Assessing community-level flood risk at the micro-scale by owner/occupant type and first-floor height

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Abstract

Evaluating flood risk is an essential component of understanding and increasing community resilience. A robust approach for quantifying flood risk in terms of average annual loss (AAL) in dollars at the community level is needed to provide valuable information for stakeholder decision-making. This research develops a computational framework to evaluate AAL at the community level by owner/occupant type (i.e., homeowner, landlord, and tenant) for increasing first-floor heights. The AAL values are calculated here by numerically integrating loss-exceedance probability distributions to represent economic annual flood risk to the building, contents, and use. A case study for a census block in Jefferson Parish, Louisiana, reveals that homeowners bear a mean AAL of $4,390 at the 100-year flood elevation (E_{100}), compared with $2,960, and $1,590 for landlords and tenants, respectively, because the homeowner incurs losses to building, contents, and use, rather than only two of the three, as for the landlord and tenant. The results of this case study show that increasing first-floor heights reduces AAL proportionately for each owner/occupant type, and that two feet of additional elevation above E_{100} may provide the most economically advantageous benefit. The modeled results suggest that Hazus Multi-Hazard (Hazus-

MH) output underestimates the AAL by 11% for building and 15% for contents. Application of this technique to the community level while partitioning the owner/occupant types will improve planning for improved resilience and assessment of impacts attributable to the costly flood hazard.

Keywords: Flood risk, Average annual loss (AAL), Natural hazard mitigation, Community resilience, First-floor height, Louisiana

1. Introduction

<u>Importance of Flood Risk Quantification</u>

Floods are one of the most severe and frequently occurring natural disasters (Mostafiz, 2022c; Sastry, 2021; Tariq & van de Giesen, 2012) and cause significant human and economic losses (Tate et al., 2014). For example, the direct damage of flooding in the U.S.A. has increased to $17 billion (USD) per year (Association of State Floodplain Managers, 2020). More than 1.1 million insurance claims were filed with the National Flood Insurance Program (NFIP) between 1998 and 2017 (Matthews et al., 2021). Further, the total average annual loss (AAL) from floods, presumably due to direct and indirect causes that are either insured or uninsured, is estimated at $104 billion USD worldwide (Eder et al., 2022) and $32.1 billion USD in the U.S.A. (Wing et al., 2022). In the next 30 years, flood-related property damage may increase by 60% as a result of climate change (Sastry, 2021), and many communities and individuals underestimate the potential for flood damage (Burningham et al., 2008; Mol et al., 2020). Therefore, in recent years, many researchers worldwide have focused on flood risk and loss assessments (e.g., Afifi et al., 2019; Dutta et al., 2003; Jin et al., 2022; Mostafiz et al., 2021a; Rahim et al., 2022b; Scawthorn et al., 2006; Tam et al., 2014).

Flood risk assessments consist of two main components: the probability of flooding and the consequences associated with its occurrence (Dalezios, 2017). In this study, AAL is used to represent the annual flood risk and includes the costs associated with three types of losses considered in previous flood loss research (e.g., National Institute of Building Sciences, 2017; Scawthorn et al., 2006; Taghinezhad et al., 2021): (1) restoring the building structure itself to its pre-flood fair market value (i.e., direct building loss); (2) replacing flood-damaged physical contents inside the building with items of the same fair market value (i.e., direct contents loss); and (3) accounting for the time and labor required for the inhabitant to repair, clean up, and inspect the building, beyond those associated with (1) and (2) above (i.e., indirect loss), represented here by loss of use. These losses vary between homeowners, landlords, and tenants (Hamideh et al., 2018; Warren-Myers et al., 2018). However, most residential flood risk assessment research to date focuses solely on building and contents risk to homeowners; risk to the landlord and tenant owner/occupant types have largely been overlooked, leading to inaccurate estimates of flood risk.

Three approaches have been used to evaluate flood risk in terms of AAL. One method is to compute the piecewise product of annual exceedance probabilities (AEPs) and the absolute economic loss associated with the available return periods (e.g., Armal et al., 2020; FEMA, 2013; Montgomery & Kunreuther, 2018; Schneider & Schauer, 2006). In this technique, the resulting piecewise products are aggregated across a range of probabilities using Riemann sums. In the second approach, the log-linear relationship between the expected loss as a percentage of the building or contents value, as a function of annual flood probability or return period, is used to interpolate or extrapolate the expected loss for events at other return periods (Arnbjerg-Nielsen & Fleischer, 2009). The third approach represents the flood hazard by using a generalized extreme value (GEV) distribution function to represent uncertainties. The AAL is computed using GEV parameters (i.e., location, shape, and scale) that are determined by fitting the data by using the Markov Chain Monte Carlo method, depth-damage functions (DDFs), and house characteristics such as area, value, and initial elevation (Zarekarizi et al., 2020).

Although these approaches have been accepted to evaluate flood AALs, recent research has identified substantial drawbacks, including the coarse estimation of AAL and unavailability of data for extreme return periods (exceeding 500 years) in the first approach described above. Also, recent research suggests that AAL can be overestimated in the log-linear and GEV approaches (Gnan , 2021; Gnan et al., 2022a).

For these reasons, estimation of flood risk using an improved, refined numerical integration of the full loss-exceedance probability distribution provides an opportunity for advancing flood risk assessment (Gnan, 2021; Gnan et al., 2022a; Rahim et al., 2022a). Application of this approach for the full set of loss-exceedance probabilities has been used successfully to overcome the mentioned drawbacks. However, it has only been attempted for a one-story, single-family home case study (Gnan et al., 2022a; 2022b). Flood risk assessment can be valuable and appropriate at many scales, from the micro- to the meso-, macro-, and supra-national, and micro-scale analyses have been shown to enable people, companies, and communities to prepare most effectively for flood disasters and develop risk maps (de Moel et al., 2015). Yet application of the improved, refined numerical integration approach across multiple homes with varying attributes will be useful for assessing community-level flood risk (Mostafiz et al., 2022a), thereby leading to more informed decision making at the second-most-local scale in the spectrum (Mostafiz et al., 2022b).

Effect of First-floor Height and Depth-damage Functions on Flood Risk

Two further fundamental, related considerations are addressed. The first involves the economically optimal height of building construction above the surface to mitigate flooding. Raising the first-floor height (FFH) above the 100-year flood elevation (E_{100}) is one of the most successful flood mitigation strategies (Taghinezhad et al., 2021). In the U.S.A., improvements in mitigating the flood hazard have involved the establishment of minimum construction elevations and increasingly active encouragement to build above the minimum height. The base flood elevation (BFE), which is approximately equal to E_{100} or the 1% annual exceedance probability (AEP; FEMA, 2011), is the national standard used by the NFIP and all federal agencies (FEMA, 2005). The regulatory standard for home construction in areas where wave heights are less than 1.5 feet (known in the U.S.A. as the V Zone and Coastal A Zone) has typically been to situate the top of the first floor at the E_{100} (ASCE, 2005), a standard that was modified (ASCE, 2014) to include an additional 1.0 foot of elevation above E_{100}. Elevating the home above E_{100} leads to reduced building and contents damage by decreasing the probability of flood occurrence above the first floor (Hawkesbury-Nepean Floodplain Management Steering Committee, 2007).

The second, related consideration involves the critical decision of DDF selection for flood loss, and therefore risk, assessment (Mostafiz et al., 2021b). The most effective DDF will characterize the relationship between the water depth in the structure (dh) and the percent of damage most appropriately while also identifying properly the flood damage initiation point with respect to dh. To optimize the risk calculations, each home category (e.g., one-story home without basement) has three DDFs – one each for losses to building, contents, and use.

The dh is an important parameter for all flood loss models (Apel et al., 2009), in part because it is used in the DDFs to estimate building and contents losses, and therefore total AAL (Pistrika et al., 2014). Several sources examine the dh-damage relationship, including USACE (2000), USACE (2006), Nofal et al. (2020) who provided loss functions for multiple models, and Wing et al. (2020) who used NFIP flood damage claims to represent the dh-damage relationships. More recent research has highlighted the importance of dh where damage is assumed to initiate. Gnan (2022a) demonstrated that AAL derived from USACE functions that initiate damage at a dh of –2 feet (i.e., 2 feet below the top of the first floor) were much higher than AAL calculated from the same function with damage initiation assumed to occur at $dh = 0$ (i.e., top of first floor; Figure 1). Consideration of flood risk reduction through optimal home elevation and the sensitivity of risk assessment to DDF selection remain as fundamental issues in the development of consistent flood risk assessment procedures.

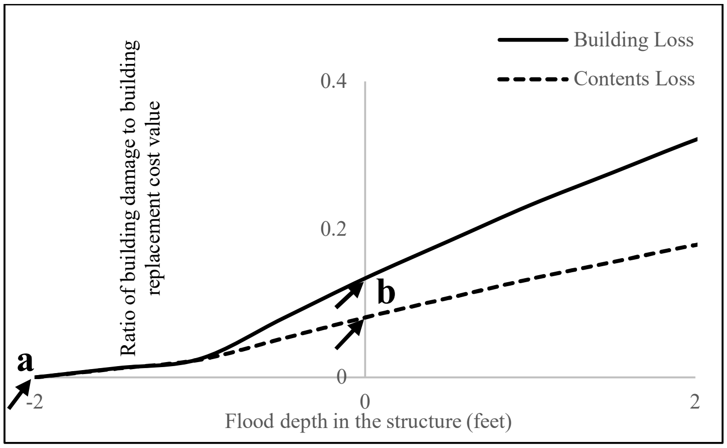

Figure 1. Depiction of USACE (2000) mean depth-damage function for a one-story, no-basement residential building, starting at flood depth of (a) –2 feet (original function), and (b) 0 feet.

<u>Goals and Contributions of This Research</u>

This paper develops a framework that applies the numerically integrated AAL approach across a multiple-homes study area to address the following research questions: (1) how does flood risk vary by owner/occupant type (i.e., homeowners vs. landlords vs. tenants)? and (2) what is the mean flood risk reduction by owner/occupant type with increasing first-floor height above an initial first-floor height (FFH_0)? The AAL reduction, partitioned by building, contents, and use, is calculated by owner/occupant type (i.e., homeowner, landlord, and tenant) and by increasing first-floor heights above FFH_0. A sensitivity analysis is conducted to assess the effect on each AAL estimation of choosing the damage initiation flood depth level in the structure. Calculations from this approach are compared to those generated by Hazus Multi-Hazard (Hazus-MH) flood model (FEMA, 2013), for a case study area consisting of 29 homes with different attributes.

The contribution of this paper is the development of a computational framework to enable micro-scale assessment of community-level flood risk by owner/occupant type and first-floor height. This paper overcomes the limitation of most community-level (meso-scale) analyses by avoiding the generalization of building types by preserving variability in building input data and flood hazard. Results can be displayed on a per-building or aggregated basis to describe the community-level risk, with individual results available for further scrutiny. In addition to expanding the Gnan et al. (2022b) method to multiple homes, understanding the absolute and relative economic effectiveness of first floor height by owner/occupant type supports hazard planning for decreasing flood risk.

2. Methodology

To address the research questions, a novel computational framework is developed (Figure 2) using the MATLAB R2019b software package to estimate the AAL for multiple homes distributed across a spatial extent with varying flood hazard. The AAL is partitioned to homes (i = 1 through n) separately for building, contents, and use. Likewise, the AAL reduction (in dollars) is calculated for M increases of increment J in first-floor height above the FFH_0 for each owner/occupant type (i.e., homeowner, landlord, and tenant). These results are compared with AAL calculations using Level 2 analysis in the Hazus-MH Flood Model (FEMA, 2013). The following sections describe the steps in more detail. The MATLAB algorithm allows the user to upload an unlimited home attribute data set to evaluate building, contents, and use risk, with these values convertible to dollar figures, for each home.

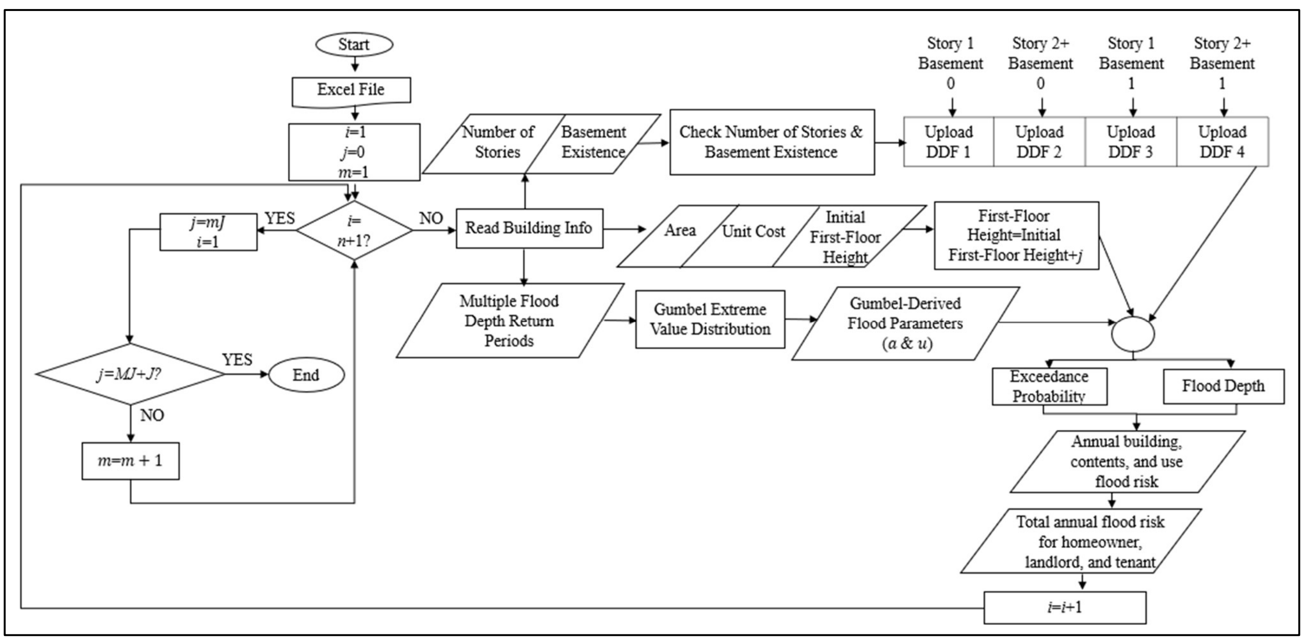

Figure 2. General outline of the research framework.

<u>Input Data</u>

The input data (e.g., Supplementary Table 1) used in the AAL analysis are the number of stories (1 or 2+), basement existence (0 = No, 1= Yes), area in square feet (A), unit area repair cost in USD per square foot (C_R), and FFH_0. FFH_0 is a general term that may represent either the actual first-floor height for existing buildings, the minimum regulatory standard for first-floor height for a particular area, a hypothetical beginning first-floor height for consideration of additional elevation, or a practical minimum first-floor height based on foundation type. Also, the flood depth above the ground for multiple AEP events at the location of each home and the corresponding AEP values for those flood depths are input.

In this study, the USACE (2000) DDFs are chosen to determine the relationship between building (or contents) loss and dh. These DDFs are selected in this study to demonstrate the methodology because they are based on generic data (1996–2000). DDFs such as USACE (2006) include flood duration and foundation type and could be substituted in cases where more descriptive input data are available. Four of the USACE (2000) home types are incorporated into the numerically integrated computational framework here: one story with no basement (DDF1), two or more stories with no basement (DDF2), one story with basement (DDF3), and two or more stories with basement (DDF4). Within the DDF, the mean and standard deviation of building and contents loss are expressed as a proportion of home replacement cost value (V_R) for each one-foot increment of dh beginning at the damage initiation point of –2 feet, up to 16 feet (USACE, 2000). Interpolation is used here to determine the percentage of building and contents losses at each 0.5-foot increment of dh. Finally, restoration time (in months) is taken from FEMA (2013) and is taken as a surrogate for use loss, at each flood depth. Because restoration time tables in FEMA (2013) define the use loss at four-foot increments, interpolation is employed to estimate the use loss function at 0.5-foot increments of dh. The four utilized DDFs are shown in Supplementary Tables 2–5. The DDF selected for each home corresponds to the number of stories and presence/absence of a basement.

Flood Risk Quantification

The Gumbel distribution function has been shown to be effective for modeling flood frequency (e.g., Mayank et al., 2020; Singh et al., 2018). Therefore, the two-parameter Gumbel distribution function is used to model the probability of exceedance for the expected flood depths. The cumulative distribution function (CDF) of the Gumbel distribution is the probability (p) that a random variable X has a value less than or equal to a threshold Y, also known as the probability of non-exceedance. That value is generally expressed in Eq. 1, with u and a representing the Gumbel location and scale parameter, respectively.

$$CDF = p(X \leq Y) = exp\left[-exp\left(-\left(\frac{Y-u}{a}\right)\right)\right] \quad (1)$$

The complement of the CDF represents the AEP of a potential flood event with depth above the ground d, as shown in Eq. 2.

$$AEP = P = 1 - exp\left[-exp\left(-\left(\frac{d-u}{a}\right)\right)\right] \quad (2)$$

where $P = p(X > d)$

The α and u parameters are the regression coefficients (slope and y-intercept, respectively) in the relationship between d and the double natural logarithm of P (or AEP; Eq. 3). Using the AEP event input data for each home location, a unique regression line is generated for each home location to yield its distinctive α and u hazard parameters (Mostafiz et al., 2021c). The flood depth within the house, represented in the DDFs as dh, is expressed as the difference between d and FFH_0 (Eq. 4).

$$d = u - \alpha \ln(-ln(P)) \quad (3)$$

$$dh = d - FFH_0 \quad (4)$$

For each 0.5-foot water depth increment of dh, the corresponding d and P are calculated. For each home, the selected DDFs are transformed into a function of P using the relationships in Eqs. 2 and 3. The functions $L_B(P)$ and $L_C(P)$ represent building and contents losses as a function of P, represented as a proportion of the total building replacement cost value. Similarly, $L_U(P)$ represents use loss in months as a function of P. AAL is calculated as the integral of loss as a function of flood probability, where P_{min} represents the lowest exceedance probability value and P_{max} is the highest exceedance probability value. Eqs. 5–7 describe the theoretical formulation of the AAL for building, contents, and use (AAL_{B/V_R}, AAL_{C/V_R}, $AAL_{\mathrm{U,months}}$, respectively) for each home. AAL_{B/V_R} and AAL_{C/V_R} represent the annual building and contents flood risk as a proportion of the total building replacement cost value, while $AAL_{\mathrm{U,months}}$ represents annual use flood risk in months.

$$AAL_{\mathrm{B}/V_R} = \int_{P_{min}}^{P_{max}} L_B(P)dP \quad (5)$$

$$AAL_{\mathrm{C}/V_R} = \int_{P_{min}}^{P_{max}} L_C(P)dP \quad (6)$$

$$AAL_{\mathrm{U,months}} = \int_{P_{min}}^{P_{max}} L_U(P)dP \quad (7)$$

Riemann summation is a computational approach to approximate an exact integration solution as the sum of trapezoidal areas under a curve. To computationally evaluate Eqs., 5–7, the area of each trapezoid under the $L(P)$ functions is estimated as the difference in exceedance probabilities multiplied by the average loss (building, contents, or use) for the corresponding probabilities. The trapezoidal Riemann sums approach is used to aggregate the product results across all probabilities to yield AAL (Gnan, 2021; Gnan et al, 2022a; Meyer et al., 2009) as generally shown in Eq. 8.

$$AAL = \sum_{k=1}^{K}\left[(P_{k+1} - P_k) * \frac{(L_k + L_{k+1})}{2}\right] \quad (8)$$

Here, K is the number of trapezoids under the $L(P)$ curve.

Flood Risk Quantification by Owner/Occupant Type

The total AAL calculations vary based on the owner/occupant type (i.e., homeowner, landlord, or tenant). Any building loss will always be incurred by the owner (i.e., homeowner or landlord), regardless of occupancy. Homeowners and tenants, but not landlords, will incur contents loss. For this study, AALs for building and contents are initially expressed as a proportion of the total building replacement cost value (Eqs. 5–6). However, because monetary values are more readily understood and appreciated when communicating risk to the public, the AAL variables are then converted to dollar figures for building ($AAL_{\mathrm{B}\$}$) and contents ($AAL_{\mathrm{C}\$}$) via V_R, which is the unit building replacement cost per square foot (C_R) multiplied by the home area (A), as shown in Eq. 9:

$$V_R = C_R \times A \quad (9)$$

Then, $AAL_{B\$}$ and $AAL_{C\$}$ are calculated as shown in Eqs. 10–11.

$$AAL_{B\$} = AAL_{\mathrm{B}/V_R} \times V_R \quad (10)$$

$$AAL_{C\$} = AAL_{\mathrm{C}/V_R} \times V_R \quad (11)$$

The AAL for use, or restoration time, is expressed in units of months ($AAL_{U,\mathrm{months}}$) and is partitioned into that assumed by the homeowner ($AAL_{UH,\mathrm{months}}$), landlord ($AAL_{UL,\mathrm{months}}$), and tenant ($AAL_{UT,\mathrm{months}}$). These three variables are then converted to economic value, as shown in Eqs. 12–14, where R_l is the monthly rent incurred (for the homeowner) or lost (for the landlord), and H_R is the nightly hotel rent. The total annual flood risk ($AAL_{T\$}$) calculated as the sum of building, contents, and use annual risk by owner/occupant type (Eq. 15). $AAL_{\mathrm{U}\$}$ is a generalized representation of use loss for which the applicable equation should be selected based on owner/occupant type. Table 1 shows the equation numbers to use when calculating $AAL_{\mathrm{B}\$}$, $AAL_{\mathrm{C}\$}$, and $AAL_{\mathrm{U}\$}$ for each owner/occupant type.

$$AAL_{UH,\$} = AAL_{UH,\mathrm{months}} \times R_l \quad (12)$$

$$AAL_{UL,\$} = AAL_{UL,\text{months}} \times R_l \quad (13)$$

$$AAL_{UT,\$} = AAL_{UT,\text{months}} \times 30_{\text{ days/month}} \times H_R \quad (14)$$

$$AAL_{T\$} = AAL_{B\$} + AAL_{C\$} + AAL_{U\$} \quad (15)$$

Table 1. Equation numbers used to calculate building, contents, and use AAL by owner/occupant type.

Owner/Occupant Type	Building AAL	Contents AAL	Use AAL
Homeowner	10	11	12
Landlord	10	n/a	13
Tenant	n/a	11	14

Relative Flood Risk Reduction with Increasing First-Floor Height

To calculate the AAL for first-floor heights above FFH_0, an increment (j) is added to FFH_0 and all calculations represented in Eqs. 3 through 15 are repeated using the new FFH value. The relative AAL reduction with each increment is calculated using Eq. 16.

$$AAL\ Reduction_j\ \% = \frac{(AAL_{FFH_0}) - (AAL_{FFH_0+j})}{AAL_{FFH_0}} * 100 \quad (16)$$

Average Annual Loss (AAL) in Hazus-MH

Flood depth grids at 10-, 25-, 50-, 100-, and 500-year return periods are required to calculate "average annualized loss." Hazus-MH represents AAL via summed calculations of the product of difference in return period (RP) flood frequency (f_{RP}; analogous to AEP) and the corresponding mean loss (L_{RP}), as shown in Eq. 17.

$$AAL = (f_{10} - f_{25}) \cdot \frac{L_{10}+L_{25}}{2} + (f_{25} - f_{50}) \cdot \frac{L_{25}+L_{50}}{2} + (f_{50} - f_{100}) \cdot \frac{L_{50}+L_{100}}{2} + (f_{100} - f_{500}) \cdot \frac{L_{100}+L_{500}}{2} + (f_{500} \cdot L_{500}) \quad (17)$$

The process begins with clicking "create a new region," and "riverine only" is selected in the study region flood hazard type. Then, the 10-, 25-, 50-, 100-, and 500-year flood depth grids under "user data" are uploaded. Next, the building input data are imported under "user defined facilities (UDF)." The proper DDFs are then selected for the flood loss calculation. Then, a new hazard scenario is created with the 10-, 25-, 50-, 100-, and 500-year flood depth grids, and the riverine floodplain is delineated for "full suite of return periods" using the default cell size (3.048 m x 3.048 m). Then, AAL analysis is run with the UDF. The result shows $AAL_{B\$}$ and $AAL_{C\$}$ for each building separately, but Hazus-MH does not provide $AAL_{U\$}$.

DDF Sensitivity

Flood waters can damage subfloor assemblies and utilities of elevated homes, which may require consideration of losses for $dh < 0$. However, the extent to which these losses may occur is unclear. A sensitivity analysis is therefore conducted to compare AAL values estimated using USACE (2000) considering damage initiation points of $dh = -1$ foot, -0.5 foot, and 0 feet, holding all input parameters and the DDF constant. While this sensitivity analysis does not identify which damage initiation point is "correct," it does shine light on the effect of DDF damage initiation point variability on flood risk assessment results.

Comparison with Hazus-MH Results

A pairwise t-test is used to assess whether a statistically significant difference (α = 0.05) exists in population mean (μ) values between $AAL_{B\$}$ (and, in a separate analysis, $AAL_{C\$}$) calculated by the AAL approach presented in this paper vs. Hazus-MH output. Because Hazus-MH ignores use risk, $AAL_{U\$}$ is not considered in this analysis. Thus, the null and alternative hypotheses for both $AAL_{B\$}$ and $AAL_{C\$}$ are provided in Eqs. 18 and 19, respectively. The intent of this test is to evaluate if the refined approach presented in this paper differs significantly from the results of the existing, widely used Hazus-MH tool.

$$H_0: \mu_{AAL} = \mu_{AAL\ Hazus} \quad (18)$$

$$H_1: \mu_{AAL} \neq \mu_{AAL\ Hazus} \quad (19)$$

3. Case Study

Several criteria should be met by the case study selected in order to address the research questions most effectively. The selected area should be subjected to flooding and be reasonably populated, so that flood impacts are detectable. Availability of high-quality flood hazard data at multiple return periods and building data for each home in the study area is also essential. The study area should also be sufficiently large and diverse to allow for meaningful calculations and transferability of results elsewhere, yet small enough to ensure uniformity in flood hazard, which promotes improved generalizability of first-floor height results across the community.

Based on these criteria, census block 220510220012004, in Metairie, Louisiana, U.S.A., which consists of n = 29 homes, none of which have basements, is selected (Figure 1). To protect the privacy of homeowners, landlords, and tenants, numbering of homes within the study area is randomized and not disclosed. The input data – area, unit cost, FFH_0 (assumed to be equal to

E_{100}), number of stories, basement existence, and 0.10, 0.02, 0.01, and 0.002 AEP flood depth point values – are used to calculate the $AAL_{B\$}$, $AAL_{C\$}$, $AAL_{UH,\$}$, $AAL_{UL,\$}$, $AAL_{UT,\$}$, and AAL_{T} for each home. Input parameters for each home, along with values for the four AEP flood depths, are listed in Supplementary Table 1; values for other AEPs can be provided upon request. To evaluate the effects of first-floor height, increases in first-floor height from 1 to 4 feet (i.e., *J* through *MJ*) are added to E_{100}. The same input parameters are analyzed using Hazus-MH with USACE (2000) DDFs and a flood depth damage initiation point at –1 foot, for comparison with results from the presented AAL approach.

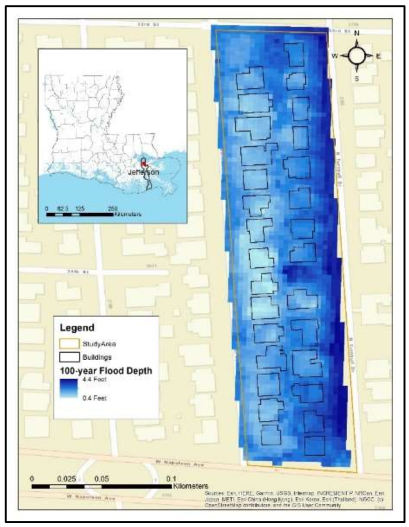

Figure 1. Location of the study area with non-numbered building footprint polygons.

4. Results

<u>Flood Risk Quantification</u>

Flood risk mean values for the 29 homes in this case study represent community-level values. For homes with first-floor height equal to the 100-year flood elevation, the mean (i.e., community-level) $AAL_{B\$}$ and $AAL_{C\$}$ is \$2,300 and \$1,500 per home, respectively, with a range of approximately \$600 to \$7,000 and \$300 to \$4,700 per home, respectively (Figure 4). Building attributes, and regression parameters for the homes with the largest and smallest AAL values are shown in Table 2.

Because the $AAL_{U\$}$ calculation depends on owner/occupant type (i.e., homeowner, landlord, and tenant), it is not shown in aggregate form. As owner/occupancy type is unknown, the sum of $AAL_{B\$}$, $AAL_{C\$}$, and $AAL_{U\$}$ for homes at E_{100} assumes that all 29 homes are homeowner-occupied (and then landlord-owned and tenant-occupied), yielding a mean $AAL_{T\$}$ of \$4,390, \$2,960, and

$1,590 per home, respectively (Figure 5). The complete set of output values for each of the 29 homes in the study area is shown in Supplementary Table 6.

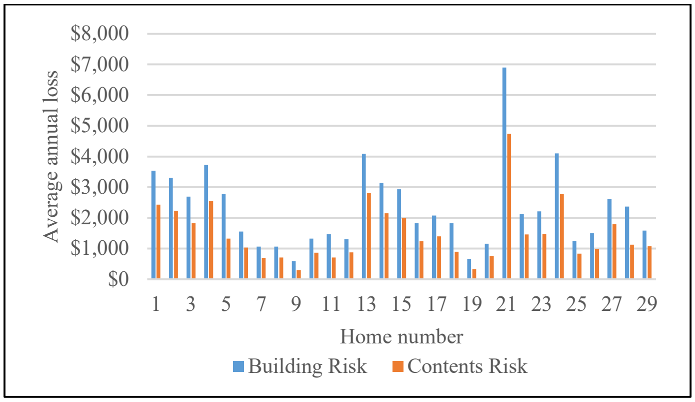

Figure 4. Building and contents AAL at 100-year flood elevation, by home.

Table 2. Building attributes, regression parameters, and average annual loss (AAL) for residences with the largest and smallest AALs.

Building Number	Number of Stories	Basement	FFH_0 (feet) $= E_{100}$	Replacement Cost Value ($)	a	u	Total Building+ Contents Loss
21	1	0	0.6	283,804	0.29	–0.64	$11,636
9	2	0	2.7	195,129	0.56	–0.03	$894

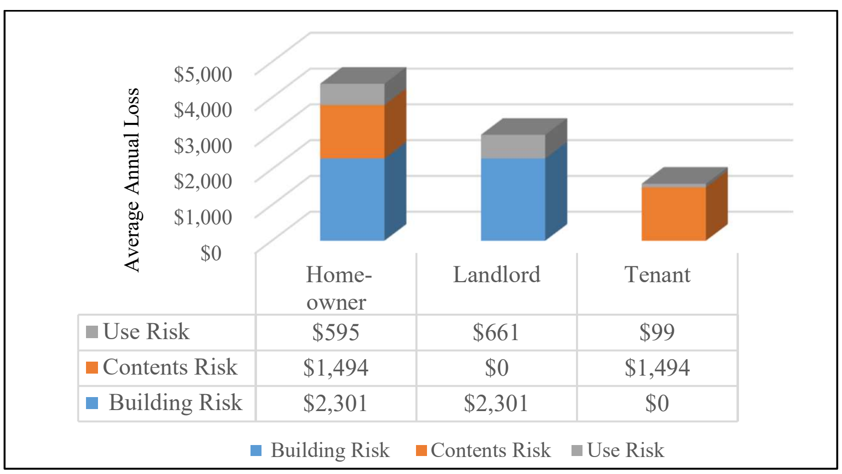

Figure 5. AAL for building, contents, and use by owner/occupant type at 100-year flood elevation, if all homes would be in the same owner/occupant type.

Flood Risk Reduction Quantification

The mean AAL_{B/V_R} (and, separately, AAL_{C/V_R}) for the 29 buildings for each increase in first-floor height above E_{100} is shown in Figure 6. The calculated $AAL_{B\$}$, $AAL_{C\$}$, and $AAL_{U\$}$ by owner/occupant type and for each increase in first-floor height above E_{100} appear in Table 3. Substantial decreases in all components of AAL are realized with a 1-foot increase in first-floor height above E_{100}, and more modest decreases in AAL occur with additional increases above E_{100}, for all owner/occupant types (Table 4).

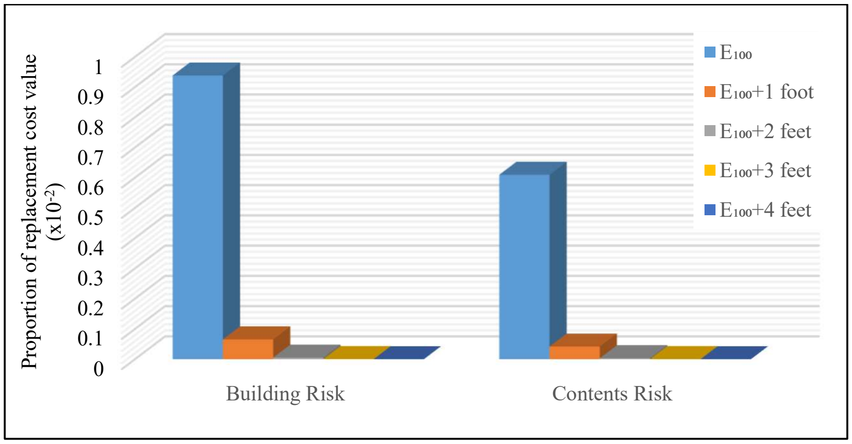

Figure 6. Mean AAL_{B/V_R} and AAL_{C/V_R} by increasing first-floor height above 100-year flood elevation.

Table 3. Mean $AAL_{B\$}$,$AAL_{C\$}$, and $AAL_{U\$}$ (USD) per home by increasing first-floor height above 100-year flood elevation.

FFH	Building AAL ($)	Contents AAL ($)	Use AAL homeowner ($)	Use AAL landlord ($)	Use AAL tenant ($)
E_{100} + 0 feet	2,300	1,494	595	661	99
E_{100} + 1 foot	157	101	42	47	7
E_{100} + 2 feet	12	8	3	4	<1
E_{100} + 3 feet	1	< 1	<1	<1	<1
E_{100} + 4 feet	< 1	< 1	<1	<1	<1

Table 4. AAL_T reduction by combination of increases in first-floor height above 100-year flood elevation and owner/occupant type.

FFH	$AAL_{T,Homeowner}$	$AAL_{T,Landlord}$	$AAL_{T,Tenant}$
E_{100} + 1 foot	93.156%	93.111%	93.267%
E_{100} + 2 feet	99.475%	99.450%	99.482%
E_{100} + 3 feet	99.949%	99.947%	99.952%
E_{100} + 4 feet	99.999%	99.999%	99.999%

DDF Sensitivity

The means of $AAL_{B\$}$ and sum of $AAL_{B\$}$ and $AAL_{C\$}$ increase about sixfold, and $AAL_{C\$}$ increases sevenfold, when the damage initiation point is considered at dh = –1.0 foot vs. 0 feet (Table 5). Similarly, use of DDFs starting at dh = –1.0 foot causes a fivefold increase in mean AAL_T (i.e., building, contents, and use) for homeowner and landlord, and a sixfold increase for tenant, compared with AAL_T at dh = 0 feet (Table 6).

Table 5. Sensitivity of mean of the average annual loss values to building and contents (USD) per home to depth-damage function damage initiation point.

dh (feet)	$AAL_{B\$}$ (\$)	$AAL_{C\$}$ (\$)	Sum (\$)
0	374	217	591
–0.5	1,004	626	1,630
–1	2,300	1,493	3,793

Table 6. Sensitivity of the average annual loss mean values (USD) per home for homeowner, landlord, and tenant to depth-damage function damage initiation point.

dh (feet)	$AAL_{T,Homeowner,\$}$ (\$)	$AAL_{T,Landlord,\$}$ (\$)	$AAL_{T,Tenant,\$}$ (\$)
0	836	646	258
–0.5	2,270	1,710	725
–1	4,390	2,960	1,590

Comparison with Hazus-MH

Test of the null hypotheses equating mean AAL with Hazus-MH output results in p-values of 0.39 and 0.23 for building and contents, respectively. These results indicate that a statistically significant difference does not exist between the AAL value from the presented approach vs. results from Hazus for both building and contents risk. The mean $AAL_{B\$}$ and $AAL_{C\$}$ are \$2,330 and \$1,513 per home, respectively, for the numerically integrated approach. In contrast, these values are \$2,069 and \$1,279 per home based on Hazus output.

5. Discussion

Flood Risk Quantification

The wide variation in AAL across the case study area, with homes 21 and 9 having the highest and lowest $AAL_{B\$}$ and $AAL_{C\$}$ (Figure 4), demonstrates the value of performing community-level risk assessment at the micro-scale. Many factors affect AAL results. First, further analysis to interpret the results presented in Supplementary Table 6 demonstrates that unique DDFs based on number of stories result in statistically significant differences in $AAL_{C\$}$ to $AAL_{B\$}$ ratios (p-value of 0.0004), with mean values of 67 percent and 49 percent for one- and two-story homes, respectively. Second, other factors affect AAL, such as a and u parameters, FFH_0, and V_R (Table 2). The finding that $AAL_{T\$}$ for homeowner-occupied homes exceeds that for the other owner/occupant types (Figure 5) is reasonable because the homeowner bears the risk for building, contents, and use, while the smallest $AAL_{T\$}$ is borne by tenants because they incur no $AAL_{B\$}$.

Flood Risk Reduction Quantification

Quantification of the flood risk is important to overcome the resistance that homeowners, landlords, and tenants tend to display to avoid taking action to mitigate flood hazards (Hollar, 2017). Results from assessing flood risk by owner/occupant type and the effect of increasing FFH on its reduction can enhance awareness and action to mitigate flood effects. For example, the substantial decrease in $AAL_{B\$}$ and $AAL_{C\$}$ by increasing the first-floor height 1 foot above E_{100} (Figure 6 and Table 3) and the virtual elimination of building and contents flood risk through elevation of 4 feet, shown in this case study, demonstrate the economic advantages of mitigation measures and flood risk reduction. The reduction of AAL by approximately 93 percent with the first foot of increase in first-floor height above E_{100}, with an additional 6, 0.48, and 0.05 percent with two through four feet of additional elevation (Table 4), regardless of owner/occupant type, provides the public with specific information for decision-making. These values suggest that adding two feet above E_{100} may provide the most effective flood risk reduction for this study area. However, it is noted that the substantial flood risk prevented by adding one foot above the E_{100} is achieved by the minimum elevation requirement for residential buildings in the U.S. specified in the ASCE (2014) technical standard.

These results vary by DDF damage initiation point and completely depend on the accuracy of flood maps particularly regarding the flood depth information for multiple return periods. Error can also be incurred if the modeling of these data does not include recent changes in development that affect rainfall runoff conditions or complete climatic data reflective of the true nature of precipitation events. Future work is needed to understand the extent to which the finding of 93 percent reduction with first foot of increase in first-floor height above E_{100} and an additional 6 percent with two feet elevation is consistent across space and time. Regardless, however, presentation of flood risk in terms of AAL and the corresponding reduction in relative flood risk with additional building information provides new opportunities to validate flood model data and DDFs through observation of future events and losses.

DDF Sensitivity

Consideration of the damage initiation point at dh = –1 and –0.5 foot increases the quantified risk substantially, as suggested by Tables 5 and 6. Given the fivefold to sevenfold increase in AAL calculation based solely on the DDF damage initiation point, this concept is an area that warrants considerable future research, as values of dh = –2 (USACE 2000; 2003), dh = –1 (FIA 1974), and dh = 0 (FEMA 2003) are employed in the literature. DDFs are available that differentiate foundation type, and floodwater characteristics and duration (e.g., GEC 1997), and standard deviation values are provided for generalized USACE (2000) DDFs. As micro-scale analysis gains more traction, the use of component-based functions (Matthews et al., 2021) may become viable to generate building-specific DDFs. However, while the current research represents a substantial step forward, without more research in this area it is likely that flood risk estimates continue to underestimate or overestimate the true risk.

Comparison with Hazus-MH

The underestimation of $AAL_{B\$}$ and $AAL_{C\$}$ by Hazus in the case study results by 11 and 15 percent, respectively, can be attributed to two factors. First, Hazus-MH does not consider flooding at shorter than 10-year and greater than 500-year return periods (Eq. 17), which leaves damage from the most common, minor floods, and the rarest, major floods, unconsidered. While at first glance such floods may be negligible either because they produce little damage or because they are unlikely to occur during the home's useful life cycle, the frequency with which nuisance floods occur and the devastating impacts of exceedingly large floods, if they do happen to occur during the home's useful life cycle, make consideration of flood risk only for return periods ranging from 10 to 500 years incomplete. A second factor contributing to the underestimation by Hazus-MH is that it only considers five return periods, which generates a coarser estimate using Riemann sums of areas under the loss-exceedance curve (Figure 7a) vs. the fine trapezoid definition used in this AAL approach, where 260 trapezoids are used.

In addition to the building and contents underestimates, other factors point to further inaccuracies by Hazus-MH. The neglect of use risk can cause substantial underestimates, especially for longer-term recoveries. Moreover, the final term in Eq. 17 (from Hazus-MH), not represented in Figure 7a, is an additional factor without theoretical basis that may ostensibly compensate for the underestimation apparent in Figure 7a, perhaps leading to the finding that the

AAL approach does not differ significantly from Hazus-MH. Future research should evaluate whether statistically significant differences are found for different flood hazard conditions.

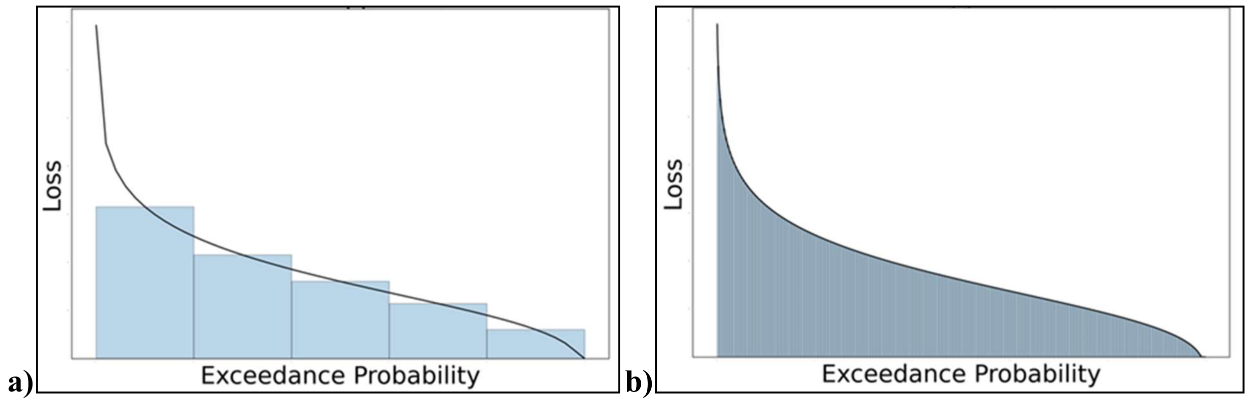

Figure 7. Comparison of coarseness using the Riemann sum approach: a) coarse trapezoidal areas under the loss-exceedance probability curve in the Hazus-MH approach vs. b) fine trapezoids used in the proposed AAL approach.

6. Conclusion

Accurate AAL estimation and sound policies and planning based on that estimation enable mitigation of flood risk to a known and tolerable level. Also, quantifying flood risk at the community level aids in selecting the most cost-effective and beneficial technique for mitigating future flood hazards. This study develops a micro-scale approach to community-level flood risk estimation that assists in identifying the home elevation that reduces flood risk most efficiently for three owner-occupant types. Moreover, this study also helps to understand the effect of increased first-floor height above FFH_0 and the effect of selecting the flood depth where damage initiates on flood risk estimates.

Home attribute data, DDFs, and FFH_0 are combined with flood depth above the ground data for multiple annual exceedance probability (AEP) events at the location of each home. Using the Gumbel extreme value distribution, flood hazard regression parameters (i.e., a and u) enable quantification of flood depth and probability of exceedance. These, in turn, are used to calculate the AAL expressed as a proportion of home replacement cost value for building, contents, and use. The proposed approach is applied to a case study 29 residences in Metairie, Louisiana, with different combinations of attributes and owner/occupant types. Sensitivity analyses are conducted to examine the effect of DDF damage initiation point on flood risk assessment results. Also, the reduction of AAL with increasing first-floor height above E_{100}, by owner/occupant type, is computed. Then, AAL for building and contents are compared with those from Hazus-MH. General conclusions are:

- Using the refined numerically integrated approach enhances AAL estimates by addressing several limitations of other approaches.
- Analyzing a large number of homes provides a clearer understanding of community flood risk.
- Home attributes such as number of stories, basement existence, FFH_0, area, unit cost, and multiple return period flood depths affect AAL calculations.

Specific conclusions, based on the case study, are:

- The ratio between contents and building AAL for single-family residences without a basement is higher for one-story than two-or-more-story homes.
- Increasing the first-floor height by one foot above E_{100} results in approximately 90 percent flood risk reduction in the case study area. However, increasing the first-floor height by two feet above E_{100} may provide the most economically advantageous benefit, at nearly 99 percent flood risk reduction.
- Homeowner AAL ($4,390) exceeds that of landlord ($2,960), with tenant AAL ($1,590) being lowest. Although flood insurance implications are not considered, this paper serves as an important methodological step that may facilitate more robust consideration of insurance scenarios by owner/occupant type.
- The DDF damage initiation point has a large impact on the AAL calculations. AAL is increased fivefold to sevenfold if the DDF damage initiation point is considered at $dh = -1$ foot vs. $dh = 0$. Therefore, future research defining the proper damage initiation point is essential.
- Although this AAL approach produces statistically insignificant differences from those generated by Hazus-MH for $AAL_{B\$}$ and $AAL_{C\$}$, Hazus incorporates an additional, theoretically unfounded term that may compensate for several sources of underestimation, and Hazus fails to incorporate $AAL_{U\$}$; it appears that the AAL approach improves representation of flood risk.

This study suggests that application of the proposed refined numerical integration approach that considers the full range of loss-exceedance probabilities for a 29-home study area enhances the accuracy of AAL estimation. In the present research, loss of use is considered, which represents a substantial step forward from previous analyses, but loss of use is only one component of indirect loss. Future research should focus on further consideration of indirect and intangible losses, which are important flood loss metrics to consider when understanding the impacts of floods on residents. Landlord contents loss should be considered more explicitly, as well as the assumptions made about homeowner costs for temporary and longer-term lodging after a flood. This paper serves as the basis for future integration of flood insurance considerations to reduce flood risk by owner/occupant type.

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8. Author Contribution Statement

AAA developed the methodology, analyzed the data, interpreted the findings, and developed the initial text. RBM selected the case study area, prepared the input data, contributed to the analysis, and supervised the research. CJF conceptualized the research idea, supervised the research, provided insight and recommendation for the research, and reviewed and edited the manuscript. MAR verified the results and reviewed the manuscript. RVR reviewed and edited the writing of the manuscript and provided insight and recommendation for the research.

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10. Supplementary Materials

Supplementary Table 1. Input Parameters for the 29 Homes in the Metairie, Louisiana, Study Area.

Building Number	Area (sq. ft.)	Unit cost per square foot	Number of stories	Basement	FFH_0 (feet)	0.10 AEP	0.02 AEP	0.01 AEP	0.002 AEP
1	2791	110.3438	1	0	1.0	0.2	0.6	1.0	1.4
2	2436	110.3438	1	0	1.4	0.6	1.3	1.4	2.1
3	2028	110.3438	1	0	0.9	0.1	0.7	0.9	1.5
4	2938	110.3438	1	0	1.4	0.6	1.0	1.4	1.8
5	2181	106.222	2	0	1.2	0.5	1.1	1.2	1.9
6	2420	110.3438	1	0	2.0	1.1	1.7	2.0	2.4
7	1677	110.3438	1	0	2.1	1.2	1.8	2.1	2.6
8	1749	110.3438	1	0	2.1	1.2	1.8	2.1	2.5
9	1837	106.222	2	0	2.7	1.8	2.3	2.7	3.1
10	2308	110.3438	1	0	2.4	1.6	2.1	2.4	2.9
11	2582	106.222	2	0	1.8	1.0	1.4	1.8	2.3
12	1695	110.3438	1	0	1.8	0.7	1.5	1.8	2.3
13	1951	110.3438	1	0	0.7	0.1	0.5	0.7	1.3
14	1914	110.3438	1	0	0.8	0.1	0.6	0.8	1.4
15	2258	110.3438	1	0	1.3	0.5	1.0	1.3	1.8
16	2306	110.3438	1	0	1.6	0.8	1.1	1.6	1.9
17	2327	110.3438	1	0	1.7	1.1	1.3	1.7	2.1
18	3458	106.222	2	0	2.1	1.4	1.8	2.1	2.7
19	1795	106.222	2	0	2.6	1.8	2.2	2.6	3.0
20	1757	110.3438	1	0	2.2	1.5	1.9	2.2	2.7
21	2572	110.3438	1	0	0.6	0.1	0.5	0.6	1.3
22	1645	110.3438	1	0	1.3	0.5	1.0	1.3	1.8
23	2613	110.3438	1	0	1.7	0.9	1.4	1.7	2.2
24	3090	110.3438	1	0	1.1	0.3	0.9	1.1	1.7
25	1590	110.3438	1	0	1.8	1.0	1.5	1.8	2.3
26	2073	110.3438	1	0	2.1	1.5	1.8	2.1	2.6
27	2062	110.3438	1	0	1.0	0.2	0.6	1.0	1.4
28	2320	106.222	2	0	1.4	0.6	1.2	1.4	2.0
29	1490	110.3438	1	0	1.5	0.6	1.2	1.5	2.0

Supplementary Table 2. Relationship between Flood Depth, Proportion of Building (or Content) Value Damaged, and Restoration Time for Each Owner/Occupant Type, for a One-Story Home without Basement (DDF1).

From USACE (2000)			From FEMA (2013)		
Flood Depth in Structure (dh, in feet)	**Structure Damage**	**Contents Damage**	**Restoration Time: Homeowner (months)**	**Restoration Time: Landlord (months)**	**Restoration Time: Tenant (months)**
–2.0	0	0	0	0	0
–1.5	0.0125	0.0120	0	0	0
–1.0	0.0250	0.0240	0	0	0
–0.5	0.0795	0.0525	0	0	0
0.0	0.1340	0.0810	9	10	1
0.5	0.1835	0.1070	9	10	1
1.0	0.2330	0.1330	9	10	1
1.5	0.2770	0.1560	9	10	1
2.0	0.3210	0.1790	9	10	1
2.5	0.3610	0.1995	9	10	1
3.0	0.4010	0.2200	9	10	1
3.5	0.4360	0.2385	9	10	1
4.0	0.4710	0.2570	12	13	1
4.5	0.5015	0.2725	12	13	1
5.0	0.5320	0.2880	12	13	1
5.5	0.5590	0.3015	12	13	1
6.0	0.5860	0.3150	12	13	1
6.5	0.6090	0.3265	12	13	1
7.0	0.6320	0.3380	12	13	1
7.5	0.6520	0.3475	12	13	1
8.0	0.6720	0.3570	15	16	1
8.5	0.6885	0.3645	24	25	1
9.0	0.7050	0.3720	24	25	1
9.5	0.7185	0.3780	24	25	1
10.0	0.7320	0.3840	24	25	1
10.5	0.7430	0.3880	24	25	1
11.0	0.7540	0.3920	24	25	1
11.5	0.7630	0.3945	24	25	1
12.0	0.7720	0.3970	24	25	1
12.5	0.7785	0.3985	24	25	1
13.0	0.7850	0.4000	24	25	1
13.5	0.7900	0.4000	24	25	1
14.0	0.7950	0.4000	24	25	1
14.5	0.7985	0.4000	24	25	1

15.0	0.8020	0.4000	24	25	1
15.5	0.8045	0.4000	24	25	1
16.0	0.8070	0.4000	24	25	1

Supplementary Table 3. As in Supplementary Table 2, but for Two-or-More-Story Home with No Basement (DDF2).

From USACE (2000)			From FEMA (2013)		
Flood Depth in Structure (dh, in feet)	**Structure Damage**	**Contents Damage**	**Restoration Time: Homeowner (months)**	**Restoration Time: Landlord (months)**	**Restoration Time: Tenant (months)**
–2.0	0	0	0	0	0
–1.5	0.0150	0.0050	0	0	0
–1.0	0.0300	0.0100	0	0	0
–0.5	0.0615	0.0300	0	0	0
0.0	0.0930	0.0500	9	10	1
0.5	0.1225	0.0685	9	10	1
1.0	0.1520	0.0870	9	10	1
1.5	0.1805	0.1045	9	10	1
2.0	0.2090	0.1220	9	10	1
2.5	0.2360	0.1385	9	10	1
3.0	0.2630	0.1550	9	10	1
3.5	0.2885	0.1700	9	10	1
4.0	0.3140	0.1850	12	13	1
4.5	0.3380	0.1990	12	13	1
5.0	0.3620	0.2130	12	13	1
5.5	0.3845	0.2260	12	13	1
6.0	0.4070	0.2390	12	13	1
6.5	0.4280	0.2510	12	13	1
7.0	0.4490	0.2630	12	13	1
7.5	0.4685	0.2735	12	13	1
8.0	0.4880	0.2840	15	16	1
8.5	0.5060	0.2935	24	25	1
9.0	0.5240	0.3030	24	25	1
9.5	0.5405	0.3115	24	25	1
10.0	0.5570	0.3200	24	25	1
10.5	0.5720	0.3270	24	25	1
11.0	0.5870	0.3340	24	25	1
11.5	0.6005	0.3405	24	25	1
12.0	0.6140	0.3470	24	25	1
12.5	0.6260	0.3515	24	25	1
13.0	0.6380	0.3560	24	25	1
13.5	0.6485	0.3600	24	25	1
14.0	0.6590	0.3640	24	25	1
14.5	0.6680	0.3665	24	25	1
15.0	0.6770	0.3690	24	25	1

15.5	0.6845	0.3705	24	25	1
16.0	0.6920	0.3720	24	25	1

Supplementary Table 4. As in Supplementary Table 2, but for One-Story Home with Basement (DDF3).

From USACE (2000)			From FEMA (2013)		
Flood Depth in Structure (dh, in feet)	**Structure Damage**	**ContentsDamage**	**Restoration Time Homeowner (months)**	**Restoration Time Landlord (months)**	**Restoration Time Tenant (months)**
–8.0	0	0	9	10	1
–7.5	0.0035	0.0040	9	10	1
–7.0	0.0070	0.0080	9	10	1
–6.5	0.0075	0.0145	9	10	1
–6.0	0.0080	0.0210	9	10	1
–5.5	0.0160	0.0290	9	10	1
–5.0	0.0240	0.0370	9	10	1
–4.5	0.0380	0.0470	9	10	1
–4.0	0.0520	0.0570	12	13	1
–3.5	0.0710	0.0685	12	13	1
–3.0	0.0900	0.0800	12	13	1
–2.5	0.1140	0.0925	12	13	1
–2.0	0.1380	0.1050	12	13	1
–1.5	0.1660	0.1185	12	13	1
–1.0	0.1940	0.1320	12	13	1
–0.5	0.2245	0.1460	12	13	1
0.0	0.2550	0.1600	15	16	1
0.5	0.2875	0.1745	15	16	1
1.0	0.3200	0.1890	15	16	1
1.5	0.3535	0.2035	15	16	1
2.0	0.3870	0.2180	15	16	1
2.5	0.4210	0.2325	15	16	1
3.0	0.4550	0.2470	15	16	1
3.5	0.4885	0.2605	15	16	1
4.0	0.5220	0.2740	15	16	1
4.5	0.5540	0.2870	15	16	1
5.0	0.5860	0.3000	15	16	1
5.5	0.6155	0.3120	15	16	1
6.0	0.6450	0.3240	18	19	1
6.5	0.6715	0.3345	24	25	1
7.0	0.6980	0.3450	24	25	1
7.5	0.7200	0.3540	24	25	1
8.0	0.7420	0.3630	24	25	1
8.5	0.7595	0.3700	24	25	1
9.0	0.7770	0.3770	24	25	1

9.5	0.7890	0.3815	24	25	1
10.0	0.8010	0.3860	24	25	1
10.5	0.8060	0.3885	24	25	1
11.0	0.8110	0.3910	24	25	1
11.5	0.8110	0.3910	24	25	1
12.0	0.8110	0.3910	24	25	1
12.5	0.8110	0.3910	24	25	1
13.0	0.8110	0.3910	24	25	1
13.5	0.8110	0.3910	24	25	1
14.0	0.8110	0.3910	24	25	1
14.5	0.8110	0.3910	24	25	1
15.0	0.8110	0.3910	24	25	1
15.5	0.8110	0.3910	24	25	1
16.0	0.8110	0.3910	24	25	1

Supplementary Table 5. As in Supplementary Table 2, but for Two-or-More-Story Home with Basement (DDF4).

From USACE (2000)			From FEMA (2013)		
Flood Depth in Structure (dh, in feet)	**Structure Damage**	**Contents Damage**	**Restoration Time: Homeowner (months)**	**Restoration Time: Landlord (months)**	**Restoration Time: Tenant (months)**
–8.0	0	0	9	10	1
–7.5	0.0085	0.0050	9	10	1
–7.0	0.0170	0.0100	9	10	1
–6.5	0.0180	0.0165	9	10	1
–6.0	0.0190	0.0230	9	10	1
–5.5	0.0240	0.0300	9	10	1
–5.0	0.0290	0.0370	9	10	1
–4.5	0.0380	0.0445	9	10	1
–4.0	0.0470	0.0520	12	13	1
–3.5	0.0595	0.0600	12	13	1
–3.0	0.0720	0.0680	12	13	1
–2.5	0.0870	0.0760	12	13	1
–2.0	0.1020	0.0840	12	13	1
–1.5	0.1205	0.0925	12	13	1
–1.0	0.1390	0.1010	12	13	1
–0.5	0.1590	0.1100	12	13	1
0.0	0.1790	0.1190	15	16	1
0.5	0.2010	0.1285	15	16	1
1.0	0.2230	0.1380	15	16	1
1.5	0.2465	0.1475	15	16	1
2.0	0.2700	0.1570	15	16	1
2.5	0.2945	0.1670	15	16	1
3.0	0.3190	0.1770	15	16	1
3.5	0.3440	0.1875	15	16	1
4.0	0.3690	0.1980	15	16	1
4.5	0.3940	0.2090	15	16	1
5.0	0.4190	0.2200	15	16	1
5.5	0.4440	0.2315	15	16	1
6.0	0.4690	0.2430	18	19	1
6.5	0.4935	0.2550	24	25	1
7.0	0.5180	0.2670	24	25	1
7.5	0.5410	0.2790	24	25	1
8.0	0.5640	0.2910	24	25	1
8.5	0.586	0.3040	24	25	1
9.0	0.6080	0.3170	24	25	1
9.5	0.6280	0.3305	24	25	1

10.0	0.6480	0.3440	24	25	1
10.5	0.6660	0.3580	24	25	1
11.0	0.6840	0.3720	24	25	1
11.5	0.6990	0.3860	24	25	1
12.0	0.7140	0.4000	24	25	1
12.5	0.7255	0.4150	24	25	1
13.0	0.7370	0.4300	24	25	1
13.5	0.7455	0.4455	24	25	1
14.0	0.7540	0.4610	24	25	1
14.5	0.7590	0.4770	24	25	1
15.0	0.7640	0.4930	24	25	1
15.5	0.7640	0.5095	24	25	1
16.0	0.7640	0.5260	24	25	1

Supplementary Table 6. Output Parameters for the 29 Homes in the Metairie, Louisiana, Study Area.

Home Number	AAL_{B/V_R}	AAL_{C/V_R}	$AAL_{B\$}$	$AAL_{C\$}$	$AAL_{UH\$}$	$AAL_{UL\$}$	$AAL_{UT\$}$	$AAL_{H\$}$	$AAL_{L\$}$	$AAL_{T\$}$
1	0.01148257	0.007882995	3536	2428	736	817	97	6700	4354	2525
2	0.012291487	0.008280812	3304	2226	859	955	130	6389	4259	2356
3	0.012013395	0.008142757	2688	1822	656	729	119	5166	3417	1941
4	0.01148257	0.007882995	3723	2556	774	860	97	7052	4583	2653
5	0.011996987	0.005688878	2779	1318	848	942	149	4945	3721	1467
6	0.00582355	0.003858238	1555	1030	466	518	71	3052	2073	1101
7	0.005712388	0.003757612	1057	695	333	370	73	2086	1427	768.5
8	0.005520101	0.003643479	1065	703	328	365	69	2097	1430	772.2
9	0.004047217	0.002610190	596	298	278	309	58	894	905	367
10	0.005196178	0.003387004	1323	509	278	309	58	2627	1814	932.9
11	0.005363381	0.002589281	1471	710	536	595	79	2717	2066	789.5
12	0.006973243	0.004663137	1304	872	363	403	79	2539	1707	950.9
13	0.018980867	0.013030256	4086	2805	853	948	161	7744	5034	2966
14	0.014873246	0.010146573	3141	2143	711	790	137	5995	3931	2280
15	0.011743161	0.008009775	2926	1996	663	737	108	5584	3662	2104
16	0.007181083	0.004869160	1827	1239	443	492	71	3509	2319	1310
17	0.008079082	0.005445602	2074	1398	536	595	85	4008	2670	1483
18	0.004978243	0.002439908	1829	896	751	835	83	3476	2664	979.3
19	0.004315560	0.002795365	663	330	302	335	64	1295	998	394
20	0.00594076	0.003904417	1152	757	365	406	77	2274	1558	833.5
21	0.02432078	0.016682273	6902	4735	1460	1623	209	13097	8525	4943
22	0.011743161	0.008009775	2132	1454	483	537	108	4068	2668	1562
23	0.007667654	0.005128669	2211	1479	614	682	86	4303	2893	1565
24	0.012013395	0.008142757	4096	2776	999	1110	119	7872	5206	2895
25	0.007146793	0.004761343	1254	835	360	400	83	2449	1654	918.7
26	0.006570546	0.004340031	1503	993	461	512	82	2957	2015	1075
27	0.01148257	0.007882995	2613	1794	543	604	97	4950	3216	1891
28	0.009599022	0.004552596	2366	1122	722	802	119	4210	3168	1241
29	0.009627856	0.006523038	1583	1072	388	431	96	3043	2014	1168