Estimating the Greenhouse Gas Emissions from Flood Damages

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# Abstract

Summarize purpose, methods, and results. (500 words).

**Keywords:** flood risk, resilience, life cycle cost analysis, environmental impact analysis, cost-benefit analysis

# 1. Introduction

Floods and storms are the most frequent and devastating natural hazards worldwide and are becoming increasingly so due to climate change ([Pörtner et al. 2022](#ref-portner2022); [CRED and Guha-Sapir 2023](#ref-cred2023a)). From 2013 to 2022 in the United States alone, more than 2.7 million people were affected by flood and storm disasters which caused an inflation-adjusted total of US$540.2 Billion according to the Centre for Research on the Epidemiology of Disasters (CRED)’s Emergency Events Database (EM-DAT)[[1]](#footnote-1) ([2023](#ref-cred2023a)). Even if immediate and dramatic efforts are implemented to reduce greenhouse gas emissions, flood losses in the U.S. are expected to increase by 24-29% by 2050 due to climate change alone and as much as 97% when considering both climate and population change, disproportionately affecting Black and low-income communities ([Wing et al. 2022](#ref-wing2022)).

* It is important to develop flood mitigation projects to reduce the risk posed by climate change. To justify the cost of these projects, a comprehensive accounting of project benefits must be performed.
* Repairing damages to homes affected by flooding results in production of GHG emissions. The benefit of preventing these emissions is not currently accounted for in existing flood risk management (FRM) practice.
* The purpose of this study is to quantify the GHG emissions that result from flood damages to single family residential structures and assess the extent to which accounting for these emissions changes the assessment of flood risk is a vulnerable region.

Literature review

* Cost benefit analysis for FRM projects driven primarily by assessment of incurred economic losses.
  + USACE (primary FRM org in the US) ostesibly requires planners to consider all benefits of FRM projects, but unless a project is granted a specific exception, the project alternative with the greatest net economic benefit must be implemented.
  + Economic benefit of FRM projects is typically estimated in terms of avoided losses to structures from floods in the study area.
  + Depth damage curves are used for this. These curves are typically developed by panels of practitioners who estimate loss ratios for structures under given conditions based on their experience and expertise ([Davis and Skaggs 1992](#ref-davis1992)).
  + Panels may supplement their judgement with empirical data, however, such data is limited and difficult to produce ([Davis and Skaggs 1992](#ref-davis1992)).
    - Flood insurance loss data - Flood Insurance Agency, Tennessee Valley Authority ([Davis and Skaggs 1992](#ref-davis1992))
    - Historical flood observations - ([Dawson 2003](#ref-dawson2003); [U.S. Army Corps of Engineers 2015](#ref-u.s.armycorpsofengineers2015))
  + Synthetic damage estimates may also be used to develop damage functions ([Dawson 2003](#ref-dawson2003))
    - GEC ([2006](#ref-gec2006)) used this approach to develop depth-damage estimates for residential structures in the USACE New Orleans district based on damage esimates to structure components.
    - Nofal et al. ([2020](#ref-nofal2020a)) used synthetic data to develop building-level fragility curves which allow for the propogation of uncertainty in flood risk assessments.

Due to the prioritization of economic losses in flood risk assessments, there is a lack of available methodologies for incorporating other potential impacts such as the greenhouse gas emissions associated with flood damages.

* There is an abundance of research assessing the life cycle environmental impacts of residential construction and material selections to support more sustainable building practices ([Salazar and Sowlati 2008](#ref-salazar2008); [Kong et al. 2010](#ref-kong2010); [Hosseinijou et al. 2014](#ref-hosseinijou2014); [Napolano et al. 2015](#ref-napolano2015); [Megange et al. 2019](#ref-megange2019); [H. Wang et al. 2020](#ref-wang2020a); [Nagireddi et al. 2022](#ref-nagireddi2022); [Schneider-Marin et al. 2022](#ref-schneider-marin2022); [Haddad et al. 2023](#ref-haddad2023)).
* Likewise, many studies have assessed the environmental impacts of material choice for maintenance and repairs to residential structures ([McGrath et al. 2013](#ref-mcgrath2013); [Dong et al. 2018](#ref-dong2018); [Caruso et al. 2020](#ref-caruso2020); [Y. Wang et al. 2020](#ref-wang2020); [Wittocx et al. 2022](#ref-wittocx2022)).
* Several studies have also considered the impacts of natural hazards on the environmental life-cycle of buildings.
  + Adhikari et al. ([2020](#ref-adhikari2020)) assessed the life-cycle carbon footprint of residential buildings exposed to tornadoes and found that selecting more tornado resistant components tended to be optimal for structures in terms of both life cycle costs and carbon footprint. Adhikari et al. ([2021](#ref-adhikari2021)) extends this analysis to assess the effect of community-level decision-making on the carbon footprint of tornado hazards (awaiting full-text from ILL).
  + Simonen et al. ([2018](#ref-simonen2018)) assessed the embodied carbon of various structural and non-structural building components using an economic input-output model to estimate the expected GHG emissions per dollar of damage to buildings impacted by earthquakes.
  + Matthews et al. ([2016](#ref-matthews2016b)) used a Monte Carlo simulation to estimate life-cycle component-level flood damages and associated environmental impacts for two design alternatives for a case-study single-family residential structure located in a flood zone. This analysis showed that a more flood resistant design significantly reduced the total lifecycle environmental impact of the structure due to the need for fewer repairs.
  + Hennequin et al. ([2019](#ref-hennequin2019a)) performed a similar assessment for a typical European single-family home, and found that experiencing a flood can increase the life-cycle environmental impact of such a building by about 4-18%.
  + These studies show that damages to structures caused by natural hazards can result in significant GHG emissions. However, because these studies focus largely on the effect of choices in material selection and construction design or are not specific to flood damages, their generalizability to flood risk assessments in a potential project study area is limited.

Matthews et al. ([2021](#ref-matthews2021)) builds upon their earlier work to address this limitation and produce damage functions for one and two story single family residential structures to estimate GHG emissions resulting from damages from a flood of a given depth. Although not applicable to all flooding scenarios, the damage functions produced by Matthews et al. ([2021](#ref-matthews2021)) could be applied by planners in a FRM project to assess the potential GHG emissions from the project design flood.

* Limitations of this study:
  + single floorplan for each structure type (no variability in component quantities) (**This is a limitation shared by all studies cited here. To my knowledge, no studies have considered floorplan variability as I have in this paper.**)
  + component damage functions are entirely deterministic.

The purpose of this study is to assess the greenhouse gas emissions associated with flood damages to single-family residential structures. With a focus on incorporating uncertainty, we develop depth-emissions curves for one- and two-story single family residential structures and apply these curves to a flood risk case study in two locations in the Mississippi River Valley to answer the following research questions.

1. What quantity of greenhouse gas emissions are produced as a result of flood damages to residential structures?
2. To what extent does accounting for these emissions affect the magnitude of quantified risk in an area exposed to flooding?
3. To what extent does accounting for these emissions affect the distribution of quantified risk in an area exposed to flooding?

Broader impacts:

* planners will be able to account for flood-related ghg emissions in their FRM projects
* emissions accounting for meeting emissions reductions targets?

# 3. Methods

We used documented expert judgement and information from residential building codes to develop synthetic damage functions for components of one- and two-story single family residential structures. We analyzed 50 real-world residential floorplans to document variability in component quantities in each structure type. We performed a Monte Carlo Simulation (MCS) to model the component-level damage, replacement cost, and associated GHG emissions across a range of flood depths. The results of the MCS were aggregated to produce damage functions for each structure type which estimate the total emissions produced from repairing damage to a structure exposed to a flood of a given depth. Finally, these damage functions were applied to a real-world flood risk case study in two locations in the Mississippi River Valley to assess how including these emissions in the assessment affects the magnitude and distribution of flood risk.

## 3.1 Structure Component Model

The structure component model seeks to do what? It uses the fragility function of every single structure component in a household to estimate the potential household flood damage at different flood depths. The structure component list was adapted from GEC ([2006](#ref-gec2006)) for our analysis. GEC ([2006](#ref-gec2006)) was co-produced by the U.S. Army Corps of Engineers New Orleans District, Gulf Engineers & Consultants ([GEC 2006](#ref-gec2006)), which developed synthetic component-level depth-damage functions for residential structures to estimate the percentage of the total quantity of a given component to be replaced at a given flood depth. These damage functions were produced by a panel of experts in the fields of flood risk and reconstruction and have been used in other studies assessing the environmental impacts of flood damages Matthews et al. ([2021](#ref-matthews2021)). Unlike previous studies, we do not directly adopt the damage functions from this report. Rather, we use the expert panel’s assumptions documented in the report about how each component will be damaged by floods to develop new damage functions that incorporate uncertainty where possible. The full component list used inthis study is shown in [Table 1](#tbl-unit).

For most components we use a triangular distribution to model the fragility, or probability of failure at a given flood depth. The triangular distribution is commonly used for risk modeling as it requires minimal information, taking just three parameters: the minimum, maximum, and mode (most likely value) of the random variable (x), and has been shown to be a suitable replacement for a beta distribution ([Johnson 1997](#ref-johnson1997)). The triangular cumulative distribution function represents the probability that the given component has failed if the depth of flooding is greater than or equal to x. For each component, we infer the parameters for the fragility function from the assumptions of the expert panel documented in the GEC report. For example, regarding flood damage to doors, the panel said:

“Most doors in residential structures are hollow and are warped and destroyed between 0.0 and 1.0 foot of floodwater. Some higher quality doors can be refinished up to 1.0 foot of floodwater. Doors in commercial structures are usually of solid sturdy wood and are sealed at the top and bottom, helping to prohibit water damage. These doors would only require refinishing at 0.5 foot of floodwater. Some would require replacement at 1.5 feet of floodwater. All doors are totaled at 4.0 feet of floodwater. Hollow metal door frames are never a total loss.”

Based on this description, we develop separate fragility functions for interior and exterior doors, assuming exterior doors are higher quality. For interior doors, we set the minimum, maximum, and most likely failure depths to 0, 0.5, and 2 respectively, and for exterior doors we set these values to 1, 2, and 4 respectively. For some components, the expert panel assumes complete loss as soon as water touches them. In these cases, we parameterize the fragility function based on the range of possible heights for the component within the structure. For example, we assume wall outlets will be located between 12 and 24 inches above the floor with 12 inches being the most likely ([The Home Depot 2023](#ref-thehomedepot2023)). [Figure 1](#fig-dmg_fns) shows the damage function for doors from GEC ([2006](#ref-gec2006)) and the fragility functions used in this study for interior doors, exterior doors, and wall outlets.

We were unable to develop a fragility function for some components based on the assumptions documented in the GEC report. For example, GEC ([2006](#ref-gec2006)) assumes that the amount of drywall that will need to be replaced will increase proportionally with flood depth until a depth of 4 feet above the floor at which point all of the drywall will require replacement. For these components, we develop damage functions that report the quantity to be replaced as a percentage of the total quantity of that component. The damage function used for drywall is included in [Figure 1](#fig-dmg_fns). We were also unable to create fragility functions for the subfloor, flooring underlayment, and finished flooring based on the assumptions in GEC ([2006](#ref-gec2006)) as they assume these components will be a total loss as soon as the flood depth reaches the first floor elevation.

|  |
| --- |
| Figure 1: Example damage functions from GEC ([2006](#ref-gec2006)) and the present study. |

We collected replacement cost and life cycle greenhouse gas emissions estimates for each component. We gathered cost data from RS Means Building Construction Costs ([The Gordian Group Inc. 2021](#ref-thegordiangroupinc.2021a)), and considered multiple material choice options for each component. For example, we assume the finished floor underlayment could be plywood, particle board, or hardboard. We gathered GHG emissions estimates from the National Institute of Standards and Technology (NIST) Building for Environmental and Economic Sustainability (BEES) LCA database ([NIST 2023](#ref-nist2023)). LCA data for some components in our model were not available from BEES. For these components, we collected data from the ecoinvent database version 3.9.1 ([Wernet et al. 2016](#ref-wernet2016); [ecoinvent 2023](#ref-ecoinvent2023)). Where possible, we compiled GHG estimates for multiple material choices for components. We then used the TRACI 2.1 impact methodology to calculate the global warming potential (GWP) of GHG emissions in terms of kg CO2 equivalents.

## 3.2 Floor Plan Analysis

Existing studies using a synthetic damage function approach develop a single representative floorplan from which to calculate quantities for each component ([GEC 2006](#ref-gec2006); [Hennequin et al. 2019](#ref-hennequin2019a); [Nofal et al. 2020](#ref-nofal2020a); [Matthews et al. 2021](#ref-matthews2021)), which fails to account for the building size and design as a source of variability in flood damage costs and GHG emissions. To address this, we analyzed 50 real-world floor plans, 38 single-story and 12 two-story, from architecturaldesigns.com and calculated material quantities for all components for each floor plan. We also estimated the total replacement cost for each floorplan using RSMeans Square Foot Costs Data ([The Gordian Group Inc. and Doheny 2021](#ref-thegordiangroupinc.2021)).

To develop structure-level damage and emissions curves, we performed a Monte Carlo analysis to estimate component-level damages for each floor plan across a range of flood depths. To do this, we generated a vector of flood depths ranging from -4 to 32 feet incrementing by 0.1 feet. Flood depths are relative to the structure’s first floor elevation, therefore negative values are included to account for components located below the first floor level. For each flood depth in this vector, we performed 50 component-level simulations for each component in all 50 floor plans in which we estimated the expected quantity of each component to be replaced due to flood damage at the given flood depth.

For components without fragility functions, we calculated the quantity to be replaced directly by multiplying the percent loss for the component at the given depth by the total quantity for that component. For components with a fragility function, we use the random.binomial method in the NumPy Python library ([Harris et al. 2020](#ref-harris2020)) to determine the quantity to be replaced by performing N Bernoulli trials, where N is the total quantity of the given component. A Bernoulli trial is a discrete experiment testing whether or not a certain outcome occurs given a certain probability of occurence ([Papoulis 1994: 43–47](#ref-papoulis1994)). The outcome in the Bernoulli trial is the failure of the given component, and the probability of the component failing is given by the fragility function for the given component at the given flood depth. For components with a quantity greater than one in a given floor plan, this method allows us to consider them as independent items that may or may not fail independently at a given flood depth (e.g. if a floor plan has 5 interior door, it is possible that only three would need to be replaced after a flood with a depth of one foot).

For each simulation, we also randomly generate a unit replacement cost and unit life cycle carbon footprint based on the cost and LCA data for each component for which we collected multiple material cost and carbon footprint estimates. We use the random.Generator.triangular() method in the NumPy Python library ([Harris et al. 2020](#ref-harris2020)) to generate random values based on a specified triangular distribution. For each component’s cost and carbon footprint distribution, the minimum and maximum parameters are set as the minimum and maximum value gathered from RS Means or LCA data respectively, and the median value is assumed to be equal to the mean. For components with only a single price or carbon footprint estimate in our database, we apply this value in all simulations.

Next, we multiply the replacement quantity for each component by the unit cost and carbon footprint value generated for each simulation to determine the total component-level cost and carbon footprint for each simulation. To make our GHG emissions estimates comensurable with our damage cost estimates, we multiply the GHG emissions by the U.S. Environmental Protection Agency (EPA)’s estimated social cost of greenhouse emissions of $190 per metric ton of CO2 ([U.S. Environmental Protection Agency 2023](#X4e93c38db10033772a973ccf417072a04bd22d1)). For each simulation, we sum the replacement costs, ghg emissions, and ghg social costs for all components in each floor plan to structure-level impacts of each simulated flood. Finally, we divide the replacement cost and social cost for each structure by its estimated replacement cost to report the impacts as a percentage of the structure’s value. This allows us to apply the damage curves produced in this step to be applied to structures of various sizes. The results of this analysis for one-story and two-story structures are described in [Section 4.2](#sec-res-floorplan).

* Linear Regression: Damage cost vs GHG emissions
  + Should I describe this here, or just include it in results?

## 3.3 Spatial Household Damage Analysis

* Burlington-Davenport & Paducah-Cairo
* Flood maps produced using AutoRoute/FloodSpreader
  + Give brief overview of this here. Point to paper with Natalie for more info.
* National Structures Inventory
* Apply custom damage functions to flooded structures.
  + Assess quantity of GHG emissions
  + Assess change in risk magnitude
  + Assess change in spatial distribution of risk

# 4. Results and Discussion

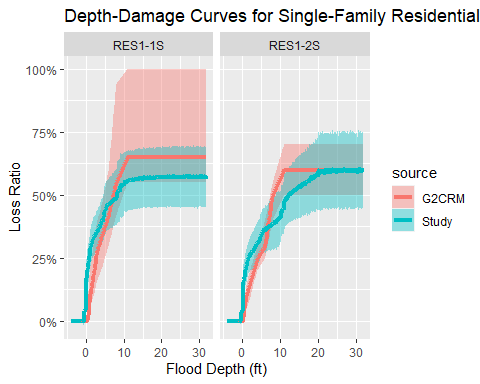
## 4.1 Structure Component Model

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Table 1: Mean and standard deviations of unit costs and GHG emissions for structure components   | component | functional\_unit | cost\_mean | cost\_sd | co2\_mean | co2\_sd | | --- | --- | --- | --- | --- | --- | | Baseboard | ft | 4.30 | 1.4e+00 | 0.31 | 6.9e-03 | | Bathroom Bottom Cabinets | ea | 530.00 | 5.9e+01 | 140.00 | 6.7e+01 | | Bathroom Top Cabinets | ea | 230.00 | 3.8e+01 | 140.00 | 6.7e+01 | | Bottom Cabinets | ea | 5500.00 | 3.9e+03 | 720.00 | 4.0e+02 | | Bottom Outlets | ea | 59.00 | 8.3e+00 | 23.00 | NA | | Ceiling | ft2 | 0.79 | 1.5e-01 | 0.38 | 8.1e-02 | | Ceiling Insulation | ft2 | 2.60 | 8.6e-01 | 0.50 | 2.6e-01 | | Ceiling Paint | ft2 | 0.35 | NA | 0.15 | 5.5e-02 | | Clothes Dryer | ea | 1100.00 | 1.7e+02 | 210.00 | NA | | Clothes Washer | ea | 1200.00 | 4.4e+02 | 380.00 | NA | | Counter Tops | ea | 700.00 | 4.7e+02 | 290.00 | 1.4e+02 | | Dishwasher | ea | 1200.00 | 3.0e+02 | 150.00 | NA | | Electrical Panel | ea | 1500.00 | 5.4e+02 | 0.00 | NA | | Exterior Doors | ea | 740.00 | 4.5e+02 | 220.00 | 1.4e+00 | | Exterior Wall Sheathing | ft2 | 1.40 | 2.6e-01 | 0.33 | 2.0e-02 | | Facade | ft2 | 7.80 | 6.0e+00 | 1.50 | 1.1e+00 | | Finished Floor | ft2 | 7.60 | 4.7e+00 | 1.30 | 1.3e+00 | | Finished Floor Underlayment | ft2 | 2.20 | 9.2e-01 | 0.29 | 2.0e-01 | | Heating/Cooling Unit or HVAC | ea | 3600.00 | 3.7e+03 | 2400.00 | 2.1e+03 | | Interior Doors | ea | 170.00 | 9.2e+01 | 120.00 | 1.7e+01 | | Light Switches | ea | 43.00 | 5.4e+00 | 23.00 | NA | | Microwave | ea | 420.00 | 2.4e+02 | 59.00 | NA | | Oven/stove | ea | 1400.00 | 7.1e+02 | 180.00 | NA | | Range hood | ea | 740.00 | 6.0e+02 | 64.00 | NA | | Refrigerator | ea | 1100.00 | 6.8e+02 | 290.00 | NA | | Roof Cover | ft2 | 4.10 | 2.2e+00 | 0.00 | 0.0e+00 | | Roof Cover Underlayment | ft2 | 0.20 | 8.8e-02 | 0.00 | 0.0e+00 | | Roof Cover and underlayment combined | ft2 | 0.00 | 0.0e+00 | 1.20 | 6.1e-01 | | Roof Sheathing | ft2 | 1.30 | 2.4e-01 | 0.33 | 2.0e-02 | | Sheetrock/drywall | ft2 | 0.78 | 8.6e-02 | 0.38 | 8.1e-02 | | Top Cabinets | ea | 5500.00 | 3.9e+03 | 720.00 | 4.0e+02 | | Top Outlets | ea | 59.00 | 8.3e+00 | 23.00 | NA | | Underfloor Ductwork | ft | 27.00 | 8.4e+00 | 2.90 | 3.1e+00 | | Underfloor Insulation | ft2 | 2.40 | 9.5e-01 | 0.51 | 2.6e-01 | | Wall Insulation | ft2 | 1.20 | 6.2e-01 | 0.29 | 1.9e-01 | | Wall Paint - Exterior | ft2 | 1.20 | NA | 0.15 | 5.5e-02 | | Wall Paint - Interior | ft2 | 0.35 | NA | 0.15 | 5.5e-02 | | Water Heater | ea | 2100.00 | 9.9e+02 | 56.00 | 0.0e+00 | | Windows | ea | 420.00 | 2.8e+02 | 390.00 | 2.1e+02 | | Wiring | ea | 0.00 | NA | NA | NA | | Wood Subfloor | ft2 | 1.40 | 1.4e-01 | 4.50 | 5.7e+00 | |

* TODO: Add failure probability or percent damaged for each component at a sample of flood depths (-2, 0, 1, 2, 4, 8, 16) to table

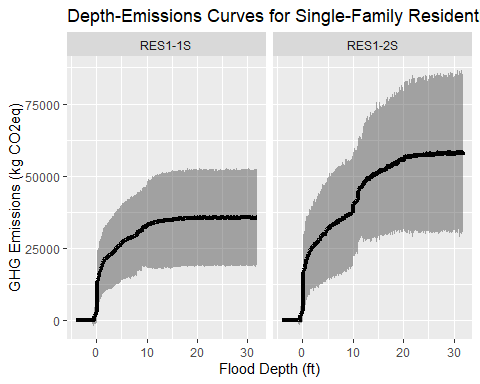
## 4.2 Damage Function Analysis

| **Characteristic** | **1-story**, N = 38 | **2-story**, N = 12 |
| --- | --- | --- |
| sqft | 1,334 (393) | 2,320 (606) |
| n\_bed |  |  |
| 1 | 0 (0%) | 1 (8.3%) |
| 2 | 11 (29%) | 0 (0%) |
| 3 | 27 (71%) | 7 (58%) |
| 4 | 0 (0%) | 3 (25%) |
| 5 | 0 (0%) | 1 (8.3%) |
| n\_bath |  |  |
| 1 | 6 (16%) | 1 (8.3%) |
| 1.5 | 1 (2.6%) | 0 (0%) |
| 2 | 28 (74%) | 0 (0%) |
| 2.5 | 2 (5.3%) | 7 (58%) |
| 3 | 1 (2.6%) | 0 (0%) |
| 3.5 | 0 (0%) | 4 (33%) |
| cost | 196,312 (37,445) | 291,914 (48,717) |
|  |  |  |

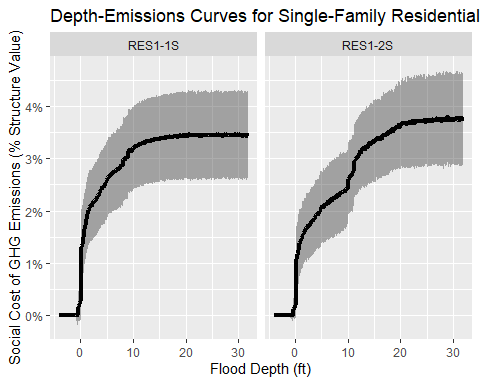


Comparison of study damage functions to G2CRM damage functions for single-family residential structures.

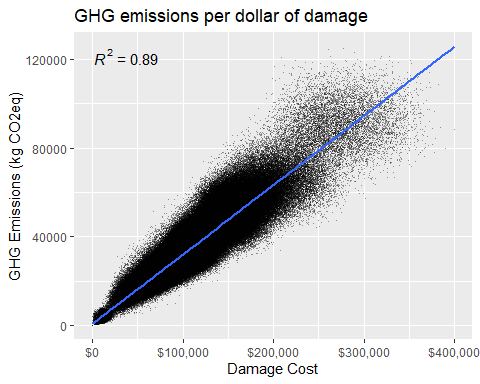
## 4.2 Cost and GHG Emissions Associated with Flood Damages



Estimated greenhouse gas emissions resulting from flood damages to single-family residential structures.



Social cost of GHG emissions resulting from flood damages as a percentage of total structure value.



Scatterplot showing the relationship between damage costs and GHG emissions from MCS results

Linear regression results of GHG emissions versus damage costs.

| **Variable** | **Estimate** | **p-value** |
| --- | --- | --- |
| (Intercept) | 841 | <0.001 |
| sum\_damage\_triang | 0.31 | <0.001 |
| R² | 0.889 |  |

## 4. 3. Spatial Analysis of Cost and GHG Emissions under 100-Year Flood for the Two Study Areas

# 5. Discussion

# 6. Conclusion

# 7. Acknowledgements

# 8. Funding

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1. EM\_DAT disaster records related to natural and technological hazards meet at least one of the following inclusion criteria: 1) At least ten deaths (including dead and missing), 2) At least 100 affected (people affected, injured, or homeless), or 3) A call for international assistance of an emergency declaration. [↑](#footnote-ref-1)