.ch/report/ar3/syr/>
- Intergovernmental Panel on Climate Change (2014). *Climate change 2014: Synthesis report*. IPCC. <https://www.ipcc.ch/report/ar5/syr/>
- Intergovernmental Panel on Climate Change (2023). *Climate change 2023: Synthesis report*. IPCC. <https://doi.org/10.59327/IPCC/AR6-9789291691647>
- Ishtiaque, A., Estoque, R. C., Eakin, H., Parajuli, J., & Rabby, Y. W. (2022). IPCC's current conceptualization of 'vulnerability' needs more clarification for climate change vulnerability assessments. *Journal of Environmental Management*, 303, 114246. <https://doi.org/10.1016/j.jenvman.2021.114246>
- Kaur, M., Sultana, S., Ishaq, S., Saleem, S., Nahiduzzaman, K. M., Hewage, K., & Sadiq, R. (2025). Building a flood vulnerability index for urban resilience: Insights from Kelowna, British Columbia [Article]. *Journal of Urban Management*, 14(4), 1034–1052. <https://doi.org/10.1016/j.jum.2025.04.002>
- Lyngdoh, V., Lynrah, M. M., Wahlang, E., Nongrang, A. L., Wahlang, N., Chiang, A., & Beda, J. (2025). District-level climate vulnerability assessment in Meghalaya using an IPCC AR5 framework. *Scientific Reports*, 15(1). <https://doi.org/10.1038/s41598-025-26651-4>
- Mester, B., Frieler, K., Korup, O., Desai, B., & Schewe, J. (2025). Socioeconomic predictors of vulnerability to flood-induced displacement. *Nature Communications*, 16(1), 8296. <https://doi.org/10.1038/s41467-025-64015-8>
- Monteiro, A., Ankrah, J., Madureira, H., & Pacheco, M. O. (2022). Climate Risk Mitigation and Adaptation Concerns in Urban Areas: A Systematic Review of the Impact of IPCC Assessment Reports. *Climate*, 10(8), 115. <https://doi.org/10.3390/cli10080115>
- Nguyen, T. L., Asahi, C., & Tran, T. A. (2025). A systematic review with bibliometric analysis of different approaches and methodologies for undertaking flood vulnerability research. *Sustainable Water Resources Management*, 11(2). <https://doi.org/10.1007/s40899-023-00865-8>
- Osheen, Kansal, M., & Bisht, D. (2024). Enhancing Urban Drainage Infrastructure Through Implementation of Low Impact Development Techniques. *Water Resources Management*, 38(12), 4517–4540. <https://doi.org/10.1007/s11269-024-03877-x>
- Prashar, N., Lakra, H., Kaur, H., & Shaw, R. (2024). Urban flood resilience: mapping knowledge, trends and structure through bibliometric analysis [Review]. *Environment*

614 Development and Sustainability, 26(4), 8235–8265. <https://doi.org/10.1007/s10668->
615 023-03094-3

616 Raduszynski, T., & Numada, M. (2023). Measure and spatial identification of social
617 vulnerability, exposure and risk to natural hazards in Japan using open data. *Scientific*
618 *Reports*, 13(1). <https://doi.org/10.1038/s41598-023-27831-w>

619 Rahimi, M., Malekmohammadi, B., Firozjaei, M. K., Kerachian, R., Arsanjani, J. J., Tan, M. L.,
620 Awange, J., Savic, D., Duan, Q., & AghaKouchak, A. (2026). Integrating geospatial
621 intelligence and machine learning for flood susceptibility mapping. *Scientific Reports*,
622 16(1), 10228. <https://doi.org/10.1038/s41598-026-41014-3>

623 Rehman, S., Sahana, M., Hong, H. Y., Sajjad, H., & Ahmed, B. B. (2019). A systematic review on
624 approaches and methods used for flood vulnerability assessment: framework for
625 future research. *Natural Hazards*, 96(2), 975–998. <https://doi.org/10.1007/s11069->
626 018-03567-z

627 Reinwald, F., Thiel, S., Kainz, A., & Hahn, C. (2024). Components of urban climate analyses for
628 the development of planning recommendation maps. *Urban Climate*, 57.
629 <https://doi.org/10.1016/j.uclim.2024.102090>

630 Sharifi, A., Seto, K. C., & Aboagye, P. D. (2026). The literature landscape on cities and climate
631 change. *Urban Climate*, 66. <https://doi.org/10.1016/j.uclim.2026.102849>

632 Shirmohammadi, M., Pirasteh, S., Li, H. X., Akhavan, M., Isazadeh, V., Ji, J. W., Chen, C., &
633 Muhammad, Y. (2026). Challenges and opportunities in flood mapping and modeling of
634 next-generation geospatial intelligence: a review. *Geomatics Natural Hazards & Risk*,
635 17(1). <https://doi.org/10.1080/19475705.2026.2660866>

636 Smith, B., Duce, S., & Diedrich, A. (2026). Beyond the IPCC frameworks: advancing vulnerability
637 and risk assessments for rural communities with the Livelihoods-Based Risk Profiling
638 Framework. *Regional Environmental Change*, 26(1). <https://doi.org/10.1007/s10113->
639 025-02497-4

640 Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K. K., Colquhoun, H., Levac, D., Moher, D., Peters, M.
641 D. J., Horsley, T., Weeks, L., Hempel, S., Akl, E. A., Chang, C., McGowan, J., Stewart, L.,
642 Hartling, L., Aldcroft, A., Wilson, M. G., Garritty, C., Lewin, S., Godfrey, C. M.,
643 Macdonald, M. T., Langlois, E. V., Soares-Weiser, K., Moriarty, J., Clifford, T., Tunçalp,
644 Ö., & Straus, S. E. (2018). PRISMA extension for scoping reviews (PRISMA-ScR):
645 Checklist and explanation. *Annals of Internal Medicine*, 169 (7), 467–473.
646 <https://doi.org/10.7326/M18-0850>

647 World Economic Forum (2026). The Global Risks Report 2026.
648 <https://www.weforum.org/publications/global-risks-report-2026/>

649 World Health Organization (2025). COP30 Special Report on Health and Climate Change.
650 [https://www.who.int/publications/m/item/cop30-special-report-on-climate-and-](https://www.who.int/publications/m/item/cop30-special-report-on-climate-and-health)
651 [health](https://www.who.int/publications/m/item/cop30-special-report-on-climate-and-health)

652 Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A.,
653 Blomberg, N., Boiten, J.-W., da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes,
654 A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers,
655 R.,...Mons, B. (2016). The FAIR guiding principles for scientific data management and
656 stewardship. *Scientific Data*, 3(1). <https://doi.org/10.1038/sdata.2016.18>

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [FLOODSUPMATERIALEMA.pdf](#)