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Flood fragility and vulnerability functions for residential buildings in the Province of Leyte, Philippines

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Abstract

The Philippines experiences frequent flooding, but, despite expansive tools for risk reduction, there remain gaps in understanding generalised relationships between flood events and damage to residential structures for regions outside the nation's capital. This gap has limited the ability to model flood risk and damage without robust functions to link hazards and housing vulnerability. This research draws on 394 household surveys to empirically derive a suite of flood fragility and vulnerability functions for residential structures in the Province of Leyte for light material, elevated light material and masonry structures. The results showed that masonry construction was more resilient to floods compared to light material counterparts. Elevated light material structures also exhibited lower damages at low inundations but tend to fail abruptly at flood depths greater than 3 m. By empirically deriving flood damage functions, the findings contribute to a more localised approach to quantifying housing vulnerability and risk that can be used for catastrophe and risk modelling, with applications for government agencies, the insurance industry and disaster risk researchers. This research lays the foundation for future flood risk mapping with growing significance under climate change.

KEYWORDS

climate resilience, disaster risk reduction, empirical analysis, flood risk, structural damage assessment

1 | INTRODUCTION

Communities in low-lying and coastal areas are anticipated to experience an increased threat of flooding under climate change, especially those with limited coping capacities (Williams et al., 2020). The Philippines, one of the most hazard-prone countries globally, experiences frequent damaging floods brought on by an average of 20 typhoons annually (Bollettino et al., 2018; World Bank, 2005). However, despite the increasing robustness of disaster risk management and flood protection policies, natural hazard impacts remain unequal, disproportionately affecting marginalised communities (Nur & Shrestha, 2017). With climate change expected to intensify extreme weather events, there is a need to understand these risks more comprehensively (Walsh et al., 2016). Such understandings would enable local governments to enact more effective disaster risk management policies and better prepare for these shocks. In engineering scholarship, there has been a shifting attention towards flood vulnerability of the built environment, with fragility and vulnerability functions playing an important role in enabling quantitative evaluation of probabilistic flood damage models (Baradaranshoraka et al., 2019; Galasso et al., 2021; McGrath et al., 2019; Suppasri et al., 2015; Thapa et al., 2020).

Although it is challenging to mitigate the impacts of flooding completely, comprehensive assessments of both structural and non-structural measures are important for reducing flood risk (Thapa et al., 2020). Existing research conducted by Huizinga et al. (2017) derives vulnerability functions on a global scale. While these repositories of data are advantageous for catastrophic modelling on a national scale where data are scarce, generalised functions fall short of capturing nuanced vulnerability relationships across structural typologies for community-scale assessments. In the Philippines, increased mainstreaming of disaster risk management assessments and policies has led to a growing repository of vulnerability and risk data. The Greater Manila Metropolitan Area (GMMA) has benefited greatly from this through comprehensive multi-hazard risk assessments (Bautista et al., 2014). These risk assessments have offered a starting place to benchmark the vulnerability of structures and assets across the country. However, applying these data inventories outside Manila presents challenges due to differing socio-economic conditions and infrastructure quality (Yust et al., 1997). In Region VIII—which comprises the eastern-central provinces and has among the highest poverty rates nationally—significant losses from flooding continue to inhibit human development gains (Healey et al., 2022). This region, particularly the Province of Leyte, has among the highest prevalence of housing vulnerability (Healey et al., 2023).

Assessing the vulnerability of residential structures to flood impacts has the potential to inform more effective planning and mitigation strategies (Uwakwe, 2015). This research takes an initial step to close gaps in the availability of residential flood fragility and vulnerability curves in the Philippines by creating a suite of functions based on empirical flood damage data in the Province of Leyte. The study aims to answer the question, *What is the fragility and vulnerability of residential structures to flooding in the Province of Leyte, Philippines?* Through an empirical approach, we contribute to the development of more localised flood risk assessments for housing damage outside the GMMA. We draw upon field surveys to identify relationships between past flood damage and the severity of flood events for three common building typologies. Our research serves to enhance flood risk assessments for residential structures, creating the tools needed for future risk mapping to inform planning and management strategies for local communities.

2 | BACKGROUND

The literature on 'vulnerability' is vast, and depending on the discipline, the concept can take different meanings (Adger, 2006; Bankoff, 2013; Bohle et al., 1994; Cardona, 2004; McEntire, 2011; Renaud, 2006; Wisner et al., 2014). The United National Office of Disaster Risk Reduction (2015, p. 9), through the Sendai Framework, defines vulnerability as 'the conditions determined by physical, social, economic factors or processes, which increase the susceptibility of a community to the impact of hazards'. While dimensions of vulnerability are interconnected (physical, social and economic), Fuchs et al. (2019) raises the physical component of vulnerability as a critical factor through an engineering lens. Within disaster risk programming, vulnerability in risk-hazard approaches tends to focus on physical attributes which are descriptive in nature rather than explanatory (Füssel, 2007). A critical aspect within risk-hazard frameworks is the clear distinction between the hazard, which relates the damaging event, whether natural or human induced, and vulnerabilities, which can be understood as the interplay between the severity of the hazard and the resultant damage incurred (United Nations, 2002).

Past studies have drawn on different approaches to assess flood vulnerability, including modelling scenarios and field damage assessments. Three common methods are used to develop vulnerability and fragility functions for natural hazards: (1) computational, (2) heuristic and (3) empirical methods. Computational methods are an analytical and mathematical approach to measure overarching damage and loss by understanding the behaviour of materials and structural responses to a hazard (Alabbad & Demir, 2022; Brody et al., 2008; Yildirim & Demir, 2021). These approaches can generally be performed at varying spatial scales provided sufficient parameters and models are available. This approach allows for new data sets to be updated continually and rapidly. Drawbacks arise from this method because it may not include non-structural elements and commonly assesses horizontal displacement as the only parameter for damage (The World Bank, 2019). Heuristic methods draw upon structured expert judgement to relate damage states for building typologies of varying hazard intensity (Martello et al., 2023; Pita et al., 2021; Zischg et al., 2021). This method allows for coherence between low and high values of the intensity measurement for more data scarce regions; however, it may result in high variability due to categorical classifications (Lagomarsino et al., 2021). A

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third suite of empirical methods assesses damage after an event has occurred (Baradaranshoraka et al., 2019; Suppasri et al., 2015; Thapa et al., 2020). This approach is based on the observed data and is considered time-intensive due to the required field collection. Hybrid approaches are also used to combine all three of the methods mentioned.

Fragility can be conceptualised as a vital link that connects hazard assessments at a specific location and the corresponding impact on an exposed structure (Pitilakis et al., 2014). Engineers express this fragility in the form of functions or curves which estimate the probability of reaching or exceeding a damage state with respect to hazard intensities (Martins & Silva, 2021; Porter, 2021), represented through a cumulative distribution function. The most common flood parameter used as a hazard intensity is inundation depth, although flow velocity, flood duration and wave action are also used or combined (Friedland, 2009; Kelman & Spence, 2004; Maijala et al., 2001; Nanayakkara & Dias, 2013). Fragility functions are essential in understanding the impact of flooding and assisting in prioritising investments in response and recovery (Thapa et al., 2020). Vulnerability functions go a step further to assess relationships between hazard intensity and damage, often expressed through a damage ratio which expresses the cost of damage relative to the cost of an asset.

When compared to more traditional actuarial approaches to creating fragility and vulnerability functions—based on claim data and insurances policies—probabilistic approaches can better capture nuance in measuring vulnerability given uncertainty (Galasso et al., 2021; Pregnolato et al., 2015; Romanescu et al., 2018). While advance flood-damage methods have allowed for extending global vulnerability functions for residential structures into regions where historical data is lacking (Huizinga et al., 2017; Scorzini & Frank, 2017), there remains high uncertainty around their applications in areas with significant rates of non-engineered construction—building work that is completed without oversight from a built environment professional such as an engineer or architect. Within the Philippines, development of both computation and heuristic vulnerability functions for the GMMA has progressed for key building types in regards to flooding (Bautista et al., 2014). However, there is a need to expand these functions to other regions of the Philippines to promote more tailored approaches to vulnerability assessment for different housing typologies outside the country's capital region. By capturing and quantifying these vulnerabilities outside the GMMA, a repository of localised data can enable future risk mapping to support flood preparedness and management—especially with uncertainties in future climate projections.

3 | METHODS

This research sought to create new empirically derived fragility and vulnerability functions for the Province of Leyte in the Philippines. The Province of Leyte has interior mountainous regions with low-lying coasts, making it prone to both pluvial and fluvial flooding, especially during heavy rainfall and typhoon seasons (Bentoso et al., 2021; Sene, 2012). We draw on field research involving household surveys to produce one of the first sets of fragility and vulnerability functions outside the GMMA for flooding. Using vulnerability data gathered through household surveys, this research evaluates and assesses generalised relationships between flood inundation and damage probabilities for residential structures. The developed fragility functions draw upon categorical damage ratings of housing components which were then aggregated into the building damage states. The vulnerability functions created draw upon detailed information provided by households and observations, in combination with material costing data from local suppliers, to calculate the building damage ratios.

3.1 | Data collection

Using 2015 *Census of Population and Housing* data from the Philippines Statistic Authority (PSA, 2018), we first evaluated different material combinations of residential structures present in the province by creating a building typology variance measure, shown in Equation (1), following the sampling methodology proposed by Gumaro et al. (2022). These data included wall and roofing materials of residential structures found in the census data. This allowed us to determine which municipalities were more likely to have a wider range of residential structure typologies. We then focused on those municipalities with higher material variance when sampling across the 40 municipalities to capture the breadth of buildings found across the province as seen in Figure 1.

$$\sigma^2 = \frac{\sum (x_i - \overline{x})^2}{N} \quad (1)$$

where σ = population house material variance; x_i = value of single observation; $\overline{x}$ = mean value of all observations; N = population size.

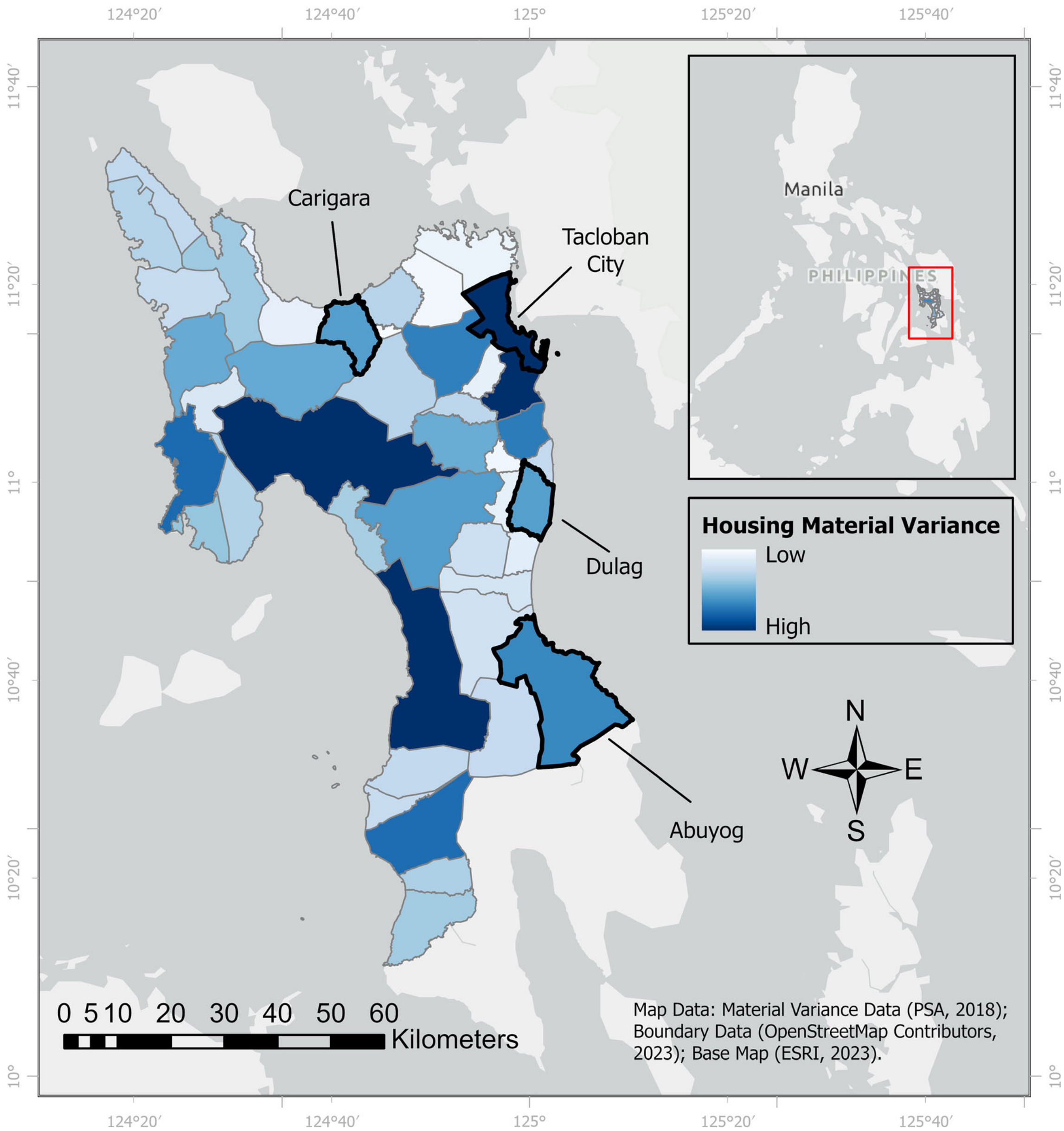

FIGURE 1 Material variance distributions and site selection for field surveys.

According to the PSA (2018), there were 449,288 residential structures as of 2015 across Leyte. We used a confidence level of 95% and a margin of error of 5% for our sampling approach. Before sampling, we distinguished municipalities and cities, which differ in their categorisation. Cities generally have higher population density and income than municipalities—resulting in more developed infrastructure and access to transportation, health services and educational institutions. These disparities were considered to avoid under or over sampling urbanised areas.

Three municipalities were purposively sampled—Abuyog, Carigara and Dulag, which were in the top quartile of variances amongst municipalities and one city—Tacloban which has the highest variance in the province. Cities (Tacloban, Baybay and Ormoc) constitute ~30% of housing across the province. We applied this same ratio in our final target sample size, giving us a target of 115 households in cities (sampled from Tacloban City) and the remaining 270 households in the three selected municipalities. The 270 households across three municipalities were split evenly, resulting in a sample of 90 residential structures per municipality. Purposeful household sampling in each selected site was conducted in coordination with Local Disaster Risk Reduction Management Offices to identify flood-prone *barangays*—the smallest administrative unit in the Philippines. To participate in the survey, households were required to have experienced flooding where water had entered their home. Consultations with each barangay captain—the highest elected official at the barangay level—were conducted to identify which households experienced flooding.

We surveyed 394 households at their residence location, which consisted of verbally asking questions to present household members knowledgeable about past flood impacts and recording structural observations through fieldnotes. Where multiple members of the same household were present during the survey, it was considered as a single household response. Questions were asked in Waray, the local language, and were digitally recorded on a tablet using Qualtrics—a web survey platform. Surveys involved visiting the households across multiple barangays at each of the case sites to assess the materials and damage of households based on previous flood events. The survey included three sections which focused on (1) maximum flood inundation, (2) building attributes and (3) damage ratings and costing. We also conducted visual assessments of housing structures to confirm damage states.

3.1.1 | Flooding inundation

Households were asked to recall the worst flood event that impacted their house. For the majority of households, these events were generally associated with Tropical Storm Agaton (2022), Super Typhoon Odette (2021) and Typhoon Ursula (2019). We assessed the inundation level of flooding by measuring the distance from the ground surface to the maximum height of water. We asked respondents to show us inundation levels on buildings to record measurements—used as the primary measurement of hazard intensity for the fragility and vulnerability functions. This was supported by observable indications of flood damage on some structures. All subsequent questions that followed in the survey on building attributes and damage were based on the point in time during which the primary flood event occurred. We considered pluvial, fluvial and coastal flooding—which are primarily induced by typhoons.

3.1.2 | Building attributes

House materials were recorded to classify structures into typologies. All materials used in construction were recorded including plywood, wood, bamboo, concrete hollow blocks (CHB; concrete masonry units), plastered CHB, amakan (woven split-bamboo mats), steel and noting the predominant material of the structure. In cases where repairs were made—households were asked to recall the materials of their homes during the flooding event. The cost of these individual materials was collected by interviewing local carpenters, masons and building material suppliers. Building characteristics, such as the year of construction, floor area (a dimensions of length of width and height), eaves and ridge height and number of stories were also captured. For structures where flooring was raised above ground level, we recorded the elevation above ground level. Structures having <0.3 m elevation above the surrounding ground surface on all sides were considered not elevated as a reasonable assumption of uneven ground surfaces.

3.1.3 | Damage ratings and costing

Ordinal damage grading was used to evaluate flood impacts on flooring, walls and roofing separately. We opted to make our damage values discrete to simplify the assessment process (Baradaranshoraka et al., 2019). To isolate flood-specific damage, a component-based approach was used which separated damage to flooring, walls and roofs. This approach allows for a more precise assessment of damage when compared to assessing whole structures (Aribisala et al., 2022; Baradaranshoraka et al., 2019; Nadal et al., 2010).

Flooring damage was based on a four-point scale with scouring, rot and cracking key indicators of damage. We rated wall damage from zero to five, where zero indicated no damage and five signified that a structure was completely washed out (Mohd et al., 2016; Rossetto et al., 2015; Schwarz & Maiwald, 2012). Walls are often a primary predicator for damage (Ahadzie et al., 2022). Roofing was based on a three-point scale with fewer expected states of damage, thus fewer categories. A summary of the damage ratings and observed attributes are shown in Table 1. When carrying out the damage assessment, structures were visually inspected, and households were asked to describe damage during the worst flooding experienced.

In addition to ordinal component damage ratings, details of damage to each house were recorded through notes based on the recollection of households. We recorded the length and height of flooring, walls and roofing sections that were damaged. These quantities were then used in conjunction with average cost data collected from interviews with local tradesmen to calculate the likely repair costs for the damage described.

TABLE 1 Flood damage rating of structural components.

Damage rating		Description
Floor		
No damage	0	Flood penetration but no permanent damage
Minor damage	1	Cracking or rotting observable on the flooring, however, still intact. For exposed floor, minor scouring at the surfaces. Floor system still habitable for households
Major damage	2	One or more large sections of flooring is damaged and unusable due to extensive rotting or cracking. For exposed flooring, deep scouring which may have exposed foundations
Total damage	3	The floor system is washed out
Walls		
No damage	0	Flood penetration but no permanent damage
Minor damage	1	Minor cracking or rotting observable on the walls
Moderate damage	2	Notable signs of deteriorating have compromised the structure integrity of the surrounding area. All walls still intact and habitable
Severe damage	3	A single section of wall has collapsed. Main living area is functional and useable for households
Major damage	4	Multiple sections of walls and columns have collapsed.
Total damage	5	Both walls and columns were washed out
Roofing		
No damage	0	No damage
Moderate damage	1	Damage to rafters or missing roof panels
Total damage	2	Roofing system has collapsed or is washed away

3.2 | Data analysis

We then categorised surveyed houses into typologies to model relationships between flood inundation and damage states, using a cumulative distribution function to fit fragility and vulnerability functions.

3.2.1 | Typologies

Building typologies were identified as common groups of building attribute combinations observed and collected during the fieldwork. We classified three main building typologies—based on the material of the exterior walls and floor height from the ground surface. The typologies created included: (1) *non-elevated* light material ($n = 167$), (2) *elevated* light material ($n = 90$) and (3) masonry/CHB ($n = 137$) structures.

Light material households were often an amalgamation of multiple components, including bamboo, steel, wood, plywood and amakan (traditional woven split bamboo mats). It was common to see multiple light materials used in a structure—in most cases, non-engineered construction, or without any involvement from a building professional in the design of structures. For example, most households used plywood in combination with a patchwork of steel or bamboo sheathing. A major and common distinction among light material structures was the elevation of flooring above ground level. This emerged as a second typology with distinctive damage states and was thus separated into its own class to capture potentially more flood-resilient construction practices. A minimum threshold of 0.3 m was assumed for houses to be considered as elevated. These structures were commonly constructed using stilts or raised sections with stair entrance into homes. The average elevation of these structures was 0.6 m above ground levels. Masonry homes consisted of plastered or exposed CHB as their primary material. These structures generally had greater engineering oversight when compared to the first two typologies. Widely used in construction across the Philippines, CHB dimensions have a standard size of 400 mm × 200 mm and are made from coarse sand and aggregates. Examples of each of the three typologies are shown in Figure 2.

3.2.2 | Damage states

We used a component-based approach in classifying structural damage of houses (Taramelli et al., 2015). Existing research into the impact of flooding on structural sub-components illustrates that walls are common predictors of damage for external finishes, followed by flooring and roofing (Ahadzie et al., 2022; Paulik et al., 2022). After assigning damage ratings for each subcomponent (flooring, walls and roofing), each house was categorised into an overall damage state. Each of the three component scores was added together to create an overall damage rating between 0 and 10. For example, a house that was recorded as having major flooring damage (2), major wall damage (4) and moderate roof damage (1) was given a total damage rating of 7. These scores were then divided into equal intervals to assign five damage states plus an additional state D0, which

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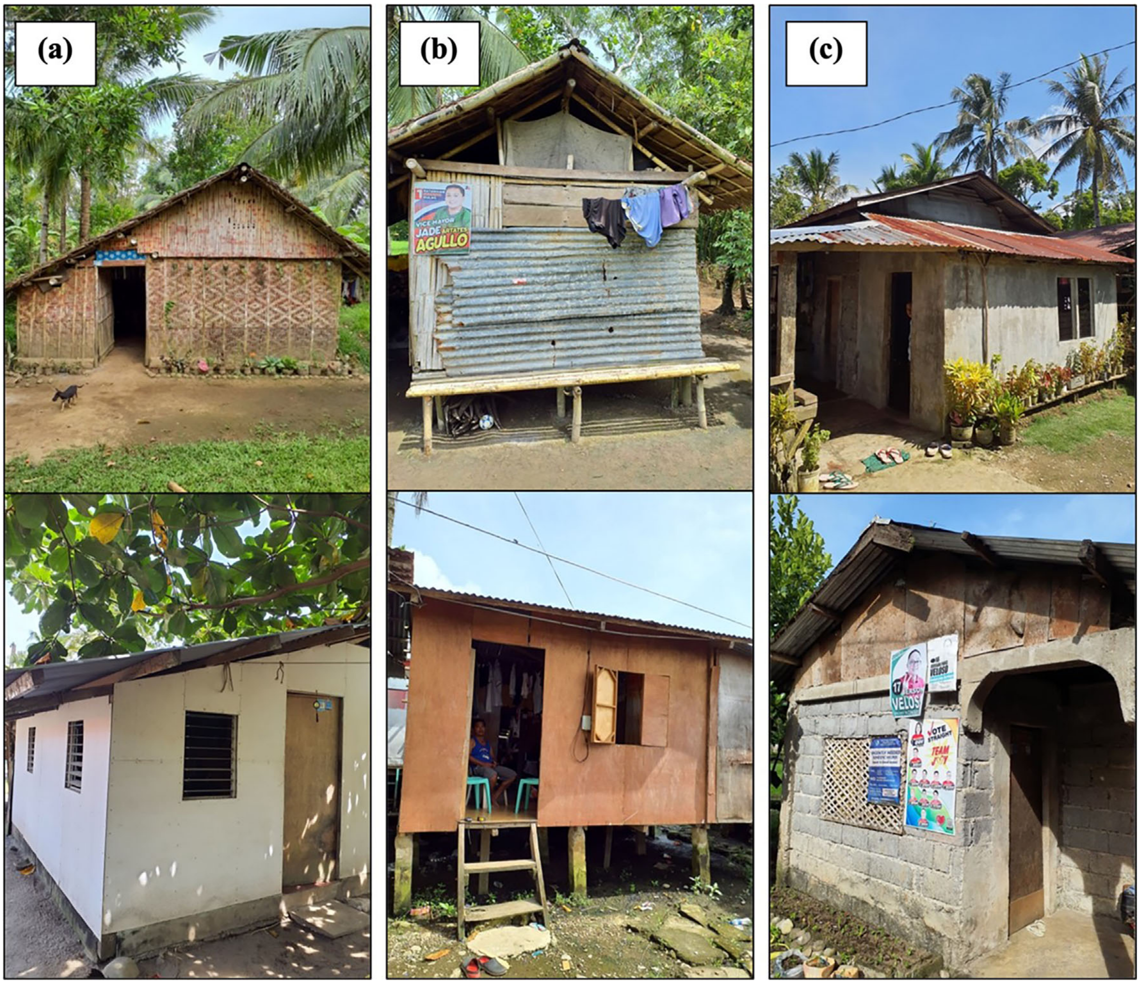

FIGURE 2 Building typologies: (a) light material (LM), (b) light material elevated (LM-E) and (c) masonry material (concrete hollow block).

TABLE 2 Damage states of housing typologies.

Damage level	Description	Damage state	Average damage ratio
Insignificant	Structure did not experience any permanent damage to the flooring, walls, and roofing. Water and debris penetration into the household	D0	0
Minor	Observable damage to both walls and flooring. Signs of rotting and cracking, sections of scouring for exposed flooring. House is habitable without needing immediate repairs	D1	0.16
Moderate	Damage to external walls and flooring. Light material damage includes missing panels allowing water to enter the structure. For masonry structures, this includes major cracks to mortar	D2	0.24
Major	Single section of house has been damaged or is missing. Immediate repairs are necessary to ensure structure is habitable for residence	D3	0.34
Severe	Large portions of the structure are damaged with foundations and columns still intact. House may have external frame intact, however, is unhabitable for residence without immediate and substantial repairs	D4	0.56
Total	Structure completely damaged. Demolition and replacement is required	D5	0.90

signified insignificant damage. Damage ratings were grouped as D1 (1–2), D2 (3–4), D3 (5–6), D4 (7–8) and D5 (9–10). In our example, a structure with a damage rating of 7 would have been assigned to D4. A summary of damage states assigned to corresponding aggregated damage ratings is shown in Table 2.

3.2.3 | Damage ratios

Vulnerability damage ratios were calculated as the fraction of the total damage repair cost against the total construction cost of the residential structure. The material pricing of components was gathered in Leyte by interviewing local construction workers and suppliers in each of the four case sites across the province. Our costings did not include internal furnishings and appliances of households. Through this, we were able to estimate the total damage for individual houses by identifying dimensions and sizes of affected structure components to estimate a repair cost. We considered foundations, stilts (elevation), flooring, external walls, bracings, columns, beams, roof truss and sheeting as components in our costings. For example, for a masonry (CHB) structure that had a collapsed wall (equivalent to Damage State 4), external walls, columns and foundations were used to estimate repair costs. After measuring and estimating sizing of the total affected damage area, wall areas and standard column and foundation sizes were used to estimate a repair cost. The damage ratio ranged from 0 to 1. An assigned value of 0 indicated that the building had no damage, whereas a value of 1 indicated total reconstruction of the structure. Each of the damage states can be associated with a damage ratio (or range of damage ratios). The average damage ratios for each corresponding damage state were as follows: 0.16 (D1), 0.24 (D2), 0.34 (D3), 0.56 (D4) and 0.90 (D5). These damage state classifications align with existing fragility and vulnerability studies (Baradaranshoraka et al., 2019; Nofal et al., 2020; Thapa et al., 2020).

3.2.4 | Fragility and vulnerability functions

To create fragility and vulnerability functions, a cumulative log-normal distribution function was applied to damage outputs against the inundation levels of flood, using Equation (2).

$$F(x) = [D = d|\mathrm{IM}]d \in \{1,2,3,\ldots,N_\mathrm{d}\} = \phi\left(\frac{\ln(x/\theta_\mathrm{d})}{\beta_\mathrm{d}}\right) \quad (2)$$

where $F(x)$ = fragility function for damage state d at intensity x; D = uncertain damage state for a system; d = specific damage state with no uncertainity; IM = intensity measure (inundation depth); x = particular value of intensity measure (IM); θ_d = median value of asset to resist damage for a single damage state; β_d = standard deviation of the natural logarithm of the asset to resist damage.

For analysing fragility, a sequential damage state was used such that the damaged states D_n is ordered. The probability of a certain intensity measure—in our case flood depth (x), can be reached or exceeded and is expressed as:

For damage state $d = 0$

$$= P[D = d|X = x] = 1 - P[D \geq d|X = x]. \quad (3)$$

For damage state $1 \leq d \leq d_\mathrm{n}$;

$$= P[D \geq d_\mathrm{i}|X = x] - P[D \geq d_{\mathrm{i}+1}|X = x] \quad (4)$$

For damage state $d = d_\mathrm{n}$;

$$= P[D = d|X = x]. \quad (5)$$

In some instances, multiple damage states for fragility functions may result in some damage states intersecting, resulting in negative probabilities in damages using the above equation. This results from different standard deviation (β) and mean (θ) values across the different damage states. We addressed this issue by reassessing the distribution of the standard deviations per equation (Equations 6 and 7) (Porter, 2017, 2021).

$$\beta' = \frac{1}{m}\sum_{d=1}^{m}\beta_\mathrm{d} \quad (6)$$

$$\theta'_\mathrm{d} = \theta_\mathrm{d}\exp(0.842 \cdot (\beta' - \beta_\mathrm{d})) \quad (7)$$

The β' and θ'_d represent the adjusted lognormal standard deviation and median for the damage stage i.

4 | RESULTS AND DISCUSSION

Our fragility and vulnerability functions are the first to systematically model flood damage relations for the Province of Leyte. We first present descriptive statistics for those houses surveyed, describing the representativeness of the building stock in the province. We then present fragility and vulnerability functions and discuss applications to advance flood modelling and management.

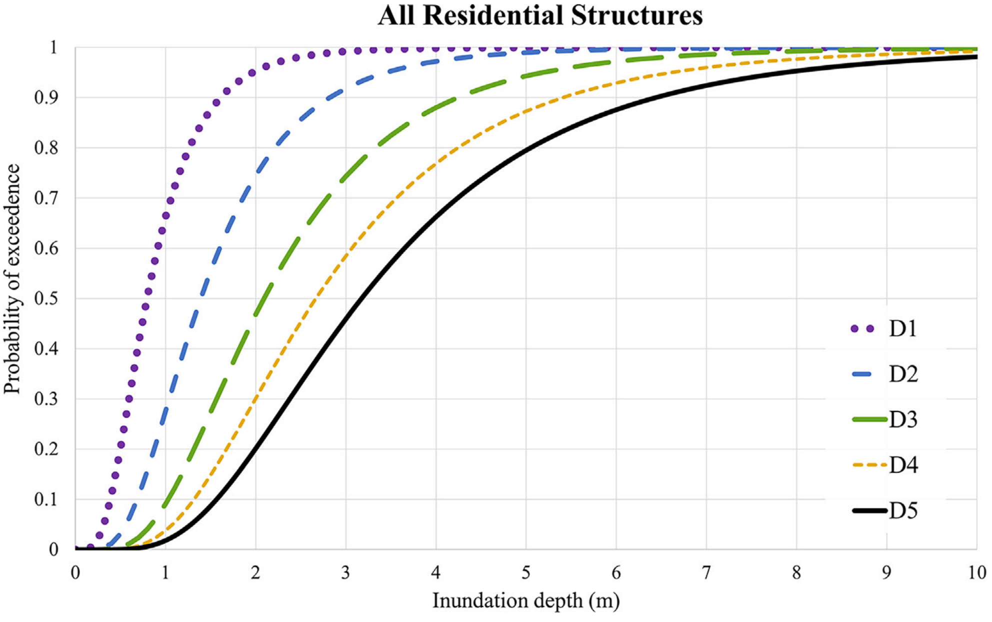

FIGURE 3 Fragility curve for all surveyed houses.

4.1 | Descriptive statistics

In our sample, 65% and 35% of structures were light and masonry construction, respectively, whilst 2015 census data showed that 54% and 46% of structures were light and masonry construction across Leyte (PSA, 2018). Our sample and the census show a majority of light material structures, so we can consider the combined fragility functions presented as an estimate of housing across the province, shown in Figure 3. It can be observed that light material and elevated light material homes had smaller floor areas on average than masonry construction, which were 25.6, 20.63 and 38.88 m^2, respectively. The average ridge roof height from the ground also varied between light material (3.2 m), light material elevated (3.7 m) and masonry (4.0 m). Understanding these building attributes allows for a contextualisation of subsequent fragility and vulnerability functions seen in Table 3.

The most common inundation events occurred due to pluvial flooding, followed by fluvial flooding and a smaller portion from coastal flooding. The descriptive analysis of these flood events included questions regarding estimated flow velocities which were categorised into stagnant, slow (0.0–0.2 m/s), medium (0.21–1 m/s) and high velocities (1+ m/s). Households were presented with these qualitative labels for flood velocities when asked about their previous observations and experiences. However, it is important to note that these water flow velocities were not the primary focus of intensity measurement for this research.

4.2 | Fragility curves

The combined fragility curves for all typologies are shown in Figure 3. There was negligible probability of damage (<1%) for all three typologies below flood depths of 0.2 m. At 0.5 m of flood inundation—the lower bound of medium flood hazard levels in existing Philippines hazard maps (UP NOAH, 2024), approximately knee level water height—there was a 10% probability of exceedance of minor damage (D1) for all structures. At high hazard levels, associated with the neck level water at 1.5 m, the probability of exceeding minor damage (D1) was 87% with a 9% probability of total damage (D5). For the average building height of 3.7 m, the cumulative probability of meeting or exceeding the minor damage state (D1) was 100%, moderate damage (D2) was 97%, major damage (D3) was 85%, severe damage (D4) was 72% and total damage (D5) was 61%.

We constructed fragility curves for the three most common building typologies found in Leyte, shown in Figures 4–6. The parameters for individual curves are shown in Table 4. The probability of exceedance for total damage (D5) was 18% and 3% for light and elevated light, respectively, for a high flood hazard of 1.5 m. In comparison, the probability of exceedance for severe damage (D4) for the masonry typology was 8%. For masonry structures, a D5 curve was not included due to limited structures exhibiting this damage state. The absence of this curve for masonry structures is reasonable as only high inundation and high flow velocities would have been expected to result in this level of damage.

TABLE 3 Descriptive statistics of surveyed residential houses.

Item	Frequency/ average (SD)	Light material $n = 167$	Light material elevated $n = 90$	Masonry (CHB) $n = 137$
Building attributes				
Age of construction	Average (SD)	21.62 (16.57)	17.44 (13.30)	26.64 (18.47)
Floor size (m^2)		28.48 (16.21)	22.67 (14.08)	44.06 (22.66)
Eaves roof height (m)		2.79 (2.67)	2.68 (0.75)	3.17 (1.19)
Ridge roof height (m)		3.43 (1.03)	3.56 (0.88)	4.16 (1.18)
Elevation from surface (m)		–	0.73 (0.37)	–
Number of materials		2.66 (1.07)	2.27 (1.08)	2.15 (1.18)
Flood characteristics				
Flood source				
Pluvial (%)	Frequency	68	63	54
Fluvial (%)		28	37	41
Coastal (%)		4	0	5
Flow velocity				
Stagnant (%)	Frequency	11	18	9
Slow, 0–0.5 m/s (%)		42	40	28
Moderate, 0.5–1.0 m/s (%)		28	23	41
High, 1+ m/s (%)		19	19	22
Duration (h)	Average (SD)	52.34 (55.54)	81.12 (68.03)	49.01 (59.88)
Depth (m)		1.13 (0.89)	1.39 (0.67)	1.15 (0.74)
Damage states				
Damage state 0 (%)	Frequency	21	19	72
Damage state 1 (%)		31	44	8
Damage state 2 (%)		26	22	4
Damage state 3 (%)		7	8	9
Damage state 4 (%)		4	3	2
Damage state 5 (%)		11	3	4

Abbreviation: CHB, concrete hollow blocks.

Light material elevated homes, usually constructed on stilts, had an average floor height of 0.6 m from ground surfaces. Represented by the elevated house fragility curve in Figure 5, there is a lower probability of damage at depths exceeding 1 m compared to the other two typologies. However, the probability of exceedance for all damage states rapidly increases past 1.5 m—jumping from a probability of 3% (at 1.5 m) to 83% (at 3 m) for D5. Field observations showed that these higher inundation depths often damaged foundations or stilts of the home—causing collapse abruptly. The abruptness of the change in damage states may also be related to increasing flow velocities, which were not explicitly incorporated into our hazard intensity measure in this study. When comparing non-elevated and elevated material structures, there is a 15% difference in probability of total structural damage at 1.5 m of inundation.

When comparing the material of households for both light material and masonry construction, there are noticeable differences in the possible failure mechanisms and causes of damage for structures. Intuitively, the use of masonry construction was more resilient to flood impacts. There was negligible probability (<1%) to experience minor damage (D1) for masonry structures below 0.4 of flood inundation, compared to the light material structures which were found to have a 45% probability of exceedance for minor damage at this same flood depth. Observationally, these discrepancies were a result of light material structures rotting or deteriorating due to prolonged exposure to water. The suite of curves suggest that the masonry structures are more resilient to floods with

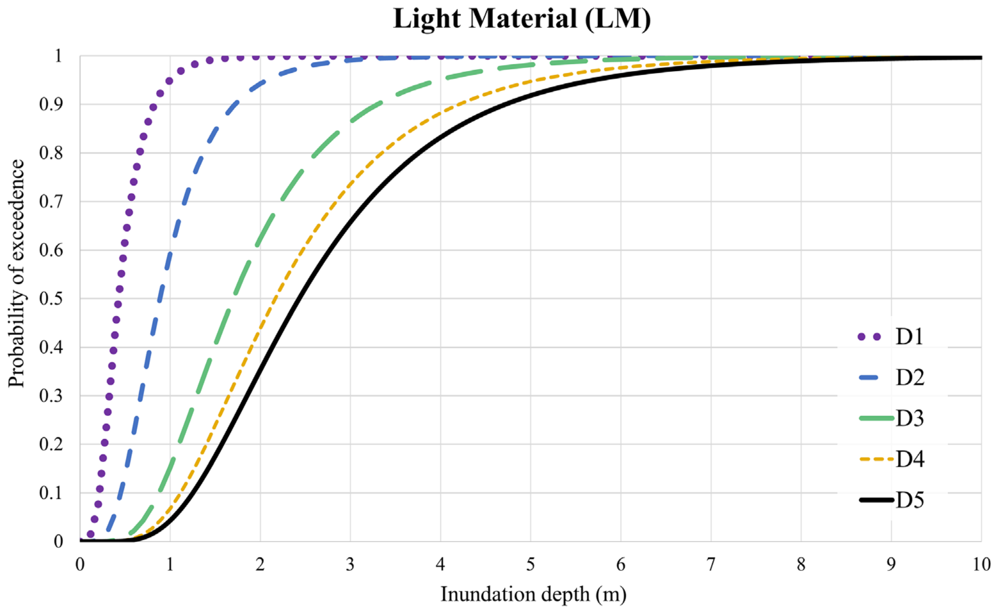

FIGURE 4 Fragility curve for light material houses.

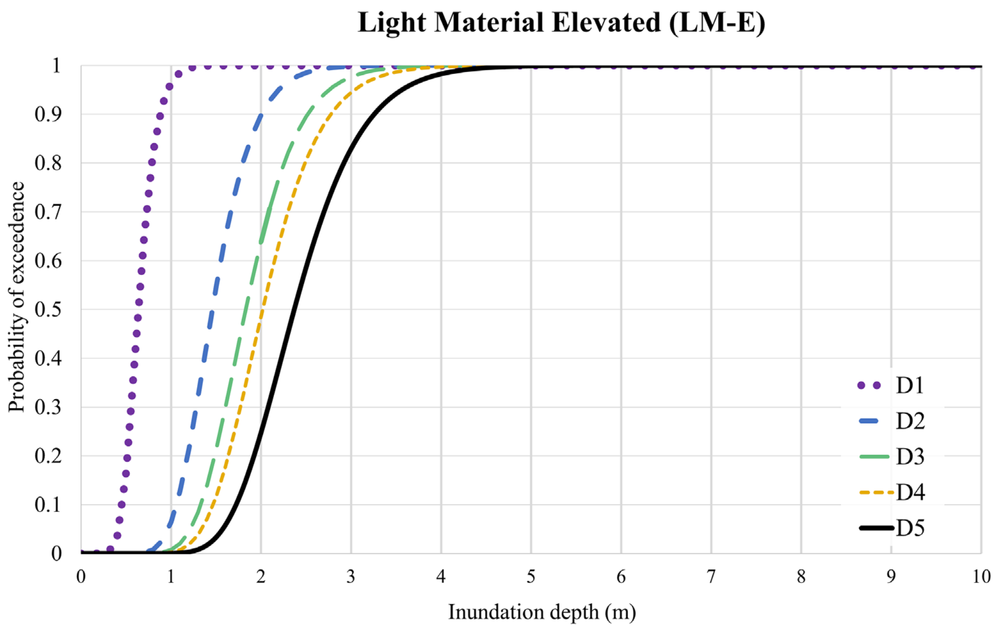

FIGURE 5 Fragility curve for light material elevated houses.

4% and 16% lower probabilities of severe damage (D4) at 1.5 m inundation compared to elevated and non-elevated light material structures.

4.3 | Vulnerability curves

These findings can be further supplemented with the applications of vulnerability functions which capture building-specific attributes such as the size, design and structural system which may be overlooked using fragility functions. The results from the vulnerability curves are shown in Figure 7. Parameters used to create the curves are shown in Table 4. Using similar thresholds mentioned above, there was a negligible damage ratio (<1%) for all three typologies at depths of 0.5 m. This value also corresponds to the lower bound of medium flood hazard in the Philippines. Considering a high flood hazard of 1.5 m, these damage ratios increased to 0.20, 0.12 and 0.02 for light material, light material elevated, and masonry structures, respectively. When considering an inundation depth that would submerge the average house (with an average roof ridge height of 3.7 m), the damage ratios for light material, light material elevated, and masonry structures increase to 0.80, 0.72 and 0.55, respectively. It was observed that damage ratios did not increase for masonry structures until an inundation level of 1.4 m, largely controlled by an absence of wall deterioration seen in light material structures.

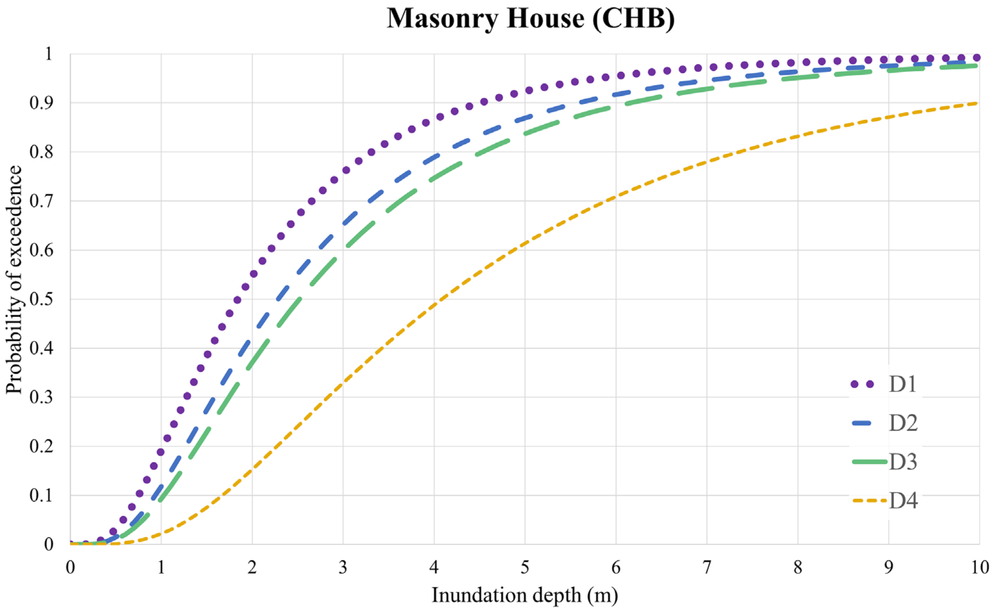

FIGURE 6 Fragility curves for masonry houses (CHB). CHB, concrete hollow blocks.

TABLE 4 Median and beta values for fragility and vulnerability functions.

		DS1	DS2	DS3	DS4	DS5	Vulnerability
Light Material (LM)	Median	−0.855	−0.122	0.530	0.773	0.889	0.865
	Beta (β)	0.518	0.518	0.518	0.518	0.518	0.536
Light Material Elevated (LM-E)	Median	−0.451	0.377	0.604	0.702	0.863	1.007
	Beta (β)	0.248	0.248	0.248	0.248	0.248	0.516
Masonry (CHB)	Median	0.610	0.826	0.923	1.408	–	1.247
	Beta (β)	0.698	0.698	0.698	0.698	–	0.419
All houses	Median	−0.232	0.330	0.738	0.980	1.15	–
	Beta (β)	0.552	0.552	0.552	0.552	0.552	–

Abbreviation: CHB, concrete hollow blocks.

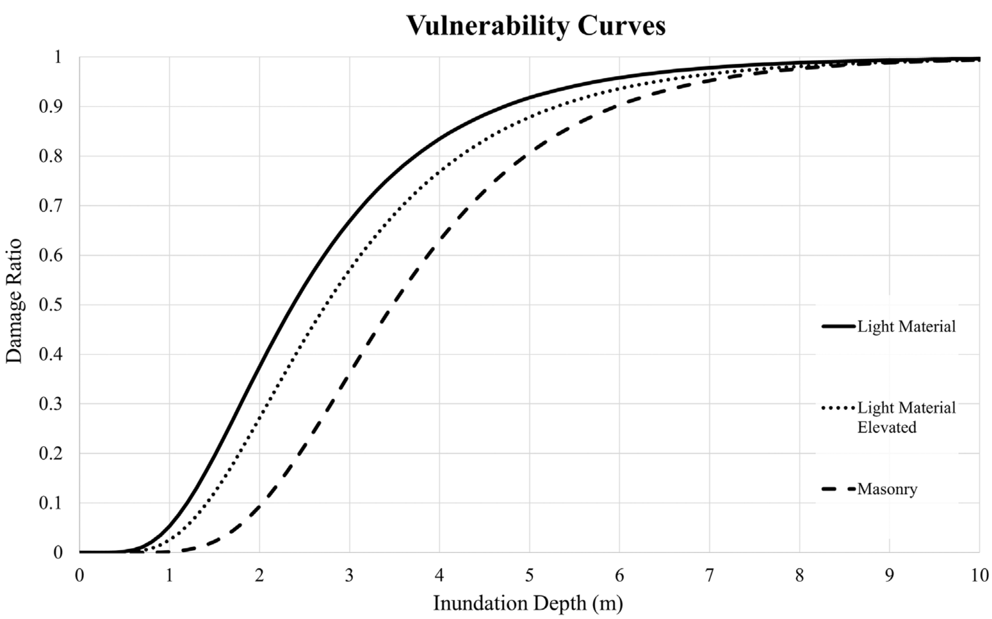

FIGURE 7 Vulnerability curves based on housing typologies.

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The average vulnerability ratios for previously observed damage states were 0.15 for minor damage (D1), 0.25 for moderate damage (D2), 0.35 for major damage (D3), 0.55 for severe damage (D4) and 0.90 for totally damage (D5). These classifications align with existing literature for residential structures across geographic contexts globally (Baradaranshoraka et al., 2019; Nofal et al., 2020; Thapa et al., 2020).

When conducting the fieldwork, we observed that most of structures in flood-prone areas were those built with limited engineering standards. These structures were generally constructed with patch-work components and in more isolated areas. The households occupying such dwellings generally lacked access to resources to build more resilient housing, resulting in a higher probability of expected damage. Those households who experienced flood damage commonly repaired their homes with scrap materials—resulting in cyclical substandard building practices. In contrast, for households building using masonry construction, damaging flood events were often derived from poor surrounding infrastructure, such as drainage. This is reflected with the damage ratios in the vulnerability curves, with average damage ratios equalling only 10% of total structure value at 2 m of flood depth. Repairs of these structures were largely not required below 1.3 m flood depths.

Compared to the study by Bautista et al. (2014), which draws on computation and heuristic methods from building stock in the GMMA, our vulnerability curves show a more uniform gradual increase in damages, largely due to the curve fitting processes applied in our method. Although Bautista et al. (2014) incorporated a broader range of variables, our analysis focused on floors, walls and roofing. As a result, the cost of electrical fixtures at depths of ~0.2 m did not directly influence our results. This is partly attributed to construction types varied across the sample houses, with some households having electrical fixtures on the ceiling—a common feature for structures frequently exposed to flooding. This variability in construction practices highlights the importance of context-specific assessments in estimating flood damages.

4.4 | Limitations

Obtaining discrete data for inundation depths and damage from households were a source of uncertainty in this study. We relied on recollection of flood events to estimate inundation depths—triangulating these where possible with neighbours' responses. Additionally, a limitation of this research was the inability to integrate quantitative flood velocities when determining the damage to houses. While our data collection was limited to the Province of Leyte, we envision a potential transferability of the generated fragility and vulnerability across rural areas of the Philippines, where housing building types and construction practices are largely similar. Further research should investigate fragility and vulnerability functions across the different regions in the Philippines to account for the presence of localised building typologies as well as to uncover the different attributes that influence building fragility and vulnerability. This is particularly important for larger scale catastrophe and risk models for planning to capture the building disparities across different localities in the Philippines.

5 | CONCLUSION

Disparities in building construction across the Philippines, combined with high flood exposure, require the development of localised functions to model flood damage and loss. We developed a new set of flood fragility and vulnerability functions for residential structures in the Province of Leyte—the first such suite of flood functions to our knowledge outside of the Metro Manila area. This drew on 394 residential structure damage assessments conducted across the municipalities of Abyuog, Carigara, Dulag and Tacloban City. Three main building typologies were identified: light material, light material elevated and masonry. Findings showed that light material homes are most susceptible to flood damage. Elevated light material homes were less susceptible to impacts at low inundations but tended to fail abruptly at depths exceeding 3 m. Masonry structures were the most resistant to flood damage among the three typologies.

Using our damage functions with probabilistic flood models, we can estimate damages to assist in enhancing flood risk reduction activities, such as comprehensive flood risk assessments. Our fragility functions serve as a tool to determine expected damage and losses to structures in the Province of Leyte and more generally in the Eastern Visayas region through probabilistic approaches. These fragility functions enable further understanding of how residential structures behave under different flooding scenarios. Additionally, this research provides valuable depth-damage functions needed to capture residential flood vulnerability by quantifying general cost impacts of flood damage through vulnerability ratios. When combined with housing cost, this can contribute to modelling of financial risks and help assess housing risk reduction investment through disaster risk reduction planning and strategies, including cost–benefit analysis for flood adaptation and mitigation efforts. By adopting this localised approach, our contribution expands understanding of flood vulnerability in the Philippines. In light of shifting risk patterns under climate change, our method can also be used to quantify and examine cost trade-offs for residential adaptation upgrades.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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