



Regular Article

Flood-Induced Loss and Damage Estimation Models: A State-of-the-Art Review

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Abstract Loss and damage (L&D) due to climate change refer to the negative consequences and impacts, causing a wide range of adverse effects, including economic, physical, social, and environmental losses. L&D discussions include adaptation and mitigation strategies and addressing the responsibility for offering financial and technical assistance to affected communities and nations. Accurate and comprehensive estimation of loss and damage provides crucial information for effective decision-making, resource allocation, and prioritization of interventions to enhance preparedness, response, and recovery capabilities, ultimately reducing the impact of disasters and promoting sustainable development. This paper comprehensively examines loss and damage, related terminologies, and its estimation models, explicitly focusing on flood-related scenarios. The paper is structured in two segments, the first segment looks into the evolution and official acknowledgment of the phrase "loss and damage" and explores its various types, such as direct and indirect damages, economic and non-economic L&D, and the distinctions between avoided, unavoided, and unavoidable risks and impacts. Additionally, it also examines the relationship between loss and damage estimation and disaster risk reduction (DRR). The second segment focuses on different models used globally for estimating loss and damage due to flood disasters. It delves into different approaches, scales, methodologies, model development, functions, and differentiation of results for flood-induced loss and damage estimation. A comparative analysis of a total of 18 models is evaluated based on criteria like input data, spatial scale, unit of analysis, cost base, empirical validation, loss or damage functions, and economic sectors among. L&D models discussed in this paper are HAZUS-MH (United States) FLEMO (Germany), ICPR (Germany), MURL (Germany), Hydrotec (Germany), LfUG (Germany), Neubert and Thiel (Germany), MEDIS-Model (Germany), Damage Scanner (The Netherlands), Hoes and Schuurmans (The Netherlands), Rhine Atlas (Rhine Basin), The Flemish Model (Belgium), Multi-Coloured Manual (United Kingdom), The JRC Model

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(European Commission), Citeau (France), Anuflood (Australia), RAM (Australia), and Dutta et al. (Japan). The study discusses the strengths, weaknesses, and limitations of each model, highlighting the gaps and areas for future research. Lastly, in order to better understand how the loss and damage estimation model works, the research provides a general matrix that can serve as a basis for the development of a new model.

Keywords: loss and damage, flood, loss estimation model, damage estimation model, climate change, HAZUS-MH

1. INTRODUCTION

Loss and damage due to climate change is a critical issue that has garnered attention in various academic disciplines and policy arenas. Irreversible loss and unbearable damage are just two examples of the many effects of climate change that have been included in the concept of loss and damage over time (Schinko & Mechler, 2017). This broader conceptualization has focused on both monetizable impacts and intangible losses and damages (Calliari et al., 2020). Moreover, when mitigation and adaptation measures are insufficient, the consequences of climate change are referred to as its “residual” or “loss and damage” (L&D) (Dorkenoo et al., 2022). The ambiguity surrounding the framing of L&D has played a significant role in international climate policy negotiations. This ambiguity has allowed parties to attach different meanings to the policy, resolving differences among the parties and embedding the idea of loss and damage in international climate policy (Vanhala & Hestbaek, 2016).

As of now, there is no official UNFCCC definition of “loss and damage,” leading to varied interpretations in Nationally Determined Contributions (NDCs). These NDCs reflect diverse national contexts, priorities, and responses to economic and non-economic losses, highlighting the need for a clear, unified definition (Calliari & Ryder, 2023; Broberg & Romera, 2021; Broberg & Romera, 2021; Karimi-Schmidt, 2020; Serdeczny et al., 2018; Vanhala & Hestbaek, 2016). L&D is used as a broader term under United Nations climate negotiations which describes it as the effects of climate change, while United Nations Framework Convention on Climate Change (UNFCCC) addresses “loss and damage” as being beyond what people can adapt to or when choices are available but a community lacks the resources to access or employ them (Sacramento 2023). In some studies, the basic distinction between loss and damage has been defined on the basis of restoration and reparation, where loss refers to irreparable negative impacts, while damage includes negative impacts that can be restored or repaired (Doktycz & Abkowitz, 2019).

L&D is intricately linked to the principles and practices of disaster risk reduction (DRR) (Mechler et al., 2019). DRR includes a spectrum of proactive measures and strategies to minimize the adverse impacts of disasters on communities, infrastructure, and the

environment. It emphasizes pre-emptive actions related to L&D, which further reduces the vulnerability and addresses the underlying risk factors to minimize potential losses and damages (Orcherton, 2023). By integrating L&D considerations into DRR frameworks, societies can work towards a more resilient and sustainable development. Comprehensive DRR strategies enhance societies' capacity to withstand and recover from disasters, directly contributing to reducing losses and damages in lives, infrastructure, economies, and the environment. Also, it has been emphasized that grassroots participation is essential for influencing policy narratives and thoughtful action on the loss and damage assessment (Sacramento, 2023).

Floods are expected to become more frequent and intense as climate change progresses, though the impacts vary regionally (Wasko et al., 2021; Bai et al., 2019; Najibi & Devineni, 2018; Arnell & Gosling, 2016; Alfieri et al., 2015). During 2010-2013, anthropogenic climate change increased the frequency of floods in certain areas while reducing it elsewhere (Hirabayashi et al., 2021). As per the April 2024 report of the Centre for Research on the Epidemiology of Disasters CRED, total economic damages in the year 2023 were estimated at around USD 202.7 billion, resulting in 86,473 loss of lives and affecting 93.1 million individuals, with the significant contribution from the flood-related disasters. The need for immediate emission reductions and strategies to mitigate loss and damage that are appropriate for supporting the most vulnerable developing nation parties has also resulted from the expanding knowledge of loss and damage (Mace & Verheyen, 2016). Collecting transparent flood-induced loss and damage data is important for better comparability of actual and estimated flood losses (Merz et al., 2004). There is an extra emphasis on estimating these losses in absolute monetary terms. Accurate and comprehensive estimation of L&D provides crucial information for effective decision-making, resource allocation, and prioritization of interventions to enhance preparedness, response, and recovery capabilities, ultimately reducing the impact of flood disasters and promoting sustainable development. This paper's review methodology involves desktop research that methodically finds, evaluates, and analyzes peer-reviewed literature using appropriate keywords from databases such as Scopus and Google Scholar. After screening studies according to inclusion criteria, the results were arranged in tabular form to meet the study's goals. This study offers a general matrix for flood-induced loss and damage estimating model and thoroughly investigates the models used globally. It presents a global perspective, identifies the need for further investigation, and suggests potential improvements in the estimation for effective decision-making.

2. EVOLUTION OF 'LOSS AND DAMAGE'

2.1 Official Acknowledgement of the Term "Loss and Damage"

The Alliance of Small Island States (AOSIS) started discussions on loss and damage (L&D) in the early 1990s, emphasizing mitigation. In the negotiations leading to the adoption

of the UNFCCC in 1992, AOSIS suggested a global insurance scheme or compensation fund funded through mandatory contributions from industrialized nations. These contributions would be determined by their gross national product and greenhouse gas emissions, aiming to provide compensation for climate-related impacts, particularly from rising sea levels, to small islands and low-lying developing nations (INC, 1991). The proposal was eventually dropped, but talks on insurance and compensation for addressing the negative impacts of climate change persisted. The term "loss and damage" was initially introduced in the 2007 Bali Action Plan (UNFCCC, 2007). The ad hoc Working Group on Long-term Cooperative Action under the Convention (AWG-LCA) received an enhanced version of the 1992 proposal from AOSIS in 2008, focusing on three interrelated components: risk management, rehabilitation/compensation, and insurance (AOSIS, 2008). The updated proposal for the COPENHAGEN Protocol was resubmitted by AOSIS (UNFCCC, 2009), advocating for an "international mechanism addressing risk management and risk reduction strategies, as well as insurance-related risk sharing and transfer mechanisms." The Cancun Adaptation Framework marked the official UNFCCC activities by creating an ad hoc work program (UNFCCC, 2010).

By 2012, focused technical efforts on Loss and Damage (L&D) began in three key areas: evaluating the risk of L&D and existing knowledge; suggesting various approaches to tackle L&D from both sudden and gradual occurrences while incorporating experiences at all levels; and defining the Convention's role in strengthening the implementation of strategies to address L&D. The Parties resolved to create institutional frameworks as part of the Doha Climate Gateway 2012, which opened the door for the creation of the Warsaw International Mechanism for loss and damage associated with climate change impacts (WIM). This mechanism fosters dialogue, addresses knowledge gaps, and strengthens action and support for those grappling with loss and damage (UNFCCC, 2012). COP19 established the Executive Committee (ExCom) to oversee the implementation of WIM tasks through a first two-year work plan (UNFCCC, 2015). The Paris Agreement's separate L&D article acknowledges institutional grounding within the UNFCCC framework. (UNFCCC, 2015, Article 8), and L&D received additional recognition at COP21. Countries created the "Santiago Network" on Loss and Damage at COP25 in Madrid in 2019 to link developing countries with technical assistance providers (UNFCCC, 2019). At COP 26 in Glasgow in 2021 (UNFCCC, 2021), a dedicated section on L&D urged developed country governments and relevant organizations to provide 'enhanced and additional support' for activities addressing loss and damage. The proposal did not gain adequate support among developed countries. Still, parties agreed to establish a dialogue 'to discuss the arrangements for funding activities to avert, minimize, and address L&D associated with the adverse impacts of climate change.'

At COP27 in Sharm el-Sheikh in 2022, an agreement was reached on operationalizing the Santiago Network. L&D finance was included on the formal negotiations agenda, resulting in the 'Loss and Damage fund.' Parties also agreed to establish a 'transitional committee' which will look into the critical decisions like where the fund will be placed, what types of activities

it will support, how it will be governed, which countries will be eligible to receive support, and who will contribute to it financially (UNFCCC, 2022). At COP 28, a consensus was made to operationalize new funding arrangements, incorporating a Fund to address L&D. All Parties, including India, endorsed this decision. Since its adoption, various countries have collectively pledged approximately USD 700 million towards this initiative (UNFCCC, 2023). At COP29, again, a resolution was made to secure the full operationalization of the Loss and Damage Fund, committing to mobilize USD 300 billion of climate finance (UNFCCC, 2024). Figure 1 provides a quick overview of the significant milestones in the official recognition of the term “Loss and Damage” in the United Nations.

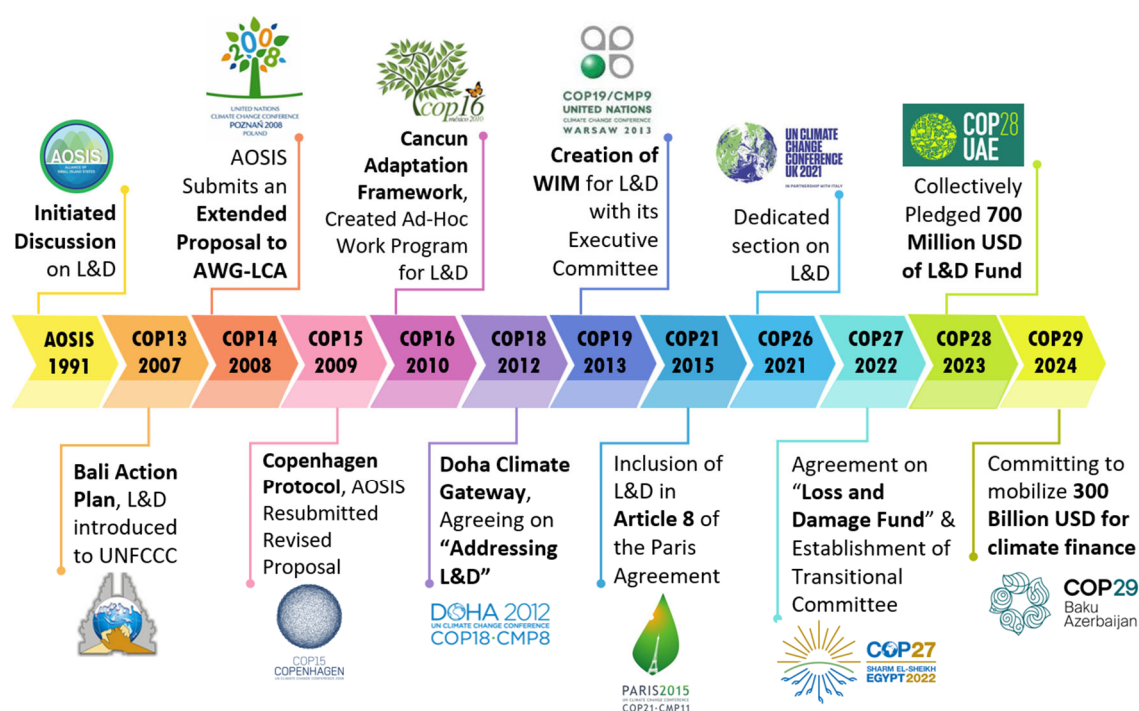


Figure 1. Milestones in the official recognition of the term "Loss and Damage" in the United Nations (Source: Author)

The debate of loss and damage (L&D) in climate negotiations has been politically contentious, with developed countries concerned about accountability and developing countries demanding compensation for disproportionate climate impacts. The Paris Agreement recognized L&D as an autonomous pillar but excluded liability, which some saw as a failure for vulnerable countries. (Taub et al., 2016). The discussion revolves around identifying L&D within or beyond adaptation while developing nations strategically leverage the "compensation argument" to influence negotiations (Hossain et al., 2021; Boyd et al., 2021; Calliari et al., 2020; Calliari, 2018). Disputes over funding and incorporation into larger financial systems continued even after the creation of a dedicated Loss and Damage Fund at COP28. In order to guarantee predictable resources, developing countries pushed for its inclusion in the New Collective Quantified Goal on Climate Finance (NCQG) at COP 29. However, developed countries, including USA and EU, refused, citing existing financial

systems and budgetary concerns. Conflicts over compensation, legitimacy as a third pillar of climate action, tensions between technical and political aspects, accountability, and links to other unresolved issues of estimation are the points of contention that now surround the L&D debate.

2.2 Classification of Loss and Damage

L&D can be categorized according to the monetary terms and tolerance based on adaptation and mitigation (see Figure 2). The two types of L&D that arise from the calculation of monetary values are Economic Loss and Damage (ELD) and Non-Economic Loss and Damage (NELD), which are frequently referred to as direct and indirect L&D, respectively. ELD refers to the quantifiable and tangible financial losses resulting from accidents, disasters, or other unfavourable events. These could be commodities, supplies, or services that are often traded in the market, including short-term expenses of fixing or rebuilding damaged buildings, revenue-losing business disruptions, and the longer-term effects on the economy from fewer earnings and job prospects (Bahinipati & Gupta, 2022). On the other hand, NELD considers the non-financial and intangible effects that go beyond simple financial calculations. This category includes a wide range of impacts on people, society, and the environment that can be difficult to quantify in monetary terms, including loss of human life, sociological issues like migration, displacement, and the collapse of social systems, cultural issues like damage to heritage and identity, and environmental concerns like biodiversity loss, ecosystem services, and pollution. The psychological and emotional pain of people and communities is another example of non-economic loss's complex and multidimensional nature (McNamara & Jackson, 2019). When combined together (ELD and NELD), they provide a comprehensive framework for understanding the diverse effects of events, especially in monetary terms, on various aspects of resilience, recovery, and well-being.

Losses and damages, based on the tolerance levels of adaptation and mitigation, are categorized into three types: 'avoided,' 'unavoided,' and 'unavoidable' impacts and risks (see Figure 2). First, "Avoided losses and damages" refer to those that can be prevented through mitigation and/or adaptation to climate change. Second, "Unavoided losses and damages" describe impacts that could have been averted but remain unaddressed despite additional mitigation or adaptation efforts, often constrained by financial, technological, and political factors and specific risk preferences. Third, "Unavoidable losses and damages" incorporate those that cannot be prevented and require further mitigation and/or adaptation measures. This category typically includes impacts from gradual ongoing processes, such as rising sea levels or glacier melting (Mechler et al., 2019).

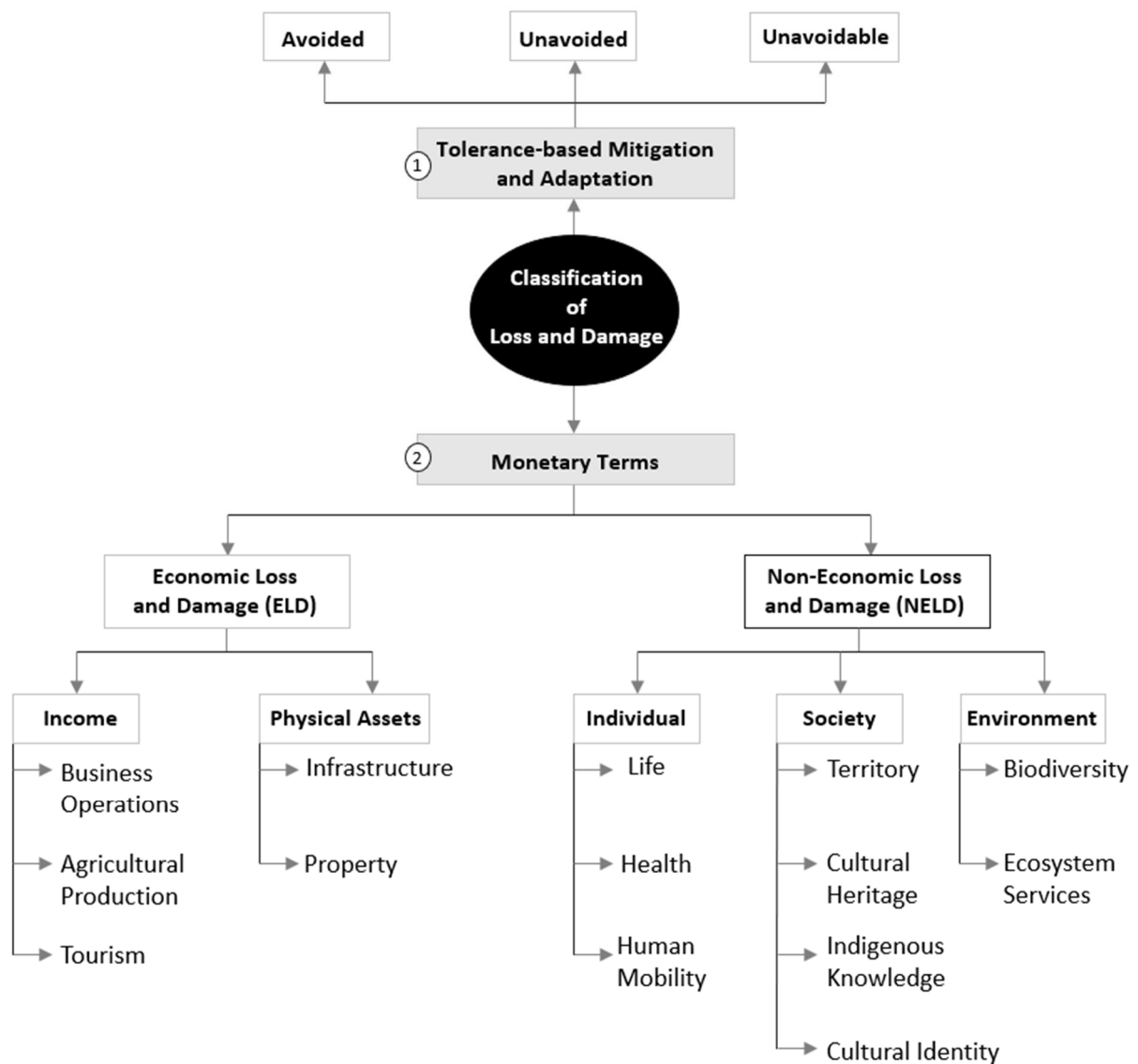


Figure 2. Types of loss and damage (Source: Author)

2.3 Importance of Loss and Damage Estimation

Loss and damage estimation are critical to disaster risk management, particularly in natural hazards such as floods, earthquakes, and extreme weather events. Accurately estimating potential losses is essential for emergency preparedness, risk assessment, and long-term planning (Messner & Meyer, 2006). However, the process of estimating loss and damage is complex and often involves uncertainty due to various factors, such as the variability in building materials, construction quality, and the lack of consistent schemes to quantify the degree of damage (McGrath et al., 2019). It is crucial to communicate this uncertainty and potential variability in any assessment to ensure the reliability of the estimates (McGrath et al., 2019). The differentiation is crucial in understanding the implications of L&D estimation in the context of disaster management. Accurate loss statistics are critical in determining the cost-benefit of any proposed mitigation technique. Non-structural losses have been found to

exceed those related to structural damage in loss estimation studies, indicating the need to consider a wide range of factors beyond just structural damage when estimating potential losses (Bianchi et al., 2021). There is a disproportionate impact of these "residual" consequences of climate change on the world's poorest populations, highlighting how urgent it is to address them (Page & Heyward, 2017). However, acquiring reliable loss data and monitoring it on a real-time basis is an issue that is shared globally. Additionally, as NELD is difficult to quantify, the available loss inventories mostly include the ELD database only.

3. FLOOD LOSS AND DAMAGE ESTIMATION MODELS

Models for estimating loss and damage have several components that are essential for calculating economic loss and damage (ELD). These components also form the basis for evaluating the monetary and non-monetary effects of disasters. A thorough categorization is given in Figure 3 below, which groups them according to pertinent criteria.

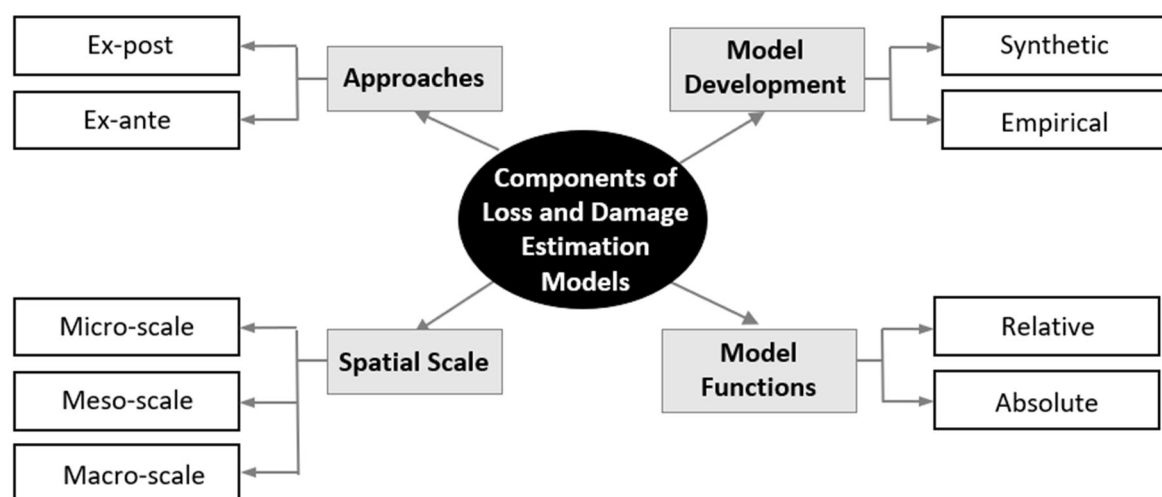


Figure 3. Components of loss and damage estimation model (Source: Author)

3.1 Approaches and Spatial Scale

Economic loss and damage estimation generally follow two approaches: ex-post and ex-ante. Ex-post estimation is the process of estimating damage and costs after a disaster, with an emphasis on emergency management and early recovery coordination. (APFM, 2007). Additionally, it will provide local or national governments with an update on the overall scope of induced losses and damages, which will serve as a basis for deciding compensation amounts and recovery assistance (Meyer et al., 2013). On the other hand, the ex-ante estimation approach aims to predict possible economic losses and damages for scenarios with anticipated hazard characteristics before an event occurs. Data from ex-post loss and damage

estimates are commonly used to calibrate ex-ante estimating models. However, economic analysis guidelines primarily address ex-ante because ex-post is less well-developed. One popular approach in ex-ante is to use damage functions, sometimes referred to as stage-damage or fragility curves (Messner et al., 2007). These functions establish the cause-and-effect relationship between the intensity of hazard parameters and the extent of damage or loss for specific asset classes. As previously noted, these functions can be articulated in absolute values, representing estimated costs, or in terms of relative damage. This dual representation aids governmental decision-making processes regarding various risk mitigation options (Merz et al., 2010).

L&D estimations are performed at various spatial scales. The computation at the microscale is based on the specific components that are at risk. For instance, determining the damages to every impacted item, such as infrastructure and buildings, is necessary to estimate the damage that would occur to a community in the event of a particular flood. At the mesoscale, land-use units like wards or residential areas are common units for estimating based on spatial aggregations. They are usually between one hectare and one square kilometer in size, which aligns with what reinsurance firms demand. Large geographical units frequently use administrative units like municipalities, regions, or entire nations, to serve as the basis for macro-scale damage estimation (Merz et al., 2010). A methodical integration of flood consequences has been made possible by the data that is currently accessible at the macroscale, which includes regional and national levels. Nevertheless, the absence of comprehensive explanations of the conditions surrounding loss, damage, and danger traits in this data makes it difficult to establish a direct correlation between expenses and particular L&D kinds. On the other hand, comprehensive data obtained from loss adjustment reports offers insights into the kinds and costs of losses and damages at the micro-scale, which involves local investigations. The establishment of a loss and damage typology and the identification of its processes are made possible by this micro-level investigation. Additionally, it makes cost distribution across many construction projects easier.

3.2 Model Development and Model Functions

Model development of L&D estimation models is categorized as synthetic and empirical, which hold significant importance across various sectors, including finance, insurance, environmental science, and engineering. Synthetic models are developed by a methodical procedure using theoretical assumptions and simulations rather than direct historical data observation. This involves a comprehensive risk assessment to identify factors contributing to potential losses and formulating mathematical or computational models based on what-if questions. Calibration of these models occurs through fine-tuning parameters based on available data or expert opinions, and their reliability is validated through comparisons with real-world data or historical events (Dutta et al., 2003). On the other hand, empirical models are based on historical records and observable data, meaning that data on past losses—such

as their frequency, severity, and event type—must be gathered. To find patterns and correlations, data analysis uses statistical methods or machine learning algorithms. (Merz et al., 2010). Model selection is based on the properties of the data, and prediction accuracy is ensured by validation processes. In some situations, an integrated strategy that combines empirical and synthetic approaches may improve model adaptability. These models have a wide range of applications, and continuous monitoring and updating are necessary to adjust models to dynamic conditions and ensure their accuracy. (Apel et al., 2009).

Model functions define the relationships between variables in a mathematical or statistical model and provide a unique methodology for estimating losses or damages. The goal of a relative model function is to provide information about the percentage impact of one variable on another by showing the proportionate or relative changes between variables. This method is frequently used in economics, finance, and some scientific fields. On the other hand, an absolute model function provides information on the actual or direct influence without considering proportional changes. It does this by expressing relationships in terms of the absolute values of variables. This model is widely used where it is essential to understand the absolute size of interactions and precise monetary loss (Romali et al., 2015).

3.3 General Matrix of Flood Loss and Damage Estimation Model

There are four steps in the fundamental flood loss and damage estimation model, as shown in Figure 4. First, the unit of analysis is fixed, and the meso or micro spatial scale is chosen to define the study's geographical scope. Second, is the input data, which includes effect and resistance parameters. For example, hydrological data like water depth, contamination, and flood duration as effect parameters, while the resistance parameters include precaution, sector, company size, crop size, and submersion period. There are three to four classes assigned to each parameter. These data provide the framework for the model's later phases. The general model approach is then decided upon, and based on the available data and the analysis goals, the empirical or synthetic approach's particular data approaches are considered. Third, is damage calculations; this involves determining the model function, which can be either absolute or relative and describes how different factors interact to affect the number of losses or damages. The empirical validation of the running model guarantees that the model's estimates will correspond with the actual observed data of the events. Fourth, the last step is differentiating the results to offer insights into the various flood consequences, such as losses or damages to building structures, machinery, supplies, and inventory in various residential, commercial, industrial, and infrastructural settings. Results in the agriculture sector take the shape of losses or damage to farm infrastructure, farmhouses, and agricultural products.

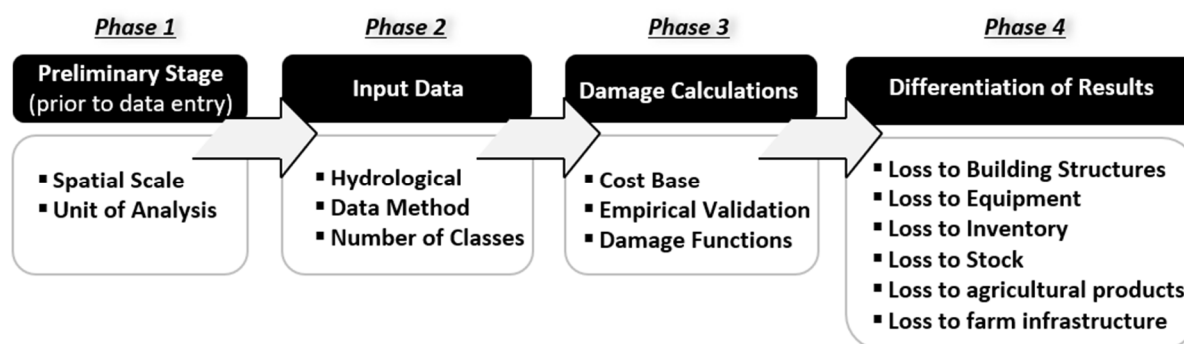


Figure 4. General matrix for flood-induced loss and damage estimation model (Source: Author)

4. FLOOD LOSS AND DAMAGE ESTIMATION MODELS USING GLOBALLY

4.1 USA

HAZUS-MH, developed by the Federal Emergency Management Agency (FEMA) in the United States, is a software package designed for estimating potential losses from natural hazards such as earthquakes, floods, hurricanes, and tsunamis (Scawthorn et al., 2006). It operates within the ArcGIS Desktop and provides estimates of potential physical, economic, and social impacts of disasters using hazard maps, fragility curves, and exposure models. It supports three levels of analysis based on available data and user expertise. The flood loss estimation module calculates physical damage and economic losses based on the hazard analysis results. It relies on a detailed database of building types, occupancy characteristics, and infrastructure assets to simulate the potential consequences of flooding. The model works on both meso and micro-scale and follows empirical-synthetic model development. It works on relative loss function and provides empirical validation. Comprehensive instructions on flood hazard analysis, methodology, inventory needs, performing basic and advanced studies, and interpreting loss estimates can be found in the HAZUS Flood User and Technical Manuals. They also cover the Comprehensive Data Management System (CDMS), which allows users to update and manage state-wide and HAZUS datasets, and the Advanced Engineering Building Module (AEBM), which provides procedures for developing building-specific damage and loss functions (FEMA, 2003).

4.2 United Kingdom (UK)

Multi-Colored Manual developed by Penning-Rowse (2005) has formulated an extensive set of depth–damage methodologies to estimate flood losses in absolute terms for residential, commercial, and industrial buildings, predominantly employing synthetic analysis and expert judgment. Damage curves for various maintenance levels and the presence of a basement are provided for each damage class. The MCM is an object-based model, similar to HAZUS, and

its estimates of maximum damage per square meter only account for expected building repair costs; they do not account for damage to the surrounding land. It operates at micro and meso scales and covers the residential, business, industrial, road, and agricultural sectors. Key parameters are water depth, flood duration, object type, and lead time, which are crucial in estimating the extent of flood damage. The model is developed using synthetic techniques and has limited empirical validation, indicating potential areas for improvement in accuracy and reliability. However, it provides absolute estimates for loss to building structures, equipment, immobile inventory, mobile inventory, and stocks, offering valuable insights for disaster preparedness and recovery planning. The model's differentiation of results allows for a detailed breakdown of losses across different categories, providing stakeholders with essential information for decision-making.

4.3 Germany

In Germany, multiple different models are employed to assess flood-related losses and damages. The FLEMO model family, created by the German Research Centre for Geosciences, is primarily utilized in flood risk assessments ranging from meso to micro dimensions to evaluate direct tangible damage (Apel et al., 2009). FLEMO is a versatile flood-induced loss and damage estimation model designed for residential, commercial, and private properties in Germany (Kreibich et al., 2010). The model evaluates damages based on surface area, water depth, contamination, and sector-specific precautions. Its empirical approach which focuses on the relative losses to building structures, equipment, and inventories, allows a detailed understanding of flood risks.

Hydrotec (Emschergenossenschaft & Hydrotec, 2004), MURL (MURL, 2000), ICPR (ICPR, 2001), LfUG-SAXONY (LfUG, 2005), Neubert and Thiel (Neubert & Thiel, 2004), and MEDIS-Model (Forster et al., 2008) are some more models. They all function at the meso scale and have relative loss or damage functions. MURL, estimations with a focus on water depth as a crucial element, specifically for the German industrial sectors (MURL, 2000). In Germany, ICPR expanded its scope to include residential areas and provided a thorough evaluation of flood risks at the mesoscale. ICPR uses synthetic and empirical methods to analyze surface area with water depth and individual objects. Its methodology makes it possible to analyze damages to building structures, equipment, and inventory in great detail, which is useful for managing the danger of flooding in residential areas (ICPR, 2001).

Hydrotec is another industrial sector estimation model that uses an empirical method to determine the overall losses to buildings and equipment, with water depth as its key parameter (Emschergenossenschaft & Hydrotec, 2004). For agricultural and industrial applications, LfUG SAXONY computes flood losses using input data on water depth or specific discharge. It uses synthetic and empirical approaches to assess relative losses to building structures, equipment, and inventory (LfUG, 2005). Neubert and Thiel's concept

emphasizes meso size and is specifically designed for the German farm industry. This model uses synthetic approaches and considers the submersion duration to assess losses to farm infrastructure, agricultural products, and farmhouses (Neubert & Thiel, 2004). Finally, the MEDIS model only calculates flood-related losses in Germany at the mesoscale within the agriculture sector. It uses both synthetic and empirical methods to calculate the relative losses to infrastructure, farmhouses, and agricultural products. Parameters including crop type, flood duration, and submersion period are considered (Forster et al., 2008).

4.4 Netherlands

The Damage Scanner is based on depth-damage curves and economic values from the HIS-SSM module (The standard method for the detailed calculation of flood damage in the Netherlands). It uses aggregated land use data instead of individual units. The Damage Scanner uses "what-if analyses" to assess the projected damage in the case of a certain flood scenario, primarily using synthetic data. It has been used to estimate flood risk in the future in the presence of changing land use and climate. Maximum damage levels are derived from replacement values. Therefore, depth-damage curves, calculated as an additional 5% of direct losses, also apply to indirect losses. Another estimation model designed especially for the Dutch agricultural sector is Hoes and Schuurmans (Hoes & Schuurmans, 2005). This model, which operates at the mesoscale, focuses on water depth as a crucial parameter in assessing flood damages. It is also based on a synthetic method and provides information on the relative losses suffered by farm infrastructure, farmhouses, and agricultural products as a result of flooding disasters. approach.

4.5 Belgium

The Flemish model, developed for the Flemish Environmental Agency in Belgium, provides detailed flood damage estimation (Vanneuville et al., 2006). Similar to the Damage Scanner, the Flemish approach is primarily meant for assessments using aggregated land use data at the national and regional levels. The model has been applied to identify susceptible areas and decide which investments in flood protection are most beneficial (Giron et al., 2010). The country's surface areas, market values, and housing expenses are averaged to produce the maximum damage values for the Flemish model. Of the structural losses, half should be accounted for by residential content damage. In addition to the direct damage, some indirect costs are included, ranging from 10% for agriculture to 40% for industry. The Flemish model has distinct structure and content classes for residential areas, and it has one industry class (industrial plus commerce) and one class for infrastructure. The model is based on a synthetic data approach to project future flood risk.

4.6 European Union

The European Commission's Joint Research Centre Institute for Environment and Sustainability (JRC-IES) developed a JRC damage model to assist with European flood risk management policies (Huizinga, 2007). The trends of flood risk in Europe under climate change have been estimated using this model (Ciscar et al., 2011; Feyen et al., 2011). The JRC Model includes maximum damage values and differentiated relative depth-damage functions for each of the EU-27-member states. Properties fall into one of five damage classes: road, industrial, commercial, residential, and agricultural. As a result, a weighted average of the maximum damage values and the relative depth-damage functions is multiplied by the flood depth of each grid cell. It empirically validates total losses to buildings, structures, and contents and proceeds with the creation of empirical-synthetic models.

4.7 Australia

The two primary models used in Australia are RAM (NRE, 2000) and Anuflood (NR&M, 2002). The RAM Model differs in development, functions, parameters, and predicted damage categories as compared to other models discussed above to quantify the direct damages suffered by companies. The model operates at the micro-scale, emphasizing individual objects within facilities. Only 1000 square meters or more businesses are eligible to use this model. Using an empirical methodology, the parameters considered are water depth, object size, and object susceptibility. It expresses damages overall for all asset classes and computes damages in absolute terms (NRE, 2000).

The Australian National University's Centre for Resource and Environmental Studies (CRES) developed Anuflood (NR&M, 2002), a second Australian model almost exact to RAM, to evaluate flood damage to residential and commercial properties using synthetic stage damage curves. It connects the floor area of the building to the size of the company. RAM is designed for industrial sector in Australia, which operates at the micro-scale, focusing on individual objects within facilities. This model considers parameters such as object type, lead time, and flood experience to assess flood risks empirically and synthetically. RAM enables the evaluation of absolute total losses to building structures and contents, providing valuable insights for mitigating flood risks and enhancing resilience in industrial environments.

4.8 Japan

Dutta et al. (2003) developed a model in Japan that accounts for the primary physical processes in a river basin when simulating flood inundation and incorporates the stage-damage relationship between flood parameters and various land use factors when estimating

economic loss. A novel approach to flood loss estimation: an integrated, grid-based model. It offers the spatial distribution of flood losses at any given time on a micro-scale and the overall losses for any given flood event. The loss estimating model has empirical model development with a relative loss function that calculates losses of agriculture products, farmhouses, and loss to farm infrastructure.

Table 1. Comparison table of 18 flood-induced loss and damage estimation models
(Source: Author)

Flood Loss and Damage Model			Preliminary Stage		Input data	Loss or Damage Calculations			Differentiation of Results
S No	Model	Country	Sector	Spatial scale	Parameters	Model Development	Empirical Validation	Loss or Damage functions	
1	HAZUS-MH	USA	Residential Commercial Industrial Roads Agriculture	Micro Scale, Meso scale	Water Depth, Object Type	Empirical-Synthetic	Yes	Relative	Loss to Building Structures, Loss to Equipment, Loss to Inventory
2	Multi-Coloured Manual	UK	Residential Commercial Industrial Roads Agriculture	Micro scale, Meso scale	Water Depth, Flood Duration, Object Type, Lead Time	Synthetic	Limited	Absolute	Loss to Building Structures, Loss to Equipment, Loss to Immobile Inventory, Loss to Mobile Inventory, Loss to Stock
3	FLEMO	Germany	Residential Commercial Industrial Roads Agriculture	Micro scale, Meso scale	Water Depth, Contamination, Precaution, Sector, Size of Company	Empirical	Yes	Relative	Loss to Building Structures, Loss to Equipment, Loss to Inventory
4	MURL	Germany	Industrial	Meso scale	Water depth	Empirical	Yes	Relative	Loss to Building Structures, Loss to Equipment, Loss to Inventory
5	Hydrotec	Germany	Industrial	Meso scale	Water depth	Empirical	Yes	Relative	Total Losses to Building and Equipment
6	ICPR	Germany	Residential	Meso scale	Water depth	Empirical-Synthetic	Yes	Relative	Loss to Building Structures, Loss to Equipment, Loss to Inventory
7	LfUG SAXONY	Germany	Agriculture Industrial	Meso scale	Water depth or Specific	Empirical-Synthetic	Yes	Relative	Loss to Building

					Discharge (in sq.m.)				Structures, Loss to Equipment, Loss to Inventory
8	Neubert and Thiel	Germany	Agriculture	Meso scale	Submersion Period	Synthetic	No	Relative	Loss of Agriculture Products, Loss to Farm Houses, Loss to Farm Infrastructure
9	MEDIS-Model	Germany	Agriculture	Meso scale	Flood duration, submersion period, crop type	Empirical-Synthetic	Yes	Relative	Loss of Agriculture Products, Loss to Farm Houses, Loss to Farm Infrastructure
10	Damage Scanner	Netherlands	Residential Commercial Industrial Roads Agriculture	Micro scale, Meso scale	Water Depth	Synthetic	No	Relative	Estimation of Future Flood Risk under climate and Land Use Changes,
11	Hoes and Schuurmans	Netherlands	Agriculture	Meso scale	Water Depth	Synthetic	No	Relative	Loss of Agriculture Products, Loss to Farm Houses, Loss to Farm Infrastructure
12	Flemish Model	Belgium	Residential Commercial Industrial Roads Agriculture	Micro scale, Meso scale	Water Depth	Synthetic	No	Relative	Total Losses to Building Structures and Contents
13	Citeau	France	Agriculture	Meso scale	Water Depth, Flood Duration, Flow Velocity, Submersion Period, Crop Type	Synthetic	No	Relative	Loss of Agriculture Products, Loss to Farm Houses, Loss to Farm Infrastructure
14	Rhine Atlas	Rhine Basin	Residential Industrial Infrastructure	Micro scale, Meso scale	Water Depth	Empirical-Synthetic	Yes	Relative	Total Losses to Building Structures and Contents
15	JRC Model	EU	Residential Commercial Industrial Roads Agriculture	Meso scale	Water depth	Empirical-Synthetic	Yes	Relative	Total Losses to Building Structures and Contents
16	RAM	Australia	Industrial	Micro scale	Object Type, Lead Time, Flood Experience	Empirical-Synthetic	Yes	Absolute	Total Losses to Building Structures and Contents
17	Anuflood	Australia	Industrial	Micro scale	Water Depth, Object Size, Object	Empirical	Yes	Absolute	Total Losses to Building Structures and

					Susceptibility				Inventory
18	Dutta et al.	Japan	Agriculture	Micro scale	Water Depth, Flood Duration, Submersion Period, Crop Type	Empirical	Yes	Relative	Loss of Agriculture Products, Loss to Farm Houses, Loss to Farm Infrastructure

5. DISCUSSION

In the context of climate change discussions, the debate over loss and damage is complex and multidimensional, often highlighting the disparities between developed and developing nations. The main points of contention in the discussion are accountability for the existing state of affairs and fair allocation of funds from the "Loss and Damage Fund" to mitigate the effects of climate change. As evidenced by the persistent use of terms like "shall" and "should" in international agreements, there is a recognized need for action; however, translating these commitments into tangible outcomes remains a challenge. One of the key issues within the discussion is the lack of clarity regarding funding mechanisms and the criteria for accessing financial assistance from entities such as the UNFCCC loss and damage fund. The distinction between economic loss and damage (ELD) and non-economic loss and damage (NELD) adds another layer of complexity, with differing opinions on which should be prioritized and how losses should be quantified. This lack of clarity disproportionately affects under-developed nations and small island states, which often bear the brunt of climate-related disasters but struggle to access adequate support. Moreover, the focus on flood hazards within the discourse underscores the urgent need for robust methodologies for estimating losses and damages. The dominance of models from developed nations highlights the significant gap in resources and capacity across various regions when mitigating loss and damage caused by climate change.

The aforementioned discussion of flood-induced loss and damage estimation models highlights the various techniques and factors that need to be considered. These include sector-specific vulnerabilities, regional complexity, and the multifaceted nature of flood risk assessment and management. Customized procedures are, therefore, necessary. The need for an intricate and context-specific approach to flood-induced loss and damage estimation, assessment, and management is highlighted by the differences in sector coverage, parameters, and the level of empirical validation, even though their model development and assessment of loss and damage share common elements. The inputs included in flood L&D models are crucial in approximating and assessing the possible consequences of flood occurrences in various industries. Water depth, as one of the key indicators, offers vital information about the amount of flooding and possible structural harm to infrastructure, buildings, and farmland. However, the duration of the flood informs us how long we were exposed to the floodwaters, which immediately impacts the amount of loss and damage. By classifying objects according to their types, vulnerabilities specific to various assets and structures—from homes to

factories—can be evaluated. Prior to a flood, lead time provides important preparation that makes proactive measures like asset protection or evacuation possible. Floodwater contaminants are attributed to contamination, which influences the degree of damage, especially in industrial and agricultural environments. The submersion period specifies how long areas or assets remain submerged, which is critical for assessing impacts on agriculture, infrastructure, and equipment. Lastly, specific discharge evaluates the force and velocity of floodwaters, providing insights into their effects on structures and land use.

In-depth sector and spatial coverage are provided by HAZUS-MH, Multi-Coloured Manual, FLEMO, Damage Scanner, Flemish model, and JRC model, which consider various residential, commercial, industrial, agricultural, and infrastructure sectors. They enable a thorough analysis of flood-induced loss and damage across many regions by operating at micro or meso sizes. Furthermore, models from Australia, Germany, the United States, and Japan have been empirically validated, demonstrating their dependability in replicating actual flood events and their aftermath. Additionally, these models assess relative or absolute loss for building structures, equipment, inventory, and other assets, providing useful information for risk management and disaster recovery planning. The inadequate empirical validation of the Multi-Coloured Manual may impact its accuracy and dependability for calculating the effects of flooding. Additionally, some models rely solely on synthetic data methods, which may introduce limitations in accurately representing the complexity of real-world flood events and their consequences. Moreover, the meso or micro-scale of some models may not fully capture the broader regional or macro-level impacts of floods, potentially limiting their applicability in larger-scale L&D estimation. HAZUS enables sector-specific damage calculations and offers more precise damage rate assessments due to its detailed flooding water depth ranges, unlike methods that rely on total area calculations without sector differentiation (Spor & Doğan, 2024).

While significant progress has been made in damage data collection, analysis, and model development, challenges persist in aligning the relevance of damage assessments with the quality of models and datasets. Many models rely on simplified approaches due to data and knowledge limitations, with results often influenced by assumptions such as spatial and temporal boundaries or valuation methods like replacement costs versus depreciated values. There is a pressing need for robust empirical and synthetic data collection to provide reliable inputs for practitioners. However, validation of damage models and uncertainty analyses are rarely conducted, leading to potential inaccuracies. Moreover, flood risk assessments often prioritize hazard evaluation over damage assessment, underscoring the need for a more balanced approach to improve methodologies across natural hazard domains.

Uncertainties in vulnerability and exposure, such as population and asset distribution, as well as building and infrastructure resilience, also play a significant role in assessing potential damage and losses. Uncertainties in socio-economic and behavioural aspects, including human response and economic resilience, introduce variability in post-flood recovery efforts. Future climate projections, data quality and availability, model parameterization, and

simplifications also contribute to uncertainties in flood impact assessments (Diaz & Moore, 2017). Flood damage models vary widely in methodology, with infrastructural damage estimation being less developed than for buildings. There is a high sensitivity of model outcomes to uncertainties in vulnerability (depth-damage functions) and exposure (asset values), with vulnerability having a greater impact (Jongman et al., 2012). A harmonized framework is needed to enhance reliability while accommodating regional adjustments. Addressing these uncertainties requires a comprehensive approach, including improved data collection and validation, robust modeling techniques, scenario-based analysis, and stakeholder engagement to account for the dynamic nature of flood losses. However, as this paper's methodology is based on desktop research, it is limited in its ability to involve stakeholders and fully incorporate socio-economic aspects directly. The depth of research is limited by the absence of participatory input and on-ground validation, especially when it comes to capturing the unique aspects of flood impact and recovery in a given area.

6. CONCLUSION AND WAY FORWARD

The concept of loss and damage, often framed as the "residual of adaptation," has emerged as a crucial component in the fight against the impacts of climate change. By acknowledging that despite efforts to adapt, some level of loss and damage still may occur. This perspective underscores the importance of addressing the residual impacts in addition to mitigation and adaptation. Incorporating loss and damage estimation into climate action strategies is essential for accurately calculating its extent and developing comprehensive and effective responses for enhancing our ability to mitigate and cope with the consequences of climate change. The predominance of models originating from developed countries underscores the significant gap in capacity and resources between different regions in addressing climate-related loss and damage. This observation highlights the need for concerted efforts to bridge this disparity, with a particular emphasis on supporting developing and under-developed nations in building their own capacities for loss and damage assessment.

Mapping the geographical distribution of hazards, estimating economic damages, and assessing potential societal repercussions of flood disasters are just a few additional practical applications for the L&D estimation model. The model's output helps in informed decision-making when creating policies for mitigation, emergency preparedness, and recovery to lower flood risk vulnerability and increase community resilience to natural hazards. The detailed comparison of various flood-induced loss and damage estimation models from different countries provides valuable insights into the diverse approaches for estimating losses. These models demonstrate a comprehensive sectoral coverage, highlighting and recognizing the multi-sectoral impact of floods and the need for specialized methodologies to address sector-specific vulnerabilities. Moreover, most models utilize empirical or empirical-synthetic model development approaches, using historical data underscoring a reliance on empirical data and scientific methods for constructing their models. However, the validation

status varies across the models, with some having undergone empirical validation while others have limited or no empirical validation. This variation in validation status may impact the reliability and accuracy of the models' results, emphasizing the importance of robust validation processes in ensuring their credibility. Despite progress in damage data and model development, gaps remain in aligning assessments with reliable data. Simplified approaches, limited validation, and insufficient uncertainty analyses hinder accuracy. Flood risk assessments often emphasize hazards over damage, highlighting the need for balanced methodologies and robust data collection.

Moreover, the study does not extensively address the potential biases or uncertainties associated with the empirical data and methodologies used in developing the models, indicating a need for a more in-depth exploration of these aspects. Lastly, while the study discusses the sectoral coverage of the models, it does not extensively delve into the interdependencies and cascading effects of flood impacts across different sectors, which could be valuable for a more holistic understanding of flood-induced loss and damage. Addressing these limitations through further research and a more comprehensive approach to loss and damage estimation would contribute to a more robust and deeper global understanding of global flood risks.

REFERENCES

- AOSIS. (1991). Submission on Behalf of AOSIS: Draft Annex Relating to Article 23 (Insurance) for Inclusion in the Revised Single Text on Elements Relating to Mechanisms. In Intergovernmental Negotiating Committee for a Framework Convention on Climate Change: Working Group II, Vanuatu, (A/AC.237/WG.II/Misc.13). Submitted by the Co-Chairmen of Working Group II, 4th session, Agenda Item 2(b), UN Doc A/AC.237/WG.II/CRP.8.
- AOSIS. (2008). Proposal to the AWG-LCA multi-window mechanism to address loss and damage from climate change impacts. 1–8.
- Alfieri, L., Burek, P., Feyen, L., & Forzieri, G. (2015). Global warming increases the frequency of river floods in Europe. *Hydrology and Earth System Sciences*, 19(5), 2247-2260.
- Apel, H., Aronica, G. T., Kreibich, H., & Thielen, A. H. (2009). Flood risk analyses—how detailed do we need to be?. *Natural hazards*, 49, 79-98.
- APFM. (2007). Guidance on flash flood management: recent experiences from central and eastern Europe.
- Arnell, N. W., & Gosling, S. N. (2016). The impacts of climate change on river flood risk at the global scale. *Climatic Change*, 134, 387-401.
- Bahinipati, C. S., & Gupta, A. K. (2022). Methodological challenges in assessing loss and damage from climate-related extreme events and slow onset disasters: Evidence from India. *International Journal of Disaster Risk Reduction*, 83, 103418.
- Bai, Y., Zhang, Z., & Zhao, W. (2019). Assessing the impact of climate change on flood events using HEC-HMS and CMIP5. *Water, Air, & Soil Pollution*, 230(6), 119.

- Bianchi, S., Ciurlanti, J., Overend, M., & Pampanin, S. (2022). A probabilistic-based framework for the integrated assessment of seismic and energy economic losses of buildings. *Engineering Structures*, 269, 114852.
- Boyd, E., Chaffin, B. C., Dorkenoo, K., Jackson, G., Harrington, L., N'guetta, A., ... & Stuart-Smith, R. (2021). Loss and damage from climate change: A new climate justice agenda. *One Earth*, 4(10), 1365-1370.
- Broberg, M., & Romera, B. M. (Eds.). (2021). The third pillar of international climate change policy: on 'loss and damage' after the Paris Agreement. Routledge.
- Broberg, M., & Romera, B. M. (2021). Loss and Damage after Paris: All Talk and No Action?. In *The Third Pillar of International Climate Change Policy* (pp. 1-8). Routledge.
- Calliari, E. (2018). Loss and damage: a critical discourse analysis of Parties' positions in climate change negotiations. *Journal of Risk Research*, 21(6), 725-747.
- Calliari, E., & Ryder, B. (2023). What Does Loss and Damage Mean at the Country Level? A Global Mapping Through Nationally Determined Contributions. *Global Environmental Politics*, 23(3), 71-94.
- Calliari, E., Serdeczny, O., & Vanhala, L. (2020). Making sense of the politics in the climate change loss & damage debate. *Global Environmental Change*, 64, 102133.
- Ciscar, J.-C., Iglesias, A., Feyen, L., Szabó, L., Van Regemorter, D., Amelung, B., Nicholls, R., Watkiss, P., Christensen, O. B., Dankers, R., Garrote, L., Goodess, C. M., Hunt, A., Moreno, A., Richards, J., & Soria, A. (2011). Physical and economic consequences of climate change in Europe. *Proceedings of the National Academy of Sciences of the United States of America*, 108, 2678–2683.
- CRED. "2023 Disasters in Number", Brussels: CRED, 2024. The full report is available at : https://files.emdat.be/reports/2023_EMDAT_report.pdf
- Diaz, D., & Moore, F. (2017). Quantifying the economic risks of climate change. *Nature Climate Change*, 7(11), 774-782.
- Doktycz, C., & Abkowitz, M. (2019). Loss and damage estimation for extreme weather events: State of the practice. *Sustainability*, 11(15), 4243.
- Dorkenoo, K., Scown, M., & Boyd, E. (2022). A critical review of disproportionality in loss and damage from climate change. *Wiley Interdisciplinary Reviews: Climate Change*, 13(4), e770.
- Dutta, D., Herath, S., & Musiaka, K. (2003). A mathematical model for flood loss estimation. *Journal of hydrology*, 277(1-2), 24-49.
- Emschergenossenschaft & Hydrotec. (2004). Hochwasser-Aktionsplan Emscher, Kapitel 1: Methodik der Schadensermittlung [Flood Action Plan Emscher, Chapter 1: Methodology of Damage Assessment]. Emschergenossenschaft.
- FEMA (Federal Emergency Management Agency) (2003). Repetitive Loss Property Action Plan Discussion and Planning Session. FEMA, Washington, DC.
- Feyen, L., Dankers, R., Bódis, K., Salamon, P., & Barredo, J. I. (2011). Fluvial flood risk in Europe in present and future climates. *Climatic Change*, 112, 47–62. <https://doi.org/10.1007/s10584-011-0339-7>

- Forster, S., Kuhlmann, B., Lindenschmidt, K.-E., & Bronstert, A. (2008). Assessing flood risk for a rural detention area. *Natural Hazards and Earth System Sciences*, 8, 311–322. <https://doi.org/10.5194/nhess-8-311-2008>
- Giron, E., Joachain, H., Degroof, A., Hecq, W., Coninx, I., Bachus, K., ... & De Sutter, R. (2010). TOWARDS AN INTEGRATED DECISION TOOL FOR ADAPTATION MEASURES—CASE STUDY: FLOODS “ADAPT”. *Final report for Belgian Science Policy Office*.
- Goyal, S. and Mukherjee, M.: Comprehensive Assessment of Climate-Induced Disaster Losses in Uttarakhand: A Time-Series Analysis and Vulnerability Mapping Approach , EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-18267, <https://doi.org/10.5194/egusphere-egu24-18267>, 2024.
- Goyal, S. and Mukherjee, M.: ELD and NELD Prioritization for Multi-Hazard Loss and Damage in Rural and Urban Areas of Uttarakhand’s Himalayan Districts, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-6259, <https://doi.org/10.5194/egusphere-egu25-6259>, 2025.
- Hirabayashi, Y., Alifu, H., Yamazaki, D., Imada, Y., Shiogama, H., & Kimura, Y. (2021). Anthropogenic climate change has changed frequency of past flood during 2010–2013. *Progress in Earth and Planetary Science*, 8(1), 1–9.
- Hoes, O., & Schuurmans, W. (2005). Flood standards or risk analyses for polder management in the Netherlands. Paper presented at the ICID 21st European Regional Conference, Frankfurt (Oder) and Slubice, Germany and Poland.
- Hossain, M. F., Huq, S., & Khan, M. R. (2021). The intractability of loss and damage issues in climate negotiations. *Soundings*, 78(78), 38–49.
- Huizinga, H. J. (2007). Flood damage functions for the EU member states. Implemented in the framework of the contract #382442-F1SC awarded by the European Commission – Joint Research Centre. HKV consultants.
- International Commission for the Protection of the Rhine. (2001). Rhine-Atlas. Koblenz: ICPR. Retrieved from <http://www.rheinatlas.de>
- INC. (1991) Vanuatu: Draft annex relating to Article 23 (Insurance) for inclusion in the revised single text on elements relating to mechanisms (A/AC.237/WG.II/Misc.13) submitted by the Co-Chairmen of Working Group II.
- Jongman, B., Kreibich, H., Apel, H., Barredo, J. I., Bates, P. D., Feyen, L., Gericke, A., Neal, J., Aerts, J. C. J. H., and Ward, P. J.: Comparative flood damage model assessment: towards a European approach, *Nat. Hazards Earth Syst. Sci.*, 12, 3733–3752, <https://doi.org/10.5194/nhess-12-3733-2012>, 2012.
- Karimi-Schmidt, Y. (2020). The Issues of Loss and Damage Within the International Climate Law.
- Kreibich, H., Seifert, I., Merz, B., & Thielen, A. H. (2010). Development of FLEMOcs—a new model for the estimation of flood losses in the commercial sector. *Hydrological Sciences Journal—Journal des Sciences Hydrologiques*, 55(8), 1302–1314.
- LfUG Sächsisches Landesamt für Umwelt und Geologie [Saxon State Office for Environment and Geology]. (2005). Hochwasser in Sachsen, Gefahrenhinweiskarten [Floods in Saxony, Hazard Warning Maps]. Report.

- Mace, M. J., & Verheyen, R. (2016). Loss, damage and responsibility after COP 21: All options open for the Paris Agreement. *Review of European, Comparative & International Environmental Law*, 25(2), 197-214.
- McGrath, H., Abo El Ezz, A., & Nastev, M. (2019). Probabilistic depth–damage curves for assessment of flood-induced building losses. *Natural Hazards*, 97, 1-14.
- McNamara, K. E., & Jackson, G. (2019). Loss and damage: A review of the literature and directions for future research. *Wiley Interdisciplinary Reviews: Climate Change*, 10(2), e564.
- Mechler, R., Calliari, E., Bouwer, L. M., Schinko, T., Surminski, S., Linnerooth-Bayer, J., ... & Zommers, Z. (2019). Science for loss and damage. Findings and propositions. *Loss and damage from climate change: Concepts, methods and policy options*, 3-37.
- Merz, B., Kreibich, H., Schwarze, R., & Thielen, A. (2010). Review article" Assessment of economic flood damage". *Natural Hazards and Earth System Sciences*, 10(8), 1697-1724.
- Merz, B., Kreibich, H., Thielen, A., & Schmidtke, R. (2004). Estimation uncertainty of direct monetary flood damage to buildings. *Natural Hazards and Earth System Sciences*, 4(1), 153-163.
- Messner, F. (2007). Evaluating flood damages: guidance and recommendations on principles and methods. *T09-06-01*.
- Messner, F., & Meyer, V. (2006). Flood damage, vulnerability and risk perception–challenges for flood damage research. In *Flood risk management: hazards, vulnerability and mitigation measures* (pp. 149-167). Dordrecht: Springer Netherlands.
- Meyer, V., Becker, N., Markantonis, V., Schwarze, R., van den Bergh, J. C., Bouwer, L. M., ... & Viavattene, C. (2013). Assessing the costs of natural hazards–state of the art and knowledge gaps. *Natural Hazards and Earth System Sciences*, 13(5), 1351-1373.
- Middelmann-Fernandes, M. H. (2010). Flood damage estimation beyond stage–damage functions: an Australian example. *Journal of Flood Risk Management*, 3(1), 88-96.
- MURL (Ministerium für Umwelt, Raumordnung und Landwirtschaft des Landes Nordrhein-Westfalen). (2000). Potentielle Hochwasserschäden am Rhein in Nordrhein-Westfalen [Potential flood damages along the Rhine in North Rhine-Westphalia]. Düsseldorf.
- Najibi, N., & Devineni, N. (2018). Recent trends in the frequency and duration of global floods. *Earth System Dynamics*, 9(2), 757-783.
- Neubert, G., & Thiel, R. (2004). Schadenpotentiale in der Landwirtschaft [Damage potentials in agriculture]. In A. Bronstert (Ed.), *Möglichkeiten zur Minderung des Hochwasserrisikos durch Nutzung von Flutpoldern an Havel und Oder* (pp. 117–129). Universitätsverlag Potsdam, Germany. Retrieved from <http://opus.kobv.de/ubp/volltexte/2005/416/pdf/Heft%2015%20Jg%202004.pdf>
- NRE Victorian Department of Natural Resources and Environment, Victoria. (2000). Rapid Appraisal Method (RAM) for Floodplain Management. Report prepared by Read Sturgess and Associates. Melbourne, Australia.
- NR&M Department of Natural Resources and Mines, Queensland Government. (2002). Guidance on the Assessment of Tangible Flood Damages. Report. Queensland, Australia.
- Orcherton, D. F. (2023). Intangible Losses, Damages and at-Risk Settlements: The Extent of Casualty and Burden of Proof for Climate Related Loss and Damage in the Fiji Islands. *J. Env'tl. L. & Pol'y*, 3, 108.

- Page, E. A., & Heyward, C. (2017). Compensating for climate change loss and damage. *Political Studies*, 65(2), 356-372.
- Penning-Rowsell, E., Johnson, C., Tunstall, S., Tapsell, S., Morris, J., Chatterton, J., & Green, C. (2005). The benefits of flood and coastal risk management: a handbook of assessment techniques. ISBN 1904750516.
- Romali, N. S., Sulaiman, M. S. A. K., Yusop, Z., & Ismail, Z. (2015). Flood damage assessment: A review of flood stage–damage function curve. In ISFRAM 2014: Proceedings of the International Symposium on Flood Research and Management (pp. 147-159). Springer Singapore.
- Sacramento, N. J. (2023). Grassroots involvement on Global South policy narratives and deliberative action on climate change loss and damage. *Public Administration and Policy*, 26(2), 156-168.
- Scawthorn, C., Flores, P., Blais, N., Seligson, H., Tate, E., Chang, S., ... & Lawrence, M. (2006). HAZUS-MH flood loss estimation methodology. II. Damage and loss assessment. *Natural Hazards Review*, 7(2), 72-81.
- Schinko, T., & Mechler, R. (2017). Applying recent insights from climate risk management to operationalize the loss and damage mechanism.
- Serdeczny, O. M., Bauer, S., & Huq, S. (2018). Non-economic losses from climate change: opportunities for policy-oriented research. *Climate and Development*, 10(2), 97-101.
- Spor, P., & Doğan, E. (2024). Comparing Flood Damages to an Industrial Region in Turkey Using Several Methods. *Water Economics & Policy*, 10(2)
- Taub, J., Nasir, N., Rahman, M. F., & Huq, S. (2016). From Paris to Marrakech: global politics around loss and damage. *India Quarterly*, 72(4), 317-329.
- UNFCCC. (2007). Decision 1/CP.13, Bali Action Plan, UN Doc FCCC/CP/2007/6/Add.1
- UNFCCC. (2009). Ideas and proposals on the elements contained in paragraph 1 of the Bali Action Plan
- UNFCCC. (2010). Decision 1/CP.16, The Cancun agreements: outcome of the work of the ad hoc working group on Long-term Cooperative Action under the Convention, UN Doc FCCC/CP/2010/7/Add.1
- UNFCCC. (2012). Decision 3/CP.18, Approaches to address loss and damage associated with climate change impacts in developing countries that are particularly vulnerable to the adverse effects of climate change to enhance adaptive capacity, UN Doc FCCC/CP/2012/8/Add.1
- UNFCCC. (2015). Decision 1/CP.21, Adoption of the Paris Agreement, UN Doc FCCC/CP/2015/10/Add.1
- UNFCCC. (2019). Decision 2/CMA.2, para 43, Report of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on its second session, held in Madrid from 2 to 15 December 2019, UN Doc FCCC/PA/CMA/2019/6/Add.1
- UNFCCC. (2021). Decision 11/CMA.3, Report of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on its third session, held in Glasgow from 31 October to 13 November 2021, UN Doc FCCC/PA/CMA/2021/10/Add.3

- UNFCCC. (2022). Decision 11/CP.27, Report of the Conference of the Parties on its twenty-seventh session, held in Sharm el-Sheikh from 6 to 20 November 2022, UN Doc FCCC/CP/2022/10/Add.1
- UNFCCC. (2023). COP28 Agreement Signals “Beginning of the End” of the Fossil Fuel Era Available at: <https://unfccc.int/news/cop28-agreement-signals-beginning-of-the-end-of-the-fossil-fuel-era>
- UNFCCC. (2024). COP29 Decision -/CMA.6 New collective quantified goal on climate finance Available at: https://unfccc.int/sites/default/files/resource/CMA_11%28a%29_NCQG.pdf
- Vanhala, L., & Hestbaek, C. (2016). Framing climate change loss and damage in UNFCCC negotiations. *Global Environmental Politics*, 16(4), 111-129.
- Vanneuville, W., Maddens, R., Collard, C., Bogaert, P., De Maeyer, P., & Antrop, M. (2006). Impact on people and the economy as a result of flooding viewed in the light of changing hydraulic conditions, environmental factors and climatic conditions.
- Wasko, C., Nathan, R., Stein, L., & O'Shea, D. (2021). Evidence of shorter more extreme rainfalls and increased flood variability under climate change. *Journal of Hydrology*, 603, 126994.