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RESEARCH

Addressing loss & damage: climate risks and flood impacts in Assam's Eastern Himalayas

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Abstract
Floods are a recurrent and intensifying hazard in Assam, a state in India, leading to widespread economic and non-economic loss and damage. This study presents a district-level assessment of climate risk and loss and damage across Assam's Eastern Himalayas, combining hazard, exposure, and vulnerability dimensions within the IPCC AR6 risk framing. By linking pre-event risk profiling with post-event impact data (2015–2023), the study provides a comprehensive analysis that makes climate risks and loss and damage outcomes comparable across districts, allowing for spatial prioritization of adaptation needs. Findings reveal that flood risk in Assam is highly differentiated. While some districts simultaneously experience high hazard, exposure, and vulnerability, several moderate-risk areas incur disproportionately high loss and damage due to socio-economic and livelihood-based vulnerabilities. Non-economic impacts such as displacement, psychological distress, and culture loss are equally significant in low-risk zones, indicating that vulnerability, rather than hazard intensity alone, often drives negative outcomes. The novelty of this study lies in establishing a consistent, scalable methodology for assessing loss and damage at the subnational level, and generating policy-relevant evidence to guide adaptation planning, resource allocation, and local resilience strategies. The findings hold broader implications for countries developing mechanisms to address loss and damage within national adaptation and loss and damage policy frameworks.

Keywords Climate change · Flood risk · Social vulnerability · Loss and damage · Sustainable adaptation

Introduction

The intensifying impacts of climate change, marked by the increasing frequency and severity of extreme weather events, have transformed floods, droughts, and other climate-related disasters from distant threats into immediate realities (IPCC 2023). These events disrupt lives, livelihoods, and economic stability globally, with disproportionate consequences for vulnerable and marginalized communities, particularly in developing regions (van der Geest and Warner 2015; Yousaf et al. 2025). Such impacts exacerbate existing inequalities,

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Highlights
- Links district-level climate risk with reported loss and damage to reveal spatial impact patterns.
- Combines ex-ante risk and ex-post loss and damage to explain uneven flood-driven impacts.
- Highlights that in low- and moderate-risk districts, vulnerability rather than hazard intensity, drives higher loss and damage.
- Provides a scalable method to guide equitable, district-specific adaptation through a risk-based assessment.

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heighten vulnerabilities, and result in significant negative outcomes, encompassing both economic (e.g., infrastructure destruction) and non-economic (e.g., displacement, loss of life and cultural heritage) loss and damage (L&D) (Birkmann and Welle 2015; OECD 2021; N'Guetta et al. 2025).

Mitigation and adaptation have long been viewed as the two central pillars of global climate action (Field and Barros 2014; Van der Geest et al. 2019; IPCC 2022). Mitigation seeks to reduce climate-related hazards by addressing the root causes of climate change, while adaptation aims to build local resilience by minimizing exposure and vulnerability (Dow et al. 2013; Schie et al. 2024; Swarnokar et al. 2025). However, inadequate mitigation and the inherent limits to adaptation have led to residual negative impacts. (Mechler et al., 2020; Panwar et al. 2025). Consequently, L&D has emerged as the "*third pillar*" of climate negotiations, addressing residual negative impacts, some of which are irreversible (Field and Barros 2014; Roberts and Huq 2015; Schie et al. 2024).

Climate risk assessment constitutes the most used analytical paradigm for managing climate change impacts, including L&D (Botzen et al. 2018; Reisinger et al. 2020; OECD 2021; New et al 2022). By analyzing hazard, exposure, and vulnerability, it identifies how and where climate risks, such as floods and droughts, translate into tangible and intangible impacts. It adopts an ex-ante (pre-event) perspective, aiming to anticipate, prevent, or reduce climate change risks by analyzing how hazards, exposure, and vulnerability interact. Integrating L&D metrics into this framework makes it possible to jointly analyze both avoided and residual climate change impacts, capturing economic (e.g., damage to assets, livelihood disruption) and non-economic (e.g., displacement, loss of cultural heritage, psychological trauma) outcomes (van der Geest and Warner 2015; Van der Geest et al. 2019; Reisinger et al. 2020). This combined approach moves beyond traditional disaster risk management, which is typically reactive and focused on post-event response, by linking ex-ante risk characteristics with the negative impacts that occur when adaptation is insufficient or exceeds its limits. This provides a more complete understanding of how economic and non-economic impacts emerge across different contexts and supports more forward-looking and equitable adaptation planning. (UNDRR 2015; van der Geest et al. 2019). L&D metrics operate from an ex-post standpoint, documenting realized impacts despite mitigation and adaptation efforts, thereby bridging the gap between anticipated risk and actual L&D. (IPCC 2023; Dasgupta et al. 2024; Vyas et al. 2024). This approach contrasts with traditional disaster management, which is typically reactive and event-focused, emphasizing post-disaster recovery and relief while neglecting the deeper socio-economic vulnerabilities that exacerbate disaster impacts (UNDRR, 2015).

Thus, instead of modelling how risks evolve over time, our approach combines ex-ante risk assessment with post-event L&D documentation to provide an overview of the residual impacts experienced across different locations. Each of these locations has its own distinct exposure and vulnerability profile, allowing us to document the economic L&D and, loss of human life, as a non-economic L&D indicator that result from specific hazard events.

By linking pre-event risk characteristics with observed post-event outcomes, the analysis highlights how varying levels of vulnerability shape residual impacts. The evidence base enables policymakers to better prioritize adaptation, recovery, and resilience strategies that are forward-looking and equitable (IPCC 2023; Dasgupta et al. 2024; Vyas et al. 2024; van der Geest et al. 2019). This, in turn, supports more proactive policy action and helps address the underlying drivers of risk to reduce future L&D effectively (IPCC 2023; Dasgupta et al. 2024; Vyas et al. 2024).

Assam, located in India's Eastern Himalayan region, offers a critical case for examining how communities experience flood-related residual impacts. In different areas of the state, each with its own vulnerability profile, we analyze the type and magnitude of flood-driven negative impacts called L&D, with a primary focus on economic L&D, while also documenting loss of human life as non-economic L&D. With nearly 9.4% of India's flood-prone areas within its territory, the state is highly susceptible to recurrent floods driven by its unique geographical and topographical features (Dasgupta et al. 2024; Barua et al. 2018; Choudhary 2022; Government of Assam, 2025). The Brahmaputra and Barak river systems, which sustain agriculture, fisheries, and domestic water use, also cause extensive flooding and erosion during the monsoon season, resulting in widespread destruction (Government of Assam 2015). Between 2015 and 2023, floods alone caused estimated economic L&D of USD 19.36 billion, while non-economic L&D such as displacement and loss of culture, psychological loss remain underreported (Bania 2022; Government of Assam 2015). Given its high exposure to flood hazards, dependence on climate-sensitive livelihoods, and recurrent displacement, Assam serves as an ideal context to explore how hazard, exposure, and vulnerability interact to shape spatial variations in flood-related L&D. Understanding these dynamics is essential for developing equitable and context-specific adaptation policies.

Accordingly, this study aims to analyze the spatial dynamics of flood risk and L&D across Assam between 2015—2023 by linking district-level climate risk assessment with empirically observed impacts. Specifically, it seeks to assess and map flood risk across the thirty-three districts of Assam incorporating the three key dimensions of hazard, exposure, and vulnerability. The study quantifies economic

L&D and, due to data limitations, considers only loss of human life as the non-economic component of L&D for the period 2015–2023. This allows us to examine how these measured impacts vary in magnitude and spatial distribution across districts. Finally, it identifies the primary drivers of risk and provides evidence-based insights for targeted adaptation planning, particularly for districts with high L&D.

To the best of our knowledge, this is among the first district-level studies explicitly linking climate risk assessment with L&D in Assam. While prior studies have examined flood hazards, vulnerability, or climate risk in India and South Asia, but the integration of comprehensive risk assessment with empirical L&D data at the sub-state level has remained very limited (NIDM and GIZ, 2019; Simpson et al. 2021; Mohanty and Wadhawan 2021; Boyd et al. 2021; Bahinipati and Gupta 2022; Gupta and Dixit 2022; Chen et al. 2022, 2013; Dasgupta et al. 2024; Joshi et al. 2025; N'Guetta et al. 2025). The study thus fills an important research and policy gap by offering a risk-based, district-level assessment that can guide equitable L&D policy and adaptation planning.

Methodology

Study area

Physical and environmental setting: geography, geomorphology, river systems, and flood hazards

Assam, a flood-prone state in India's Eastern Himalayan region, covers an area of 78,438 sq. km and is endowed with rich biodiversity (Government of Assam 2015). It is the largest state in the North Eastern Region (NER), accounting for about 30% of its total area and home to over 35 million people. Administratively, the state currently comprises thirty-five districts, following the bifurcation of two new districts on August 25, 2023 (Districts, Government of Assam 2025). However, for this study, data were available only for the earlier configuration of thirty-three districts, accordingly, the analysis is limited to these thirty-three districts (Fig. 1).

Assam's diverse geomorphology is defined by two major river systems- the Brahmaputra in the north and the Barak

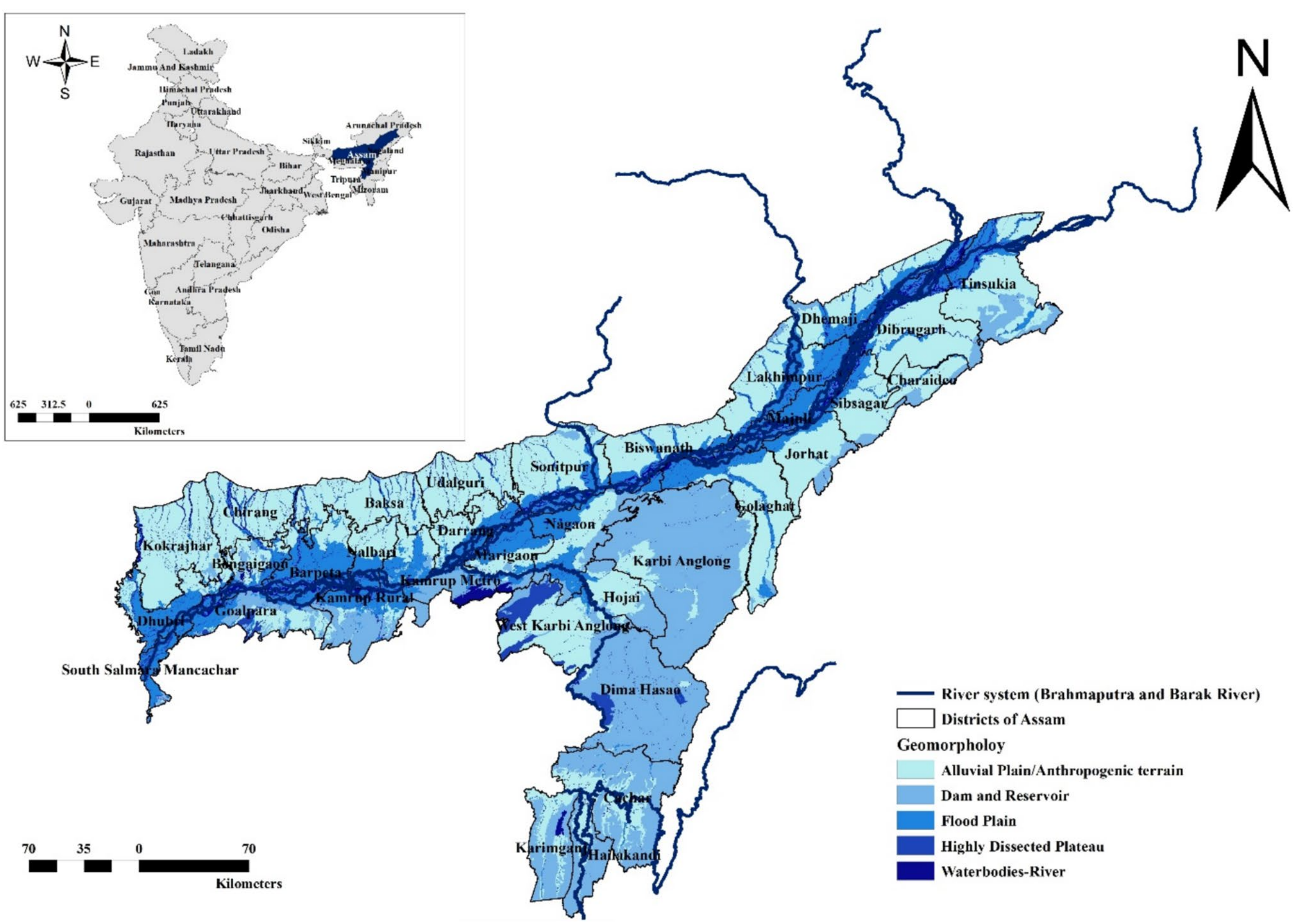

Fig. 1 Location, geographical extent and geomorphology characteristics for the state of Assam

in the south. The Brahmaputra Valley, covering nearly 90% of the state's area, is characterized by low-lying floodplains that are highly susceptible to flooding and riverbank erosion (Brahmaputra River System, Government of Assam, 2025). The Barak Valley, located in southern Assam, is shaped by the Barak River and its tributaries, supporting dense forests and extensive tea cultivation (Barak River System, Government of Assam, India, 2025).

Due to this geomorphological setting and intense monsoonal rainfall, Assam experiences recurrent and severe flooding. Nearly 31,050 sq. km-about 40% of the state's total area- is affected by floods annually (Ministry of Jal Shakti 2021). According to the *District-level Climate Risk Assessment for India* (Dasgupta et al. 2024), the state remains one of the most flood-prone in the country, facing increasing hazard intensity and frequency, particularly since the 1950 s earthquake that altered the Brahmaputra's flow dynamics.

Economy and socio-economic vulnerability

Assam's economy is predominantly agrarian, with over 70% of its population engaged in agriculture and allied activities (Government of India 2020; Department of Agriculture & Horticulture, Government of Assam 2025). Rice is the principal crop, alongside mustard, maize, and tea, with floods frequently disrupting kharif crop cycles and livelihoods. The state also supports extensive fisheries and horticulture sectors, with approximately 2.58 lakh hectares of water bodies and diverse cultivation of fruits, vegetables, spices, and medicinal plants (Fishery, Government of Assam 2025; Horticulture, Government of Assam 2020).

However, Assam's socio-economic conditions significantly amplify its climate vulnerability. Low per capita income, high poverty rates, and heavy dependence on climate-sensitive sectors increase exposure to flood-related L&D (Barua et al. 2014; Bezgrebelna et al. 2024; Birkmann et al. 2022). Inadequate infrastructure, weak flood control systems, and outdated topographic data further constrain disaster preparedness and response (Gupta and Dixit 2022; Rahman and Rahman 2015). These factors create a self-reinforcing cycle of risk, where economic fragility, livelihood dependency, and environmental exposure compound one another.

Need for a district-level risk and L&D assessment

Given Assam's high exposure to floods, complex socio-economic vulnerabilities, and dependence on natural-resource-based livelihoods, a district-level assessment of risk and associated L&D can provide critical insights for climate-resilient planning. Such an approach allows for spatial differentiation of risk drivers- hazard, exposure, and vulnerability-helping identify districts where socio-economic fragility, rather than hazard intensity, drives flood impacts. Integrating L&D data within a risk assessment framework facilitates efforts such as prioritizing adaptation investments, strengthening early warning systems, and designing locally relevant interventions that address both economic and non-economic dimensions of L&D.

Method

Flood Risk Index (FRI)

The study uses the IPCC AR6 risk framework, which defines risk as "*the potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems, arising from the interaction of climate-related hazards, exposure and vulnerability of the affected system*" (IPCC 2022, Annexe II, Glossary). These components of risk are distinct yet interrelated, jointly shaping climate risk (OECD 2021; Jurgilevich et al. 2017). The IPCC AR6 risk framework provides a globally standardized and policy relevant approach for assessing climate risk and adaptation options (Simpson et al. 2021; IPCC 2022; Ayanlade et al. 2023; Dasgupta et al. 2024). The Flood Risk Index (FRI) is calculated based on the geometric mean of the Flood Hazard Index (FHI), Flood Exposure Index (FEI), and Flood Vulnerability Index (FVI). The steps followed for a flood risk assessment are shown in Fig. 2, part (A). The section below briefly describes the data used and the steps undertaken.

Flood Hazard Index (FHI) For flood hazard assessment, the study uses the meteorological, hydrological, topographical, environmental, and geological data (Mahmoud & Gan 2018; Mudashiru et al. 2022; Gupta and Dixit 2022; Fenglin et al. 2023; Dasgupta et al. 2024; Dutta and Deka 2024). The detailed list of indicators, their rationale and data sources is provided in Table 1.

Flood Exposure and Vulnerability Indices (FEI and FVI) Flood exposure indicators reflect the extent to which people and livelihoods are exposed to flood hazard. (Dasgupta et al. 2024; Shah and Malakar 2024; Vyas et al. 2024). Vulnerability assessments, capture socio-economic sensitivity and adaptive capacity. Initially, 25 indicators were selected based on data availability and insights from the literature (Mondal et al. 2020; Gupta and Dixit 2022; Alam et al. 2022; Dasgupta et al. 2024; Shah and Malakar 2024). However, to avoid redundancy and improve interpretability, only non-correlated indicators with high coefficients of variation were retained for the final analysis, ensuring that each provides a distinct and analytically meaningful contribution. (Dasgupta et al. 2024; Alam et al. 2022; Vyas et al. 2024). Table 1 provides the list of indicators, data sources, and impact on flood, and the rationale and construction of indicators are provided

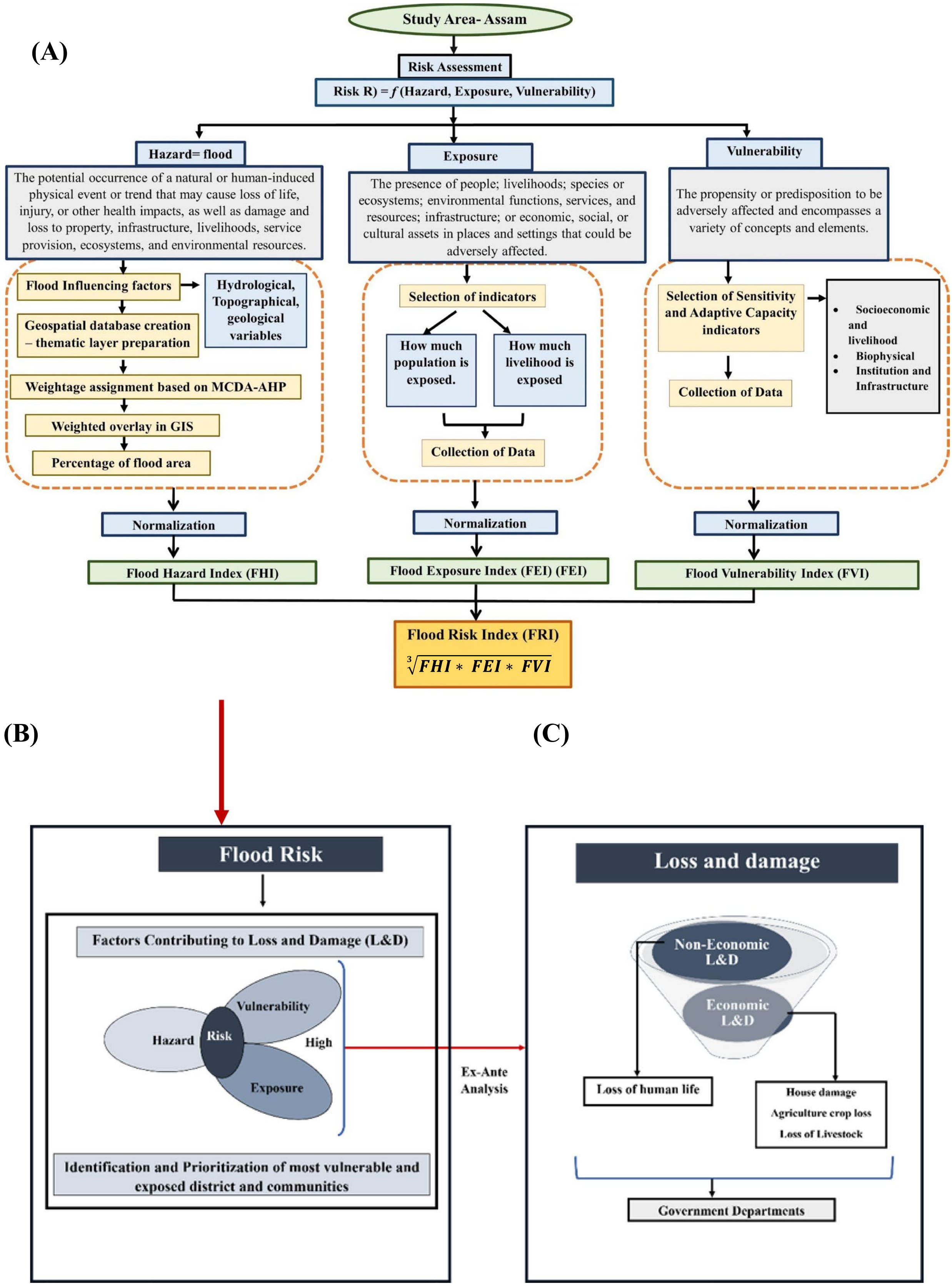

Fig. 2 Methodological framework *(Risk assessment part has been adapted from IPCC AR6, WGII, figure SPM.1)*

Table 1 Flood risk factors, indicators, and sources

Flood risk factor	Indicator	Indicators Impact	Data Source
Flood Hazard			
	Land use Landcover (LULC)	Depends on class	Impact Observatory for Esri 2021,
	Rainfall Intensity (RI)	Positive	Indian Meteorological Department (1952-2022) https://www.imdpune.gov.in/cmpg/Griddata/Rainfall_25_NetCDF.html (Pai et al. 2014)
	Slope (S)	Negative	ALOS PALSAR 12.5 m https://search.asf.alaska.edu/ (Khal et al. 2020)
	Topographic Wetness Index (TWI)	Positive	ALOS PALSAR 12.5 m https://search.asf.alaska.edu/ (Khal et al. 2020)
	Distance from river (DR)	Negative	ALOS PALSAR 12.5 m https://search.asf.alaska.edu/ (Khal et al. 2020)
	Geomorphology (GM)	Depends on landform type	Bhukosh Geological Survey of India (GSI) 2021
	Elevation (E)	Negative	ALOS PALSAR 12.5 m https://search.asf.alaska.edu/ (Khal et al. 2020)
	Drainage Density (DD)	Context dependent	ALOS PALSAR 12.5 m https://search.asf.alaska.edu/ (Khal et al. 2020)
	Rainfall erosivity factor (REF)	Positive	Indian Meteorological Department (1952-2022) https://www.imdpune.gov.in/cmpg/Griddata/Rainfall_25_NetCDF.html (Pai et al. 2014)
	Soil Texture (ST)	Depends on texture	Food and Agricultural Organization of the United Nations (FAO)- UNESCO; 1:5 000 000, https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/ (Gupta and Dixit, 2022)
Exposure	Proportion of land under agriculture	Positive	Land Use Statistics Information System, 2022-23 https://desagri.gov.in/wp-content/uploads/2024/09/Final-file-of-LUS-2022-23-for-uploading.pdf (DES, 2024)
	Population density	Positive	Economic Survey of Assam 2021–22
Vulnerability			
Sensitivity	Multidimensional Poverty Index	Positive	National Multidimensional Poverty, A progress review 2023; NITI Aayog, Government of India, 2023 (NITI Aayog 2023; Davis et al. 2019)
	Yield variability of food grains	Positive	(Crop Production Statistics Information System, 2006–2018) (Bernabucci 2019; DES, 2021)
Adaptive Capacity	Livestock to Human ratio	Negative	Twentieth (20th) Livestock census 2019; WorldPop (Ebinger & Vandycke 2015; Bondarenko et al. 2025)
	Road density (km/100 sq. km)	Negative	OpenStreet Map
	Health infrastructure per thousand population	Negative	Rural Health Statistics 21–22 (Adam 2015)
	Average person days per household employed under MGNREGA	Negative	Mahatma Gandhi National Rural Employment Guarantee Act 2005 (MGNREGA), 2014–15 to 2023–2024 (Sambath et al. 2022)
	Number of ASHA workers per 1000 population	Negative	Annual ASHA update, 2020-21 (NHSRC, 2022)
	Women participation in the workforce	Negative	Periodic Labour Force Survey (PLFS) 2022–2023 (DeFraites et al. 2020; MoSPI, 2024)
	Percentage of vulnerable population	Negative	(Bondarenko et al. 2020) https://hub.worldpop.org/geodata/summary?id=50199

in Tables S1 and S4 of the supplementary material. Detailed assessment of risk and its components, Hazard, Exposure and Vulnerability, is provided in the supplementary material S1.1.

Normalization Exposure and vulnerability indicators were expressed in different units and thus normalized to dimensionless values between 0 and 1(Alam et al. 2022) based on the functional relationship between exposure and vulnerability with the climate change risk. A detailed description of the normalization process is provided in Section S1.1.2 of the supplementary material.

Categorization of risk components Flood risk and its components are categorized into high, moderate, and low using the natural breaks (Dasgupta et al. 2024; Shah and Malakar 2024) in ArcGIS. This method identifies natural groupings in the data, maximizing differences between classes while minimizing variance within classes, providing clearer and more interpretable patterns (Chen et al. 2013).

Drivers of Risk

To prioritize targeted interventions more precisely, it is important to identify what is driving the risk. Districts with high index values for hazard, exposure or vulnerability are considered key risk drivers for any district of Assam. The next step involves identifying the specific indicators influencing exposure and vulnerability. In this study, a threshold normalized value (NV) of 0.70 has been set, and any indicator exceeding this value ($NV > 0.70$) is regarded as the driver of exposure and vulnerability for the respective district. This method allows for a systematic and data-driven identification of the most influential factors contributing to flood risk (Alam et al. 2022) (See Fig. 2 (B)).

Loss and damage

In this study, L&D was assessed using data from the Assam State Disaster Management Authority (ASDMA) for the period 2015–2023 (ASDMA, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023). Based on the indicators of exposure and vulnerability, we analyzed three economic L&D indicators and loss of human life as non-economic L&D indicator (see Fig. 2 (C)).

Economic indicators were assigned monetary value, based on government rates provided by the Government of Assam (ASDMA and UNICEF 2024) (as shown in Table 2), to calculate total L&D for each district. No monetary value was assigned to loss of human life, due to its intrinsic, irreversible nature and lack of data for adjustments like age (UNFCCC 2013; IPCC WGII chapter 17, 2022). L&D was then assessed, ranked, and categorized following the risk assessment framework. Based on this ranking and the identified risk drivers, we examined how the risk-influencing factors affect the extent and nature of L&D across Assam. The risk index values help to explain the magnitude of L&D, while the driving factors of risk and vulnerability provide insight to understand the nature of loss and damage.

Results

Flood risk assessment and L&D in assam

The findings section explores the complex relationship between flood risk and the nature and extent of L&D experienced across districts in Assam. Specifically, it examines how the components of flood risk- hazard, exposure and vulnerability, interact to influence economic and loss of human life, across high, moderate and low risk categories. Detailed results of Flood hazard, exposure and vulnerability are presented in section S1.2.1, S1.2.2 and S1.2.3 respectively.

Flood risk assessment and drivers of risk

Flood risk is determined by the interplay of hazard (H), exposure (E), and vulnerability (V) (refer to Fig. 3). A district-wise analysis of flood risk across Assam highlights significant variability in the Flood Risk Index (FRI), with values ranging widely from 0.018 to 0.719, reflecting the diverse levels of risk faced by different districts. Given this variability, the analysis emphasizes the component (H, E, V) that primarily drives flood risk in Assam, examining the underlying factors within each component that contribute to its prominence and its connection to L&D in the region. Linking the FRI with L&D elucidates the direct relationship between flood risk and the resulting impacts, highlighting the nature and extent of L&D in affected areas.

While analyzing the contributing factors, the focus is on exposure and vulnerability indicators, as these can be addressed in the short to medium term. On the other hand, indicators under the hazard component, such as the region's physical characteristics (e.g., slope, distance from rivers) and factors like land use and land cover- are either difficult to alter or require extensive time and resources to change (Li et al. 2020). Consequently, while addressing flood hazards through structural investments is vital, this study also emphasizes the critical importance of non-structural interventions aimed at reducing exposure and vulnerability. Such measures are essential for managing flood risks effectively in the near term and serve as a complementary approach to long-term structural strategies. Detailed assessment of flood hazard, exposure and vulnerability is given in section S1.1 of the supplementary material. The findings are discussed under three categories: high, moderate and low, based on natural breaks (ESRI 2025) in ArcGIS. The details are outlined in the sections below.

Table 2 Indicators with their construction and corresponding monetary values

Sr. No	Indicator	Construction	Monetary value by the Government of Assam (in INR and US Dollar)
Economic L&D- quantifiable monetary negative impacts			
1	House Damage	The sum of fully, severely, partially, and damaged kutcha and pacca houses, cattle sheds attached to houses and huts	**From 2015 to 2021-** • Fully/severely damaged (plain area)- 95,100 ($1030 USD) • Fully/severely damaged (hilly area)- 101,900 ($1100 USD) • Partially damaged Pucca house- 5200 ($56.21 USD) • Partially damaged kutcha house- 3200 ($ 38.55 USD) • Huts damaged/destroyed (pucca and kutcha)- 4100 ($49.40 USD) • Cattle shed attached to house- 2100 ($25.30 USD) **From 2022 onwards-** • Fully/severely damaged (plain area)- 120,000 ($1295 USD) • Fully/severely damaged (hilly area)- 130,000 ($1400 USD) • Partially damaged Pucca house- 6500 ($70 USD) • Partially damaged kutcha house- 4000 ($43 USD) • Huts damaged/destroyed (pucca and kutcha)- 8000 ($86 USD) • Cattle shed attached to house- 3000 ($32 USD)
2	Livestock loss	Sum of buffalo, cow, goat, sheep, horse, pig, bullock, calf, donkey, pony and poultry lost during the flood	**From 2015 to 2021-** **Draught** Camel/horse/bullock- 25,000 ($270 USD) Calf/donkey/pony- 16,000 ($173 USD) Poultary-50 ($0.54 USD) **Milching** Cow/buffalo/camel- 30,000 ($324 USD) Pig/sheep/goat- 3000 ($324 USD) **From 2022 onwards-** **Draught** Camel/horse/bullock- 32,000 ($346 USD) Calf/donkey/pony- 20,000 ($216 USD) Poultary-50 ($0.54 USD) **Milching** Cow/buffalo/camel- 30,000 ($324 USD) Pig/sheep/goat- 4000 ($43 USD)
3	Agriculture crop loss	Sum of agricultural land where crop loss is > 33% (In hectares)	**From 2015 to 2021-** Rainfed-6800 ($73.38 USD) Irrigated-13500 ($145 USD) Perennial-18000 ($194 USD) **From 2022 onwards-** Rainfed-8500 ($92 USD) Irrigated-17000 ($183 USD) Perennial-22500 ($243 USD)
Non-economic L&D: negative impacts that are hard to quantify and often go unnoticed by the outside world			
1	Loss of human life	Number of lives lost each year	

Flood Risk and L&D dynamics in Assam's high-risk districts

The high flood risk category (FRI: 0.388–0.719) encompasses eight districts in Assam, spanning the upper, central, and lower parts of the Brahmaputra Valley (Fig. 4(a)). This highlights the widespread flood risks across Assam, with these districts representing 24% of the identified flood risk hotspots. The risks in these districts result from the interaction of hazard, exposure and vulnerability, although the relative contribution of each component varies across districts, as shown in Fig. 4(b).

In the upper Brahmaputra Valley, districts like Majuli and Dibrugarh are predominantly influenced by hazard and exposure (refer to Fig. 4(a)). The region's riverine geography and

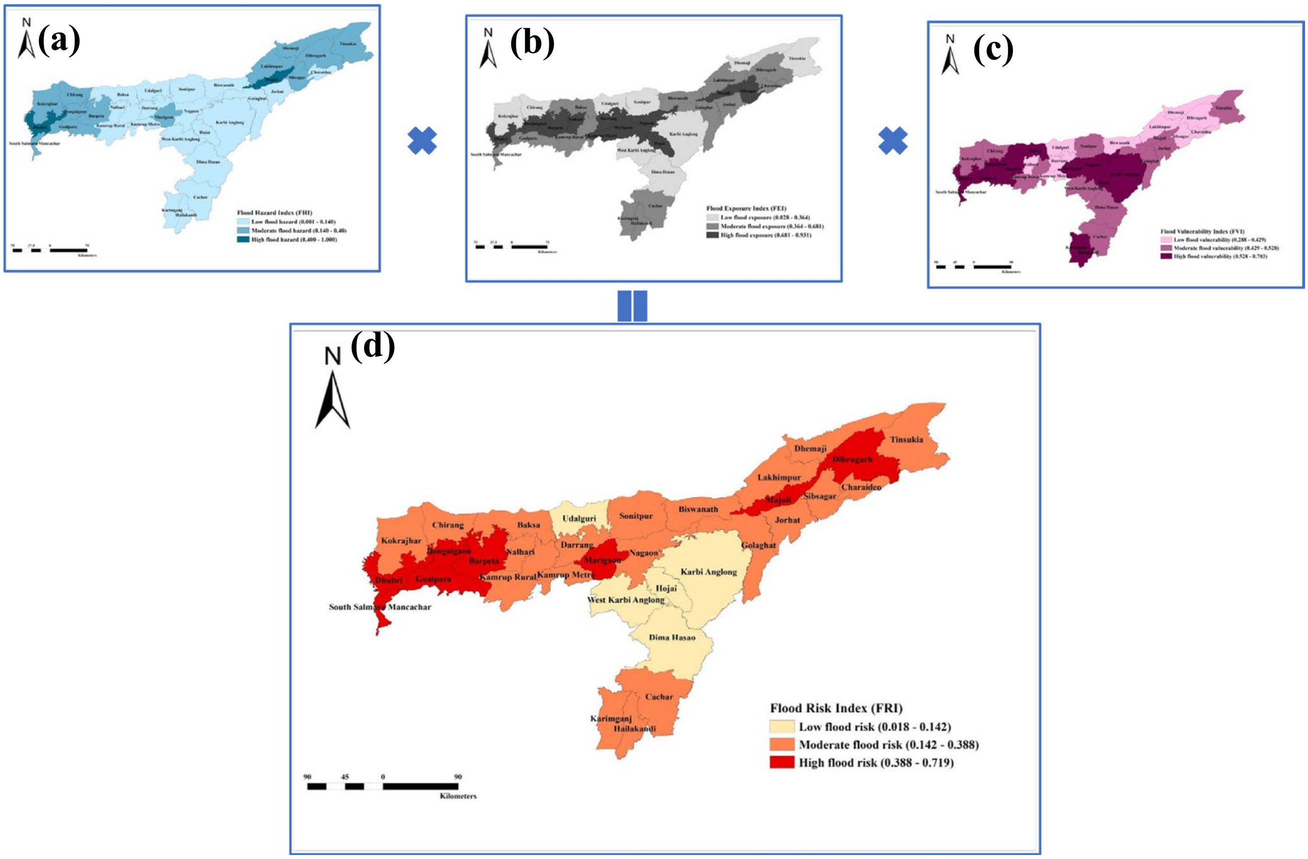

Fig. 3 **a** Flood hazard, (**b**) exposure, (**c**) vulnerability and (**d**) risk map

extensive agricultural landscapes make it especially prone to flooding. Economic L&D in these areas (Figs. 4(b)-(c)) are driven largely by agricultural crop damage, reflecting the region's heavy reliance on agriculture for livelihood. Livestock loss is also a significant contributor to the overall L&D. However, due to relatively lower socio-economic vulnerability in these districts (see Figure S3(a)-(b) in the supplementary material for rankings) loss of human life, remain comparatively lower (Figs. 4(d)).

The central Brahmaputra Valley (Morigaon) and the lower Brahmaputra Valley (five districts- Dhubri, South Salmara, Bongaigaon, Barpeta) face a more complex combination of hazard, exposure, and vulnerability. Along with significant flood hazards, these districts are critically impacted by high exposure and acute vulnerability (see Figure S4(b), highlighting high rankings for Morigaon (E = 9; V = 7), Dhubri (E = 1; V = 6), South Salmara (E = 14; V = 2), Bongaigaon (E = 5; V = 10), Barpeta (E = 3; V = 9)[1]). All six districts fall under the high to moderate flood risk category (See Figure S2 (a)-(b) of the supplementary material), driven by high population density and extensive agricultural land use, which reflects their predominantly rural nature (Ricker-Gilbert et al. 2014).

In terms of vulnerability, these districts rank from moderate to high due to several interrelated factors (see Figure S3 (a)-(b) of the supplementary material). Limited livelihood diversification and heavy dependence on climate-sensitive agriculture with high variability in food grain yields and inadequate road infrastructure impede timely relief and recovery efforts. Limited access to essential health services and low female workforce participation undermines economic resilience and recovery capacity. These factors collectively highlight a lack of resilience to flood risks, leading to both economic L&D and loss of human life.

Figure 4(c) underscores the substantial economic L&D experienced in these districts due to high exposure and vulnerability. Barpeta and Dhubri, located in the lower Brahmaputra Valley, recorded the highest economic losses among all districts of Assam, amounting to $31.39 million USD and $19.13 million USD, respectively. These losses are primarily driven by housing damage and agricultural crop losses.

The damage to houses in these districts is disproportionately high among kutcha houses (temporary structures),

[1] E= exposure; V= vulnerability.

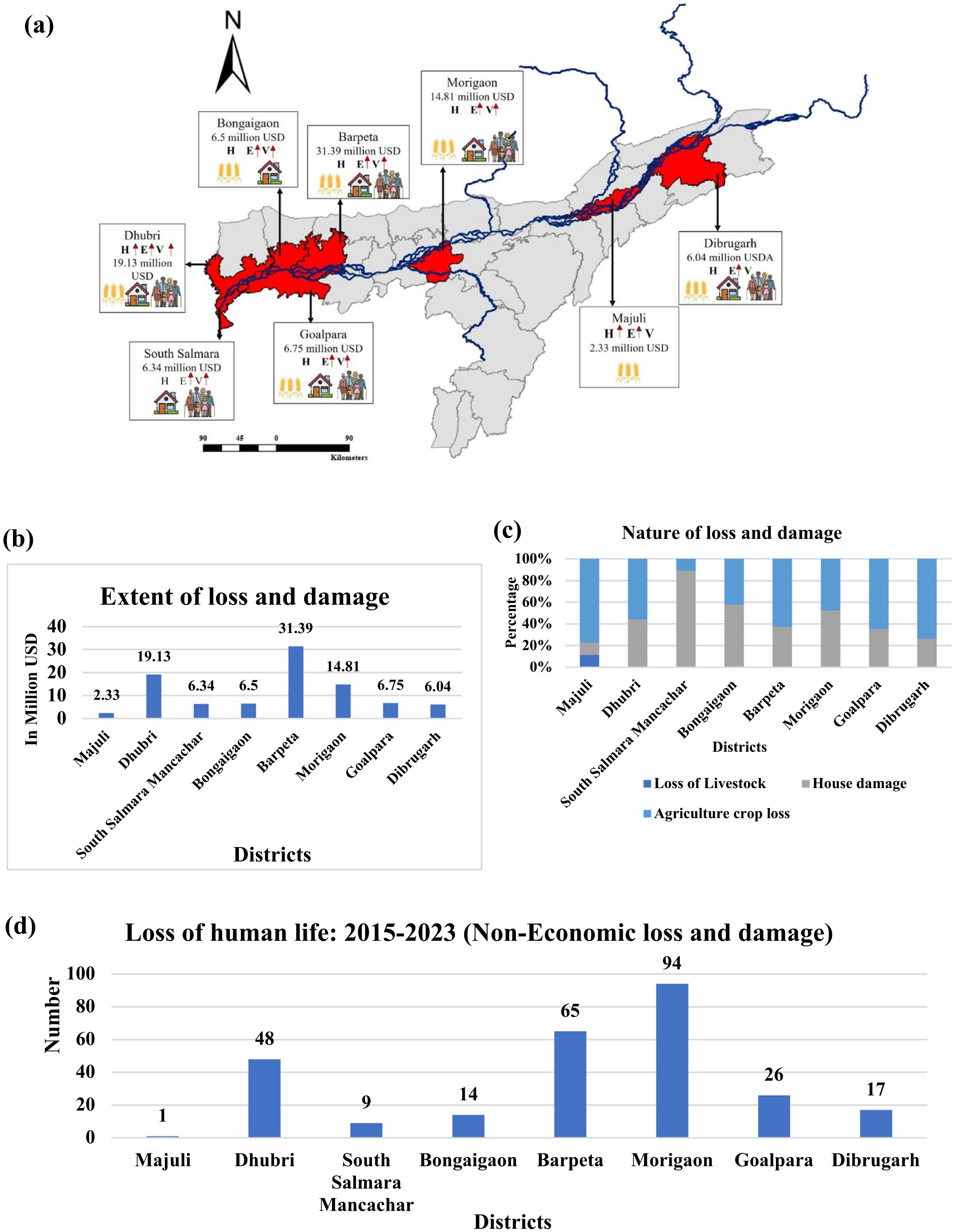

Fig. 4 **a** Components driving flood risk and underlying factors, (**b**) Extent of L&D, (**c**) Nature of L&D, (**d**) Loss of human life: 2015–2023 (non-economic L&D)

which are particularly vulnerable to flooding. The widespread prevalence of such structures reflects not only physical vulnerability but also deep-rooted socio-economic and systemic challenges that increase community susceptibility to disasters.

The high vulnerability of these districts is further evident in the significant loss of life. For instance, Morigaon, recorded the highest death toll, with 94 lives lost to flooding. This underscores the region's economic underdevelopment and limited adaptive capacity, both of which compound their susceptibility to flood impacts.

Flood Risk and L&D dynamics in Assam's moderate-risk districts

The moderate flood risk category (FRI: 0.142–0.388) encompasses 20 districts, accounting for 61% of Assam's total area. These districts are distributed across the Upper Brahmaputra Valley (35%), Lower Brahmaputra Valley (30%), Central Brahmaputra Valley (20%), and Barak Valley (15%) (see Fig. 5(a)). This highlights the widespread nature of flood risk in Assam, where a significant proportion of districts are flood-prone. Unlike high-risk districts, these areas experience relatively low hazard levels, with exposure and vulnerability serving as the primary contributors to flood risk (see Fig. 5(a)). In nearly 80% of these districts, flood risk is predominantly driven by exposure and vulnerability, while only 20% experience risks shaped by all three components- hazard, exposure, and vulnerability (Fig. 5(a)).

These districts face significant exposure due to high population density and extensive agricultural land use, both of which increase susceptibility to flood-related damages (Goyari 2005) (see Figure S6(a) in the supplementary material). Their flood risk is further intensified by elevated vulnerability, shaped by a combination of contributing factors (see Figure S3(c)–(d) in the supplementary material), which together drive their high vulnerability rankings.

Beyond these structural constraints- limited alternative livelihoods, poor connectivity, and inadequate healthcare- these districts also experience high levels of multidimensional poverty. A high Multidimensional Poverty Index (MDPI) further amplifies overall risk (see Figure S6(b) in the supplementary material). Multidimensional poverty, reflected in deprivations in education, health, and living standards (Balestri 2025), heightens vulnerability, reduces resilience, and limits the capacity of affected populations to recover from flood events.

Although classified as moderate flood-risk areas, these districts incur disproportionately high economic L&D and loss of human life, driven primarily by exposure and vulnerability. Much of the economic L&D stems from agricultural crop damage, underscoring the region's dependence on farming. The prevalence of kutcha houses (temporary structures) and limited flood-resistant infrastructure also leads to extensive housing damage. Notable districts with substantial L&D include Nagaon in the Central Brahmaputra Valley ($9.15 million USD); Hailakandi ($7.49 million USD) and Cachar ($7.35 million USD) in the Barak Valley; and Dhemaji ($8.86 million USD) and Golaghat ($7.63 million USD) in the Upper Brahmaputra Valley. Interestingly, districts such as Golaghat-despite being farther from the Brahmaputra River-experience greater L&D than high-risk districts like Majuli, primarily due to higher vulnerability. (see Fig. 5(b)).

The elevated vulnerability in these regions, closely associated with high MDPI, is reflected in severe housing damage, significant agricultural losses, and higher loss of human lives (see Fig. 5(c)). High population density and inadequate infrastructure further exacerbate the consequences of flooding. Regions such as the Barak Valley (15%) and parts of the Upper and Lower Brahmaputra Valley, though experiencing fewer flood events than high-risk districts, remain highly susceptible to substantial L&D because of high sensitivity and limited adaptive capacity.

Thus, the concentration of populations in flood-prone areas, combined with inadequate infrastructure and low resilience, magnifies the impacts of moderate flood risks. Even with lower hazard levels, exposure and vulnerability remain the dominant drivers of risk, resulting in considerable economic L&D and loss of human life (see Fig. 5(c)–(d)).

Flood Risk and L&D dynamics in Assam's low-risk districts

The low flood risk category (FRI: 0.018–0.142) comprises five districts in Assam, largely located in the central Brahmaputra Valley. These districts account for roughly 15% of the state's flood risk hotspots (Fig. 6(a)). Although situated away from the active Brahmaputra floodplains and therefore exposed to relatively low flood hazard, their elevated vulnerability and moderate exposure make them particularly susceptible to flood-induced L&D, despite their low-risk classification.

The exposure levels in these districts remain moderate, owing to lower population densities compared with high- and moderate-risk districts (see Figure S7(a) in the supplementary material). The predominance of subsistence agriculture (NABARD 2023) also limits the scale of agricultural L&D, as smaller landholdings naturally reduce potential crop losses. While floods do result in crop damage, their magnitude remains modest because of the limited size of agricultural plots.

These districts are socio-economically disadvantaged, with substantial indigenous populations and historically

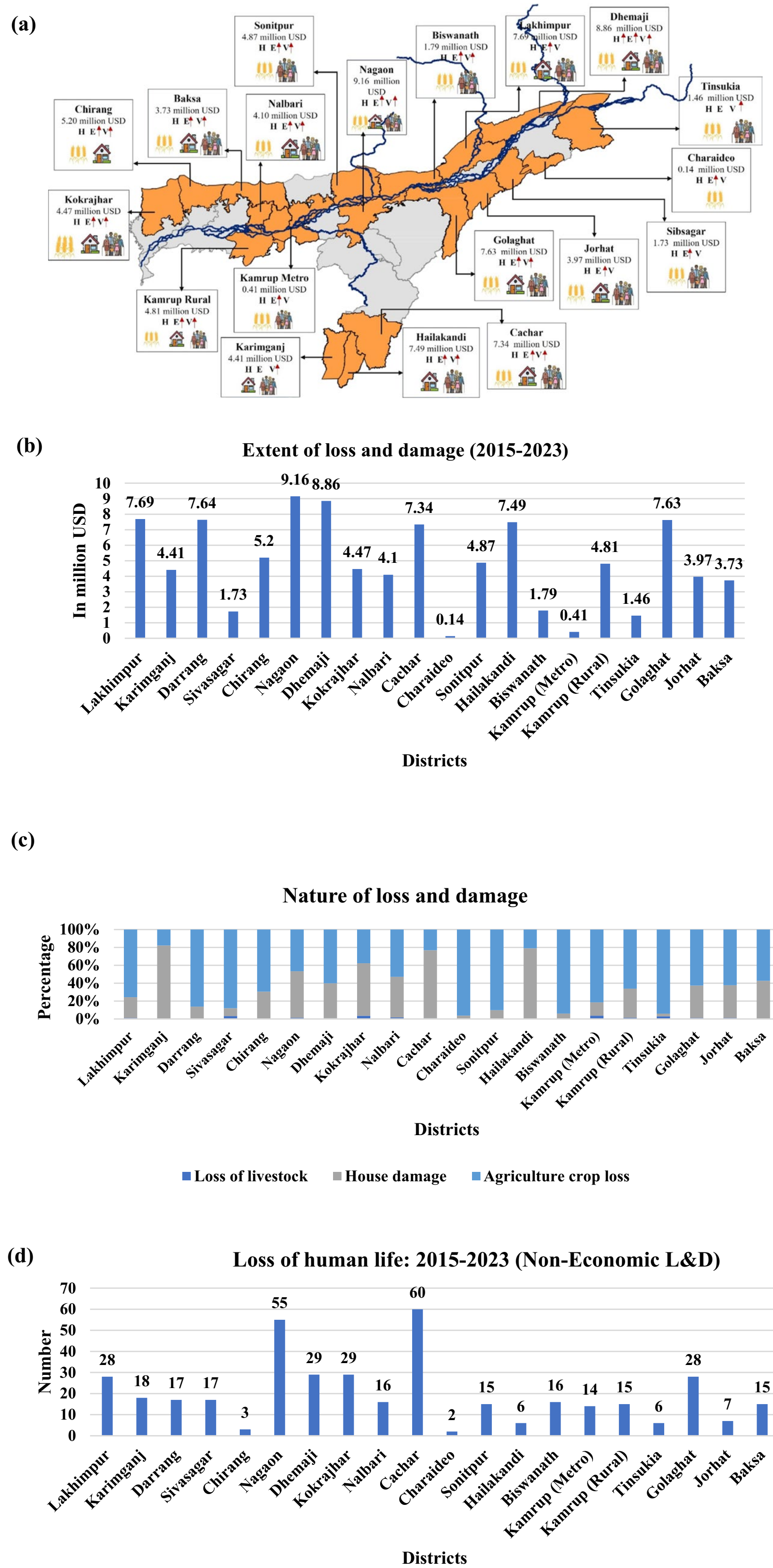

Fig. 5 **a** Components driving flood risk and underlying factors, (**b**) Extent of L&D, (**c**) Nature of L&D (**d**) Loss of human life: 2015–2023 (non-economic L&D)

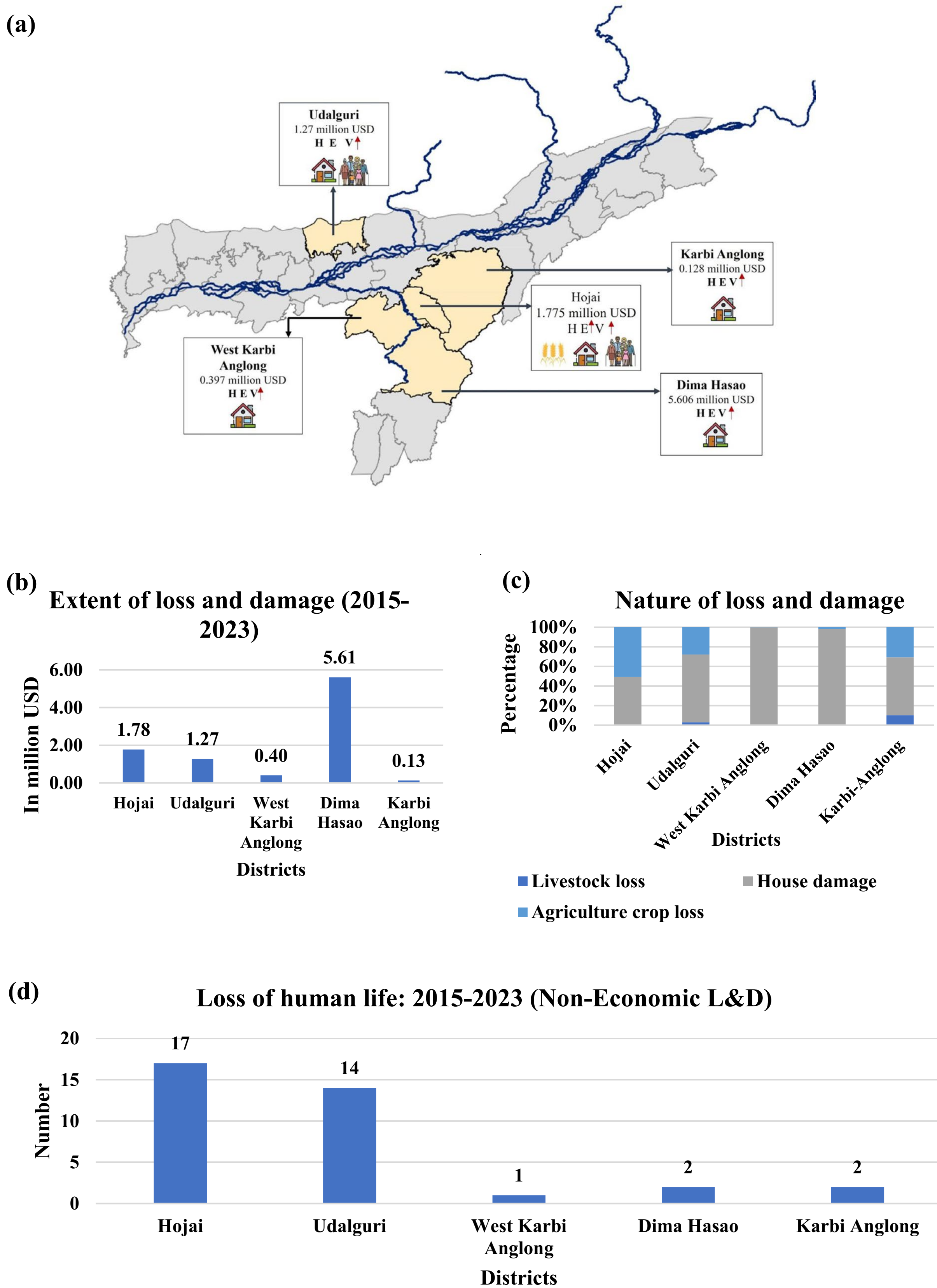

Fig. 6 (**a**) Components driving flood risk and underlying factors, (**b**) Extent of L&D, (**c**) Nature of L&D, (**d**) Loss of human life: 2015–2022 (non-economic L&D)

marginalized communities (Bosumatary 2019). Reliance on subsistence farming is reinforced by the absence of large agricultural landholdings, and most households depend on small or marginal plots for survival. This socio-economic marginalization is reflected in their high vulnerability rankings- for example, Hojai (12), Udalguri (28), West Karbi Anglong (15), Dima Hasao (16), and Karbi Anglong (11).

Multiple drivers of vulnerability converge in these districts, heightening their susceptibility even to moderate flood events. Poor connectivity, inadequate health infrastructure, limited alternative livelihood options, and broader socio-economic deprivations, including those captured by multidimensional poverty indicators (see Figure S7(b) in the supplementary material)- collectively contribute to their elevated vulnerability. These structural deficits align with their persistently low Human Development Index (HDI) rankings (Phukan 2012; Government of Assam, 2014; Government of Assam 2015).

Despite being classified as low flood-risk areas, these districts experience substantial economic L&D, with particularly notable levels of loss of human life, a pattern directly linked to their vulnerability profiles. Weak transportation networks and limited access to timely healthcare impede evacuation and emergency response, while the absence of resilient housing increases the likelihood of casualties during even low-intensity flood events.

The monetary estimates of L&D show that although L&D are lower than in high-risk districts, they remain significant, particularly in housing damage and livelihood impacts. Dima Hasao, for instance, reported USD 5.6 million in L&D, largely driven by high casualty rates and extensive housing destruction (see Fig. 6(b), (c)). Strikingly, this exceeds the L&D reported in Majuli, a high-risk district recording USD 2.3 million in L&D, underscoring how poor infrastructure and socio-economic vulnerability magnify impacts even when hazard levels are low. Udalguri similarly reported considerable housing losses, reflecting infrastructural deficits.

Moreover, loss of human life remains disproportionately high in districts such as Hojai and Udalguri (Fig. 6(d)). This pattern clearly demonstrates that in low-hazard contexts, high vulnerability, not hazard intensity is the dominant driver of severe outcomes, resulting in both significant economic loss and elevated mortality.

Discussion

The findings from the risk assessment reveal that the drivers of flood risk in Assam- hazard, exposure, and vulnerability- exhibit considerable disparities across districts. Only a few districts show a convergence of all three factors, while in most cases, one or two dominate the risk profile. This indicates that while all districts face some degree of flood risk, the underlying causes and resulting L&D vary significantly. In some districts, flood risk is primarily driven by high hazard and exposure, whereas in others, socio-economic vulnerability alone plays a defining role even in the absence of severe flood hazards. This differentiation highlights the need for targeted, driver-specific interventions rather than a uniform approach to flood risk management.

For instance, while Gupta and Dixit (2022) classified Cachar as a *moderate flood-risk district* based on the AR3 risk framework, our study- employing the more comprehensive AR6 framework—shows that the district's high exposure and social vulnerability render it highly susceptible to significant L&D, even during moderate flood events. Unlike the AR3 approach, which implicitly links exposure to vulnerability, the AR6 framework examines hazard, exposure, and vulnerability independently, allowing a more nuanced understanding of district-level flood risk. In the case of Cachar, limited adaptive capacity, dependence on flood-prone agriculture, and inadequate preparedness collectively elevate its vulnerability. Consequently, Cachar exemplifies districts that require non-structural interventions, such as community-based flood preparedness and livelihood diversification, rather than only large-scale structural measures. This reinforces the importance of comprehensive frameworks that can inform policy and intervention design beyond hazard-based assessments.

Fig. 7 a–c illustrates the spatial diversity of flood risk and L&D across districts

- Fig. 7(a) identifies districts categorized as *high flood risk* based on our assessment.
- Fig. 7(b) highlights the *top ten districts with high economic L&D*, including damages to agriculture, infrastructure, and livelihoods.
- Fig. 7(c) presents *districts with high loss of human life, a non-economic L&D indicator.*

Together, these figures illustrate that while eight districts in the upper, central, and lower Brahmaputra valley are classified as high-risk, the distribution of L&D extends well beyond these districts. Some high-risk districts, such as Majuli, have benefited from long-standing structural interventions like embankment systems that have reduced the intensity of flood related negative impacts (Dasgupta et al. 2024; Dutta et al. 2025). However, a concerning trend is the emergence of substantial economic L&D and loss of human life in moderate and low flood-risk districts, which have historically received less policy attention. These findings emphasize the need to shift from a hazard-centric paradigm to a multi-dimensional, vulnerability-informed approach in Assam's flood risk governance.

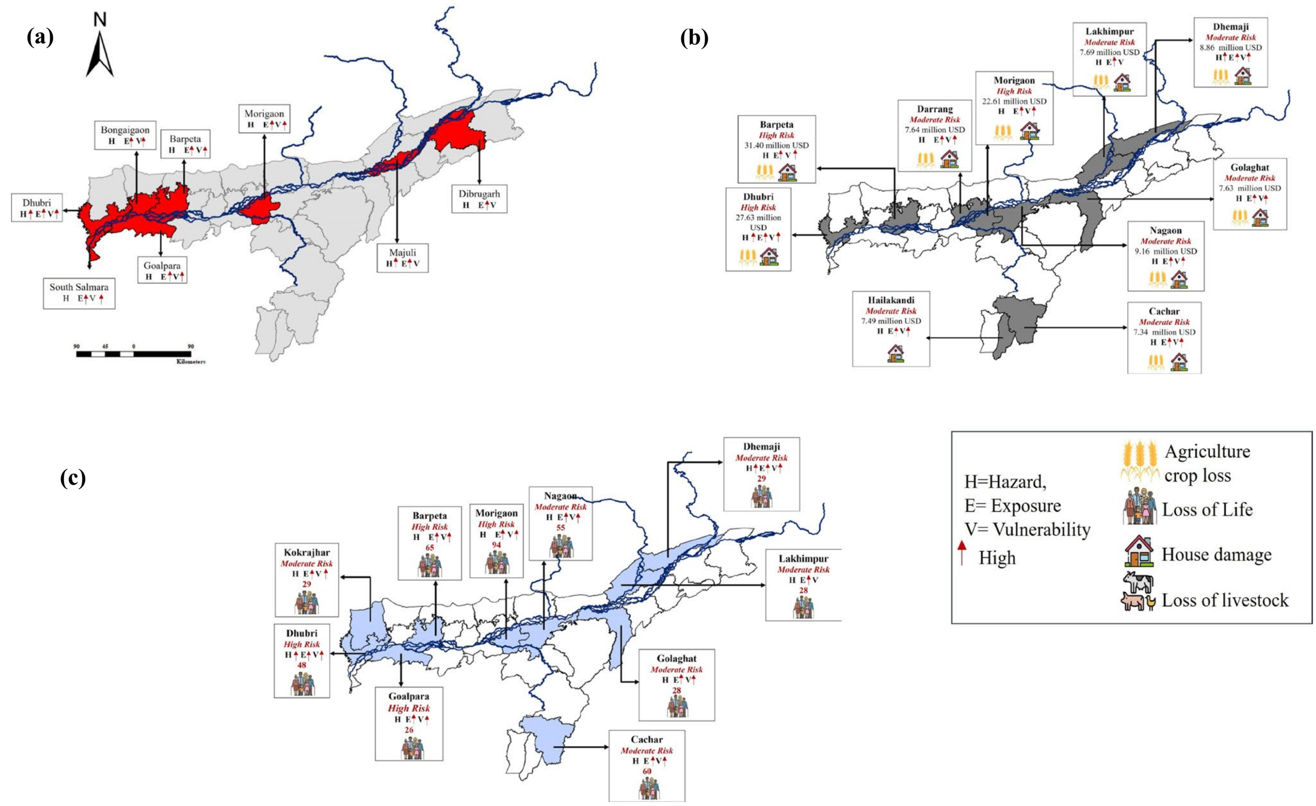

Fig. 7 (**a**) High flood risk districts; (**b**) Top 10 high economic L&D districts; (**c**) Top 10 districts with high loss of human life

Districts with high flood risk, economic L&D, and loss of human life

Among the eight high-risk districts, Dhubri, Barpeta, and Morigaon emerge as key areas where high hazard, exposure, and vulnerability converge. Their geographical location along the Brahmaputra and its tributaries exposes them to recurrent flooding, compounded by dense populations, critical infrastructure, and livelihood dependence on agriculture and fisheries. Socio-economic vulnerabilities-such as poverty, landlessness, and limited access to flood shelters-further intensify their risks (Dasgupta et al. 2024; Dawkins et al. 2023; Nur and Shrestha 2017).

Compared to other high-risk districts, Dhubri and Barpeta exhibit higher population exposure, while Morigaon demonstrates greater livelihood dependency on flood-prone ecosystems. These differences suggest the need for district-specific adaptation pathways. For instance, while infrastructure reinforcement (e.g., embankment upgrading) is critical for Dhubri and Barpeta, strengthening livelihood diversification and micro insurance mechanisms may be more relevant for Morigaon. Such targeted policy differentiation ensures that interventions are context-appropriate and equity-driven (see Fig. 7 (a)).

Districts with economic L&D and loss of human life but not classified as high flood risk

Districts such as Cachar, Dhemaji, Golaghat, and Lakhimpur experience substantial economic L&D and loss of human life, despite being categorized as moderate-risk districts. The L&D in these areas are primarily driven by high exposure and socio-economic vulnerability rather than extreme flood hazards. These finding challenges conventional hazard-based classifications and suggests that exposure and adaptive capacity must be central to flood risk evaluation.

The persistence of loss of human life (Fig. 7 (b))- highlights the limitations of existing flood risk management systems that prioritize only measurable, economic L&D. These districts often fall outside formal flood mitigation programs due to their "moderate" hazard status. Policymakers should, therefore, integrate social vulnerability indicators (e.g., poverty incidence, livelihood fragility, gender dimensions) into risk mapping to ensure that unattended risks are addressed through non-structural interventions like community training, local disaster committees, and early warning dissemination networks.

Districts with high loss of human life but not classified as high flood risk or high economic L&D

A third category includes districts such as Kokrajhar (29), which face limited flood frequency or economic L&D yet suffer significant non-economic impacts. These impacts- loss of human lives, displacement, and disruption of cultural and social networks- are particularly pronounced among marginalized and resource-poor communities. Because these districts are not traditionally recognized as flood-prone, early warning systems and institutional support remain minimal, further deepening vulnerability during flood events (see Fig. 7 (c)).

For example, in Kokrajhar, despite relatively low hazard exposure, limited flood preparedness and weak institutional response systems lead to disproportionate social suffering. Similarly, Udalguri's forest-dependent communities experience loss of cultural assets and ecosystem services, which remain underrepresented in conventional flood impact statistics. Recognizing these non-economic dimensions of L&D is essential to ensuring that equity and inclusivity are embedded within flood management strategies.

Policymakers must therefore integrate non-economic L&D indicators- such as loss of human life, displacement, mental health impacts, and social disruption- into flood risk frameworks. Interventions like community-based risk monitoring, context-sensitive compensation mechanisms, and inclusion of marginalized groups in disaster governance are necessary to strengthen resilience in these overlooked districts.

Policy implications

The differentiated nature of flood risk across Assam underscores that *one-size-fits-all strategies* are inadequate. High-risk districts require structural and infrastructural measures, while moderate and low-hazard but high-vulnerability districts demand social protection mechanisms, awareness, and adaptive capacity-building. Incorporating the AR6 multidimensional framework into policy design enables more equitable prioritization and resource allocation.

Ultimately, flood risk governance in Assam must evolve toward integrated, vulnerability-sensitive planning that acknowledges both economic L&D and loss of human life as a key non-economic dimension of L&D. This approach would strengthen resilience not only to recurring floods but also to emerging climate-induced risks in the Brahmaputra basin.

Conclusion and way forward

This study demonstrates the complex and multi-dimensional nature of flood risk in Assam, emphasizing that L&D outcomes are shaped not only by flood hazards but also by the spatial interplay of exposure and vulnerability. The findings reveal that while high-risk districts experience more frequent flood events; moderate- and low-risk districts such as Dhemaji and Udalguri also endure substantial economic L&D and loss of human life, largely due to low adaptive capacity, poor infrastructure, and high socio-economic vulnerability (for instance, high poverty levels, low road density, limited livestock to human ratio, and high population density). These results challenge hazard-centric approaches and highlights the need to integrate exposure and vulnerability dimensions more explicitly within climate risk assessments (Zscheischler et al., 2020; Lawrence et al. 2020; Raymond et al. 2020; Simpson et al. 2021).

By distinguishing which risk-drivers- hazard, exposure or vulnerability, predominantly influence L&D in each district, the study offers evidence-based, actionable insights for policymakers. Districts where all three drivers' coverage should be prioritized for comprehensive interventions, combining structural measures (improved embankments, drainage systems and housing design) with non-structural strategies such as livelihood diversification, social protection schemes, and community-based early warning systems). In districts where vulnerability rather than hazard dominates, targeted social investments and capacity-building programs can substantially reduce overall risk without large infrastructure spending.

The study also highlights the broader importance of non-economic L&D such as psychological, social, and cultural impacts as critical components of disaster management (Miller et al. 2023; Quinn et al. 2023). Although our analysis was limited to loss of human life as the only measurable non-economic indicator due to data constraints, we acknowledge that these wider dimensions are essential for ensuring equitable and inclusive recovery and adaptation policies, particularly for marginalized communities whose L&D often remain invisible in monetary terms.

Integrating L&D metrics within climate risk assessments provides a pathway to move from reactive to proactive disaster governance. It allows decision-makers to anticipate which districts are likely to experience disproportionate future L&D and to tailor ex-ante interventions accordingly. In doing so, this study contributes to emerging frameworks that link climate risk assessment and L&D analytics, enabling both the reduction of future risks and the strengthening of long-term community resilience (Simpson et al. 2021; Awasthi and Bhatt 2024).

The study acknowledges a few limitations. First, the risk assessment relies primarily on quantitative indicators, which are useful for comparability, but cannot fully capture complex, non-measurable dimensions such as cultural values, social capital, governance quality, and broader equity concerns. Second, data constraints at the district level meant that certain indicators, including health and vector-borne disease data, could not be incorporated, and some variables were based on 2021–22 data. As exposure and vulnerability are dynamic, future updates with richer datasets will enhance precision. Third, vulnerability is inherently multi-dimensional and shaped by interacting socio-economic, demographic, infrastructural, and environmental factors. Some important aspects- such as governance capacity, cultural practices, and informal coping mechanisms- remain outside the scope of the present analysis due to the scale of assessment and data limitations. More granular, context-specific datasets would strengthen understanding of how these factors influence residual flood impacts. Finally, while loss of human life was included as the measurable non-economic L&D indicator, other non-economic dimensions- such as cultural, psychological, and health-related L&D-could not be quantified due to unavailable data.

Despite these constraints, the study provides one of the first district-level analyses linking climate risk assessment with L&D in Assam, offering a robust empirical foundation for future, data-rich extensions across India and South Asia. Beyond the regional context, these insights are also relevant to international climate policy, particularly in relation to the UNFCCC's Global Stocktake (GST)1.[2] By identifying how the drivers of L&D vary across spatial and socio-economic contexts, this study offers a support that can inform subnational reporting and aggregation of L&D data, a critical gap highlighted in the GST process (Puig 2022). The findings show how localized empirical assessments can complement global efforts to track progress under the Paris Agreement by improving understanding of where and why L&D occur. This in turn, strengthens the evidence base for adaptation and response measures within the GST's five-year review cycles.

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Author contribution S.V.—Writing—original draft, review & editing, visualization, validation, software, resources, methodology, formal analysis, data curation, conceptualization. A.B.—Writing—original draft, review & editing, supervision, validation, visualization, conceptualization. C.M.—Review & editing, validation, supervision, methodology, conceptualization. All authors reviewed the manuscript.

[2] The UNFCCC's Global Stocktake (GST) is a five-year global assessment of climate progress under the Paris Agreement—helping countries understand what is working, what is not, and how to enhance future action on mitigation, adaptation, and loss and damage.

Data availability Data will be made available on request.

Declarations

Competing interests The authors declare no competing interests.

References

20th Livestock Census (2019) https://dahd.gov.in/schemes/programmes/animal-husbandry-statistics,2019

Adam HN (2015) Mainstreaming adaptation in India – the Mahatma Gandhi National Rural Employment Guarantee Act and climate change. Climate and Development. https://doi.org/10.1080/17565529.2014.934772

Alam MK, Dasgupta S, Barua A, Ravindranath NH (2022) Assessing climate-relevant vulnerability of the Indian Himalayan Region (IHR): a district-level analysis. Nat Hazards 112:1395–1421. https://doi.org/10.1007/s11069-022-05233-x

ASDMA and UNICEF (2024) Financial assistance during disasters. Assam State Disaster Management Authority. https://asdma.assam.gov.in/documents-detail/financial-assistance-during-disaster-a-complete-handbook

Assam State Disaster Management Authority (ASDMA) (2017) Assam Flood Memorandum, Government of Assam, https://asdma.assam.gov.in/sites/default/files/swf_utility_folder/departments/asdma_revenue_uneecopscloud_com_oid_70/menu/document/assam_flood_memorand

Assam State Disaster Management Authority (ASDMA) (2016) Assam Flood Memorandum, Government of Assam. https://asdma.assam.gov.in/sites/default/files/swf_utility_folder/departments/asdma_revenue_uneecopscloud_com_oid_70/menu/document/assam_flood_memorand

Assam at a Glance (2025) Government of Assam, India. https://des.assam.gov.in/sites/default/files/swf_utility_folder/departments/ecostat_medhassu_in_oid_3/this_comm/assam_at_a_glance_-_2025.pdf

Assam State Disaster Management Authority (ASDMA) (2021) Assam Flood Memorandum, Government of Assam. https://asdma.assam.gov.in/sites/default/files/swf_utility_folder/departments/asdma_revenue_uneecopscloud_com_oid_70/menu/document/assam_flood_memorand

Assam State Disaster Management Authority (ASDMA) (2022) Assam Flood Memorandum, Government of Assam. https://asdma.assam.gov.in/sites/default/files/swf_utility_folder/departments/asdma_revenue_uneecopscloud_com_oid_70/menu/document/assam_flood_memorand

Assam State Disaster Management Authority (ASDMA) (2018) Assam Flood Memorandum, Government of Assam. https://asdma.assam.gov.in/sites/default/files/swf_utility_folder/departments/asdma_revenue_uneecopscloud_com_oid_70/menu/document/assam_flood_memorand

Assam State Disaster Management Authority (ASDMA) (2019) Assam Flood Memorandum, Government of Assam. https://asdma.assam.gov.in/sites/default/files/swf_utility_folder/departments/asdma_revenue_uneecopscloud_com_oid_70/menu/document/assam_flood_memorand

Assam State Disaster Management Authority (ASDMA) (2020) Assam Flood Memorandum, Government of Assam. https://asdma.assam.gov.in/sites/default/files/swf_utility_folder/departments/asdma_revenue_uneecopscloud_com_oid_70/menu/document/assam_flood_memorand

Assam State Disaster Management Authority (ASDMA) (2023) Assam State Memorandum, Government of Assam. https://asdma.assam.gov.in/sites/default/files/swf_utility_folder/departments/asdma_revenue_uneecopscloud_com_oid_70/menu/document/assam_flood_memorand

Assam State Disaster Management Authority (ASDMA) (2015) Assam Flood Memorandum, Government of Assam. https://asdma.assam.gov.in/sites/default/files/swf_utility_folder/departments/asdma_revenue_uneecopscloud_com_oid_70/menu/document/assam_flood_memorand

Awasthi K, Bhatt S (2024) Risk management for averting, addressing and minimizing climate related loss and damage. In: Gupta AK, Gupta A, Acharya P (eds) Disaster risk and management under climate change. Disaster Resilience and Green Growth. Springer, Singapore. https://doi.org/10.1007/978-981-99-4105-6_25

Ayanlade A, Smucker TA, Nyasimi M, Sterly H, Weldemariam LF, et al. (2023) Complex climate change risk and emerging directions for vulnerability research in Africa. Clim Risk Manag 20:100497. https://doi.org/10.1016/j.crm.2023.100497

Bahinipati CS, Gupta AK (2022) Methodological challenges in assessing loss and damage from climate-related extreme events and slow onset disasters: evidence from India. Int J Disaster Risk Reduct 83:103418. https://doi.org/10.1016/j.ijdrr.2022.103418

Balestri S (2025) A double constraint to development: how multidimensional poverty interacts with vulnerability to climate change. J Econ Interact Coord. https://doi.org/10.1007/s11403-025-00468-w

Bania J (2022) A historical understanding of Assam's floods | Economic and Political Weekly. https://www.epw.in/engage/article/historical-understanding-assams-floods

Barak River System (2025) Water resources. Government of Assam, India. https://waterresources.assam.gov.in/portlet-innerpage/barak-river-system

Barua A, Dasgupta S, Ravindranath NH (2018–19) Climate vulnerability assessment for the Indian Himalayan Region using a common framework. https://dst.gov.in/sites/default/files/IHCAP_Climate%20Vulnerability%20Assessment_30Nov2018_Final_aw.pdf

Barua A, Katyaini S, Mili B, Gooch P (2014) Climate change and poverty: building resilience of rural mountain communities in South Sikkim, Eastern Himalaya, India. Reg Environ Change 14:267–280. https://doi.org/10.1007/s10113-013-0471-1

Bernabucci U (2019) Climate change: impact on livestock and how can we adapt. Anim Front 9:3–5. https://doi.org/10.1093/af/vfy039

Bezgrebelna M, Aliyev E, Amoah YSA, Atkinson D, Chiblow SB et al (2024) Climate change, poverty, and health: a scoping review of the Canadian context. The Journal of Climate Change and Health 20:100348. https://doi.org/10.1016/j.joclim.2024.100348

Bhukosh Geological Survey of India (GSI) (2021). https://bhukosh.gsi.gov.in/Bhukosh/MapViewer.aspx.

Birkmann J, Welle T (2015) Assessing the risk of loss and damage: exposure, vulnerability and risk to climate-related hazards for different country classifications. Int J Glob Warm 8:191. https://doi.org/10.1504/IJGW.2015.071963

Birkmann J, Liwenga E, Pandey R, Boyd E, Djalante R, Gemenne F, Leal Filho W, Pinho PF, Stringer L, Wrathall D (2022) Poverty, livelihoods, and sustainable development. In: Pörtner H-O, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, Rama B (eds) Climate change 2022: impacts, adaptation, and vulnerability. contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK, and New York, NY, pp 1171–1274. https://doi.org/10.1017/9781009325844.010

Bondarenko M, Kerr D, Sorichetta A, and Tatem A.J. (2020). Estimates of the 2020 total number of people per grid square broken down by gender and age groupings using Built-Settlement Growth Model (BSGM) outputs. WorldPop, University of Southampton, UK. https://doi.org/10.5258/SOTON/WP00695

Bondarenko M, Priyatikanto R, Tejedor-Garavito N, Zhang W, McKeen T, Cunningham A, Woods T, Hilton J, Cihan D, Nosatiuk B, Brinkhoff T, Tatem A, Sorichetta A (2025) Constrained estimates of 2015-2030 total number of people per grid square at a resolution of 3 arc (approximately 100 m at the equator) R2025A version v1. In: Global demographic data project—funded by The Bill and Melinda Gates Foundation (INV-045237). WorldPop—School of Geography and Environmental Science, University of Southampton. https://doi.org/10.5258/SOTON/WP00839

Bosumatary S (2019) Social inequality and health: a study of tribes in Assam. DNGCRJ 4:7–14. https://doi.org/10.56405/dngcrj.2019.04.01.02

Botzen WJW, Bouwer LM, Scussolini P, Kuil O, Haasnoot M, Lawrence J, Aerts JCJH (2018) Integrated Disaster Risk Management and Adaptation. In: Mechler R, Bouwer LM, Schinko T, Surminski S, Linnerooth-Bayer J (eds) Loss and Damage from Climate Change. Climate Risk Management, Policy and Governance. Springer, Cham, pp 287–315. https://doi.org/10.1007/978-3-319-72026-5_12

Boyd E, Chaffin BC, Dorkenoo K, Jackson G, Harrington L et al (2021) Loss and damage from climate change: a new climate justice agenda. One Earth 4(10):1365–1370. https://doi.org/10.1016/j.oneear.2021.09.015

Brahmaputra River System (2025). Water Resources, Government of Assam, India https://waterresources.assam.gov.in/portlet-innerpage/brahmaputra-river-system.

Chen J, Yang S, Li H, Zhang B, Lv J (2013) Research on geographical environment unit division based on the method of natural breaks (Jenks). The international archives of the photogrammetry, remote sensing and spatial information sciences. XL-4/W3. https://doi.org/10.5194/isprsarchives-XL-4-W3-47-2013

Chen Y (2022) Flood hazard zone mapping incorporating geographic information system (GIS) and multi-criteria analysis (MCA) techniques. J Hydrol 612:128268. https://doi.org/10.1016/j.jhydrol.2022.128268

Choudhary A (2022) Unattended catastrophe? https://www.milenniumpost.in/sundaypost/in-retrospect/unattended-catastrophe-484337

Dasgupta S, Barua A, Murthy IK, Borgohain PL, Baghel T, Sankhyayan P, Vidya S, Narwal H, Jan A, Vyas S, Luniwal Y, Ghosh S, Cheranda TM, Alam MK, Matthew S, Pradeep MS (2024) District-level climate risk assessment for India: mapping flood and drought risks using IPCC framework. Department of Science and Technology, Government of India and the Swiss Agency for Development and Cooperation (SDC), Embassy of Switzerland. https://dst.gov.in/sites/default/files/Full%20Report_District-Level%20Climate%20Risk%20Assessment%20for%20India_Mapping%20Flood%20and%20Drought%20Risks%20Using%20IPCC%20Framework.pdf

Davis KF, Chhatre A, Rao ND, Singh D, DeFries R (2019) Sensitivity of grain yields to historical climate variability in India. Environ Res Lett 14:064013. https://doi.org/10.1088/1748-9326/ab22db

Dawkins LC, Bernie DJ, Pianosi F, Lowe JA, Economou T (2023) Quantifying uncertainty and sensitivity in climate risk assessments: varying hazard, exposure and vulnerability modelling choices. Clim Risk Manag 40:100511. https://doi.org/10.1016/j.crm.2023.100511

DeFraites, R.F., Hickey, P., Sharp, T.W., Beadling, C.W. (2020). The Health Care Response to Disasters Complex Emergencies,

and Population Displacement. Hunter's Tropical Medicine and Emerging Infectious Diseases (Tenth Edition). 219–227. https://doi.org/10.1016/B978-0-323-55512-8.00029-6
Directorate of Economic and Statistics (DES) (2024) Land Use Statistics at a Glance: 2022–23. Ministry of Agriculture & Farmers Welfare. Department of Agriculture & Farmers Welfare. Economics, Statistics, and Evaluation Division. Government of India. Final-file-of-LUS-2022–23-for-uploading.pdf
Directorate of Economics and Statistics (DES) (2021) Area. Production & Yield Reports, Department of Agriculture, Government of India. https://data.desagri.gov.in/website/crops-apy-report-web
Districts (2025) Government of Assam, India. https://assam.gov.in/about-us/396
Dow K, Berkhout F, Preston BL (2013) Limits to adaptation to climate change: a risk approach. Curr Opin Environ Sustain 5:384–391. https://doi.org/10.1016/j.cosust.2013.07.005
Dutta P, Deka S (2024) A novel approach to flood risk assessment: synergizing with geospatial based MCDM-AHP model, multicollinearity, and sensitivity analysis in the Lower Brahmaputra Floodplain, Assam. J Clean Prod 467:142985. https://doi.org/10.1016/j.jclepro.2024.142985
Dutta D, Misra AK, Srivastava A (2025) Assessing river bank erosion on Majuli Island for strength and stability in resilient protection. Geomech Geoengin 20:313–327. https://doi.org/10.1080/17486025.2024.2401011
Ebinger JO, Vandycke N (2015) Moving toward climate-resilient transport. In: Transport & ICT global practice. The World Bank Group. https://thedocs.worldbank.org/en/doc/326861449253395299-0190022015/render/WorldBankPublicationResilientTransport.pdf
ESRI (2025). Data classification methods—ArcGIS Pro | Documentation. https://pro.arcgis.com/en/pro-app/latest/help/mapping/layer-properties/data-classification-methods.htm
Fenglin W, Ahmad I, Zelenakova M, Fenta A, Dar MA et al (2023) Exploratory regression modeling for flood susceptibility mapping in the GIS environment. Sci Rep 13:247. https://doi.org/10.1038/s41598-023-27447-0
Field CB, Barros VR (2014) Climate change 2014: impacts, adaptation, and vulnerability working group II contribution to the fifth assessment report of the Intergovernmental panel on climate change. Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-FrontMatterA_FINAL.pdf
Fishery (2025) Government of Assam. https://fisheries.assam.gov.in/portlets/background-relevancy-of-the-sector
Government of Assam (2014) Assam Human Development Report (2014) Transformation and Development, Government of Assam, India. https://sita.assam.gov.in/portlets/assam-human-development-report-0
Government of Assam (2015) Assam state action plan on climate change (2015–2020). Department of Environment and Forest. Government of Assam. https://moef.gov.in/uploads/2017/08/ASSAM-SAPCC.pdf
Government of Assam (2025) Flood & erosion problems. Water Resources. https://waterresources.assam.gov.in/portlets/flood-erosion-problems#:~:te
Government of India (2020) All India report on agriculture census 2015–2016. Agriculture Census Division. Department of Agriculture, Cooperation, and Farmers Welfare. Ministry of Agriculture and Farmers Welfare, Government of India. https://agcensus.da.gov.in/document/agcen1516/ac_1516_report_final-220221.pdf
Goyari P (2005) Flood damages and sustainability of agriculture in Assam. Econ Polit Wkly 40:2723–2729. https://doi.org/10.2307/4416819
Gupta L, Dixit J (2022) A GIS-based flood risk mapping of Assam, India, using the MCDA-AHP approach at the regional and administrative level. Geocarto Int 37:11867–11899. https://doi.org/10.1080/10106049.2022.2060329
Horticulture (2020) Government of Assam. https://dirhorti.assam.gov.in/
Impact Observatory for Esri (2021). https://www.esri.com/partners/impact-observatory-a2T5x0000084pJXEAY
Intergovernmental Panel on Climate Change (IPCC) (2023) Climate change 2022 – impacts, adaptation and vulnerability: working group II contribution to the sixth assessment report of the Intergovernmental Panel on Climate Change, 1st ed. Cambridge University Press. https://doi.org/10.1017/9781009325844
IPCC (2022) Annex II: glossary [Möller V, van Diemen R, Matthews JBR, Méndez C, Semenov S, Fuglestvedt JS, Reisinger A (eds)] In: Climate change 2022: impacts, adaptation and vulnerability. contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change [Pörtner H-O, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, Rama B (eds)]. Cambridge University Press, Cambridge, UK and New York, NY, pp 2897–2930. https://doi.org/10.1017/9781009325844.029
Joshi N, Ranjit N, Peddibhotla A, Singh C (2025) Lost and damaged: a systematic review of current loss and damage due to climate change in India. Clim Dev. https://doi.org/10.1080/17565529.2025.2488382
Jurgilevich A, Räsänen A, Groundstroem F, Juhola S (2017) A systematic review of dynamics in climate risk and vulnerability assessments. Environ Res Lett. https://doi.org/10.1088/1748-9326/aa5508
Khal M, Alhouti A, Algouti A, Akdim N, Stankevich SA, Menenti M (2020) Evaluation of open digital elevation models: estimation of topographic indices relevant to erosion risk in the Wadi M'Goun watershed, Morocco. AIMS Geosciences 6(2):231–257. https://doi.org/10.3934/geosci.2020014
Lawrence C, Blackett P, Cradock-Henry NA (2020) Cascading climate change impacts and implications. Clim Risk Manag 29:100234. https://doi.org/10.1016/j.crm.2020.100234
Li K, Feng M, Biswas A, Su H, Niu Y et al (2020) Driving factors and future prediction of land use and cover change based on satellite remote sensing data by the LCM model: a case study from Gansu Province, China. Sensors 20:2757. https://doi.org/10.3390/s20102757
Mahmoud SH, Gan TY (2018) Multi-criteria approach to develop flood susceptibility maps in arid regions of Middle East. J Clean Prod 196:216–229. https://doi.org/10.1016/j.jclepro.2018.06.047
Mechler M, Singh C, Ebi K, Djalante R, Thomas A, James R, Tschakert P, Wewerinke-Singh M, Schinko T, Ley D, Nalau J, Bouwer LM, Huggel C, Huq S, Linnerooth-Bayer J, Surminski S, Pinho P, Jones R, Revi A (2020) Loss and Damage and limits to adaptation: recent IPCC insights and implications for climate science and policy. Sust Sci. https://doi.org/10.1007/s11625-020-00807-9
Miller ME, Nwosu CO, Nyamwanza AM, Jacobs PT (2023) Assessing psychosocial health impacts of climate adaptation: a critical review. New Solutions: A Journal of Environmental and Occupational Health Policy 33(1). https://doi.org/10.1177/10482911231173068
Ministry of Jal Shakti, Department of Water Resources, River Development and Ganga Rejuvenation (2021) Flood management in the country including international water treaties in the field of water resource management with particular reference to treaty/agreement entered into with China, Pakistan and Bhutan. In: Standing committee on water resources (2020–2021). Seventeenth Lok Sabha. Lok Sabha Secretariat, New Delhi. https://sansad.in/getFile/lsscommittee/Water%20Resources/17_Water_Resources_17.pdf?source=loksabhadocs

Ministry of Statistics and Programme Implementation (MoSPI) (2024) Annual report, periodic labour force survey, 2022–23. National Sample Survey Office, Government of India. https://microdata.gov.in/NADA/index.php/catalog/210/related-materials
Mohanty A, Wadhawan S (2021) Mapping India's climate vulnerability: a district-level assessment. CEEW, India Climate Collaborative, EdelGive Foundation. https://www.ceew.in/sites/default/files/ceew-study-on-climate-change-vulnerability-index-and-district-level-risk-assessment.pdf
Mondal MSH, Murayama T, Nishikizawa S (2020) Assessing the flood risk of riverine households: a case study from the right bank of the Teesta River, Bangladesh. Int J Disaster Risk Reduct 51:101758. https://doi.org/10.1016/j.ijdrr.2020.101758
Mudashiru RB, Sabtu N, Abdullah R, Saleh A, Abustan I (2022) Optimality of flood influencing factors for flood hazard mapping: an evaluation of two multi-criteria decision-making methods. J Hydrol. https://doi.org/10.1016/j.jhydrol.2022.128055
N'Guetta A, Boyd E, Krause T, Jackson G (2025) Loss and damage in tropical fisheries: a systematic review of people, climate, and fisheries. Reg Environ Change 25:36. https://doi.org/10.1007/s10113-025-02374-0
National Bank for Agriculture and Rural Development. (2023). Potential Linked Credit Plan for Dima Hasao, Assam (2023–24). National Bank for Agriculture and Rural Development. Assam Regional Office, Guwahati. https://www.nabard.org/auth/writereaddata/tender/ASS_Dima_Haso.pdf
National Health Systems Resource Centre (NHSRC) (2022) Annual ASHA update 2020–21. National Health Mission, Ministry of Health and Family Welfare, Government of India. https://nhsrcindia.org/sites/default/files/2022-07/Annual%20ASHA%20Update%202020-21.pdf
National Institute of Disaster Management (NIDM) and DEUTSCHE GESELLSCHAFT FÜR INTERNATIONALE ZUSAMMENARBEIT (GIZ) GmbH (2019) Climate risk management [CRM] framework for India addressing loss and damage (L&D). https://nidm.gov.in/PDF/pubs/GIZ_NIDM_Climate%20RiskManagementFramework.pdf
New M, Reckien D, Viner D, Adler C, Cheong SM, Conde C, Constable A, Coughlan de Perez E, Lammel A, Mechler R, Orlove B, Solecki W (2022) Decision-making options for managing risk. In: Pörtner HO, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, Rama B (eds) Climate Change 2022: impacts, adaptation, and vulnerability. contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge and New York, NY, pp 2539–2654. https://doi.org/10.1017/9781009325844.026
NITI Aayog (2023) India National multidimensional poverty index 2023.pdf. OPHI. UNDP. NITI Aayog, Government of India. https://www.niti.gov.in/sites/default/files/2023-08/India-National-Multidimentional-Poverty-Index-2023.pdf
Nur I, Shrestha KK (2017) An integrative perspective on community vulnerability to flooding in cities of developing countries. Procedia Eng 198:958–967. https://doi.org/10.1016/j.proeng.2017.07.141
OECD (2021) Managing climate risks, facing up to losses and damages: understanding. Reduc Manag Risks (OECD). https://doi.org/10.1787/55ea1cc9-en
Pai DS, Sridhar L, Rajeevan M, Sreejith OP, Satbai NS, Mukhopadhyay B (2014) Development of a new high spatial resolution (0.25° × 0.25°) long period (1901-2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region. MAUSAM 65(1):1–18
Panwar V, Noy I, Wilkinson E (2025) Calculating loss and damage from extreme weather events in Small Island Developing States. Reg Environ Change 25(2):73. https://doi.org/10.1007/s10113-025-02408-7
Phukan A, Goswami R, Borah D, Nath A, Mailanta C (2012) River bank erosion and restoration in the Brahmaputra River in India. Clarion Int Multidiscip J 1(1):1–7. https://www.semanticscholar.org/paper/River-Bank-Erosion-and-Restoration-in-the-River-in-Phukan-Goswami/5a28ecf8fa23b5e416048a0a52198792d1868296C
Puig D (2022) Loss and damage in the global stocktake. Clim Policy 22(2):175–183. https://doi.org/10.1080/14693062.2021.2023452
Quinn T, Heath S, Adger WN, Abu M, Butler C et al (2023) Health and wellbeing implications of adaptation to flood risk. Ambio 52:952–962. https://doi.org/10.1007/s13280-023-01834-3
Rahman S, Rahman MA (2015) Climate extremes and challenges to infrastructure development in coastal cities in Bangladesh. Weather Clim Extrem 7:96–108. https://doi.org/10.1016/j.wace.2014.07.004
Raymond C, Horton RM, Zscheischler J, Martius O, AghaKouchak A et al (2020) Understanding and managing connected extreme events. Nat Clim Chang 10:611–621. https://doi.org/10.1038/s41558-020-0790-4
Reisinger A., Howden M., Vera C., Garschagen M., Hurlbert M., Kreibiehl S., Mach K.J., Mintenbeck K., O'Neill B., Pathak M., Pedace R., Portner H.O., Poloczanska E., Corradi M.R., Sillmann J., Aalst M.V., Viner D., Jones R., Ruane A.C., Ranasinghe R. (2020). The concept of risk in the IPCC Sixth Assessment Report: a summary of cross-Working Group Discussions. Intergovernmental Panel on Climate Change, Geneva Switzerland. 1–15. https://www.ipcc.ch/site/assets/uploads/2021/01/The-concept-of-risk-in-the-IPCC-Sixth-Assessment-Report.pdf
Ricker-Gilbert J, Jumbe C, Chamberlin J (2014) How does population density influence agricultural intensification and productivity? Evidence from Malawi. Food Policy 48:114–128. https://doi.org/10.1016/j.foodpol.2014.02.006
Roberts E, Huq S (2015) Coming full circle: the history of loss and damage under the UNFCCC. Int J Glob Warm 8:141. https://doi.org/10.1504/IJGW.2015.071964
Sambath V, Narayan S, Kumar P, Kumar P, Pradyumna A (2022) Knowledge, attitudes and practices related to climate change and its health aspects among the healthcare workforce in India – a cross-sectional study. The Journal of Climate Change and Health 6:100147. https://doi.org/10.1016/j.joclim.2022.100147
Shah A, Malakar K (2024) Climate-change-induced risk mapping of the Indian Himalayan districts using the latest IPCC framework. Int J Disaster Risk Reduct 102:104283. https://doi.org/10.1016/j.ijdrr.2024.104283
Simpson NP, Mach KJ, Constable A, Hess J, Hogarth R et al (2021) A framework for complex climate change risk assessment. One Earth 4:489–501. https://doi.org/10.1016/j.oneear.2021.03.005
Swarnokar SC, Mou SI, Sharmi SD, Iftikhar A, Jesmin S (2025) Climate-induced risks, adaptation, and mitigation responses: a comparative study on climate-stressed coastal communities. Front Clim 7:1553579. https://doi.org/10.3389/fclim.2025.1553579
The Mahatma Gandhi National Rural Employment Guarantee Act (2005) 2025. Ministry of Rural development, Government of India. https://nrega.dord.gov.in/MGNREGA_new/Nrega_home.aspx
UNDRR. (2015). Sendai Framework for Disaster Risk Reduction 2015 - 2030. The United Nations Office for Disaster Risk Reduction. https://www.undrr.org/media/16176/download?startDownload=20250614
United Nations Framework Convention on Climate Change (UNFCCC) (2013) Non-economic losses in the context of the work programme on loss and damage. https://unfccc.int/resource/docs/2013/tp/02.pdf

Van der Geest K, de Sherbinin A, Kienberger S, Zommers Z, Sitati A, Roberts E, James R, Mechler R, Bouwer Laurens M, Schinko T, Surminski S, Linnerooth-Bayer J (2019) Loss and damage from climate change: concepts, methods, and policy options the impacts of climate change on ecosystem services and resulting losses and damages to people and society. Springer International Publishing Cham, pp 221–236

Van Der Geest K, Warner K (2015) Vulnerability, coping and loss and damage from climate events. hazards, risks, and disasters in society. Elsevier, pp 121–144. https://doi.org/10.1016/B978-0-12-396451-9.00008-1

Van Schie D, Jackson G, Serdeczny O, van der Geest K (2024) Economic and non-economic loss and damage: a harmful dichotomy? Glob Sustain 7:e42. https://doi.org/10.1017/sus.2024.40

Vyas S, Barua A, Mallikarjuna C, Baghel T (2024) An integrated approach for managing drought risks in the Eastern Himalayan Region of India. Int J Disaster Risk Reduct 112:104789. https://doi.org/10.1016/j.ijdrr.2024.104789

Yousaf A, Kiran A, Iqbal MA, Murtiza G, Hussain M (2025) Climate change effects on rural livelihoods in Pakistan: legal and policy analysis. GeoJournal 90:25. https://doi.org/10.1007/s10708-024-11273-6