

Flood Loss and Recovery Models for Residential Housing Stock: A Case Study of the 2013 Boulder, Colorado Floods

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Abstract: The disaster-resilience of a community is determined, in large part, by its ability to recover its full functionality within a reasonable time after the occurrence of a hazardous event. Among the essential ingredients for evaluating disaster resilience of communities are models for the assessment of losses from the hazardous event and recovery of the built environment. Using a case study based on the 2013 Boulder, Colorado flood, this paper presents an assembly-based methodology to estimate economic losses associated with residential building damage. The impacts of uncertainties associated with building properties and replacement costs on flood loss estimates are considered, and spatial correlations in hazard demand and common building configurations and practices are reflected in an aggregated assessment of flood loss models. The proposed methodology can be adapted to risk and resilience assessment of other building portfolios involving different occupancies (retail, commercial, etc.) in Boulder and for other communities.

1 Introduction

The recent catastrophic Boulder, Colorado flood of September, 2013, an event with a return period estimated as between 500 and 1,000 years [1], has shown how vulnerable a community can be to natural disasters and how the recovery of such a community is contingent on appropriate preparedness. Community resilience measurement and assessment are thus essential to support public policies and collective actions to reduce a disaster's associated potential social disruptions and economic losses to the community and to improve community ability to adapt, withstand, and quickly recover from extreme hazard events. Among the essential ingredients for evaluating disaster resilience of communities are reliable and accurate models for the assessment of hazard-related losses for the built environment.

Using a case study based on the 2013 Boulder flood, this paper presents a methodology to assess flood losses (repair costs) and their uncertainties for the residential housing stock of Boulder, Colorado. An assembly-based methodology is extended and validated to estimate total direct economic losses associated with residential building damage. The assessment is performed on a building-by-building basis and accounts for flood damage to structural and nonstructural components and building contents [2]. The methodology assesses damage to

building components as a function of flood intensity parameters, such as depth, which are then combined with cost functions quantifying the cost of replacement of flood-damaged building components. Monte Carlo simulations are performed to quantify expected costs and uncertainties associated with replacement costs and building properties, and the impact of these uncertainties on the loss is evaluated. Finally, an approach is presented for treating the spatial correlations in common flood demand and common building configurations and practices within the residential building inventory to obtain an aggregated assessment of flood loss model for the residential housing stock in Boulder.

This paper focuses on development of flood damage and losses for the residential housing stock of Boulder, Colorado. It is the first step in a broader effort to study the uncertainties in post-flood recovery of building portfolios as a function of flood intensity parameters such as depth and velocity. The proposed flood loss models are intended not only to provide an improved understanding of the vulnerability of residential construction to flood-induced damage, but also to set the stage for future exploration of these models in risk and resilience assessment of residential housing stock. The proposed methodology can be adapted to risk and resilience assessment of other building portfolios for different occupancies (retail, commercial, etc.) in Boulder and for other communities.

2 The 2013 Boulder, Colorado Flood

Boulder, CO, a suburb of Denver, is a moderate-sized community with approximately 100,000 inhabitants. A major rainstorm in 2013 caused widespread flooding in the City of Boulder and major damage to buildings and infrastructure in the community (see Figure 1) [2,3,4,5]. The flooded areas exceeded the 100-year floodplains in some places. All major waterways overflowed their banks, and the city's storm-water system was overwhelmed. In addition, there was significant damage to residential buildings. Over 6,000 houses in the City of Boulder, comprising approximately 14% of the city's housing stock, were damaged. Most of this damage was to non-structural components and building contents. Only about 10% of Boulder residents had private flood insurance policies and most homeowners' policies excluded damage caused by floods, leaving many responsible for repair costs. However, City of Boulder homeowners received recovery assistance from several sources including nearly \$14M in Individual Assistance (IA) funds from the Federal Emergency Management Agency (FEMA) and approximately \$17M in payouts from the National Flood Insurance Program (NFIP) [2,3,5,7].

To support the development of flood loss models, empirical data were gathered for the affected residential buildings in the City of Boulder. These data included post-flood inspection data (an estimate of the damage and the water depth) from FEMA IA claims, NFIP claims, and a survey conducted by the City of Boulder immediately after the flood. Data from the Boulder County assessor's office, which contained information on general building properties (such as building type, building area, basement type, assessed building and land values, and the year of construction) [8], were also utilized. The expected estimate of repair costs were available for only a fraction of the 6,000 damaged houses, and some of the data sources were not consistent with each other [2]. Before analyzing the collected information from different sources, the datasets were organized and merged, and some part of data points that show inconsistencies

were eliminated [2]. A final dataset of 5195 damaged properties with FEMA IA claims were obtained. Out of the 5195 damaged properties, only 361 households filed NFIP claims. While FEMA IA claims include the flood depth occurred at a household, they provide only a part of total losses observed on the household. In the following section, the NFIP claims were thus used for validation studies to compare the loss estimates from the model with the total damage cost observed on the building properties. The FEMA IA data for flood depth was more consistently defined, and was thus used for the depth input.

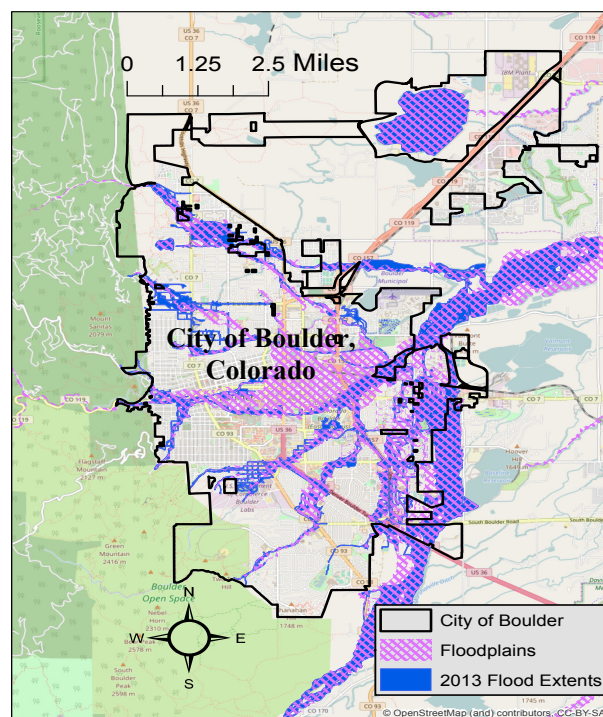


Figure 1: Map of the 2013 flooded areas in the City of Boulder with the existing 100-year floodplains (Data for flood extents from the FEMA Modeling Task Force [6])

3 Assembly-Based Loss Models for Residential Buildings

3.1 Assembly-based Loss Analyses

Considering typical residential construction practices and construction items, a methodology based on assembly-based loss (ABL) was developed to assess the individual losses and repair times for flood damage to residential building structures [2]. This methodology is based on building-by-building assessment, and accounts for structural, nonstructural and building content flood damage. The methodology includes damage to homes constructed with basement, slab and crawlspace foundations, which are common in U.S. construction, and considers three levels of construction and finish quality: low, average and high. It estimates damage to building components as a function of flood intensity parameters, such as depth, which are then combined with costs and repair times associated with replacement of flood-damaged building components.

Most of the losses to residential buildings during the 2013 Boulder flood were due to non-structural damage to building components, such as non-load bearing walls, flooring, windows

as well as to contents; only a few homes suffered structural or foundation failure. Non-structural building components account for the majority of building construction costs and, as a result, their damage in disasters can dominate repair costs. This section thus focuses on development of flood loss models for residential buildings in Boulder considering parameters that are related directly or indirectly to non-structural finishes and contents that may be severely damaged by inundation. The ABL methodology is utilized in this study to assess nonstructural losses for a typical single-story residential building plan using construction and material costs in Boulder at the time of the flood, extending models developed in [2]. An example of the results of the model is provided in Figure 2.

Based on parametric ABL analyses performed on residential buildings in Boulder, the following parameters were found to be important predictors of damage: the foundation type (e.g., basement, crawlspace, or slab foundation), house dimensions, the construction quality, and basement type (finished or unfinished). Buildings with finished basement foundations suffered higher losses, on average, compared to other foundation types (see Figure 2), incurring significant losses at the flooring level that led to jumps in the losses around -60 and 48 inches (1524 and 1219 mm respectively) based on ground level (note that 9 ft (2.7 m) is assumed for the full story height, and the floor of basement is assumed to be at 5 ft (1.5 m) below the grade level). Conversely, homes with crawlspaces suffered lower mean losses since, at lower water depths, the most serious damage for homes with crawlspaces is mold (a crawlspace height of 3.5 ft (1.1 m) is assumed). As more building area is exposed to flooding, more damages are observed. Finished basements expect to show more losses. Moreover, buildings with higher quality finishes (for example, bathroom countertops with granite instead of plastic laminate) yield higher loss estimates.

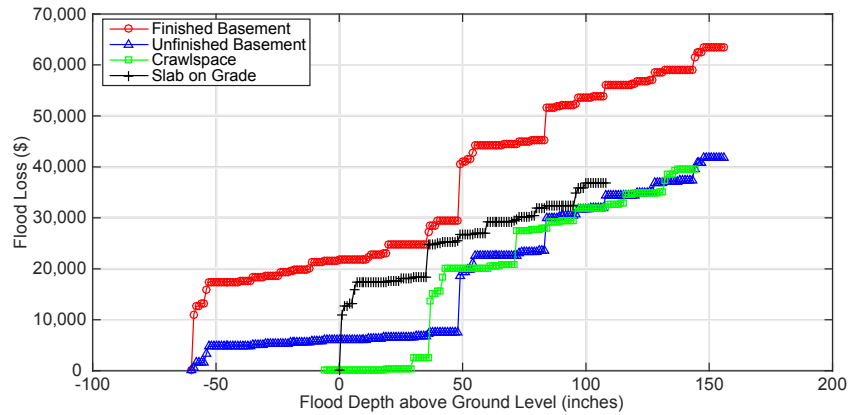


Figure 2: Impact of foundation type on nonstructural flood losses for one-story residential buildings with average finish quality using a typical floor area of $1,200 \text{ ft}^2$ ($1 \text{ in} = 25.4 \text{ mm}$, $1 \text{ ft}^2 = 0.09 \text{ m}^2$)

3.2 Uncertainty Quantification

Risk management decisions rely on the consideration and quantification of uncertain parameters [9]. To predict the flood risk facing a community, a reliable probabilistic model is needed to estimate the cost of repairing flood-damaged buildings, while considering the uncertainties in building characteristics (e.g., construction quality and house dimensions) and flood hazard (e.g., depth and velocity). In this sense, the ABL approach is easily adjustable to account for any variabilities in itemized construction cost estimates (for example, any

upgraded flooring or larger building floor area). Therefore, ABL modeling supports the probabilistic estimation of losses that accounts for the inherent uncertainties associated with the nature of the flooding event, the building characteristics and the costs to repair the damage.

To quantify the impact of these uncertainties on the loss estimates for residential buildings, we performed a series of Monte Carlo simulations, in which the distributions and statistical values for the selected random parameters that were assumed in the ABL models summarized, for illustrative purposes, in Table 1. The selected distributions are assumed to be independent to each other and similar to those reported in other studies [9]. To estimate flood losses, we chose the ratio of the replacement cost to floor area as a damage indicator to provide a uniform basis for comparing damage severity among different homes; this ratio is referred to as the “Normalized Loss (NL)” in this paper. Also, the flood depth within the building (d) is considered here for the development of simulations. A suite of 50 sample realizations was obtained for each random variable summarized in Table 1 at each inch (25.4 mm) of flood depth (in total, around 10,000 simulations for a fully flooded one-story home with basement). The ABL analyses were then performed to obtain the damage estimates in terms of 2013 losses (expressed in \$US) sustained by single-story residential homes for each realization, which are used to compute losses probabilistically at each depth.

Table 1: Statistical values of flood loss parameters assumed in Monte Carlo simulations performed on one-story residential buildings (1 ft = 0.3 m)

<i>Parameters</i>	<i>Units</i>	<i>Probability Distribution</i>		
		<i>Type</i>	<i>Mean</i>	<i>c.o.v</i>
House and Room Dimensions	ft	Normal	Overall: 40 by 30 Bedroom: 15 by 10 Bathroom: 8 by 10 Storage/Closet: 7 by 10	0.30
Construction Cost Modifier	-	Normal	1	0.15
Construction Quality: 1: Low, 2: Average, and 3: High	Categorical	Equal probability		
Indicator for Basement Type: 0: Finished, 1: Unfinished	Categorical	Equal probability		

The results for homes with basements are presented in Figure 3. Through performing ABL analyses on Monte Carlo simulations, normalized loss estimates are obtained at each increment of flood depth for both finished and unfinished cases (circles and triangles in Figure 3, respectively). Unfinished basements in residential construction tend to have exposed utility and structural elements, typically without material finishes, and indicate lower average losses as expected. The loss estimates for both basement types show significant variability (representing epistemic uncertainty in the predictions) due to the nature of residential construction (i.e., construction quality, construction unit price, and house dimensions). This variability is even more noticeable at higher flood depths and must be accounted for in the assessment of loss estimates.

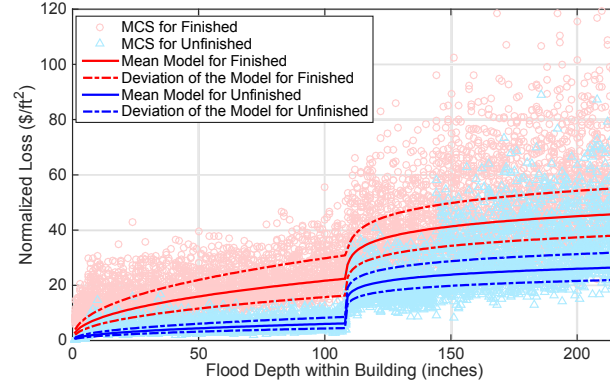


Figure 3: Monte Carlo simulations (MCS) for basements using a variety of building properties and construction cost values; and flood loss models for basements using average finish quality and unit prices (1 in = 25.4 mm)

3.3 Modelling Flood Losses

Regression analyses were performed utilizing the results of the above Monte Carlo simulations to obtain functional forms that can be used to predict losses for each foundation type. The predictive damage models were obtained using the predictor Normalized Loss NL in $\$/\text{ft}^2$ ($1 \text{ ft}^2 = 0.09 \text{ m}^2$) and the following key damage variables: d , the flood depth in inches within the building (1 in = 25.4 mm); Q , the quality grade factor (for example, high: 160%, average: 100%, and low: 80% are assumed based on common guidelines for valuation process of residential homes [8]); and R , an indicator for unfinished basement (applicable to only models for basements, where 1 is true, 0 is false). Logarithmic transformations of the normalized losses were used to preserve the constant conditional variance in the predictive equation [10]. The results of these regression analyses are presented in Equations (1)-(3):

$$\log(NL) = 0.441 \log(d) - 1.286 R + 1.042 Q \quad (1a)$$

$$\log(NL) = 2.573 + 0.109 \log(d - 108) - 0.550 R + 0.741 Q \quad (1b)$$

$$\log(NL) = 0.111 d - 4.108 Q^{-1} \quad (2)$$

$$\log(NL) = 0.472 \log(d) + 1.127 Q \quad (3)$$

As an example, the mean trend models of the regression results are presented in Figure 3 for homes with finished or unfinished basements, using average finish quality and unit prices. The coefficient of determination, R^2 , and residual mean square error (RMSE) values for the models are reported in Table 2. All the models show R^2 values that are sufficient to predict the normalized losses with reasonable confidence using information about flood depth and the characteristics of the building. Other functional forms (with and without logarithmic transformations) were also considered, but did not improve the R^2 and RMSE values.

To account for significant variability associated with loss estimates in Figure 3, it is necessary to characterize probabilistic distribution of building loss NL for a given set of flood input and building variables. In the linear regression analyses performed above, a normal random error was assumed with zero mean and unit variance. The probabilistic model of building loss NL is then assumed to be described by a lognormal distribution for each foundation type, with the median values given by the exponent of the values in Equations (1)-(3), and their standard deviations given by RMSE values reported in Table 2.

Table 2: Regression results obtained for the flood loss models (1 in = 25.4 mm)

Foundation:	Equation	Depth Range with- in Building (inch)	R^2	RMSE
Basement	1a	$0 < d \leq 108$	0.88	0.32
Above Basement	1b	$108 < d \leq 216$	0.84	0.19
Crawlspace	2	$0 < d \leq 42$	0.87	0.59
Slab on Grade	3	$0 < d \leq 108$	0.85	0.26

3.4 Validation of Estimated Flood Losses

A comparison of the predictions from the assembly-based flood loss models identified in Equations (1)-(3) with the collected post-flood inspection data was performed for homes within the City of Boulder. The loss predictions are compared to the sum of NFIP payment amounts and deductible amounts for each building claim (including all building-related flood damage, but excluding losses from personal possessions). Examining the basement model with the available 180 NFIP claims for homes with basements (95 finished and 85 unfinished basements) in Figure 4, the ABL models appear to capture the mean trend in the data points at lower depths. The scatter in the data points in Figure 4 (the standard deviation in normalized losses per each flood depth is around $11\$/\text{ft}^2$ on average, corresponding to \$13,000 for a typical home with a floor area of $1,200\text{ ft}^2$) is typical of variability in loss estimates in studies for natural hazards and needs to be accounted in the loss models. To include this variability and the bias associated with the loss predictions from the regression analyses (summarized by Equations (1) – (3)), stochastic tools are currently being investigated to correct the loss estimates with respect to observed data points.

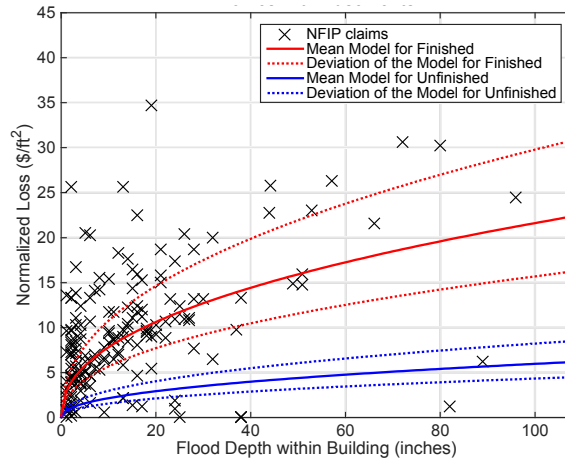


Figure 4: Comparison of the regression models for basements with average finish quality to NFIP claims (1 in = 25.4 mm, $1\text{ ft}^2 = 0.09\text{ m}^2$)

4 Community Loss Models for Residential Building Stock

Insurance companies that issue coverage for natural hazards, or city officials who plan post-disaster recovery actions, usually require risk assessments for building inventories, rather than individual buildings. This assessment requires an aggregation of risks to individual buildings considering uncertainties in repair and replacements costs. Previous research on loss estima-

tion for building portfolios has often ignored statistical dependence in the performance between individual buildings, leading to a non-conservative estimate of total loss at lower probabilities of exceedance (or higher fractile of losses) [11, 12]. Spatial correlation that exists in both hazard demand (due to similar terrain conditions and nearby flood sources) and building capacity (due to common building construction and design practices and occupancy characteristics) should be taken into account to aggregate individual losses for accurate and reliable hazard risk assessment of building portfolios.

As part of the Boulder study, a framework is being developed to account for these correlations in the residential building stock. Following Vitoontus and Ellingwood [11], the expected value and variance of total loss are given in Equations (4) and (5), respectively, where, L_i is the flood loss at the i^{th} building, N is the number of buildings in a selected region, and ρ_{L_i, L_j} is the correlation between losses for the pairs of i^{th} and j^{th} buildings. $E[L_i]$, $Var[L_i]$, and $SD[L_i]$ represents the expected values, variances, and standard deviations for the flood loss L_i , respectively.

$$E[L_T] = \sum_{i=1}^N E[L_i] \quad (4)$$

$$Var[L_T] = \sum_{i=1}^N Var[L_i] + \sum_{i=1}^N \sum_{j=1}^N \rho_{L_i, L_j} SD[L_i] SD[L_j] \quad (5)$$

Note the role played by spatial correlation in the evaluation of Equation (5), where the correlation in losses to buildings i and j is invariably positive due to correlated demands and common construction practices.

An illustration of this methodology is carried out to assess flood loss for the residential housing stock in the city of Boulder, CO in Figure 5. First, the proposed probabilistic ABL-based loss models using typical Boulder construction practices and local construction and material costs in Equations (1)-(3) are utilized to assess the individual losses (expected values) for each 5,195 residential building in Boulder reported by FEMA claims (Figure 5a). Second, the correlation in losses between the i^{th} and j^{th} pair of buildings is assumed, for illustration, to be a function of distance between those buildings:

$$\rho_{L_i, L_j} = \exp^{-r_{i,j}/r_o} \quad (6)$$

where $r_{i,j}$ the distance between the buildings in miles, and r_o is the correlation distance, which represents the strength of the spatial correlation. For an assumed value $r_o = 1$ mile, the relationship of the correlation to the distance between residences is shown in Figure 5b. Next, using the assessed individual losses and standard deviations reported for the probabilistic loss models in Section 3, the total loss to the building inventory can then be obtained from Equations (4) and (5). The probability that the total loss exceeds any particular value is shown in Figure 5c for both uncorrelated and correlated cases. Neglecting spatial correlation in losses due to commonality in hazard demand and building performance may underestimate the overall loss and recovery assessments for the upper extremes of the loss distribution, the region of significance for public safety and insurance underwriting purposes [12].

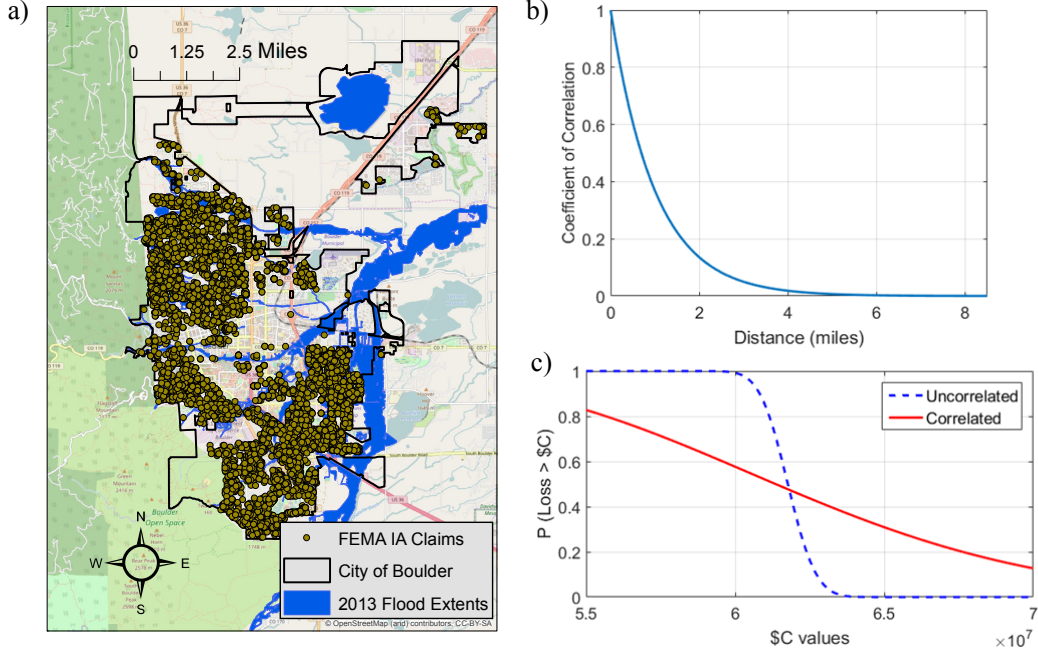


Figure 5: Assessment of community flood loss models: a) Affected households reported by FEMA IA claims (1 mile=1.61 km); b) Assumed correlation relationship in losses of the affected households as a function of building separate distance; c) Probability of exceedance for the aggregated flood losses for residential building stock of Boulder

5 Conclusions and Future Work

An assembly-based methodology has been developed to estimate total direct economic losses to residential buildings due to both structural and nonstructural flood damages on a building-specific basis. It assembles unit prices to replace each flood damaged building components as functions of flood intensity parameters such as depth. Uncertainties associated with unit prices and building properties and the impact of these uncertainties on the loss quantities are evaluated. The spatial correlations in demand and capacity of buildings to withstand flooding are incorporated to assess the overall loss estimation for a particular region.

The proposed ABL methodology is currently being validated with damage and loss data from the 2013 Boulder, CO flood on a building-by-building basis, and is intended for use in assessing community flood loss and recovery models for residential building stock. Such an analysis would be difficult to implement for a large urban area consisting of several hundred thousand buildings. The impact of the spatial resolution of buildings within the community on the estimation of loss and recovery is being investigated through aggregating the individual buildings to census tract or zipcode areas or downscaling the loss models. Using the empirical data and the ABL methodology, a flood recovery model is also currently under development to assess the nature of the recovery time and cost to repair damages for residential building portfolio stochastically.

The proposed methodology is sufficiently general to be applied to other building inventories and construction practices. It can be adapted to risk and resilience assessment of building portfolios for different occupancies (retail, commercial, etc.) in other communities and can be

utilized by research, engineering and urban planning constituencies seeking to improve public policy, insurance portfolio risk, and disaster response and management plans.

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