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Review

Flood Damage Assessment: A Review of Microscale Methodologies for Residential Buildings

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Abstract: Flood damage assessment (FDA) is an essential tool for evaluating flood damage, vulnerability, and risk to civil systems such as residential buildings. The outcome of an FDA depends on the spatial limits of the study and the complexity of the data. For microscale FDA, a high level of detail is required to assess flood damage. This study reviewed the existing methodologies in microscale FDA based on empirical and synthetic data selection methods for model development. The merits and challenges of these approaches are discussed. This review also proposes an integrated step for assessing the stages of FDA. This study contributes to the literature by providing insights into the methodologies adopted, particularly on a microscale basis, which has not been comprehensively discussed in the previous reviews. The findings of this study reveal that univariate modeling of flood damage is nevertheless popular among researchers. New advanced approaches, such as advanced machine learning and 3D models, are yet to gain prominence when compared with the univariate modeling that has recorded a high success. This review concludes that there is a need to adopt a combined empirical–synthetic approach in the selection of data for developing damage models. Further research is required in the areas of multivariate modeling (advanced machine learning), 3D BIM-GIS modeling, 3D visualization of damages, and projection of probabilities in flood damage predictions to buildings. These are essential for performance flood-based building designs and for promoting building resilience to flood damage.

Keywords: flood damage assessment; microscale; damage model; vulnerability function; building damage; 3D BIM-GIS modeling

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1. Introduction

Flooding is one of the most widespread natural disasters that cause fatal and costly damage to the economy, infrastructure, environment, people, and other aspects of life [1]. The current climate crisis combined with the intensifying effects of global warming adversely impact the environment and increases the frequency of flood events and the associated damages. Since 1980, losses related to flooding have accounted for approximately 40% of all natural catastrophes, with estimated losses of more than U.S. $1 trillion (www.marshmclennan.com). Flooding events topped the list of the most disastrous incidences worldwide, with 223 documented occurrences in 2021 alone which is significantly more than the total number of flood disasters in the previous 10 years [2]. Similarly, in 2021, Asia experienced the highest flood damage among all continents in the world, as shown in Figure 1. Furthermore, the recent climate change is expected to increase flood hazards in many regions worldwide [3,4].

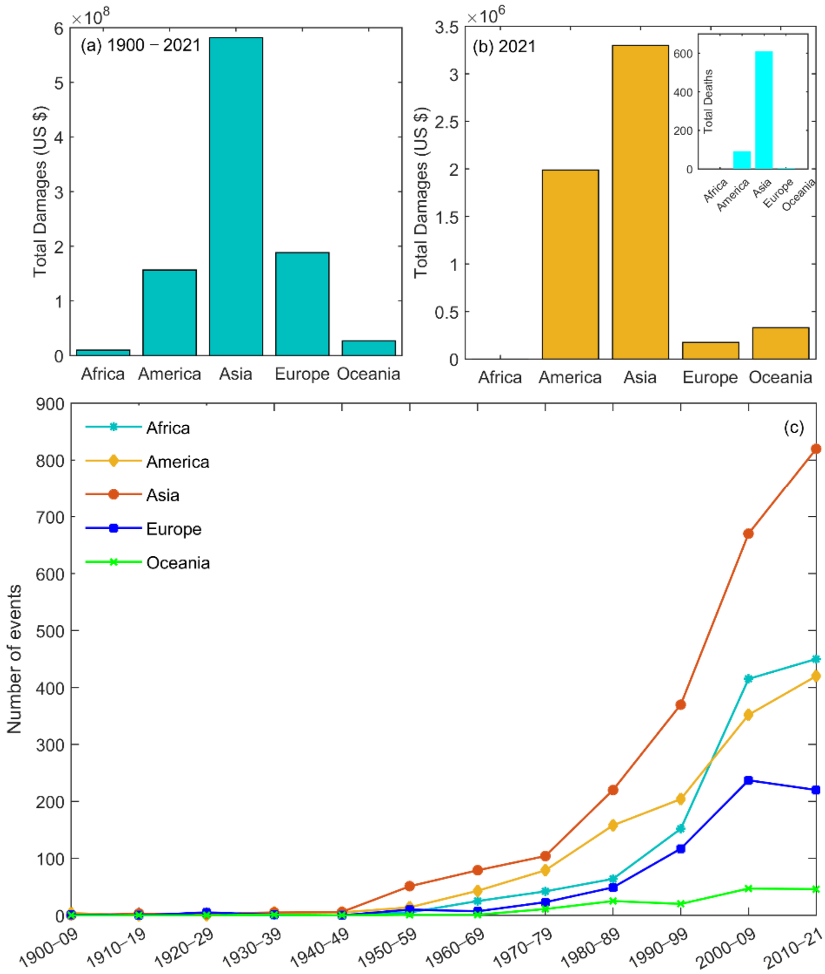

Figure 1. Flood disaster: (**a**) total damages caused by floods in each continent since 1900, (**b**) total damage and human deaths caused by flash floods and riverine floods in 2021, and (**c**) number of major floods reported in each continent since 1900 (Source: EM–DAT, www.emdat.be).

In most regions, flooding disasters are caused by heavy rainfall [4–6]. It typically precedes the occurrence of other causal factors, such as broken dams and overflowing rivers [7]. For instance, in countries, such as Australia, South Korea, India, and Myanmar, the bulk of flood damage is related to heavy rain [8–10]. Zurich [1] categorized flooding into three types: fluvial floods (riverine flooding), coastal floods (tidal/storm surge), and pluvial floods (flash floods and surface water). Fluvial and pluvial flooding are known to cause extensive damage globally, and their frequency of occurrence is higher than coastal floods [11]. Therefore, this review focuses on fluvial and pluvial flooding, since they are both triggered by rainfall and follow similar damage assessment methodologies [12]. Flood damage is generally divided into two groups: direct and indirect damage [13]. Indirect damage is the financial consequence of flood disasters due to the disruption of economic and social activities, whereas direct damage is caused by water directly hitting physical structures or items such as buildings [14,15]. These two groups of damage are subcategorised into intangible and tangible damages. Intangible damages cannot be quantified. However, tangible damages can be traded or transferred in monetary values and may therefore be described in economic terms [13,16]. The flood damage assessment (FDA) quantifies losses resulting from flood events. The outcomes are useful in the flood risk management recovery, preparation, mitigation, and response phases. The FDA evaluates potential flood consequences which are vital for stakeholder decision-making and policy development. It is useful for assessing flood vulnerability, risk mapping, and comparing risk analyses [17]. Other areas of importance include mapping the adverse effects of risks, flood financial appraisals for insurance and reinsurance sectors, and compensation after the occurrence of flood events [13,18,19].

According to [16,20], FDA methodologies are generally developed for three major spatial scales: macro, meso, and micro scales. The macro scale is for a larger nationwide coverage such as municipalities and can extend to countries, whereas the mesoscale is for land unit assessment, such as residential and administrative units, among others [21]. The microscale addresses building-specific risk reduction compared with the other two scales of spatial analysis and captures the heterogeneity of the exposed or at-risk elements [22,23]. The spatial scale of an FDA determines the complexity of the data to be utilized in the preparation of flood damage models [24]. For microscale assessment, comprehensive non-spatial and higher spatial resolution data significantly influenced the quality of the flood damage model. A flood damage model predicts building damage based on flood parameters (usually flood depth), building data, average building repair, and monetary cost [25,26]. The construction of the flood damage model was based on two modes of data selection: empirical (real) data and synthetic (hypothetical) data.

In the conventional approach, empirical and synthetic data were sourced through surveys, census, insurance claims payouts, and interviews. In later periods, GIS, satellite, and remote sensing techniques provided a more convenient solution as sources of data for building and flood-related information which improved time and cost efficiency and reduced the effort spent on field surveys [27,28]. Moreover, these data sources are typically applied in conjunction with traditional data sources, thus providing better solutions to the challenges of limited data availability [12]. In the conventional approach, linear regression analysis is used to construct the damage curves/functions [16,29]. Damage curves are graphical representations of building damage at a certain flood depth, mostly deterministic and quantitative in estimating damage [30,31]. The curves have been criticized for being univariate in the analysis of flood damage because they employ only flood depth as the explanatory flood parameter. These factors limit the reliability of providing an accurate prediction of flood damage and propagating uncertainties using the stage damage curves [32,33]. In general, the conventional approach often neglects the distribution of flood damage, the effects of building characteristics, and flood actions. A popular study on the overview of flood actions on buildings by Kelman and Spence [34] triggered a significant increase in the number of studies conducted on analytical/engineering damage analysis. For instance, the structural process of assessing the effects of flood damage on building components has gained considerable prominence [23,35,36]. Other areas that have gained substantial improvement are the probabilistic approach to modeling damages and fragility functions based on the damage states of buildings [36,37]. All these have contributed significantly to understanding the performance of buildings for certain attributes of flood, and the field of microscale FDA as well as the demand for more performance-based building designs have received continuous attention.

However, various researchers [10,23,38–41] have noted that there is a persistent need to bridge the gaps in achieving a reliable and accurate damage model. Such impediments include limited data availability; damage variations within building classes; limited knowledge of the model building, geometries of the building and flood parameters; uncertainties, and validation of models. Multivariate modeling and data mining approaches combined with machine learning models have recently gained prominence as advanced solutions to some of these limiting factors. In particular, the problem of data availability and the propagation of uncertainties. Similarly, a 3D modeling assessment of flood damage was also proposed to overcome the data availability challenges of past approaches. Amirebrahimi et al. [23] proposed a 3D model technology for building-specific damage assessment to provide high-quality information about building characteristics as well as damage visualization. These new approaches, i.e., advanced multivariate modeling and 3D modeling, are gradually gaining prominence. In recent times, more research has been conducted on the former than on the latter.

Rationally, irrespective of the attempt of new approaches to resolve these challenges, no unanimous solution to the challenges encountered while predicting accurate damage models is obtained [31]. To solve some of these challenges, these identified gaps need to be dealt with. Hence, no method embodies concerted solutions to the limitations of microscale flood damage assessment. This study aims to review the existing methodologies utilized in microscale FDA. Previously review works were conducted on general spatial scales of FDA [12,13] and specific methodologies of FDA, such as stage damage curves [16]. This study is specific in that it will consider various methodologies that have been utilized under the microscale FDA. Articles were selected to appraise these methodologies under empirical and synthetic modes of data selection. The merits and disadvantages of these approaches were also considered. In addition, the microscale FDA are carried out with dissimilar steps. The steps followed in conducting flood assessments are subject to the judgment and expertise of researchers. However, there are similarities between these steps. Such elements are aggregated in this review and proposed as an integrated step in assessing flood damage under microscale spatial analysis. In summary, this review is important to the literature, since it (i) reviews the existing methodologies utilized in the microscale FDA (ii) proposes an integrated step drawn from the literature for assessing flood damages under the microscale FDA and (iii) provides an extensive discussion on the stages of assessing flood damages under the microscale FDA. Therefore, providing insight into the past and current methodologies under the microscale FDA, the review is expected to support the evaluation and development of methodologies for microscale FDA by administrators, decision-makers in government agencies and emergency management organizations, and researchers on risk assessment, academics, as well as insurance companies. Moreover, this will help in improving the performance-based capabilities of buildings, and promoting building resilience to flood damages. This will further mitigate flood damages to buildings and strengthen the overall flood risk management process.

2. Methods: An Overview of Flood Damage Assessment

The purpose of this study is to review the methodologies utilized by previous researchers and propose an integrated step for assessing flood damage under microscale spatial analysis. We reviewed articles from the literature that spanned conventional and advanced methodologies. These review articles represent the existing methodologies that have been adopted for microscale FDA (see Table 1).

Table 1. Reviewed studies and their distinguishing features.

Studies	Data for Model Development	Hazard Parameter	Primary Techniques of Analysis
[10]	Empirical-synthetic	Flood depth	Regression model
[23]	Synthetic	Flood actions (hydrostatic and Hydrodynamics)	Engineering & 3D modeling framework
[35]	Synthetic	Flood depth Flood velocity	Probabilistic methodology- Monte Carlo simulation
[36]	Empirical-synthetic	Flood depth	Probabilistic Fragility analysis
[41]	Synthetic	Flood depth	UAV, Machine learning
[42]	Empirical	Flood depth	Multivariate regression analysis
[43]	Synthetic	Flood depth, flow velocity	Damage curves
[44]	Synthetic	Flood depth	Depth damage curves and the modeling techniques
[45]	Synthetic	An extensive list comprising flood depth, flood duration, water quality, sediment load, building characteristics, flood velocity, etc.	Probabilistic approach- Fragility curves
[46]	Empirical	Flood depth	Simple regression analysis
[47]	Synthetic	Flood depth	Depth-damage curves
[48]	Empirical	Flood depth Flood duration	Multiple regression model
[49]	Synthetic	Flood depth	Depth Damage Curves
[50]	Empirical	Flood depth	Vulnerability function
[51]	Empirical	Flood depth	Multiple regression analysis

Table 1. *Cont.*

Studies	Data for Model Development	Hazard Parameter	Primary Techniques of Analysis
[52]	Synthetic	Flood depth Flood duration	Single and multivariate Fragility curves
[53]	Synthetic	Flood depth Flood duration	Multiple regression analysis
[54]	Empirical	Flood extent, flood duration, flow velocity	Random forest and Artificial neural networks
[55]	Synthetic	Flood depth	GIS computational modeling
[56]	Emprical	Flood depth	Risk analysis
[57]	Empirical	Flood depth, floor space of building, return period, contamination, flood duration, precautionary measures	Tree-based analysis-regression trees & bagging decision trees

The remainder of this paper is structured into five sections. Section 2 covers the basics, categories, and spatial scales of FDA. A discussion of these fundamentals is pertinent to the understanding of this paper. Section 3 highlights the existing approaches of the microscale FDA, considering various research works under empirical and synthetic modes of data collection for model development. In Section 4, there are two sub-sections. Section 4.1 discusses the stages in assessing the FDA, as obtained from the literature. Section 4.2 discusses emerging concerns and future directions for research in the microscale FDA. Section 5 discusses the implications of the study. Section 6 summarises and highlights the conclusions of this study. In this study, the term "buildings" represents residential buildings. Thus, this study focused on residential buildings as elements at risk in a microscale spatial division.

2.1. Basics in Flood Damage Assessment

Building damage evaluation is conducted by the FDA in two categories: actual and potential damage. Actual damage is an estimation of the damage that occurs during a specific flood event, whereas potential damage is defined as the damage that occurs in the absence of any damage reduction measures [58,59]. These damages are evaluated based on the type of data input which may be real or hypothetical data. Furthermore, the FDA uses specific flood parameters or characteristics known as damage-influencing factors [13,60]. These factors are divided into two categories: resistance (vulnerability) and impact (hazard) parameters. Resistance parameters refer to the properties of the exposed objects (e.g., buildings) that are prone to flooding. These properties are reflected in their ability to resist the impacts of floods. Resistance parameters include residential buildings, type of buildings, building materials, emergency measures and responses, early flood warnings, and various precautionary measures [61–63].

The impact parameters refer to the flood's characteristic effects on buildings which can be determined by the type and magnitude of the flood. According to Clausen [64], the impact parameters are the water depth, flow velocity, bed shear stress, dynamic forces (flow momentum, stream power, and depth times speed), rate of flood rise, and debris potential of the landscape. Flood depth, also referred to as flood height, is the most commonly used parameter for determining the damage functions for buildings affected by a flood [32,65]. This is because the depth of a flood is easy to measure through visual means immediately after a flood occurrence and captures most of the variation in damage that occurs in certain types of buildings [48,66]. The floor depth is usually plotted against the damage ratio in terms of the actual damage or total value of the structure occurring at each flood depth.

Another important parameter is flood velocity which is commonly observed to have a negligible effect on buildings [60,67,68]. Nadal et al. [35] and Nofal and van de Lindt [36] used flood depth and flood velocity to estimate the extent of flood damage to buildings. Flood duration is often used as an arbitrary modifier for flood depth and is regarded as a critical damage factor [34]. During field surveys, flood duration cannot be visually recorded by respondents compared to flood depth which can be identified visually [10,69,70]. Other parameters include flood warning time, isolation, occurrence probability, debris impact loads, wave loads, and uplift pressures. These flood parameters are primarily ignored in flood damage modeling because of their heterogeneity in space and time, difficulty in prediction, and the paucity of records on their effects on buildings. In most situations, these effects cannot be measured numerically [13]. The relationship between flood parameters (flood depth) and flood damage is represented by the stage damage curves. These curves indicate the vulnerability of buildings at risk based on flood parameters. The water depth is called the depth function. Velocity is called the velocity-damage curve [35]. In contrast, fragility curves express the damage probability of a building in a set of damage states based on a given value of a flood parameter [37]. These curves can be developed using both synthetic and empirical approaches [71]. Irrespective of the flood parameters through which the curves are constructed, they are commonly referred to as damage curves.

2.2. Categories of FDA

FDA has been evaluated by considering certain factors. These factors include spatial scales, methods of cost estimation, data collection methods for model development, and the mode of expressing a form of loss/damage. Figure 2 shows a diagrammatic representation of these factors [13,19]. Factors based on spatial scales [13,19] are divided into macroscale, mesoscale, and microscale assessments (further discussion are provided in Section 2.3). Factors based on the methods of cost estimation [19] are also grouped into three methods: damage assessments through insurance data which is effective as an indicator of the physical damage from flooding. The challenge pertaining to this methodology is that not all affected households may be insured. Thus, there is an under-representation of the number of households affected, which also affects the outcome of damage quantification. The second group uses the unit cost or average method which applies an average loss value to each type of damage. Damage types can range from single damage types to hundreds of damage-type subcategories [19]. The total damage costs within the type are calculated by determining the type of objects flooded within a damage type and multiplying the number by the unit cost estimation. The stage damage curve is the third which estimates flood damage in an area based on the extent and magnitude of the flood. Damage curves were plotted against flood depth [54,72].

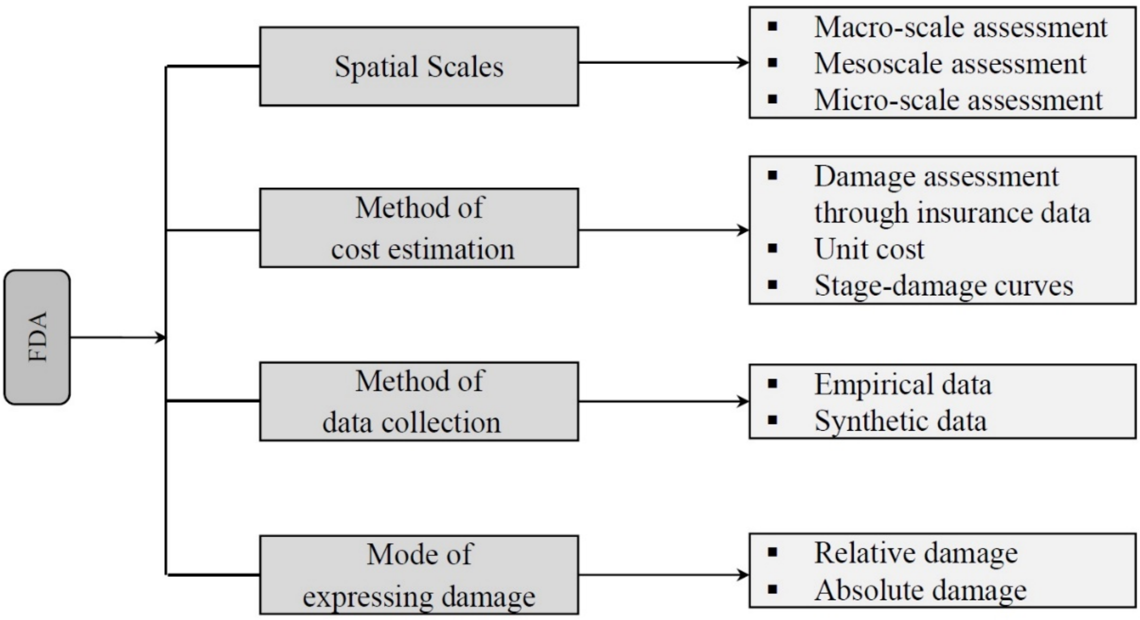

Figure 2. Diagrammatic representation of the categories of FDA.

FDA classification based on data collection methods for model development is grouped under two approaches: the empirical approach and the synthetic approach [12,13,73]. The empirical approach estimates actual or potential damage to a building from an actual flood event. The synthetic approach estimates potential damage to buildings from simulated/hypothetical flood events. It relies on information from hypothetical analysis and simulation modeling of real-life events. These two approaches are discussed in Section 3. The last classification is based on the mode of expressing a form of loss/damage, which includes relative damage and absolute damage [74]. The former considered the damage as a percentage of the total building value, whereas the latter expressed damage in monetary forms [40].

2.3. FDA at Different Spatial Scales

Flood damage assessment is significantly influenced by the spatial boundaries of the study [13]. FDA is performed at three spatial scales: macroscale, mesoscale, and microscale, based on the extent of the flood damage [13,19,21]. There has been considerable emphasis on the macro and meso scales, both in the literature and in government parastatals [20]. The distinction among the scales is evident in the extent of analysis and the data complexity required, as presented in Table 2. A macroscale assessment is conducted at the global or national level or based on the aggregation of cities such as municipalities and provinces. This assessment is less detailed in terms of data inputs, less precise, and requires less effort than the other two scales. The mesoscale assessment is based on land use categories connected to particular economic sectors, such as regions, cities, part of a large river, or the catchment of a smaller river [21]. Both the macroscale and mesoscale are essential for national and regional broad-scale flood risk management plans and development. However, they are insufficient for representing the needs of microscale applications because they have been found to ignore the uncertainty of the coefficient of regional differences and household diversity [42].

Table 2. Features of the three spatial scales for FDA (modified after [13,71]).

Spatial Scale	Size of Measurement	Data Complexity
Macroscale	Largest scale International/national boundaries or river basin Municipalities Countries	Less detailed data Low precision required
Mesoscale	Medium scale Sub-national Regional Large cities Certain watershed/catchment	Moderate data input than microscale Medium precision required
Microscale	Smallest scale A town, Community-scale Individual buildings Specific river stretch/single floodplains	Comprehensive data required Higher resolution of DEM and precision

Local studies employ a microscale assessment approach to calculate the damages for single properties. Thus, flood damage models are derived from object-specific data, related to single objects [22]. The development of building-specific damage models characterizes microscale damage assessments. Data collection is based on an empirical method to calculate the actual damage after an event or a synthetic method to calculate the potential damage after a flood [75]. Thereafter, damage curves or functions have been developed for each flood-prone or flood-damaged building using information collected regarding the exposed buildings and flood parameters which are typically flood depths [76]. Furthermore, microscale assessment considers the homogeneity of the buildings under analysis, with higher spatial resolution and differentiation. Therefore, it uses a higher level of detailed information [24,77]. A schematic framework of the microscale FDA considered in this study is presented in Figure 3.

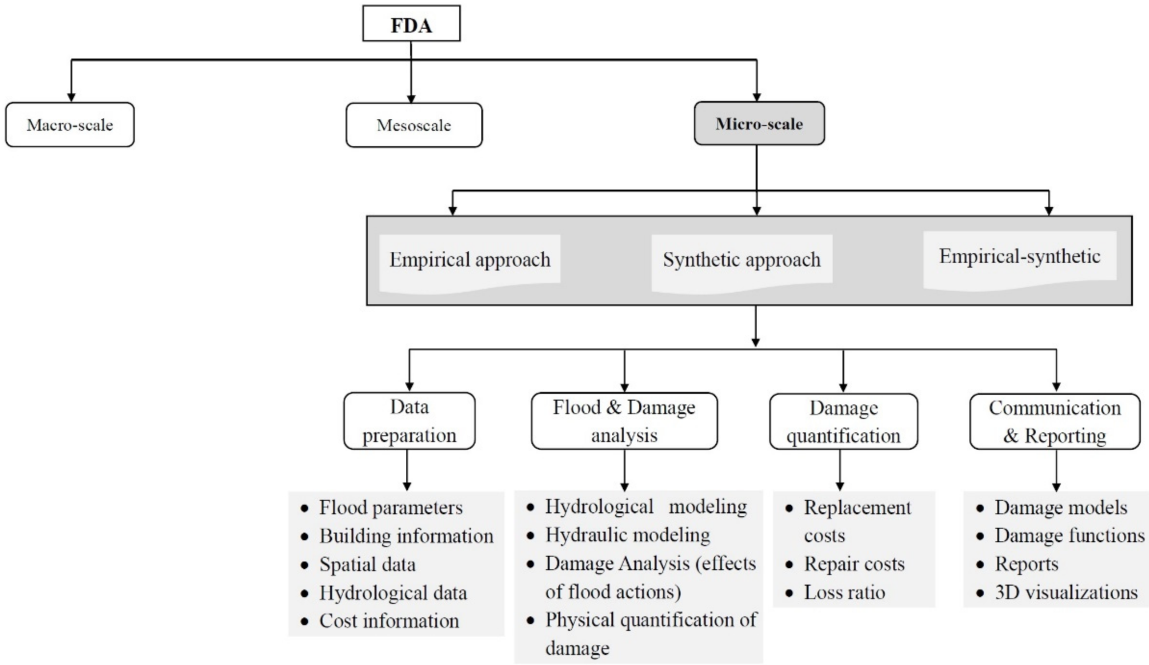

Figure 3. Schematic representation of microscale Flood Damage Assessment.

3. Approaches to Microscale Flood Damage Assessment

This research has considered previous studies under the category of conventional and modern methodologies and sub-category of data collection methods for developing damage models based on empirical and synthetic approaches. The differences between the two approaches are summarised in Table 3. The studies of [42,46,50,51,57] are examples of the studies reviewed based on the empirical approach, while the studies of [35,43–45] are few examples reviewed based on the synthetic approach. Nofal and van de Lindt [36] and Shrestha et al. [10] combined both approaches in their studies. In addition, the merits and demerits of each approach are discussed.

Table 3. Merit and demerit of the empirical and synthetic approaches.

Approach	Merit	Demerit
Empirical	1. Greater accuracy of information 2. Allowed for easy quantification of uncertainty. 3. High implementation rate among stakeholders	1. Poor quality of post-flood data due to less detailed and quality surveys after a flood event 2. Models could not be transferred in time and space due to the uniqueness of the actual data. 3. Utilization of one flood damage e.g., flood depth
Synthetic	1. Not constrained by actual data from flood events, thus can be applied to different places and areas. 2. In-depth analysis and description of damage mechanisms 3. Hypothetical analysis of damage data and modeling of potential damage 4. Challenge of over-estimation 5. Useful for data-scarce regions	1. Insufficient data to predict damages to buildings 2. Contains a higher amount of uncertainties 3. Analyses are expert-based 4. More efforts required to produce comprehensive data

3.1. Empirical Approach

The empirical approach uses damage data from an actual flood [54]. It uses systematically applied survey procedures, analysis of insurance claims data, historical flood data, or a combination of all these sources. The empirical approach demonstrates a greater accuracy of information and allows for easy quantification of uncertainties because it employs actual data recorded from the flood event [78]. It also enables a correlation between hazard intensity and degree of damage [17]. This approach has been considered the most utilized in the construction of damage curves compared with the synthetic approach, owing to its high implementation rate among stakeholders [79,80]. The steps employed in developing the damage curves and models are summarised in four stages. Data preparation is the first of these steps, followed by flood and damage analysis. The third step is the quantification of damage loss, and the last step is communication and reporting. These steps are described in Section 4. Studies that utilize empirical data for modeling curves and damage models are reviewed and presented in Table 4.

Table 4. Stages of assessing microscale FDA in the empirical and synthetic approaches as generated from the reviewed literature.

Studies	Source of Primary Data	Flood & Damage Analysis	Damage Quantification	Mode of Reporting	Validation
[10]	Household questionnaire survey	Hydrologic-hydraulic models	Replacement cost	Vulnerability curves	Yes
[23]	3DBIM models from BIM	Hydrodynamic & hydrological analysis	Refurbishment cost	Tabular report & 3D BIM models	Yes
[35]	Structural and geometric data of buildings	Hydrodynamic analysis	-	3D-damage functions	No
[36]	Existing online database	Hydrodynamic & hydrologic analysis, HAZUS-MH	Replacement cost	Fragility curves	Yes
[41]	UAV imagery, opensource database, field survey, statistical report	Surface interpolation methods	Replacement cost	Damage curves	Yes
[42]	Questionnaire	-	-	Doughnut structure model	No
[43]	Micro census data, local damage reports	Hydrologic and hydrodynamic modeling	-	Damage functions	No
[44]	GIS Spatial data	Hydrodynamic modeling	Refurbishment cost	HOWAD model	Yes
[45]	Expert-based existing literature, loss adjustment studies, surveys	-	Loss adjustment	INSYDE Model	Yes
[46]	One-one interview	-	-	Damage functions	Yes
[47]	LiDAR DEM and depth-damage relationship	Hydraulic modeling	Average of the economic values	Stage damage curves, Damage-discharge curves	Yes
[48]	Questionnaire survey	-	Repair cost	Stage damage curves	No
[49]	Government Report	-	Loss thresholds	Probabilistic depth-damage curves	Yes
[50]	Questionnaire and mobile GIS devices, building inventory and observation	-	-	Vulnerability curves	No
[51]	Facial Interview-questionnaire based	-	Replacement cost	Depth-damage curves	Yes
[52]	Existing online database	Hydrodynamic& hydrological analysis	-	Fragility curves	Yes
[53]	Interviews and surveys	-	-	Vulnerability curves	Yes
[54]	Lidar DEM OpenStreetMap, Databases, local administrator databases	-	Replacement cost& Reconstruction costs	Multivariable &single-variae models	Yes
[55]	DTM, GIS data, rainfall data databases	Hydrologic-hydraulic modeling	Unit loss	GIS model	No
[56]	Field surveys, literature and databases	-	-	Stage-damage curves	No
[57]	Computer-aided telephone interviews	-	Loss ratio	Tree-based models	Yes

After the 2000 Tokai Flood in Japan, Zhai et al. [42] collected information from the residents on the effects of flood depth and several socioeconomic factors such as house type, house ownership, etc., to model flood damage functions. The study employed multivariate regression analysis. Choi et al. [46] developed damage functions for single-family houses in flood-affected areas of South Korea. This study compared the results to the multidimensional flood damage assessment (MD-FDA) used in the country and found significant differences in the damage to building structures and their contents. Romali and Yusop [51] developed a flood damage function model for Kuantan, Malaysia, using interview survey data. Balasbaneh et al. [50] also assessed the vulnerability of building materials by revealing the degree of loss for five structural types. The results of this study revealed that an increase in flood depth leads to an increase in damage to walls made from wood. Festa et al. [56] compared two different methods of collecting data at the microscale level for the analysis of buildings. The study concluded that the generalized methods of acquiring data are the most efficient because of their short-term risk valuation ability. Win et al. [48] derived a flood damage function model based on flood inundation parameters and damage-aggravating factors for residential and agricultural lands. The study adopted a questionnaire survey as its primary data collection method. Amadio et al. [54] utilized probabilistic supervised learning algorithms to estimate the structural damage to buildings at a microscale level.

Despite its usefulness in providing damage assessments with real and substantial data, there are numerous challenges encountered while employing the empirical approach. In its collection of suitable data for analysis, buildings have to be divided into different groups because of the different responses elicited by buildings to flood situations. This is due to differences in materials, construction methods, floor plans, and other building characteristics [81,82]. These differences generate variations in damage that can occur in a building in a similar flood event and magnitude. The empirical approach is also subject to expert judgment, but only for the selection of a range of methods for estimating the depreciation cost while ensuring its suitability for damage analysis. This has been considered to require more time and effort and add another level of uncertainty to the outcome of the FDA [13,19]. Most of these analyses based on empirical data, considered bulk economic losses that neglected the assessment of direct flood damage to buildings or did not account for the effects of flooding hydrodynamics and flood actions [35]. Another challenge is that securing data from insurance companies may be hectic, since certain policies consider client information confidential, thereby rendering them unavailable for damage assessment and consequently affecting the details and data quality [83]. The collection of data from empirical sources is both time-and effort-demanding. Empirically derived models are found to be less suitable when the microscale spatial context is considered for the FDA. This is because they only consider the use of one parameter, mainly flood depth, or a few other parameters which are not sufficient for effectively predicting the damage situation, coupled with the unavailability of records immediately after a flood event [45]. Conclusively, in most cases, the models suffered from the inability to be transferred and applied to other places at different times because the datasets utilized are unique to their source and the time of the event alone [84]. Irrespective of the various shortcomings, empirical data remain a reliable source for authentic flood and damage records based on real-life events.

3.2. Synthetic Approach

The synthetic approach uses data based on extrapolation and deduction from hypothetical analysis (also referred to as the "what-if" analysis) [85]. It provides high credence to conceptual expert judgment and is also beneficial for collecting data where there is data scarcity on historical flood events and building inventories [86–88]. White [30] first used the synthetic approach, and a wide range of studies have adopted it in creating damage functions and estimations for building damage states [23,35,45,48,53]. The synthetic approach offers an in-depth analysis and description of damage mechanisms, and it is useful for stakeholders to make decisions to mitigate damage to buildings based on the likelihood of their occurrence [16]. In addition, it considers other associated costs, such as cleaning costs for buildings that suffer from contamination effects [13]. The researches reviewed under the category of synthetic approach were also assessed in four steps. The first stage is data preparation which is subsequently followed by damage and flood analysis, loss quantification, and finally, report and communication. These stages are discussed in Section 4.

Studies on stage damage curves have been conducted by [53], wherein the stage damage relationship is applied to assess the flood vulnerability of a community in Malaysia. Nofal et al. [52] used fragility curves to propagate the uncertainties in flood damage models. Using flood depth and duration as parameters, they developed a probabilistic vulnerability function that can be assigned to a real community based on archetype and occupancy. The study proposes methods for extracting data without empirically generated information. A probabilistic methodology was utilized to derive synthetic damage curves for residential buildings [45]. This methodology is called the In-Depth Synthetic Model for Flood Damage Estimation (INSYDE). The method adopts a component-by-component analysis of physical damage to buildings, accounting for uncertainties in the damage estimations. Neuhold [43] conducted a microscale risk assessment to establish damage functions for single objects prone to flooding in the municipality of Gleisdorf. This study considered the number of people exposed to flood hazards, residential buildings, and industrial sites. Mcgrath et al. [49] developed probabilistic depth-damage curves and loss thresholds to classify building damage based on different ranges of flood levels. Rehan [47] stressed the importance of conducting FDA on a microscale basis. The study estimated economic damage for a range of flood events, considering the heterogeneous distribution of exposed residential buildings at risk in the study community. In addition, studies such as [44] used HOWAD, a geographic information system (GIS)-based flood damage simulation model, to model potential damage for buildings on a microscale basis. The model uses an object-based approach that allows for a detailed assessment of flood impacts from the high spatial and contextual resolution of buildings. The method also used the developed synthetic-depth damage curves for each building type to calculate refurbishment costs for the buildings. Luino et al. [55] developed a GIS model to estimate the flood damage. The model elaborates on the stage damage curves for the exposed elements of buildings.

Under the synthetic approach, some studies have adopted the analytical/engineering method, and the vulnerability of buildings has been modeled based on analytical representations of the failure mechanisms of individual building components. These are assessed based on the effects of flood actions and by comparing the resistance of individual building components to these flood actions [23,35]. Flood actions are a major factor that must be considered during structural assessment or analysis of building damage on a microscale basis. Since the research of [89], studies using the analytical method based on synthetic approach estimated the actions of flood on buildings in their analysis, unlike other studies that focused on economic damage analysis. Flood actions are known to trigger damage to buildings and can be measured qualitatively or quantitatively. According to [23,34,90], these flood actions are described below.

The *hydrostatic action* of a flood is caused by the flood depth. The flood difference produces a force (lateral forces acting in the horizontal direction) that is equal in all directions and acts perpendicular to any surface with which flood waters come in contact. Differences in the water height on the sides of the building wall component cause bending forces in the structure [12,23]. A direct relationship exists between hydrostatic flood actions and flood depth [35]. *The hydrodynamic action* of a flood is caused by the velocity of water. They are most evident in rivers and streams with high velocities and in coastal waves with higher wave turbulence. Hydrodynamic action occurs in the form of a lateral pressure generated by the flowing water. The *buoyancy action* of a flood is the generated upward force applied to a building which is a function of the submerged volume of the building. As a force, buildings are lifted off their foundation, and when combined with hydrostatic lateral pressures or hydrodynamic pressure, they may lead to the displacement of the floating buildings and thus damage, destabilize, or destroy the building in the process [34]. The *erosion action* of a flood is caused by water scouring away soil from the sides or bed along which the water flows. Flood damage due to erosion may occur after a flooding event, as there may be a loss in the bearing capacity or anchoring resistance around the posts, piles, and piers of the foundation. This may lead to building settlements or collapse. Thus, models of soil erosion and scour are regarded as dependent on the time factor, thereby making the effects of this action an indirect effect of velocity on a building [35]. *Non-physical actions* refer to damage from chemical, nuclear, or biological actions. In this case, water (fresh or contaminated) comes into contact with water-sensitive building elements. The hydrostatic, hydrodynamic, buoyancy, and erosion actions of a flood are the physical actions of floods which can overlap with the non-physical actions of flood. Studies have combined one or more flood actions for analysis because more than one flood action is required to determine the actions of floods on buildings [23].

Nadal et al. [35] used a probabilistic methodology to estimate the influence of flood actions on individual building components and determine the expected damage to buildings. The study was conducted on individual buildings to differentiate the effect of building damage as a result of flood action. The major flood actions considered in the study were hydrostatic actions and hydrodynamic forces, and the study also accounted for uncertainty in the input parameters. The study was an improvement on previous studies utilizing statistical analyses of economic damage to buildings without considering other damage-influencing parameters such as flood actions. Amirebrahimi et al. [23] presented a framework for the use of 3D building models in the assessment and visualization of building damage caused by floods. The building was modelled according to the distinct behaviour of the individual components of the building against flood actions, such as hydrostatic and hydrodynamic actions. This study is an advancement to the FDA methodologies because it proposes the extraction of building components from 3D models in the form of building information modelling (BIM), as they are beneficial in providing detailed information based on the geometry and materials of these building components.

Other studies also deviated from conventional flood damage modeling to the use of machine learning in conjunction with other multivariate models. These models allow for the analysis of more than one damage-influencing factor. Such techniques used by researchers include artificial neural networks (ANN), Bayesian networks, random forests, and tree decision models [91]. Merz et al. [57] used machine learning methods to estimate damage to buildings. This study derived multivariable flood loss models at the microscale level via tree-based methods. The study investigated further beyond the traditional single variate method of modeling stage damage functions based on buildings or elements at risk and the flood depth. The study also included various damage influencing parameters, such as early warning and emergency measures undertaken, building characteristics, socioeconomic status of the households under consideration, hydrological and hydraulic aspects of the flooding situation, and state of precaution of the household. The results of the study were robust because they used an extensive set of detailed and object-specific flood damage data. The multivariate models performed better than traditional damage models. To resolve the challenge of insufficient data in data-scarce regions of Malawi, Wouters et al. [41] utilized an object-based image analysis (OBIA) of high-resolution unmanned aerial vehicle (UAV) imagery to extract building characteristics at an individual level and evaluated building damage using local depth-damage curves.

The limitations of the synthetic approach include that the data evaluated are not sufficient for the prediction of damage to buildings, and they are mostly based on expert judgment and do not comprehensively consider other factors that may influence building damage [44]. Synthetic data have also been criticized for being subjective, therefore leading to a higher chance of producing uncertainty that is not usually propagated in damage quantification. In addition, the data are also hypothetically generated, and thus not all data are fit for an efficient representation of real-life flood events [13,21,72]. The collection of comprehensive synthetic data requires considerable effort [92]. Synthetic data have their advantages and disadvantages. Nevertheless, for a microscale FDA, the synthetic data supports the possibility of collecting large-scale data for predicting damages, thereby strengthening the mitigation of buildings against flood disasters.

3.3. Empirical-Synthetic Approach

Shrestha et al. [10] combined empirical and synthetic approaches to develop flood damage functions that account for variability in house types and household assets. Combining these two approaches provides accuracy in predicting extreme flood events. The studies in [36] used empirical damage fragilities to model damage and loss for the Lumberton community and performed hydrodynamic and hydrologic analyses to predict discharges. An important aspect of this approach is that it offers the possibility of the merits of both empirical and synthetic data. The real data enable validation, and the synthetic data suffice for predictions in the event of insufficient or scarce data. This approach can provide an extensive set of available data, which is a critical requirement for accurate damage models.

4. Discussion

4.1. Stages of Assessing Damages in the Microscale FDA Methodologies

In the literature, the steps followed by studies in conducting microscale flood damage assessment can be generally categorized into four categories. These steps include data preparation, flood and damage analysis, damage quantification, and communication and reporting. This section discusses these steps, and the studies reviewed in Section 3 are assessed following these steps and summarised in Table 4 and Figure 3.

4.1.1. Data Preparation

Data preparation is essential for developing a flood damage model [91,93]. This involves collecting and extracting data on the impact and resistance factors. It precedes the evaluation and quantification of damages. Sufficient information is required to accurately estimate flood damage at the microscale level [47]. Extensive data on flood hazard characteristics, exposed elements, and their vulnerabilities are required to construct damage models. This is because insufficient or incomprehensive data affect the reliability and precision of the damage models. The types of data used by the FDA are classified and discussed in the subsequent sections.

Geospatial Data

Spatial data provide information on geographical delineations, locations, and patterns of flood damage concerning geographic coordinates and building information. Geographic information systems (GIS) have played a significant role in the pre-and post-processing of spatial inputs and outputs [3]. Flood risk assessment, flood hazard mapping, and flood inundation modeling are a few instances of the spatial analysis attributes of GIS [94]. GIS has been used alongside satellite or aerial images and remote sensing data collected after flood events to obtain elevation models and create vulnerability exposure attributes [10,27,95,96]. Although remote sensing is incapable of quantifying damage on its own, it has proven to be efficient when combined with other techniques and tools, such as machine learning [84]. Recently, high-resolution UAV images have been used by the FDA to obtain basic information on buildings [41]. However, it has become common for aerial and satellite images to be manually digitized and labeled to create building footprints, roads, and other utilities [39]. GIS is a valuable technology for the generation, management, analysis, and storage of spatial data.

Exposure/Building Information

The data on the buildings are the characteristics of the buildings in terms of their features and geometry. Most building inventory data are sourced from field surveys, local authority databases and buildings records (online and offline), cadastral maps, google street maps, and other such primary databases [10,36,41–43,46,48,50–53,93]. Essential to the microscale FDA, building data should be detailed to provide higher and more accurate flood damage predictions [41,54]. The extracted data include building locations, area, the value of the building in currency, flood zone, occupancy type, year built, first-floor elevation, age, and level of maintenance [10,58,97]. Blanco-Vogt and Schanze [98] posited that while evaluating the physical susceptibility of buildings, the following should be considered: the building components should be identified, the building material susceptibility should be assessed, and the depth physical impact functions should be derived. Studies such as [36,97] have adopted Google Street maps and street views to examine the characteristics of flood-affected buildings. They were able to capture the quantitative and qualitative characteristics of buildings. Amirebrahimi et al. [23] also used a 3D BIM model to extract high-quality non-spatial information, such as type, material, and use in their studies. Wouters et al. [41] used high-resolution UAV-OBIA to extract building characteristics with the aid of machine learning. More information on data preparation through a microscale approach can be found in the study of [93]. This significantly affects the accuracy of the flood risk assessment process.

Flood Parameters

These are the data used for flood analysis, such as the depth, velocity, duration of the flood, and hydrological and hydraulic data. These data are sourced in raw or processed forms as post-flood data through visual inspection, questionnaire and interview methods, surveys, and remote sensing [46]. In other cases, flood parameters were extracted from the hydrodynamic and hydrological processes. Regmi et al. [99] indicated that large databases are often required in natural hazard-related research. Post-flood data are also collected in their refined forms from flood damage databases such as Emergency Events Database (EM-DAT) NatCatSERVICE (MunichRe), and HOWAS21. These websites offer flood damage records, insured losses, and total damage, both in person and monetary value, according to spatio–temporal distribution and relevance. HOWAS-21 is known to provide object-specific flood damage data [100]. GFZ, the German Research Centre for Geosciences, is another database that records flood losses, including other information about flood events. However, these databases rely on voluntary data contributions [100] and essentially harmonize existing data on flood parameters.

Cost Information

Cost information is important in damage quantification processes because it pertains to the market value of building components. The cost information that is usually extracted includes the type and costs of all buildings and repairs affected. Most cost information is sourced from databases and records such as construction cost databases [23]. Certain studies also sourced cost information from field surveys and expert (civil engineer, quantity surveyors, valuers, and assessors) judgments [10]. Other studies source information from insurance companies' databases [42]. Insurance claim payouts are an estimation of structures made by insurance companies for building-related policies. It is an actual cost approach based on assessments of the compensation requests submitted by building owners, according to companies or regional and/or national authority funds available at different times after the event [101]. This method is often used in countries such as South Korea, where there is no sufficient formal database on the loss records of buildings [102]. One challenge with this data source is that value estimations are made for specific purposes, implying that the estimated values are not the same. This becomes the basis for bias in the estimation of the value of the building. For example, insurance companies' estimations are highly dependent on the policies they offer. The damage a policy covers in the event of an accident (flood) affects the estimation of the building value exposed to risk [83].

4.1.2. Flood and Damage Analysis

Flood Analysis

Flood analysis are conducted to assess the vulnerability of buildings to flood parameters. In cases of inadequate data on flood events and damage, studies employing synthetic approaches require large amounts of data to construct flood scenarios. Flood and geospatial data are major inputs for flood analysis. Hydrological analysis and hydraulic modeling are used to determine the flood inundation. The former determines real or hypothetical flood discharge which is used as a reference for damage calculation, whereas the latter generates stream flow estimates and trends. Hence, these studies often employed simulations to predict and calculate discharges from rivers [10,55,103]. Other studies performed hydrodynamic and hydrologic analyses using a digital elevation map (DEM) to calculate flow direction, flow accumulation, catchment delineation, etc. [36,47,104].

Damage Analysis

Damage analysis evaluates the effects of flood actions on building components as a function of the flood parameters identified in flood analysis. Building data are a valued input in damage analysis. Damages are calculated as actual damages based on the available empirical data, or expected damages are predicted based on simulation or estimation from synthetic data [44]. This process describes the component-by-component analysis (basically the structural and load-bearing components) of flood actions (parameters) on building components based on engineering/analytical mechanisms [35,36,45]. This is exclusive to the estimation of the costs of building damage. For instance, Amirebrahimi et al. [23] recommended the use of finite element analysis and assembly-specific fragility curves to perform simple load and resistance capacity analysis for the effects of flood actions on building components. The results of the analysis suggest the major cause of damage to the building which is used for the (economic) quantification of damages.

4.1.3. Damage and Loss Quantification

Damage and loss quantification involve the calculation of monetary damage or loss to individual building components based on the flood parameter [105]. According to [13], assessing monetary loss to a flood-damaged building entails three steps: classification of elements at risk based on homogenous features; performance of exposure analysis and asset assessment by estimating the asset value and describing the number and type of elements. The last step is to conduct a susceptibility analysis correlating the relative damage of the elements at risk to the flood impact. The cost was determined by estimating the unit price of each component of the building and the rate of damage resulting from the flood. The sum of all the damage costs constitutes the total damage to the building. The cost method used to quantify damage includes refurbishment costs or replacement cost method that considers the value of the building until the time of its damage and considers the cost of constructing new buildings or components as a replacement for the completely old ones [36,44,45,48,51]. This is summarised as the ratio of the overall replacement cost to the estimated total replacement value of the building, where the overall replacement is the expenses incurred by the flood victims for repairing their properties after flood damage.

4.1.4. Communication and Reporting

The outputs of FDA are commonly reported and communicated in the form of flood damage models which show the relationship between flood parameters and flood damage to a building [16]. Flood damage models can be in the form of stage damage curves which can also be referred to as vulnerability curves, depth–damage curves, velocity damage curves, fragility curves, etc., based on the flood hazard considered (see Table 4 for the list of such studies). Studies utilizing the multi-variables and machine learning algorithms have reported their output as multivariate flood damage models [57]. Flood damage models have also been reported in 3D damage functions and fragility curves [35,36], 3D models, and 2D forms (e.g., tabular reports) [23]. The integrated flood damage model is another form of communicating the outcomes of the FDA, often reported as a methodology that can be adopted and applied in other cases. The INSYDE model [45] and HOWAD model [44] are examples of such integrated damage models of FDA.

4.2. Integrated Step on Assessing Microscale FDA

From the literature, this review agglomerates the steps of conducting FDA. These steps are categorized into four stages: data preparation stage, flood analysis and damage analysis, damage quantification, and output stage. These steps can be applied to the various modeling in FDA, which are the univariate, multivariate (Machine learning and non-machine learning), 3D models, among others. Table 5 presents the distinct features of these models. These stages are discussed in Section 4.1. The integrated framework is illustrated in Figure 4. A summary of these stages is presented in this section.

- Data preparation: This stage is required for all methodologies. However, the type of data required depends on the purpose of the assessment.
- Flood and damage analyses: These analyses are primarily utilized in studies conducting analytical/engineering methods. These studies utilized component-by-component analysis of buildings. Some flood damage modelings using fragility curves, stage-damage curves, and 3D models are examples of such methodologies. Multivariate modeling (with machine learning) may not fall under these categories.
- Damage quantification: Often, univariate damage models which are also deterministic, basically proceed to the damage quantification of building damage. All methodologies economically quantify damage to buildings using mainly the replacement methods/unit cost.
- Output: The outputs are the resultant damage curves, 3D models, damage functions, multivariate models, fragility curves, vulnerability curves, tabular reports, and other forms of representation.

Table 5. Distinguishing features of the 3 types of modeling emphasized in this study.

Features	**Univariate Modeling**		**Multivariate Modeling**	**3D Modeling**
	Deterministic	**Probabilistic**	**Machine Learning**	**BIM**
Training of models	-	-	Required	-
Structural Analysis (Effects of flood actions)	No	Yes	Depends	Yes
Economic quantification of damage	Yes	Yes	Yes	Yes
Physical quantification of damage	No	Yes	Yes	Yes
Statistical techniques	Linear regression	Linear or multiple regression	Multiple linear regression, Bayesian Network, Random Forest, Artificial Neural Network	Depends
Probabilistic (uncertainties) prediction	Depends on data input	Yes	Yes	No
Example of models from the study	Hazus-MH	INSYDE models	Tree-based models	3D BIM

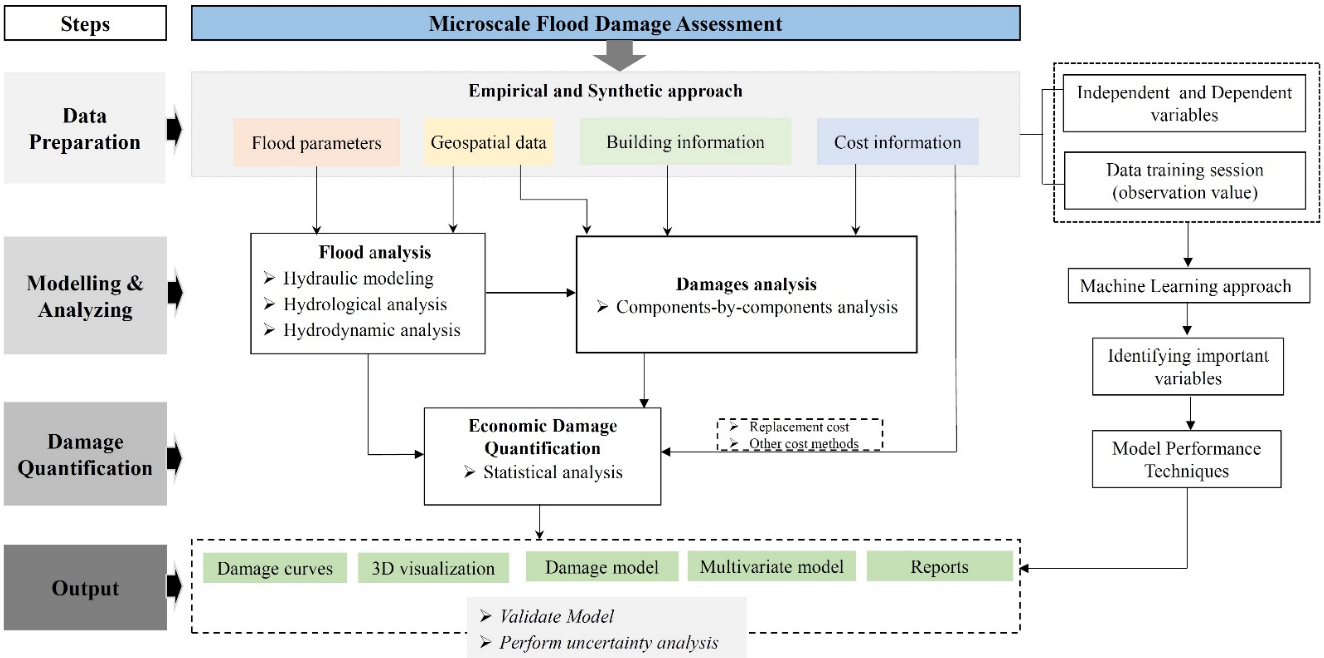

Figure 4. Integrated steps for microscale FDA (as adapted from the literature [13,23,45,90]).

4.3. Current Concerns and Trends in Microscale FDA

Peculiar to other scales of the FDA, microscale FDA also shares common challenges. Challenges, such as the effect of uncertainties on flood damage models and the validation of models, were considered. Specific concerns in the field of microscale FDA, such as 3D building information extraction and damage visualization and the use of machine learning, are discussed.

4.3.1. The Effect of Uncertainties

Errors in predictions arise from the complexity of human actions and infinite complexities encountered in the course of the FDA [106]. Initially, there were speculations that uncertainties in damage estimation models were limited. This was also confirmed by [107], staking it at a +/−20%. However, a few recent studies such as [21,34] discovered large discrepancies in the damage functions for physical damage assessments in different countries. There are many sources of uncertainty that affect complex FDA. For example, uncertainty may arise from sparse and short datasets, poor knowledge of hydraulic structures, such as dams and weirs along rivers, assumptions and extrapolations in statistical analyses of extreme floods, and depth-damage functions [13]. At a microscale, uncertainty exists in the estimation of buildings and depth-damage functions, owing to the disregard of many damage-influencing factors [21]. Estimation of uncertainties thus provides an effective guideline for the use of a damage model and is useful for sensitivity analyses, guiding stakeholders in making various decisions and effectively indicating the accuracy of the outcome of flood damage models [106,108]. Dottori et al. [45] considered these previous studies and assessed uncertainties in their formulation of the INSYDE models, thus becoming the first to include them under the category of a synthetic damage model. As noted in the study, there has not been sufficient research work outlining methods to estimate uncertainties in flood damage assessments.

4.3.2. Peculiarities of Damage Functions

Data from damage functions are not applicable to the same flood event. In the cases where these data are applied to the same area they have been previously collated, it does not function practically. Hence, damage functions are found to be most peculiar to the flood events they have been modeled for as locations, policy measures, human responses, climate change, rise in environmental and human interference, and infinite complexities/phenomena render a damage function distinct for a particular event. Damage functions are also influenced by being limited to a certain range of flood parameters. One damage function based on the explanation from one flood parameter is not sufficient for explaining or predicting building damage sufficiently. Thus, FDA models must be able to capture other factors inclusive of uncertainties. As also advanced by [109], meteorological, physiographic, and human factors, such as rainfall, terrain, and flood prevention measures, could influence flood damage. Therefore, the right FDA must be all-encompassing, taking into consideration factors, such as emanates from the building, social, economic, physical, engineering, policy, socioeconomic, and other parameters that may influence the assessment of flood damage to buildings. In this manner, a suitable estimate may be obtained.

4.3.3. Validating Flood Damage Models

The application of the flood damage model in practice has been observed to be often incomplete and biased owing to uncertainties. However, greater concerns arise when it is not subjected to validation. Validation affects the reliability and precision of damage models. Validation can be conducted in three ways: by using empirical data, that is, validation using historical records such as actual loss data from field surveys, records, and databases. Validation is further conducted by cross-validation which is a comparison of the outcomes of the flood damage models under study with other models that have previously been established and validated [54,91]. The third approach to validation is by employing the statistical error performance indicators, such as mean absolute error (MAE), root mean square error (RMSE), mean base error (MBE), coefficient of variation (CV), and other error estimation analyses for the studies reviewed in this work. The number of studies with validated models are shown in Table 4.

4.3.4. Damage Visualization

GIS and BIM are two tools that have been useful in the visualization of 3D images because they are more vivid and understandable than 2D visualizations, and visualizing damage to buildings has been found to have great utility in the better comprehension of the effects of a flood [110,111]. GIS technology has been used in studies to model and analyze the multidimensional phenomenon of flooding and damage characteristics of residential buildings [44]. It is commonly used in two-dimensional (2D) formats for various hydrological and spatial flood analyses. Amirebrahimi et al. [23] used BIM for a microscale spatial analysis. BIM was utilized to extract building information for damage analysis and was also used alongside GIS to communicate the visualized damage to the building. This, as revealed by the study, provides approximate building geometries and flood parameters, while also presenting a visual representation of the damage to the building. Both GIS and BIM tools are useful in visualizing the relationship between flood depth and flood damage. This methodology can be transferred to a region. However, a major drawback of the integration of the two tools for a successful FDA is the difference in the semantic makeup of the two tools, as there are no records of smooth exchange and conversion of all information between BIM and GIS [112]. The research is also novel and is surrounded by uncertainties in its applicability to multiple flood parameters and existing buildings.

4.3.5. Use of Multivariate Modeling Methods

The utilization of machine learning algorithms in microscale FDA is conventionally recorded via basic statistical techniques such as linear regression which is a basic technique for evaluating depth-damage functions [113]. However, there has been improvement in their usage, and recently, there have been more advanced techniques that allow for more complex non-linear functions to be fitted to the data [57,91]. However, they are yet to gain popularity. Few studies on this emerging concept have used the current advanced machine learning in the area of microscale FDA [41,57]. The incomprehensiveness or detailing of building information and other vulnerable parameters, such as the building and its components, can affect the reliability and outcomes of a microscale FDA, particularly in data-scarce regions such as developing countries. This method was employed in [41]. Certain studies [41,57] also proposed the use of multivariate regression models, such as artificial neural network (ANN), random forest (RF), support vector machine (SVM), multiple linear regression (MLR), Bayesian network (BN), and tree decision models, to address the problems of insufficient and missing data. These models can provide probabilistic predictions which are useful in the synthetic estimation of potential damage to buildings and have higher prediction accuracy. However, these models require extensive and high-quality data.

In the study of [84], machine learning techniques are beneficial in the phases of data preparation, damage and flood analysis, damage quantification, and communication of the FDA outcome, as proposed in this study. Amadio et al. [54] also opined that multivariable models are best suited to microscale applications. The use of machine learning can be further explored in the microscale development of flood damage models.

5. Implications of the Study

For microscale FDA, the existing traditional methods of collecting data are insufficient and do not provide extensive information for a precise and reliable damage model. Studies have developed ways to overcome these challenges. However, these challenges persist. Furthermore, it is necessary to document the problem of non-unified methodology for assessing flood damage to buildings. This study extensively discusses the stages for researchers. The findings from this study show that the univariate modeling of flood damage is still popular among researchers, and the newly advanced methodologies, such as advanced machine learning and 3D modeling, are yet to gain popularity when compared with the high success recorded by the univariate modeling (stage damage curves).

6. Conclusions and Future Direction

The main purpose of the FDA is to identify areas at risk for which mitigation actions are necessary. However, stakeholder attention has been primarily focused on the macro and mesoscale approaches of the FDA with almost negligible emphasis on the microscale approach which is considered more suitable for cost-benefit analysis [19,47]. Data availability is a key factor for estimating flood damage and formulating flood damage models. Based on this, the study reviewed the literature on microscale FDA, with a focus on conventional methodologies and modern methodologies, through empirical and synthetic data collection methods. Studies based on both approaches adopted four stages for assessing flood damage to residential buildings.

The implication of this review is as follows: researchers and stakeholders are provided with insights into extant research on microscale FDA methodologies. This has not been suitably documented in the literature; major reviews have focused on the agglomeration of all spatial scales. Furthermore, the review proposes an integrated and more comprehensive step in assessing flood damage for researchers and stakeholders. However, it is worth mentioning that, given the small sample size of the review papers considered primarily as the underpinning for this work, it is not sufficient to state that the findings of this study are exhaustive. It can be reasonably stated that insights have been provided on the developments in the field of microscale FDA until now, and this has been well-segregated into headings that can guide researchers and stakeholders in their research activities.

The key points of this study are summarized as follows:

- Traditional approaches to data collection can be combined with modern approaches to provide detailed information at high spatial resolutions which are required for microscale FDA.
- Various approaches exist for evaluating flood damages for residential buildings. However, to aggregate the different approaches, there is a need to combine the criteria for these assessments under common terms to guide researchers and stakeholders in adopting common methods for flood damage assessment.

- Quantifying damages economically and deterministically is not sufficient for providing details on the effects of flood damage at a microscale. Further research on the analysis of flood actions, single buildings, and object-specific assessments of flood damage should be encouraged, as it improves the qualitative assessment and performance-based abilities of buildings, thereby rendering buildings more resilient and decreasing their vulnerability to flood hazards.
- The use of multi-flood parameters other than flood depth will help decrease the uncertainties associated with flood damage models and encourage a comprehensive evaluation of flood damage.
- Overcoming data scarcity which has been a major issue in microscale flood damage modeling is imperative. Adopting a combination of both empirical and synthetic approaches enables researchers to evaluate various flood and hazard parameters based on first-hand data and supplement inadequate data by estimating potential damages to buildings.
- The review also appeals for a comprehensive description of flood damage assessment steps that can combine various methods used by researchers in their activities.
- In addition, studies conducted by [39,41,84,91] emphasized the increased use of multivariate damage models and the employment of advanced machine learning. Further research is required to overcome the impediment to the integration of BIM-GIS technologies which can facilitate improved adoption of 3D modeling of flood damage. This will be an essential improvement to the microscale FDA, specifically because it is beneficial in object-specific data analysis and improves the limited data availability and quality in remote areas and countries with inadequate data records on flood losses.

In conclusion, this review observes that a large amount of detailed data is crucial to microscale FDA, as the adoption of a combined empirical and synthetic approach in data selection and damage modeling provides more detailed information and enables accurate predictions of damage models. This conclusion is supported by a previous study [54]. The study further concludes that the combination of multivariate modeling (machine learning) with the use of 3D BIM-GIS, and 3D visualization of damages via conventional methods of sourcing for data is capable of overcoming the limited availability of data for predictions of damage models. In addition, the improvement in building-specific damage models strengthen the performance-based capabilities of buildings. Nevertheless, in these identified aspects, further research is needed.

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