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Assessing Flood Risk: Identifying Indicators and Indices for Period-Specific Flood Measures

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Abstract. Flood risk assessment is pivotal for comprehending and mitigating flood impacts. Although various indicators and indices are employed for flood risk assessment, the precise selection criteria for these indicators, particularly, concerning their roles and applicability during flood periods, remain unclear. This paper seeks to address this gap by identifying indicators and indices crucial for determining appropriate measures tailored to different flood periods. We conducted a systematic literature review, focusing on articles utilizing the Analytic Hierarchy Process (AHP) methodology to evaluate indicators across diverse risk factors, including sensitivity. By analysing these studies, we identified the most frequently used indicators for each index and risk factor. The intricate interplay among indicators and risk factors necessitated a clear conceptual framework. Our findings offer recommendations for selecting risk indicators and indices aligned with specific actions and measures corresponding to distinct flood periods. By bridging this gap in understanding, our research contributes to enhancing flood risk assessment methodologies and informing effective mitigation strategies.

Keywords: Risk assessment, vulnerability, hazard, exposure, flood risk factors, flood indicators

1 Introduction

Floods are natural disasters that occur when there is an overflow of water that exceeds the capacity of the area to absorb it. They can cause significant damage to infrastructure, homes, and natural habitats, and pose a threat to human health, life and safety. The duration and severity of floods can vary depending on the physical conditions and regional and local climate patterns, besides the impacts of global climate change.

Risk assessment is an important tool for understanding and mitigating the impacts of flood periods. According to IPCC AR5 (IPCC, 2014) and IPCC AR6 (IPCC, 2022), risk is a function of three factors, which are hazard, exposure, and vulnerability (hereinafter referred to as factors). IPCC AR4 (IPCC, 2007, p.89) referred "*vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.*" However, since IPCC AR6 uses exposure as a risk factor, vulnerability in IPCC AR6 includes the concepts of sensitivity (susceptibility to harm) and adaptive capacity. These factors have several indicators based on their definitions and related indices (combinations of indicators), besides varying according to the district

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or region and people's needs, approaches and perceptions (Ekmekcioglu et al., 2021). Indicators and indices can be used to assess flood risk regarding the factors and different flood period. An indicator-based approach provides a more precise assessment of the flood risk and vulnerability in each area compared to alternative approaches (Nasiri et al., 2019). Heink and Kowarik (2010, p.592) suggested a definition for an indicator: "*An indicator in ecology and environmental planning is a component or a measure of environmentally relevant phenomena used to depict or evaluate environmental conditions or changes or to set environmental goals. Environmentally relevant phenomena are pressures, states, and responses as defined by the OECD (2003)*". Starting from this point of view, an indicator regarding a risk assessment is a variable that can be qualitative, quantitative, measurable, observable or changing local conditions to determine or define the presence, likelihood or impact of a particular risk. From this perspective, *an indicator in the context of risk assessment is a variable that may be qualitative or quantitative, measurable, observable, or reflective of changing local conditions. It serves to determine or define the presence, likelihood, or impact of a specific risk.* By assessing related indicators and indices, and understanding the factors that contribute to flood risk evaluation and monitoring, it is possible to develop strategies to mitigate the impacts of flood periods. These strategies can include measures such as land use planning, flood protection infrastructure, emergency preparedness, and insurance programs. In addition to risk evaluation and monitoring, the precise definition of a risk significantly affects risk assessment and management in practice. For instance, vulnerability, being a context-specific factor in flooding, can be assessed more accurately when its indices and indicators are well defined. However, how to select risk indicators concerning their roles during flood periods in the risk assessment have not yet been defined precisely in the literature. Moreover, the calculation of flood risk is not clear. A consistent approach and methodology are essential for ensuring comparability across diverse locations and varying circumstances. The risk definition on the report of the IPCC (2022) gives this chance. In order to put them into the expressions (Kelly et al., 2023), *Risk = Probability x Consequence* is a basic formulation of risk assessment. It multiplies the probability of an event occurring by the consequence or impact if it does occur. This approach helps in prioritizing risks based on their likelihood and potential impact. Higher probability and consequence lead to higher risk. *Risk = Hazard x (Exposure x Vulnerability)* considers the interaction between hazard, exposure, and vulnerability. Hazard refers to the potential occurrence of a physical event or trend, and exposure is the presence of something (like people, assets, or the environment) is exposed to the hazard. Vulnerability represents the susceptibility or sensitivity to harm and adaptive capacity. This formulation expands on the second expression by introducing adaptive capacity and sensitivity. *Risk = Hazard x [Exposure x (Adaptive Capacity + Sensitivity)]*. By multiplying these factors, the expression captures the overall risk, considering both the characteristics of the hazard and the vulnerability and exposure of what is at risk. Each of these formulations offers a different perspective on risk assessment, allowing for a comprehensive understanding of the factors involved in determining risk levels and aiding in the development of effective risk management strategies. In addition, the way of calculation of the flood risk, there is often a focus on "negative" indicators, yet it is essential to incorporate "positive" indicators into the analysis. These could include factors such as flood protection infrastructure (such as dams and barriers), wetlands, land use restrictions (such as those in

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freshwater watersheds), healthy vegetation cover, improved urban drainage systems, blue-green infrastructure, early warning systems, and effective emergency response and flood management protocols.

It is extremely important to identify and understand challenges and impacts of floods on people and ecosystems, with the participation of decision makers and planners or people who are/will be affected by a flood. Thus, the main interactions and trends between climate change, people and ecosystems can be predicted in situ and more realistically. When the current situation is perceived adequate, mitigation actions and adaptation measures to be taken to reduce or cope with flood or other effects of climate change will also be more effective. In other words, the participatory risk approach (incl. participatory flood risk mapping) could help to change the point of view, increase the quality of decisions and the implementation of the measures and actions considering prioritization and budget allocation of the governments. Besides, the approach can be used for defining the cause of risk and/or risk factors (ACF, 2012), vulnerability assessment (de Brito et al., 2018), social resilience (Cantoni et., 2020), public perception and attitudes (Brilly and Polic, 2005; AlQahtany and Abubakar, 2020), communication gaps (Bustillos Ardaya et al., 2019), and knowledge management (Sinthumule and Mudau, 2019). Multi-criteria decision-making methods (MCDM) are useful for evaluating multiple influencing or conflicting criteria in decision-making. Several methods have been established to identify and prioritize indicators. The most common is the Analytical Hierarchy Process (AHP), which is one of the MCDM approaches for risk assessment. It can be implemented while considering the relationships between vulnerability components. AHP provides a structured and systematic approach to evaluate and prioritize various indices and indicators that contribute to flood risk. By allowing decision-makers to compare the importance of indicators, indices and factors such as flood severity and occurrence, vulnerability, and potential consequences, AHP helps in making informed decisions about flood risk mitigation strategies and resource allocation.

A number of actions and measures can be taken during flood periods to help mitigate their impacts. Pre-flood actions and measures include public awareness and preparedness (O`Grady et al., 2019), while emergency/escape routes for evacuation and meeting points are needs during floods. Post-flood period is about not only recovering but also measures and management considering lessons learned. Although these three flood periods are consecutive and interlinked, different stakeholders, decision makers or people who are/will be affected by the flood can play crucial roles and have different perceptions (Ekmekcioglu et al., 2021). A coherent and context-specific risk approach is a need to consider public awareness and stakeholder perceptions, to manage flood with minimum flood potential incidents and to cope with hydro-meteorological alterations in a city, in a watershed or in a specific area (i.e. coastal belt). This approach supports decisions regarding pre-flood measures (new settlements planning, effective water management, early warning systems and evacuation plans etc.), during-flood actions (emergency/escape routes and meeting points estimating inundation areas and/or flood prone areas) and post-flood management. Flood periods require a coordinated and comprehensive response that involves a range of measures, from preparation and protection to emergency response and recovery. By taking proactive measures to mitigate the impacts of floods, it is possible to help minimize damage and protect human safety and the environment.

This paper aims to understand the ambiguity among risk factors and identify indicators and indices that can help determine appropriate measures for different flood periods. A systematic literature review was conducted on articles assessing flood

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risk using the AHP methodology to weight indicators for different risk factors (including sensitivity). The most commonly used indicators for each index and risk factor were determined and defined taking into consideration the ambiguity of flood risk factors. The findings of the study include recommendations on which risk indicators and indices can be used for actions and measures at which flood periods.

2 Material and method

2.1 The systematic literature review

2.1.1 Search strategy

In order to evaluate primary flood risk indices and indicators for each risk factor, a comprehensive literature review was conducted spanning the years 2017 to 2022. The search utilized keywords such as "AHP" OR "analytic hierarchy process" combined with "flood" OR "floods." Research studies that employed a hybrid approach incorporating fuzzy AHP and TOPSIS methods were included as well. 27 selected papers from Science Direct, two articles from Springer Link, and one book chapter were thoroughly reviewed (see Supplements). These papers met the inclusion criteria, being highly relevant and cited among thousands of available papers. During the review process, certain papers were identified as beyond the scope of the study, addressing topics such as analytic network process, groundwater, erosion, drought, community perceptions, and avalanches. Additionally, some papers were inaccessible in full text. Furthermore, redundant papers from the same authors were eliminated to avoid duplication.

2.1.2 Classification scheme

All papers were classified according to key domains: publication year, country of application, purpose of AHP utilization, scale, flood risk factors (vulnerability, hazard, exposure, susceptibility, and flood potential), and their respective indices and indicators. The indices were classified into seven classes based on their attributes, including socio-economic, built environment, topographical, hydrological, geological, meteorological, and vegetation indicators. The number of papers was counted for each indicator considering its index and risk factor in order to determine the relationship between each indicator of indices and flood risk factors. For the visualisation, we created the Sankey diagrams via the website "Visual Paradigm Online (https://online.visual-paradigm.com/)".

2.2 Proposals on definitions of flood indices and indicators regarding their contributions to flooding

A definitional analysis was conducted on the key indicators of each index with regard to their relevance to flooding, and these key indicators are considered if they are used more than one time for the indices. In this context, we carefully examined every paper to assess their definitions of these key indicators. We created tables to include impacts of these critical indicators on the floods. In some instances, all or some of the reviewed papers employed these indicators to support their

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impacts. In other cases, none of the papers utilized the indicator in the intended manner; however, it could still serve as an indicator for a specific index and flood risk factor. These variations have been elucidated in the tables.

2.3 Effects of flood risk indicators on flood periods

An assessment was conducted to examine the impacts of vulnerability, hazard, and exposure indicators during flood periods and to establish their correlation with the specific period. In most cases, the reviewed papers supported these effects and relationships. Three primary effects were observed: (1) Indicators exhibited a negative effect during specific flood periods, implying that flood risk increased as the indicator values either increased or decreased; (2) Conversely, indicators displayed a positive effect during certain flood periods, indicating that flood risk decreased as the indicator values either increased or decreased; and (3) "Neutral" was used as an effect in instances where no findings regarding effects or relationships were identified. For certain indicators, their range or values depended on various factors such as land use classes, making it challenging to categorize them as strictly negative or positive. In such cases, we considered these variations as "different levels of effects or relationships." Besides effects, the relationships between the indicators and flood periods were assessed as either direct or inverse proportions.

3 Results

3.1 Definitional analysis of flood factors

3.1.1 Flood risk

The disparity in the calculation of flood risk indices and indicators stems from variations in their definitions across different studies. In essence, the definitions and conceptual frameworks of flood risk exhibit variability, leading to divergent methods of calculation. According to Das (2020), flood risk is the function of flood hazard to the flood vulnerability and calculated by multiplying flood susceptibility and vulnerability indices. Another definition is that flood risk is defined as a function (*Risk = Hazard x Vulnerability*, Ologunorisa, 2001) and a product of the hazard and vulnerability (Mishra and Sinha, 2020), while Lin et al. (2020) clarified that risk indicates the probability and potential loss based on different intensity floods and used the equation (*Risk = Hazard + Vulnerability*) from Maskrey (1989). Pham et al. (2021) shows that the concept of flood risk involves three main elements: hazard, exposure, and vulnerability factor in line with the IPCC AR5 (IPCC, 2014) and flood risk is calculated by multiplied each factor, while Lyu et al. (2020) sum up these three factors to calculate the inundation risk.

3.1.2 Vulnerability

Vulnerability in IPCC AR6 (IPCC, 2022a) includes the concepts and elements of sensitivity or susceptibility to harm and adaptive capacity. In this case, *flood vulnerability refers to the sensitivity of a system, community, or region to harm,* *damage, or adverse consequences resulting from flooding, often influenced by factors such as socio-economic conditions, infrastructure quality, and preparedness measures, and the capacity to adapt and recover in the face of changing flood patterns and intensities.* Different scientific papers provide varying definitions of vulnerability, each focusing on distinct aspects. One perspective defines vulnerability as a reflection of the socio-economic circumstances within a given region, encompassing potential losses that may occur (Lin et al., 2020). Another viewpoint characterizes vulnerability as the susceptibility of properties to be harmed or lost due to hazards (Li et al., 2020). A more detailed description emphasizes flood vulnerability, which involves evaluating the potential harm under specific socio-economic and infrastructural conditions, along with the capacity for resilience, all within a particular region and period (Mishra and Sinha, 2020). Another understanding suggests that vulnerability relates to the potential damage that may arise based on criteria such as socio-economic factors, infrastructure, and preventative capacity within a defined region (Das, 2020). Additionally, according to Lyu et al. (2020), the concept of a vulnerability index is introduced, denoting the capacity of a community or system to endure the impacts of disasters. Particularly in flood-prone areas, vulnerability is intricately linked to the attributes of communities and the nature of infrastructure present (Tsakiris, 2014). This multifaceted and subjective concept finds expression using damage curves for physical assets and indices for human well-being (de Brito et al., 2018), allowing for a comprehensive assessment of vulnerability in diverse contexts.

3.1.3 Hazard

Various scientific papers offer diverse interpretations of hazard definitions, each highlighting specific aspects of risk assessment. One perspective entails the construction of a flood hazard index, facilitating the creation of flood hazard maps that convey the risk level or intensity of flooding across different sections of a watershed (Kabenge et al., 2017). Mishra and Sinha (2020) defined the flood hazard is conceptualized as the probability of a location experiencing a flooding event, rooted in the hydrological and geomorphological characteristics of the area. According to Li et al. (2020), hazard can be understood as the combined measure of flood event frequency and severity. Hossain and Meng (2020) shows that hazards are broadly defined as extreme geophysical events with the potential to harm humans and induce disasters, in the context of floods, encompassing both naturally occurring meteorological variations and anthropogenic factors like deforestation or land use changes. Another viewpoint (Lin et al., 2020) asserts that hazard constitutes a foundation that characterizes the natural environment and hydro-climatic conditions of the assessment region. IPCC (2022c, p.2911) states that hazard is *"the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources"*. Considering the abovementioned studies, briefly, *hazard is related to meteorological and/or hydrological conditions that includes level of flood risk, intensity, frequency and severity*. Another approach involves flood hazard mapping to identify potential flood areas (Uddin and Matin, 2021; Qi et al., 2022), while Pham et al. (2021) defined that flood hazard encompasses potential harm, loss of life, and property damage. Flood hazard also appears as a factor of flood susceptibility (Ekmekcioglu et al., 2021).

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3.1.4 Exposure

Flood exposure, as framed by IPCC AR6 (IPCC, 2022), pertains to the assessment of elements, including people, assets, ecosystems, and infrastructure, that are at risk of being adversely affected by flood events, encompassing both physical presence in flood-prone areas and the potential for harm or damage resulting from such inundation.

Exposure is a term addressed across various scientific papers, each contributing distinct viewpoints to its definition within the context of risk assessment. One perspective simply defines exposure as the (surface) properties or elements that are subject to the influence of a given hazard (Li et al., 2020; Qi et al., 2022). According to Pham et al. (2021), the concept of flood exposure is intertwined with the potential risks posed to individuals and property, encompassing the dangers of personal harm and damage to physical assets. This understanding of exposure involves *considering topographic attributes and other relevant factors that contribute to gauging the extent of risk.* The exposure factor involves quantifying and assessing physical characteristics, offering a means to better comprehend and manage the potential impact of hazards on the areas and assets at risk.

3.1.5 Susceptibility/Sensitivity

As mentioned above, in IPCC AR6, vulnerability includes the concepts and elements of sensitivity or susceptibility to harm and lack of capacity to cope and adapt. In this point of view, sensitivity is a part of vulnerability and more related to communities and/or across societies (IPCC, 2022b) or regions to harm, resulting from flooding, due to socio-economic and/or infrastructures. According to the literature reviewed, flood susceptibility was used for flood hazard modelling or evaluation of flood potential/risk (Abu El-Magd et al., 2020; Costache et al., 2020) (Table 1).

3.2 Aspects and applications of flood assessment

Table 1 provides an overview of the different aspects and applications used for flood assessment and mapping, the countries studied, and the scales of analysis. It indicates the diverse efforts in understanding and addressing flood-related issues worldwide.

Table 1. General information about AHP flood papers reviewed.

Aspects and applications to assess flood		**# of papers reviewed**	**Year**	**Country**	**Scale**
Flood hazard risk/areas → **Flood hazard maps OR flood risk maps OR flood susceptibility map**	**defining/assessing flood hazard risk/areas:** by developing flood hazard maps	1	2017	Uganda	watershed
		1	2018	Thailand	basin
		1	2019	Iran	basin
		2	2020	Thailand; Iran	city; basin
		2	2021	Algeria; Bangladesh	basin; country

Aspects and applications to assess flood		**# of papers reviewed**	**Year**	**Country**	**Scale**
	defining/assessing flood hazard risk/areas: by developing flood hazard maps to generate flood risk map	1	2020	USA	city
	flood hazard modelling to generate flood susceptibility map	1 1	2019 2020	Tunisia Egypt	an area an area
Flood hazard and vulnerability maps → **Flood hazard and vulnerability maps OR flood risk maps**	**generating flood hazard and vulnerability maps**	1	2020	India	city
	generating flood hazard and vulnerability maps to generate flood risk maps	1 1 1	2020 2020 2021	Nepal China Türkiye	region province city
Flood susceptibility maps → **Flood susceptible/ potential for the areas**	**flood susceptibility assessment = the evaluation of flood potential**	1	2020	Romania	basin
	flood susceptibility to identify flood-susceptible areas	1 3 2 1	2019 2020 2021 2022	Brazil; India Austria; Romania; India India; Tanzania Cameroon	city; basin basin; catchment; along the stream catchment; region watershed
Flood susceptibility and vulnerability maps → **Flood risk maps**	flood susceptibility and vulnerability mapping **to generate flood risk maps**	1	2020	India	coastal bed
Flood vulnerability	flood vulnerability	1	2020	Ethiopia	basin
Flood risk factors → **Flood risk**	to identify prioritisation **(for flood interventions, green infrastructure etc.) using hazard, exposure and vulnerability factors**	1 1	2019 2022	Belgium China	city sub watersheds
	assessing inundation risk/flood risk assessment **by combining hazard, exposure, and vulnerability**	1	2020	China	city
	flood risk components = exposure, vulnerability and flood susceptibility **(it is a factor of flood hazard)**	1	2021	Vietnam	city
Flood potential/ risk	flood potential/risk	1	2022	Türkiye	watershed

Fifteen out of the thirty papers (50%) examined the scale of their case studies as either “basin”, “watershed/sub-watershed”, or “catchment”, while the remaining half focused on various other areas such as along the stream, province/city, region, or country. The majority of the reviewed papers originate from South Asia and Africa, suggesting that these regions have a significant focus on AHP for flood-related research and case studies.

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3.3 Indices and indicators

3.3.1 Indices and flood risk factors

According to the papers reviewed, Figure 1 illustrates the correlation between the indices and flood risk factors, considering indicators for each index.

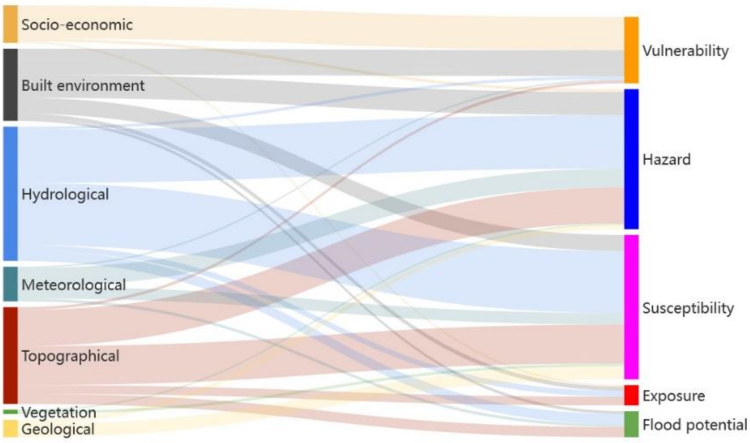

Figure 1. The relationship between the indices (combinations of indicators) and flood risk factors.

As illustrated in the Figure 1, *the hydrological index* plays a pivotal role in flood-related hazard and susceptibility assessments. A diverse range of hydrological indicators was employed in the articles reviewed for this study. The index encompasses indicators associated with drainage, rivers, flow, runoff, soil characteristics, and hydrological processes. Understanding hydrological factors is essential in flood risk management and planning interventions to mitigate flood impacts. The emphasis on vulnerability in the reviewed papers indicates the significance of understanding how *social and economic indicators* influence a community's capacity to cope with and recover from flood events. By considering socio-economic vulnerability, researchers aim to identify populations that are more susceptible to the adverse impacts of floods and develop targeted interventions to enhance their resilience. *The built-environment index* focuses on the characteristics of transportation networks, land use/land cover, building areas, and imperviousness, as well as proximity to roads, rivers, and settlements. These indicators are recognized as significant factors influencing vulnerability, hazard, exposure, and susceptibility related to floods. The built environment's role in flood risk is evident from the diverse range of indicators used in the papers, reflecting the complexity of urban and rural settings' vulnerability to floods. The indicator of transportation networks including road density and length plays a significant role in influencing vulnerability and hazard related to floods. Land use/land cover characteristics play a crucial role in understanding the built environment's vulnerability to floods and its implications for hazard and risk. The *topography* plays a significant role in flood-related assessments, especially in hazard and susceptibility evaluations. Indicators like slope, elevation, and various topographical features help to understand the terrain's characteristics and its influence on flood-related aspects. *Meteorological index*, especially daily and maximum rainfall as indicators, is crucial in assessing flood hazard, susceptibility, and risk. It also plays a role in vulnerability assessment when considering exposure to heavy rainfall events. The presence of *vegetation* (i.e. green spaces) may influence flood hazard, possibly through infiltration and runoff control (Li et al., 2020). NDVI is a remote sensing index that can help assess vegetation density and health, influencing flood susceptibility. Evaluating flood hazard and susceptibility also involves considering the *geological composition and geomorphology* of an area.

3.3.2 Indicators and flood risk factors

Socio-economic indicators

Population density (number of individuals per unit area: number of people km^{-2}) (5 papers), education level/literacy level/literate population density (sub-criteria or percentage) (4 papers), vulnerable population (gender, under and over certain age, foreigner, unemployed etc., or age as a sub-criteria or percentage) (3 papers) and number of households/household density (number of houses km^{-2}) (3 papers) are the most used indicators for the flood vulnerability (Figure 2 and Table 2). In the reviewed papers, except *population density*, no other indicator was used for the factors of hazard (2 papers) and exposure (1 paper).

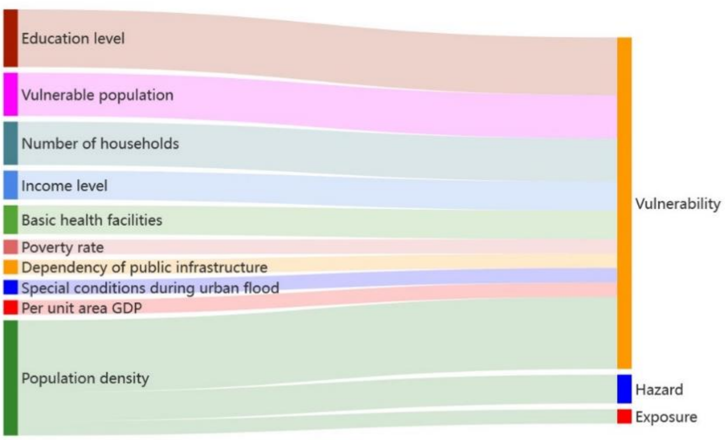

Figure 2. Socio-economic indicators and flood risk factors regarding number of papers that used the indicators for each factor.

The focus of papers was primarily on *socio-economic vulnerability* and its various dimensions rather than other indices of flood assessment. Table 2 shows common indicators that provide insights into the socio-economic context of flood-prone areas and how they might be affected by and respond to flooding events.

Table 2. The common indicators of socio-economic index that impact flooding.

Indicators	Flood factors	Impacts	Papers support the defined impacts (Y/N)*
Population density	**Vulnerability (5 papers)**	**Sensitivity or susceptibility to harm & Lack of capacity to cope and adapt:**	***Y*** *- Papers (1, 2, 4, 18, 20) utilizing this indicator either fully or partially support the*

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Indicators	Flood factors	Impacts	Papers support the defined impacts (Y/N)*
		Higher population density could indicate a higher risk during floods due to ability against flood impacts, effective flood preparation, a large number of casualties, life and property losses, limited access to health/government services, potential difficulties in evacuation due to congestion, increased strain on resources, and strained emergency response systems.	*defined impacts.*
	Hazard (2 papers)	More people living in an area prone to flooding can contribute to the vulnerability of the area (limited evacuation routes, impervious areas etc.), and this can increase the physical impact of the flood on this flood-prone area.	***Y*** *- The paper (5) used the population density as an indicator of vulnerability to generate an urban flood hazard map.* ***N*** *- According to the paper (15), population is at the flood risk due to low-elevated and flat areas; the hazard of flooding is increased. However, this definition supports the exposure factor (topographical indicators).*
	Exposure (1 paper)	More people living in an area prone to flooding means a higher number of individuals at risk.	***Y*** *(10)*
Education level	**Vulnerability (4 papers)**	**Lack of capacity to cope and adapt:** Lower literacy levels might affect the ability of individuals to understand flood warnings and respond effectively.	***Y*** *(1, 2, 5, 20)*
Vulnerable population	**Vulnerability (3 papers)**	**Lack of capacity to cope and adapt:** These groups are more susceptible to the negative impacts of flooding due to their age, physical attributes, independence, knowledge and understanding, community participation, decision-making abilities and difficulties during recovery.	***Y*** *(2, 19, 20)*
Number of households	**Vulnerability (3 papers)**	**Lack of capacity to cope and adapt:** More households at risk can strain or make easy emergency response in the house. Moreover, after the floods, the close proximity of households in the area also facilitates the transmission of negative health issues from one person to another.	***Y*** *(2, 5, 20)*
Income level	**Vulnerability (2 papers)**	**Lack of capacity to cope and adapt:** Lower-income individuals might have limited resources to cope with flood-related damages, evacuation, recovery, and rebuilding.	***Y*** *(2, 5)*
Basic health facilities/ number of doctors and nurses	**Vulnerability (2 papers)**	**Lack of capacity to cope and adapt:** During floods, access to healthcare becomes crucial, and areas with limited healthcare resources might be more vulnerable.	***Y*** *(5, 10)*

* Papers reviewed that used the indicator support the defined impacts

In the context of contribution of flooding, *socio-economic vulnerability* is about lack of capacity to cope and adapt. The common indicators of *socio-economic vulnerability* contribute to flooding by influencing the severity of its impact on communities or infrastructures. Additionally, they make people more vulnerable by affecting their ability to respond effectively and cope with the challenges posed by flooding. Vulnerable populations, in particular, are at higher risk due to physical, economic, and social factors that limit their capacity to adapt and recover from flood events. Addressing these

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vulnerabilities through better preparedness, education, and resource allocation is crucial for reducing the overall impact of flooding on communities.

Built-environment indicators

The built environment indicators provide insights into the physical characteristics of an area that influence vulnerability, hazard, exposure, susceptibility, and potential flood impacts. Different indicators capture various aspects of how the built environment interacts with flood risk factors. Land use/land cover and transportation network are the most used built-environment indicators for flood risks (Figure 3).

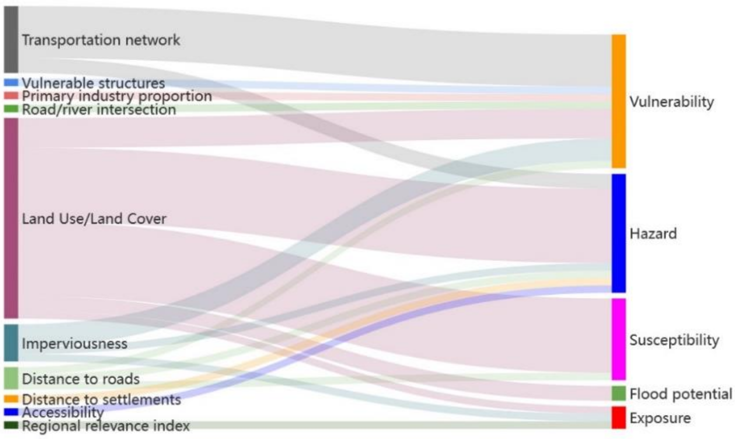

Figure 3. Built-environment indicators and flood risk factors regarding number of papers that used the indicators for each factor.

Table 3 presents essential indicators offering insights into the built environment of flood-prone regions and their potential responses to flooding events. The majority of the reviewed papers utilized land use/land cover to evaluate vulnerability, susceptibility, and hazard. On occasion, various land use classifications were employed, with considerations given to their infiltration and runoff capacities. Additionally, some papers focused solely on urban areas or building density as weighting factors for ranking purposes.

Table 3. The common indicators of built-environment index that impact flooding.

Indicators	Flood factors	Impacts	Papers support the defined impacts (Y/N)*
Transportation network	**Vulnerability (7 papers)**	**As critical infrastructure:** The transportation network can influence vulnerability positively or negatively through accessibility by affecting the ability of people to evacuate during floods. Areas with poorly designed or susceptible transportation systems can increase the vulnerability of the population.	***Y*** *- Papers (1, 2, 10, 18, 19, 20, 29) utilizing this indicator either fully or partially support the defined impacts.*
	Hazard	The transportation network's susceptibility to	***Y*** *(3, 5)*

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Indicators	Flood factors	Impacts	Papers support the defined impacts (Y/N)*
	(2 papers)	flooding can contribute to the hazard (resulting flooded roads or becoming waterways) itself, as damage to transportation infrastructure can worsen the flood impact. In addition, the transportation network can increase urban discharge and surface runoff due to its imperviousness.	
	Exposure	The transportation network could be adversely affected by floods due to its location or its deficient infrastructure.	***N*** *- None of the papers used transportation network as an indicator of exposure. However, it can be an indicator for the exposure factor.*
Land Use/Land Cover	**Vulnerability (incl. susceptibility) (4+10 papers)**	**Lack of capacity to cope and adapt:** Areas with certain land uses (agricultural, residential, commercial, forests etc.) might have different levels of preparedness and response to flooding.	***N*** *- Papers (2, 18, 20, 26 + 1, 6, 11, 12, 13, 14, 17, 22, 27, 28) took into consideration this indicator for vulnerability because of their impact on surface runoff or different inundation risks or infiltration differences of land use. However, in this case, this explanation supports the hazard factor.*
	Hazard (10 papers)	Land use/land cover influence infiltration, groundwater level, interception and evapotranspiration rates, and can contribute to the hazard itself. For example, urban areas with extensive impervious surfaces can increase runoff and flood probability.	***Y*** *(3, 5, 8, 9, 15, 19, 21, 23, 24, 25) Land use was considered due to its runoff for flood potential as a flood-influencing factor in the paper (16) and as a flood factor in the book chapter (30).*
	Exposure (1 paper)	People may be affected in various ways by flooding due to different land uses, with the impact varying depending on their location, particularly if they are situated in flood-prone areas.	***Y*** *(10)*
Imperviousness (incl. urbanization, buildings)	**Vulnerability (incl. susceptibility) (3 papers)**	**As critical infrastructure:** Buildings can be highly vulnerable during flooding due to their design, materials, location and various factors that can exacerbate the impact of flooding. **Lack of capacity to cope and adapt:** Lower urbanization rate can be a flood factor in rural areas.	***Y*** *(19, 29)* ***Y*** *(4)*
	Hazard	While buildings themselves are not the primary cause of flooding, certain design, construction, and land use practices can exacerbate flood hazards. For example, the construction of large buildings and extensive paved surfaces in urban areas leads to increased runoff and peak discharge during heavy rainfall.	***Y*** *(2)*
	Exposure (1 paper)	Buildings (and imperviousness) in flood-prone zones, such as coastal areas, floodplains, and areas with a history of flooding, increases the exposure to potential flood events. Such locations are more likely to experience floods, putting the building and its occupants at higher risk.	***Y*** *(29)*

Topographical indicators

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The topographical indicators help assess flood risk by capturing the physical characteristics of the terrain that contribute to vulnerability, hazard, exposure, susceptibility, and potential flood impacts. Slope and elevation are the most used topographical indicators for flood risks (Figure 4).

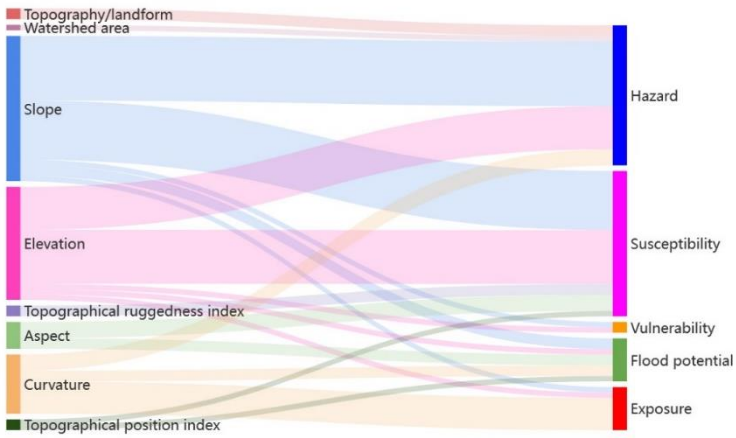

Figure 4. Topographical indicators and flood risk factors regarding number of papers that used the indicators for each factor.

Table 4 provides insights into the topographical index and its potential responses to flooding events through various indicators. In the majority of the reviewed papers, slope and elevation were commonly employed to assess susceptibility and hazard. Slope and elevation were used as an indicator for susceptibility and hazard factor.

Table 4. The common indicators of topographical index that impact flooding.

Indicators	Flood factors	Impacts	Papers reviewed that used the indicator support the defined impacts (Y/N)
Slope	**Vulnerability (incl. susceptibility) (1 + 11 papers)**	**Sensitive or susceptible to harm:** Slope might indicate vulnerability by affecting the stability of structures on steep terrain. In other words, steep slopes are often more susceptible to erosion and soil destabilization during flooding, contributing to vulnerability.	***N*** *- Papers (26 +1, 6, 7, 11, 12, 13, 14, 17, 22, 27, 28) took into consideration slope as an indicator of vulnerability due to its contribution to runoff. However, in this case, this explanation supports the hazard factor.*
	Hazard (12 papers)	Slope plays a significant role in hazard regarding rainwater infiltration and surface water (flow direction and accumulation) thus flow velocity and duration. Thus, lower slopes have high flood risk. In contrast, from the perspective of watershed scale, steeper slopes can lead to faster runoff, potentially causing more severe flooding.	***Y*** *- Papers (2, 3, 4, 5, 8, 9, 10, 20, 21, 23, 24, 25) that used this indicator support the defined impacts.* *Slope was considered as a flood-influencing factor due to its contribution to surface runoff in the paper (16) and as a flood factor in the book chapter (30).*
	Exposure (1 paper)	Slope can also influence exposure by affecting how likely an area is to be affected by flooding due to its location relative to water sources and/or watershed.	***N*** *- The paper (29) took into consideration this indicator for exposure because of its contribution to runoff. However, in this case, this explanation supports the hazard factor.*
Elevation	**Vulnerability (incl. susceptibility)**	Elevation can increase vulnerability. Areas at lower elevations are more prone to flooding and its impacts.	***Y*** *- Papers (26 + 1, 6, 7, 11, 12, 14, 17, 22, 27, 28) used this indicator for vulnerability and stated that as areas at lower elevations*

Indicators	Flood factors	Impacts	Papers reviewed that used the indicator support the defined impacts (Y/N)
	(1+10 papers)		*might be more prone to flooding and its impacts. However, in this case, this explanation may support the exposure factor as well.*
	Hazard (8 papers)	Elevation can increase hazard by facilitating the faster flow from higher to lower areas.	***Y** (3, 8, 9, 10, 15, 21, 24, 25)*
	Exposure (1 paper)	Low-lying areas are at a higher risk of flooding because of their flat topography and/or its height relative to water sources (higher river discharge, high tide in coastal areas etc.)	***Y** (29)* *Elevation was considered as a flood-influencing factor due to the direction of water runoff from high to low altitudes in the paper (16).*
Aspect	**Susceptibility (3 papers)**	-	*Papers (11, 13, 14) used this indicator for susceptibility due to the contribution of surface runoff, soil water content, and rainfall direction. However, in this case, this explanation supports the hazard factor.*
	Hazard	Aspect plays a role on surface runoff, soil water content, and rainfall direction etc. due to its shaded/sunny positions.	*Aspect was considered as a flood-influencing factor due to its contribution to soil humidity and water evapotranspiration in the paper (16) and due to the impacts on the amount of runoff as a flood factor in the book chapter (30).*
Curvature (incl. Plan and Profile Curvature)	**Hazard (1 paper)**	Topographic curvature influences runoff and infiltration.	*Paper (10) does not provide an explanation for the use of this indicator as a hazard indicator.*
	Exposure (2 papers)	Flat surfaces have a higher risk of flooding.	***Y** (6)* *Papers (13, 14, 16, 17) used this indicator(s) due to their contribution to runoff and infiltration process or separation of the areas with a convergent and divergent runoff. However, in this case, this explanation supports the hazard factor.*

Hydrological indicators

The hydrological indicators provide insights into the water-related characteristics of an area that influence vulnerability, hazard, exposure, susceptibility, and potential flood impacts. Drainage/drainage density/river network, distance from/to rivers or drainage (network), soil (type, texture, and hydrologic soil groups), flow accumulation, runoff/runoff coefficient and Topographical Wetness Index (TWI) are the most used hydrological indicators for flood risks (Figure 5). Drainage density is calculated as the total length of all streams and rivers within a drainage area divided by the total land area of that drainage. TWI helps to characterize and map the wetness or moisture content of different terrain based on its elevation and slope.

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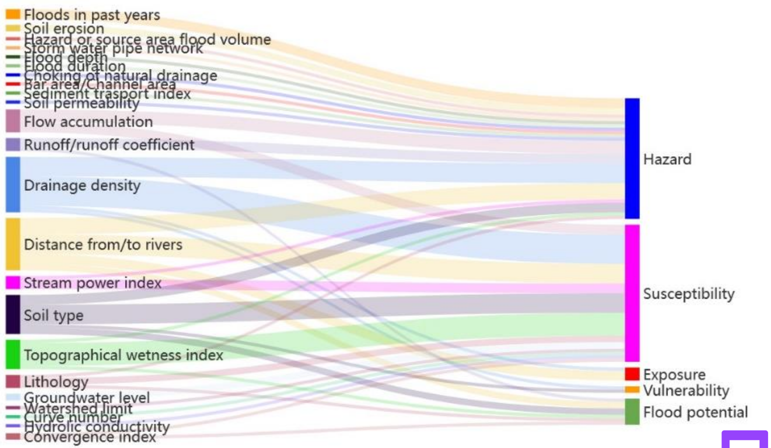

Figure 5. Hydrological indicators and flood risk factors regarding number of papers that used the indicators for each factor.

Table 5 illustrates that drainage density, distance from/to rivers, and soil were frequently utilized in the evaluation of susceptibility and hazard.

Table 5. The common indicators of hydrological index that impact flooding.

Indicators	Flood factors	Impacts	Papers reviewed that used the indicator support the defined impacts (Y/N)
Drainage density	**Vulnerability (incl. susceptibility + coping/adaptation capacity) (1 + 9 papers)**	High drainage density can increase vulnerability due to a dense stream network with high surface runoff.	***Y*** *- Papers (26 + 1, 6, 7, 12, 14, 17, 22, 27, 28) that used this indicator due to its contribution to surface runoff. However, in this case, this explanation may support the hazard factor as well.*
	Hazard (6 papers)	High drainage density can increase hazard due to a dense stream network with high surface runoff. Conversely, low drainage density might affect hazard if it is linked to areas prone to flooding due to poor drainage capacity. In addition, drainage density can be a hazard factor by affecting how efficiently water can be carried away from an area.	***Y*** *(3, 4, 8, 9, 10, 23)*
	Exposure (1 paper)	Drainage density can indicate areas that are more exposed to flooding due to their proximity to water bodies.	***Y*** *(18)*
Distance from/to rivers	**Susceptibility + coping/adaptation capacity (6 papers)**	Being close to rivers might imply higher susceptibility due to the risk of flooding during river events.	***Y*** *- Papers (1, 6, 11, 14, 17, 28) that used this indicator due to the contribution to the flood risk during flood events. However, in this case, this explanation may support the exposure factor as well.*
	Hazard (5 papers)	Proximity to rivers can increase flood hazard due to the potential for overflow of active channels and transportation of debris during heavy rainfall.	***Y*** *(20, 21, 23, 24, 25). Distance from/to rivers was considered as a flood-influencing factor in the paper (16) and as a flood factor in the book chapter (30) due*

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			to its contribution to flood risk. However, this indicator can be used for exposure instead of hazard in the case of inundation areas due to their proximity of rivers, unless it is really accelerating the flood.
	Exposure (3 papers)	Areas close to rivers are exposed to flooding, especially during riverbank overflow.	***Y*** *(10, 18, 29)*
Flow accumulation	**Susceptibility + coping/adaptation capacity (3 papers)**	High flow accumulation areas might be more susceptible to flooding due to increased potential for water accumulation.	***Y*** *- Regarding this indicator, the aim of the usage in the papers (1, 12, 17) are similar and may point out hazard, even it is used for susceptibility.*
	Hazard (4 papers)	More water accumulation increases flood risk. Moreover, flow accumulation can contribute to hazard by indicating areas that might experience rapid runoff and increased flood risk.	***Y*** *(8, 10, 21, 23)*
Soil (type, texture, hydrological soil groups)	**Vulnerability (incl. susceptibility + coping/adaptation capacity) (1+6 papers)**	Soil can indicate vulnerability if certain soil types/textures are more prone to landslide, erosion and sediment transport during floods.	***N*** *- The definitions in all papers (26 + 1, 6, 12, 13, 14, 22) are similar and point out hazard. However, only one paper (5) which used this indicator as hazard indicator mentioned that the granular soil tends to cause landslide.*
	Hazard (3 papers)	Soil type/texture/hydrological groups affect hazard, as it determines how well water is absorbed or retained in the soil. They can contribute flood hazard due to landslide, erosion and sediment transport.	***Y*** *(5, 8, 24)* *Soil was considered as a flood-influencing factor in the paper (16) due to its influence of water infiltration. The book chapter (30) considered hydrological soil groups as a flood factor.*
Runoff/Runoff coefficient	**Hazard (3 papers)**	Runoff and runoff coefficient contribute to hazard by indicating the potential for surface runoff and flooding during heavy rainfall.	***Y*** *(3, 24, 25)* *The book chapter (30) considered amount of runoff in different land use as a flood factor.*
Topographical Wetness Index (TWI)	**Susceptibility + coping/adaptation capacity (7 papers)**	Wetness index indicates susceptibility to flooding, as it points to areas with high potential for surface saturation.	***Y*** *- Papers (1, 6, 11, 14, 17, 27, 28) that used this indicator to determine wet surfaces that have potential to contribute flooding. However, in this case, this explanation may support the hazard factor as well.*
	Hazard (1 paper)	Wetness index indicates hazard by highlighting areas prone to flood due to water accumulation and surface runoff (discharge). These areas are wet and/or water saturated areas that have potential contribution to floods.	*In the paper (10), there is no explanation about the reason why and how this indicator used.* *TWI was considered as a flood-influencing factor in the paper (16) due to its influence of water accumulation.*

Geo(-morpho)logical indicators

Geology and geomorphology as indicators were used for flood susceptibility and hazard (Figure 6 and Table 6) regarding 320 their impacts on infiltration, runoff and drainage, and topographical features as well.

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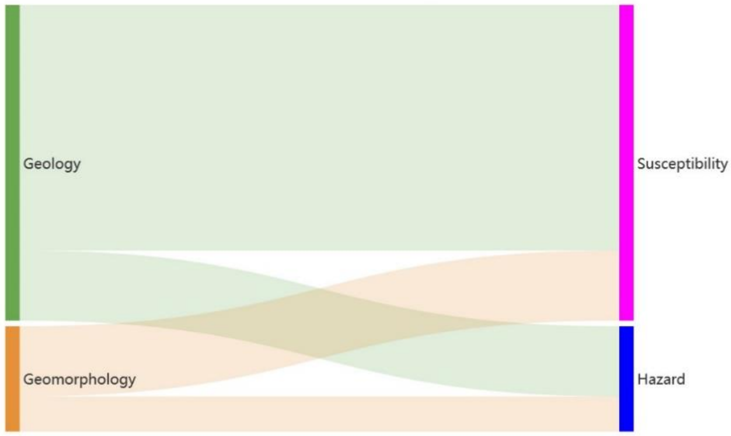

Figure 6. Geo(-morpho)logical indicators and flood risk factors regarding number of papers that used the indicators for each factor.

Table 6. The common indicators of geo(-morpho)logical index that impact flooding.

Indicators	Flood factors	Impacts	Papers reviewed that used the indicator support the defined impacts (Y/N)
Geology	**Susceptibility (7 papers)**	-	*Papers (1, 6, 11, 12, 14, 17, 28) used this indicator due to its impact on infiltration, runoff or drainage. However, in this case, this explanation supports the hazard factor.*
	Hazard (2 papers)	Geology (soil and rock formations) affects infiltration and runoff process considering permeability and porosity, and drainage density.	***Y*** *(21, 23)*
Geomorphology	**Susceptibility (2 papers)**	-	*Papers (6, 17) used this indicator regarding the elevation and flatness of the areas. However, in this case, this explanation supports hazard factor.*
	Hazard (1 paper)	Geomorphic units can influence flooding diversely depending on drainage, channel characteristics, sediment transport, erodibility, floodplain features (elevation, slope, vegetation etc.) etc.	***Y*** *(20)*

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Meteorological indicators

The meteorological indicators focus on rainfall-related factors that influence flood factors. Rainfall is a crucial driver of flooding, and these indicators help to assess how different rainfall characteristics contribute to flood risk in various ways.

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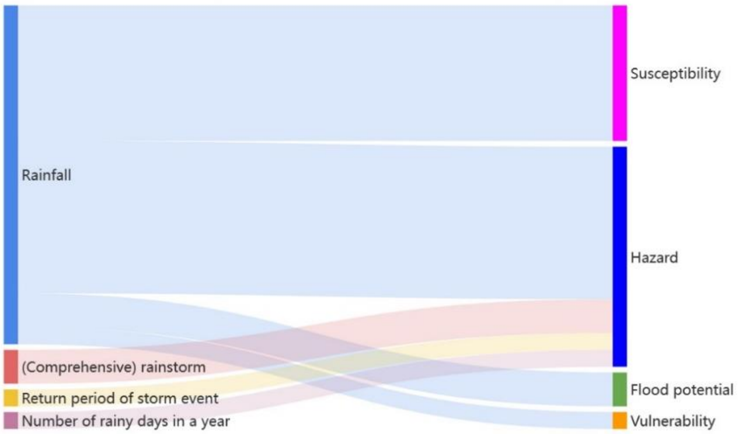

Figure 7. Meteorological indicators and flood risk factors regarding number of papers that used the indicators for each factor.

Table 7. The common indicators of meteorological index that contribute to flooding.

Indicators	Flood factors	Impacts	Papers reviewed that used the indicator support the defined impacts (Y/N)
Rainfall	**Vulnerability (incl. susceptibility) (1+8 papers)**	Rainfall might indicate vulnerability if it is linked to areas prone to flooding due to poor drainage or vulnerable infrastructure. Furthermore, rainfall is often used as a susceptibility indicator since areas with heavy and sustained rainfall are more likely to experience flooding.	*Papers (26 + 1, 6, 7, 11, 14, 17, 22, 28) used this indicator due the contribution of flooding. In this case, this indicator can be used for hazard instead of vulnerability.*
	Hazard (9 papers)	Rainfall is a key hazard factor. Heavy rainfall can lead to increased surface runoff and flooding due to poor drainage or vulnerable infrastructure, flood hazard can be accelerated.	***Y*** *(3, 5, 8, 9, 10, 18, 20, 23, 25) Rainfall was considered as a flood-influencing factor in the paper (16) and as a flood factor in the book chapter (30) due to its contribution to flood risk.*
(Comprehensive) Rainstorm	**Hazard (2 papers)**	A comprehensive rainstorm can indicate hazard by describing an event with potential for heavy and sustained rainfall, which increases the risk of flooding.	***Y*** *(4, 18)*

3.4 Effects of flood risk indicators on flood periods

There are diverse effects of key indicators on different flood periods, along with varied relationships between these indicators and the corresponding flood periods. Table 8, Table 9 and Table 10 present the effects of the key vulnerability, hazard, and exposure indicators during flood periods, respectively.

Table 8. Effects of the key vulnerability indicators during flood periods.

Vulnerability	Indicators	Effect on flood	Effect on flood	Effect on flood

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indices		**preparation and mitigation (pre-flood)**	**responses (during flood)**	**recovery (post-flood)**
Socio-economic	Population density	*N - dp*	*N - dp*	*N - dp*
	Education level	*P - ip*	*P - ip*	*Nt*
	Vulnerable population	*N - dp*	*N - dp*	*N - dp*
	Number of households	*Nt*	*N - dp or N - ip*	*N - dp*
	Income level	*P - ip*	*Nt*	*P - ip*
	Basic health facilities	*Nt*	*P - ip*	*P - ip*
Built-environment	Transportation network	*Nt*	*N - dp, N - ip or P - ip*	*Nt*
	Land Use/Land Cover	*Diff.*	*Diff.*	*Nt*
	Imperviousness	*Nt*	*N - dp*	*Nt*
Topographical	Slope	*Nt*	*N - dp or N - ip*	*Nt*
	Elevation	*Nt*	*N - ip*	*Nt*
Hydrological	Drainage density	*Nt*	*N - dp or N - ip*	*Nt*
	Distance from/to rivers	*Nt*	*P - ip*	*Nt*
	Flow accumulation	*Nt*	*N - dp*	*Nt*
	Soil type	*Nt*	*Diff.*	*Nt*
	TWI	*Nt*	*N - dp*	*Nt*
Meteorological	Rainfall	*Nt*	*N - dp*	*Nt*

N: Negative - The indicator has a negative effect during the certain flood period. The flood risk increases as the indicator value either increases or decreases; *P:* Positive - The indicator has a positive effect during the certain flood period. The flood risk decrease as the indicator value either increases or decreases; *Nt:* Neutral – No findings for the effects or relationship; *Diff.:* Different levels of effects or relationships; *dp:* Direct proportion; *ip:* Inverse proportion.

Among the socio-economic vulnerability indicators (Table 2 and Table 8), *population density and the presence of vulnerable populations* exhibit a negative effect and a direct proportion relationship during the pre-flood, flooding and post-flood. In other words, the increase in population density and vulnerable populations directly correlates with negative impacts by floods, signifying a proportional relationship – higher (vulnerable) populations can face inherent challenges during these periods. Conversely, according to the papers reviewed, indicators such as *education levels* have a positive effect during the pre-flood and flood periods, whereas *income levels* show a positive impact before and after flooding events. For the post-flood, the impact of education and income levels might be less significant as other factors become more prominent in the recovery efforts focus on broader community needs. *The presence of basic health facilities* is consistently beneficial during floods and post-flood phases, highlighting the importance of such infrastructure in disaster resilience and recovery efforts. *The number of households* can strain or make easy emergency response in the house. Among the built-environment vulnerability indicators (Table 3 and Table 8), *different land use/land cover* might have different levels of preparedness and response to flooding, whereas *imperviousness* often presents a negative impact during flooding events. This is attributed to its limited capacity to cope and adapt, as well as its critical infrastructure vulnerabilities. *The transportation network* can exert both positive and negative influences on vulnerability, primarily through its impact on accessibility. Topographical, meteorological, and hydrological vulnerabilities can be secondary and linked to either hazard or exposure during flooding rather than vulnerability.

Table 9. Effects of the key hazard indicators during flood periods.

Hazard indices	**Indicators**	**Effect on flood responses**

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		(during flood)
Socio-economic	Population density	*N - dp*
Built-environment	Transportation network	*N - dp*
	Land Use/Land Cover	*Diff.*
	Imperviousness	*N - dp*
Topographical	Slope	*N - ip, N - dp*
	Elevation	*N - ip*
	Aspect	*Diff.*
	Curvature	*N - ip*
Hydrological	Drainage density	*N - ip, N - dp*
	Distance from/to rivers	*P - ip*
	Flow accumulation	*N - dp*
	Soil	*Diff.*
	Runoff/Runoff coefficient	*N - dp*
	TWI	*N - dp*
Geo(-morpho)logical	Geology	*Diff.*
	Geomorphology	*Diff.*
Meteorological	Rainfall	*N - dp*
	(Comprehensive) Rainstorm	*N - dp*

N: Negative - The indicator has a negative effect during the certain flood period. The flood risk increases as the indicator value either increases or decreases; *P:* Positive - The indicator has a positive effect during the certain flood period. The flood risk decrease as the indicator value either increases or decreases; *Nt:* Neutral – No findings for the effects or relationship; *Diff.:* Different levels of effects or relationships; *dp:* Direct proportion; *ip:* Inverse proportion.

Considering the literature reviewed, hazard indicators are related to flood events. For instance, *population density* contributes to the vulnerability of the area and leads physical hazard impacts. *A transportation network* can transform into a waterway, while *impervious surfaces* lead to increased runoff, thus accelerating flood hazards. *Different land use/land cover, different aspects, soil types, geology* and *geomorphology* might have different impact on flood events. *Slope* affect infiltration and surface runoff that contribute to flood hazard, while *elevation* facilitates faster flow higher to lower areas. Regarding hydrological indicators, factors such as *flow accumulation, runoff,* and *topographic wetness index (TWI)* play significant roles on flood events. Similarly, meteorological indicators such as *rainfall* and *rainstorm* can have a negative impact on floods.

Table 10. Effects of the key exposure indicators during flood periods.

Exposure indices	**Indicators**	**Effect on flood responses (during flood)**
Socio-economic	Population density	*N - dp*
Built-environment	Transportation network	*Diff.*
	Land Use/Land Cover	*Diff.*
	Imperviousness	*N - dp*
Topographical	Slope	*N - ip, N - dp*
	Elevation	*N - ip*
	Curvature	*N - ip*
Hydrological	Drainage density	*N - dp*
	Distance from/to rivers	*P - ip*

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N: Negative - The indicator has a negative effect during the certain flood period. The flood risk increases as the indicator value either increases or decreases; *P:* Positive - The indicator has a positive effect during the certain flood period. The flood risk decrease as the indicator value either increases or decreases; *Nt:* Neutral – No findings for the effects or relationship; *Diff.:* Different levels of effects or relationships; *dp:* Direct proportion; *ip:* Inverse proportion.

As shown in Table 10, considering the literature reviewed, exposure indicators are related to flood events, and have similar effects on flood responses as hazard indicators.

4 Discussion

4.1 Defining and selecting of indicators

Before defining and selecting indicators, clarifying the objective of the study is crucial. Is the aim to create a flood risk map for identifying flood-prone areas to prevent adverse consequences of flooding, establish evacuation routes or assist vulnerable groups during floods? Alternatively, is it to determine pre-emptive actions and measures before a flood occurs? On the other hand, perhaps the goal is to develop strategies for post-flood recovery. Based on the findings, the selection of flood risk indicators should be context-specific, taking into account local and/or regional circumstances as well as the target flood period. For instance, depending on the location of the inundation area/flood-prone area, the sea level rise as an indicator can play a crucial role on the flood risk assessment (Sun et al., 2022). Similarly, the health vulnerability or social differences (Srivastava and Roy, 2023) or structural vulnerability (i.e. households with open sewage) (de Brito et al., 2018) can be important to consider of vulnerability regarding susceptible or unable to cope with the adverse effect of flooding. Moreover, researchers should elucidate their rationale behind selecting criteria for flood risk indicators, drawing from sources such as literature reviews, expert opinions and approaches. One of the most used tools is the Analytic Hierarchy Process (AHP) to analyse participatory multi-criteria decision-making (MCDA) in flood assessment (de Brito and Evers, 2016) by allowing decision-makers to assign weights and priorities based on their preferences and expertise. Supplementary methodologies such as participatory mapping (Almoradie et al., 2020; Klonner et al., 2021), stakeholder consultations, and scenario planning can complement AHP, offering varied insights and enhancing the inclusivity of decision-making processes. For instance, participatory mapping enables local knowledge integration, while stakeholder consultations foster consensus building and social learning (Evers et al., 2016). There are some studies and projects that utilize a combination of AHP, participatory mapping, collaboration with local communities, and community consultations in flood risk management, especially in countries where flooding is a significant issue (Nguyen, 2014; de Brito et al., 2018). However, it is still a need to have more research on this integrated approach.

It is essential to define these indicators clearly within the context of local conditions and the aim of the study, ensuring relevance and applicability to the specific study area. One of the paper reviewed in this study (5) indicate that population density plays a significant role in amplifying vulnerability in flood-prone areas and exacerbating the physical impact of floods. Moreover, high population density increases exposure to flood risks due to the existence of communities in these

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areas (10; Srivastava and Roy, 2023). Consequently, populations residing in flood-prone regions are exposed to flood hazard and because of that, they face heightened vulnerability to floods and their associated impacts. In this case, population density can be used as an indicator for all three factors as long as explained well. Transportation network can be another example. None of the papers reviewed used transportation network as an indicator of exposure. However, it can be an indicator for the flood exposure (Papilloud et al., 2020), because the transportation network could be adversely affected by floods due to its location or its non-flood-resilient infrastructure (Szymczak et al., 2022).

It is imperative to carefully consider the selection of indicators in risk assessments. While some indicators may provide valuable insights into risk factors, others may not be taken into account despite their relevance to the same risk factor. For instance, the indicator *flow accumulation* encompasses factors such as *lower elevation* and *low slope,* which are indicative of heightened flood risk. In this case, it should be considered that indicators should not overlap in the risk assessment. Conversely, the *topographical wetness index* offers insights into *soil moisture levels,* which can also be pertinent in flood risk assessments. However, the decision to include or exclude specific indicators should be made judiciously, considering their individual contributions to the overall understanding of risk dynamics. Therefore, a comprehensive evaluation of each indicator's relevance, reliability, and applicability within the context of the study area is essential to ensure the robustness and accuracy of flood risk assessments.

There are different aspects and applications for flood assessment and mapping at different scale (Table 1). Vulnerability indicators can be used for different purposes on flood assessment. On one hand, an indicator can refer itself as vulnerable groups or infrastructures, or can be related to adaptive capacity or susceptibility to flood. On the other hand, some indicators make the area susceptible and exposed to flooding. For example, if stability of soil or structures on steep terrain are taken into consideration, steep slopes are more susceptible to erosion during flooding compared to areas with a gentler slope. According to our results, the indicators used for “susceptibility” (land use/land cover, slope, aspect, drainage density, flow accumulation, TWI, geology, geomorphology, and rainfall) support more “flood hazard” than “flood vulnerability” considering IPCC (2022) risk definition. In this study, when an indicator contributes to or accelerates floods and their negative consequences through infiltration and runoff processes, it is evaluated as a hazard indicator. In this case, if we acknowledge that vulnerability is primarily associated with people and infrastructure, then topographical, meteorological, and hydrological vulnerabilities may be linked to either hazard or exposure. None of the reviewed papers in this study used land use/land cover as a vulnerability indicator that distinguishes between various land uses/land covers, where people might exhibit varying levels of preparedness and response to flooding. However, for instance, agricultural and urban resilience and preparedness to floods differ in terms of both the land uses themselves and the individuals who reside in and/or benefit from these land uses. Steep slopes are frequently highly vulnerable to erosion and soil destabilization during flooding, intensifying overall susceptibility, whereas lower elevations are more prone to inundation. Consequently, slope and elevation serve as indicators of vulnerability, whether it pertains to people sensitivity, topographic susceptibility, infrastructure vulnerability, coping mechanisms, or adaptive capacity. Isia et al. (2023) defined "social vulnerability" as the degree to which individuals, populations, or communities are exposed to flood hazards, considering factors such as socioeconomic status, educational

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level, family structure, age distribution, and other demographic characteristics, as well as their capacity to recover from flood consequences. This concept underscores the susceptibility of a population or community to harm or lack of capacity in the face of such hazards. In this case, it is crucial to clearly specify the context for selecting such indicators and the specific aspect of vulnerability under discussion, whether it involves people, topography, infrastructure, coping strategies, or adaptive capabilities.

4.2 Effects of flood risk indicators on flood periods

As a result of the assessment to examine the impacts of vulnerability, hazard, and exposure indicators during flood periods and to establish their correlation with the specific period, indicators of socio-economic and built-environment vulnerability can display positive and negative effects during all flood periods. For example, citizens who are unprepared for floods and are potentially at risk of being affected may engage in various measures and actions (Evers et al., 2016; Bernardini et al., 2024). Topographical, hydrological, and meteorological vulnerabilities are related to flood responses during flooding. Based on the literature reviewed, it is evident that hazard and exposure indicators are closely linked to flood events and exhibit similar effects on flood responses. In this scenario, it would be beneficial to prioritize specific indicators for each index during particular flood periods in order to avoid the overlap of indicators and their effects.

5 Conclusions

This paper seeks to understand the ambiguity among risk factors and identify indicators and indices suitable for determining appropriate measures tailored to different flood periods. A systematic literature review was conducted focusing on articles that assessed flood risk utilizing the Analytic Hierarchy Process (AHP) methodology to weigh indicators across various risk factors, including sensitivity. Through this review, the most frequently used indicators for each index and risk factor were identified and defined taking into consideration the ambiguity of flood risk factors. It was necessary to build a clear concept due to mutual interactions among indicators and risk factors, and their roles and applicability for risk assessments. The findings of this study provide recommendations regarding the selection of risk indicators and indices aligned with specific actions and measures corresponding to distinct flood periods.

While this study aimed to provide a comprehensive review of the relevant literature, it is essential to acknowledge certain limitations, particularly pertaining to the time constraints imposed on the research process. The exhaustive nature of the definitional review, while integral to the depth and accuracy of the study, posed a challenge in terms of time consumption. Due to resource constraints, the scope of the review was constrained, limiting the number of papers spanning the years 2017 to 2022 that could be thoroughly examined within the given timeframe. As a result, there may be a possibility that some valuable contributions, relationships and perspectives on indicator-based flood risk assessment were not included in this analysis. Future research endeavours may benefit from a more extensive timeframe or additional resources to further broaden the scope of the review and ensure a more comprehensive understanding of the subject matter. Moreover, researches could

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significantly benefit from a spatial analysis that employs primary (suggested) indicators to distinguish and evaluate risk factors individually. By focusing on hazard, vulnerability, and exposure separately, researchers can gain valuable insights into the nuanced dynamics of each component. This approach would contribute to a more nuanced understanding of the multifaceted nature of flood risk. Moreover, conducting a comprehensive evaluation that combines these three components would provide a holistic view of the overall flood risk. Identifying and utilizing primary indicators specific to each component can enhance the precision of risk assessments, aiding policymakers and stakeholders in devising targeted and effective mitigation strategies. Emphasizing participatory risk assessment is crucial for future research endeavours. Engaging various stakeholders and decision-makers representing diverse regions is essential in capturing a broad spectrum of perspectives. This diversity not only stems from the different backgrounds of participants, such as universities, NGOs, and public institutions, but also from the unique characteristics of the towns, cities, or regions they represent. For example, the priorities and critical indicators for flood risk assessment may vary between countries or even between regions along the Elbe River Basin in Germany. Conducting participatory assessments allows for a more inclusive and comprehensive understanding of the factors influencing flood risk, ensuring that the mitigation strategies developed are contextually relevant and effective. Additionally, this approach fosters collaboration and knowledge sharing among stakeholders, promoting a more integrated and sustainable approach to managing flood risk across diverse geographical areas. Another suggestion can be that in order to optimise and/or verify the indicator-based flood risk assessment it can be crucial to work with the stakeholders and/or local communities in the field.

Code/Data availability. Aggregated data to perform the analyses and to create the diagrams can be acquired from the first author.

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