Customising flood damage functions to estimate the carbon footprint of flood-related home repairs

Elizabeth Matthews1 | Carol Friedland2 | Ahossin Alsadi3

1Civil Engineering & Construction Engineering Technology, Louisiana Tech University, Ruston, Louisiana
2Bert S. Turner Department of Construction Management, Louisiana State University, Baton Rouge, Louisiana
3Trenchless Technology Center, Louisiana Tech University, Ruston, Louisiana

Correspondence
Elizabeth Matthews, Civil Engineering & Construction Engineering Technology, College of Engineering Science, Louisiana Tech University, P.O. Box 10384, Ruston, LA 71270.
Email: ematt@latech.edu

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Abstract
Flood damage functions are important tools used to estimate potential damage to the built environment from various types of flood-related hazard events (e.g., hurricanes, riverine flooding). Oftentimes these damage estimates are used to determine the feasibility of flood protection or mitigation projects or to plan for future disasters. While existing standardised functions are used to estimate potential economic loss for residential buildings, functions can be customised to assess the environmental impacts of flood damages for specific building designs. This study presents a methodology for customising functions to estimate the carbon footprint of flood-related building repairs. Unlike regular home repairs, which are based on material life expectancy, flood repairs are dependent on the severity of the flood hazard (i.e., flood depth) and probability of hazard occurrence within the lifespan of a building. To demonstrate the methodology, customised functions are developed for a case study home design in Saint Petersburg, Florida.

KEYWORDS
benefit-cost appraisal, flood damages, sustainability

1 | INTRODUCTION

Every year flood events in the US account for billions of dollars in damage to communities. Some data indicates that these events are only becoming more common and the frequency of these events are predicted to increase in the future (NOAA National Centers for Environmental Information (NCEI), 2020). The US National Flood Insurance Program (NFIP) has experienced over 1.1 million flood insurance claims in the 20-year period 1998–2017, with total payments of nearly $69 billion (Federal Emergency Management Agency (FEMA), 2019). For the same period, National Oceanic and Atmospheric Administration (NOAA) (2018) estimates that total (insured and uninsured) direct flood losses exceed $233 billion (2019 dollars) – a loss of over $11 billion every year with approximately 70% of that cost borne by the uninsured (National Oceanic and Atmospheric Administration (NOAA), 2018). These losses are crippling for individuals and local economies and further stress federal resources through disaster response and recovery. However, while economic loss is the most commonly used metric to communicate the impacts of natural hazards, this metric ignores the immense environmental resources needed to remediate and rebuild flood-damaged homes. In an effort to build sustainable communities in flood-prone areas, it is important to assess the environmental impact of building designs considering flood damage.
1.1 Flood damage estimation

Flood damage or loss functions are often used to estimate the impact of flood events on the built environment. These functions have specific uses, such as providing a measure for determining the feasibility of flood control structures and flood proofing projects, or as a tool for assessing the need for changes in policy or building code requirements. Typically flood functions quantify the economic loss associated with damage.

Standard flood loss functions for single-family residential (SFR) buildings typically relate the percent building damage as a function of economic loss (relative) or monetary damages (absolute) for multiple residential building types over a range of flood depths (Merz, Kreibich, Schwarze, & Thieken, 2010). Two primary methods are used to create flood damage functions for residential buildings: (a) empirical or historical and (b) synthetic (Friedland, 2009; Merz et al., 2010). The historical method involves averaging historical damage or loss data, whereas the synthetic method derives potential damage or loss data using expert opinion or theoretical analysis (Friedland, 2009). While historical flood damage data can be collected for existing residential buildings, synthetic functions (Gulf Engineers & Consultants (GEC), 1996, 1997, 2006; Penning-Rossell et al., 2005), which are developed based on an assumed building model, are more readily customizable to different building configurations and designs.

In the development of synthetic functions, panels of construction experts derive a list of itemised building components and estimate the damage (i.e., cost to repair) for each component over an incremental range of flood depths. Component damages are summed and the percent damage (PD) for each flood depth increment is calculated according to Equation (1):

$$\text{PD} = \sum \frac{\text{Component repair cost ($)}}{\text{Total new building replacement value ($)}} \times 100$$

(1)

The result is a function showing the total percent building damage over a range of flood depths. These functions can then be used to estimate total building damage ($) for similar residential buildings. While functions are useful in estimating damage to buildings, there is great interest in quantifying other impacts (e.g., environmental).

1.2 Life-cycle assessment

Life-cycle assessment (LCA), which quantifies life-cycle environmental impacts, is a widely accepted methodology that considers multiple indicators for environmental impact (e.g., energy consumption, carbon footprint, and water consumption) (Ashby, 2009; Scientific Applications International Corporation (SAIC), 2006; Dixit, Fernández-Solís, Lavy, & Culp, 2012) LCA has been utilised in many studies to quantify the environmental impacts of SFR buildings (Asif, Muneer, & Kelley, 2005; Hammond & Jones, 2008; Rossi, Mariche, & Reiter, 2012; Zabalza Bribián, Aranda Usón, & Scarpellini, 2009). Life-cycle impacts are typically calculated for the manufacturing of building materials, initial construction, operation, and end-of-life activities associated with the building. LCA has also been utilised to calculate the environmental impacts of life-cycle SFR repairs due to regular maintenance (Blengini, 2009; Keoleian, Blanchard, & Reppe, 2000; Mithraratne & Vale, 2004; Peuportier, 2001), as well as natural hazard repairs (Matthews, Friedland, & Orooji, 2016; Petit-Boix et al., 2017).

Carbon footprint, which is a measure of the total greenhouse gas (GHG) emissions (CO₂, Methane, etc.), is often used to evaluate the environmental impact of products and activities (Alsadi, 2019). Carbon footprint is often expressed in terms of carbon dioxide equivalents, where GHG emission are summed by first converting all greenhouse gasses by their corresponding global warming potential (Environmental Protection Agency (EPA), 2020). Defining the carbon emissions of flood damage repairs helps to further define life-cycle impacts tied to the operation phase of a building. To define the carbon footprint of flood damages, it is necessary to break down damages into separate material components, which requires component-level damage functions.

Stand-alone component-level depth-damage functions are rarely presented in literature. Instead these functions are presented as part of the methodology for synthetic aggregated damage curves for specific building types (Gulf Engineers & Consultants (GEC), 1996, 1997, 2006), calculated using Equation (1). In one of the few sources describing component-level flood damage, Gulf Engineers and Consultants (GEC) (1997) developed synthetic, depth-loss relationships for five residential structure types for the US Army Corps of Engineers (USACE) New Orleans District. GEC developed a set of 18 tables presenting component-level flood damage dollar estimates for five residential building types (one-story on piers, one-story on slab, two-story on piers, two-story on slab, and manufactured home) for three flood conditions (short-duration: freshwater and saltwater; long-duration: saltwater; and long-duration: freshwater). A model design was assumed for each building type and damages in dollars were estimated for 23 components using opinions from a panel of experts. While the GEC tables are a useful source for estimating damage, the design component list...
used to develop these tables is limited in the variety of some materials (e.g., flooring) and level of detail of components which can be broken down more specifically (e.g., built-in appliances) (Gulf Engineers & Consultants (GEC), 2006).

FEMA’s “Substantial Damage Estimator (SDE) User Manual and Workbook” (Federal Emergency Management Agency (FEMA), 2014), provides guidance on assigning percent damage for building components while using the SDE to estimate damage to flood-damaged residential buildings. The guidance includes a table of component-level damage descriptions that are associated with ranges of percent damage and flood depths. The descriptions are organised according to 11 major categories: foundation; superstructure; roof covering; exterior finish; interior finish; doors and windows; cabinets and countertops; floor finish; plumbing; electrical; appliances and heating, ventilating and air conditioning (HVAC) (Federal Emergency Management Agency (FEMA), 2014). The SDE manual does not include damage functions but does provide standardised descriptions of damage that are useful for building synthetic damage functions or expanding existing sets of functions.

While previous work has introduced integrated methodologies for quantifying the environmental impacts of flood damages (Hennequin et al., 2018, 2019; Matthews et al., 2016; Petit-Boix et al., 2017), this study’s focus is on presenting an expanded methodology for developing customised carbon footprint functions associated with flood damages for user-specific SFR designs. Demonstrating application of these curves to design optimization and specific cost–benefit case studies is beyond the scope of this article; however, Matthews et al. (2016) and Hennequin et al. (2018, 2019) demonstrate how quantifying customised carbon footprint and other environmental impacts can be utilised for design optimization and cost–benefit analysis.

While these studies (Hennequin et al., 2018, 2019; Matthews et al., 2016) explore defining environmental impacts due to flood damages utilising similar approaches, the primary purpose of this article is the expand upon the methodology for creating carbon footprint curves for flood damages related to specific building configurations. It is possible to apply this same approach to other environmental impact indicators so as to take a full LCA approach; however, the main intent of this study is to show how to adapt very detailed component flood depth–damage curves so that anyone can customise curves for a specific analysis. This is important because LCAs are dependent on material quantities which can vary from building to building. This is especially applicable for small-scale cost–benefit studies that incorporate one or a few SFR buildings (e.g., house elevations).

The aim of this study is to present a set of synthetic flood depth–damage, component-level functions for SFR type structures that are (a) flexible in their application to individual SFR building designs and (b) can be utilised to create customised whole-building functions for estimating the environmental impact (i.e., carbon footprint) associated with flood repairs. Inundation-only, non-velocity flooding is considered in the development of the component-level depth–damage functions. The functions are also applicable to both one-story and two-story SFR wood-frame building designs, and flexible enough to account for variations in design (e.g., interior finishes).

This methodology can be utilised to develop customised flood damage functions for specific projects, which are more applicable and appropriate to a specific design rather than relying on functions developed using model designs or averaged historical data. To demonstrate how the component-level functions are utilised to develop whole-building functions for estimating the carbon footprint of hazard-related repairs for specific designs, a case study is presented. The case study SFR building is a one-story home located in Saint Petersburg, Florida. A sensitivity analysis to investigate the variability in the carbon footprint curves developed for the case study building is also presented.

2 | DEVELOPMENT OF COMPONENT DEPTH–DAMAGE FUNCTIONS

The set of customizable component-level, SFR depth–damage functions were developed utilising (Gulf Engineers & Consultants (GEC), 2006) and (Federal Emergency Management Agency (FEMA), 2014) for the purpose of quantifying the carbon footprint of repairs. Since the approach taken utilizes damage assumptions and does not rely on historical data, the methodology used to create these functions is synthetic. There were three main steps taken to develop the functions:

1. Compile a list of building components.
2. Develop a set of building and damage assumptions.
3. Derive customizable component functions based on the assumption made.

The list of building components was adapted and expanded from the component lists within Gulf Engineers and Consultants (GEC) (2006) and Federal Emergency Management Agency (FEMA) (2014). The goal was to capture as many components as possible; however, some components connected to the site were not included due to difficulty in quantifying damage as a...
| Component                        | Assumptions                                                                 | Source                                                                                      |
|---------------------------------|-----------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| Gypsum board                    | GEC, 2006                                                                   | GEC, 2006                                                                   |
| 1 Gypsum board                  | GEC, 2006                                                                   | GEC, 2006                                                                   |
| Wall paper-faced                | 25% damage (0–0.5 m); 50% damage at 0.6 m; 100% damage at 1.2 m.             | GEC, 2006                                                                   |
| Wall/ceiling, paperless         | No damage.                                                                   | a                                                                          |
| Ceiling paper-faced             | 100% damage at 2.4 m.                                                      | b                                                                          |
| 2 Bottom cabinets               | All cabinets are particle board cabinets. Damaged as soon as flooded.       | GEC, 2006                                                                   |
| 3 Upper cabinets                | All cabinets are particle board cabinets. Replace at 1.2 m flood water.     | FEMA, 2014                                                                  |
| 4 Countertops                   | Replace when bottom cabinets are replaced.                                  | GEC, 2006                                                                   |
| 5 Water heater                  | Water heater is on first floor level. Replace water heater at 0 m of water. | GEC, 2006                                                                   |
| 6 Insulation                    | GEC, 2006                                                                   | GEC, 2006                                                                   |
| Floor insulation                | Completely damaged at −0.3 m of water.                                      | GEC, 2006                                                                   |
| 7 Subflooring                   | Warps at 0 m. Needs to be replaced when warped.                             | GEC, 2006                                                                   |
| 8 Exterior siding and sheathing | GEC, 2006                                                                   | GEC, 2006                                                                   |
| One-story, short duration       | Average of GEC exterior siding functions for one-story, short duration flooding. | GEC, 2006                                                                   |
| One-story, long duration        | Average of GEC exterior siding functions for one-story, long duration flooding. | GEC, 2006                                                                   |
| Two-story, short duration       | Average of GEC exterior siding functions for two-story, short duration flooding. | GEC, 2006                                                                   |
| Two-story, long duration        | Average of GEC exterior siding functions for two-story, long duration flooding. | GEC, 2006                                                                   |
| 9 Brick/stone siding materials  | No damage sustained. Siding remains adhered (cleaning and drying needed).   | GEC, 2006, FEMA, 2014                                                        |
| 10 Base moulding                | Totally damaged at 0 m of water.                                           | GEC, 2006                                                                   |
| 11 Interior paint/ wallpaper    | At 0 m, entire wall covering replaced because of colour matching.            | GEC, 2006                                                                   |
| 12 Exterior paint               | At 0.2 m, entire wall covering replaced because of colour matching.          | GEC, 2006                                                                   |
| 13 Wainscoting                  | Graduate rate from 0 to 1.2 m, cut and replace.                             | GEC, 2006                                                                   |
| 14 Electrical                   | Destroyed at 0 m. Wiring with wet ends replaced.                           | GEC, 2006                                                                   |
| Floor receptacles               | Destroyed at 0 m. Wiring with wet ends replaced.                           | GEC, 2006, FEMA, 2014                                                        |
| Wall receptacles                | Destroyed at 0.2 m. Wiring with wet ends replaced.                         | FEMA, 2014                                                                  |
| Switches                        | Destroyed at 1.5 m. Wiring with wet ends replaced.                         | GEC, 2006                                                                   |
| Fixtures                        | Destroyed at 1.5 m. Wiring with wet ends replaced.                         | GEC, 2006                                                                   |
| Component          | Assumptions                                      | Source                                               |
|--------------------|--------------------------------------------------|------------------------------------------------------|
| 15 Built-in appliances |                                                 |                                                      |
| Dishwasher         | Replace at 0 m.                                   | Gulf Engineers & Consultants (GEC), 2006             |
| Clothes dryer      | Replace at 0.2 m.                                 | Federal Emergency Management Agency (FEMA), 2014     |
| Clothes washer     | Replace at 1.2 m.                                 | Federal Emergency Management Agency (FEMA), 2014     |
| Hood               | Replace at 1.2 m.                                 | Gulf Engineers & Consultants (GEC), 2006             |
| 16 Foundation      |                                                 |                                                      |
| Pier               | Average of GEC foundation functions for pier buildings. | Gulf Engineers & Consultants (GEC), 2006             |
| Slab               | Average of GEC foundation functions for slab buildings. | Gulf Engineers & Consultants (GEC), 2006             |
| 17 Structural frame | Average of GEC all structural frame functions.    | Gulf Engineers & Consultants (GEC), 2006             |
| 18 Windows         |                                                 |                                                      |
| Floor level        | Replace at 0.2 m.                                 | Federal Emergency Management Agency (FEMA), 2014     |
| Sill height        | Replace at 1.2 m.                                 | Federal Emergency Management Agency (FEMA), 2014     |
| High windows       | Replace at 1.5 m (window 1.2 m from floor).       | Federal Emergency Management Agency (FEMA), 2014     |
| 19 Doors           |                                                 |                                                      |
| Interior           | Replace at 0.3 m.                                 | Federal Emergency Management Agency (FEMA), 2014     |
| Exterior           | Replace at 0.5 m.                                 | Federal Emergency Management Agency (FEMA), 2014     |
| 20 Finish flooring |                                                 |                                                      |
| All wood substrate | Replace at 0 m.                                   | Federal Emergency Management Agency (FEMA), 2014     |
| Vinyl, carpet, wood on slab | Replace at 0 m.                                   | Federal Emergency Management Agency (FEMA), 2014     |
| Ceramic on slab    | No damage.                                        | Federal Emergency Management Agency (FEMA), 2014     |
| 21 Roof            |                                                 |                                                      |
| Covering           | Replace at >2.1 m of water or when any portion inundated. | Gulf Engineers & Consultants (GEC), 2006             |
| Sheathing          | Replace inundated portions.                       |                                                      |
| Soffits, one-story | Average of GEC soffit functions for one-story buildings. | Gulf Engineers & Consultants (GEC), 2006             |
| Soffits, two-story | Average of GEC soffit functions for two-story buildings. | Gulf Engineers & Consultants (GEC), 2006             |
| 22 Condenser unit  | Replace at 0.3 m of flooding. Condenser unit assumed to be at first floor. | Federal Emergency Management Agency (FEMA), 2014     |
| 23 Heating         |                                                 |                                                      |
| Heating unit (first floor) | Assumed to be gas or oil fired. Replaced when unit is flooded with 0.3 m. | Federal Emergency Management Agency (FEMA), 2014     |
| Ductwork (below first) | Totally damaged when flooded. Assumed to be flooded at −0.3 m. | Federal Emergency Management Agency (FEMA), 2014     |
LANDSCAPING, for example, can vary from one site to another making it difficult to predict damage. Further, only permanent components of the structures were considered, and any components considered movable were outside the scope of this study (e.g., contents). In total, 25 component categories were compiled. Of the 25 component categories, interior wallboard, insulation, electrical, windows, doors, finished flooring, built-in appliances, roof, and heating were subdivided into more detailed components.

General building assumptions were defined to develop the curves, which limits the applicability of these curves to some structures. While some of these assumptions may exclude certain building designs, the general assumptions are meant to capture most designs (especially in the southern and coastal regions) and simplify the development of customizable functions. It was assumed that buildings are constructed with wood stud framing, floor to ceiling heights are 2.4 m and there is a one-foot gap between first and second stories. It was also assumed; no HVAC or built-in appliance equipment exists below the first-floor level (excluding ductwork) and there are no basements (typical of southern and coastal construction). Plumbing outside of the building footprint were excluded and only simple roof configurations were considered to simplify the development of the depth–damage functions.

Damage assumptions that define the level of damage associated with specific flood conditions and depths for all components are shown in Table 1. Further, the level of detail provided in the methodology is intended to allow development of component level functions for other building designs (e.g., different ceiling heights). Most of the damage assumptions were adapted from assumptions and damage descriptions provided in Gulf Engineers and Consultants (GEC) (2006), Federal Emergency Management Agency (FEMA) (2014), and information regarding the source of the assumptions is provided in Table 1. Flood depths shown in Table 1 are referenced to the top of the first-floor elevation. To further define assumptions for materials that are more flood resistant, Federal Emergency Management Agency (FEMA) (2014) was consulted to determine if certain materials are less likely to result in damage.

**TABLE 1** (Continued)

| Component                        | Assumptions                                                                 | Source                                           |
|----------------------------------|-----------------------------------------------------------------------------|-------------------------------------------------|
| Heating unit (second floor)      | Assumed to be gas or oil fired. Replaced when unit is flooded with 0.3 m.  | Federal Emergency Management Agency (FEMA), 2014|
| Ductwork (second flood)          | Totally damaged when flooded. Assumed to be flooded at 2.7 m.              | Federal Emergency Management Agency (FEMA), 2014|
| Ductwork (third floor)           | Totally damaged when flooded. Assumed to be at 5.5 m.                      | Federal Emergency Management Agency (FEMA), 2014|
| Pier foundation                  | Average of GEC stair functions for pier foundation                          | Gulf Engineers & Consultants (GEC), 2006         |
| Slab foundation                  | Average of GEC stair functions for slab foundation                           | Gulf Engineers & Consultants (GEC), 2006         |
| Fireplace                        | Two-story, short duration Average of GEC fireplace functions for short duration flooding. | Gulf Engineers & Consultants (GEC), 2006         |
|                                  | Two-story, long duration Average of GEC fireplace functions for long duration flooding. | Gulf Engineers & Consultants (GEC), 2006         |

*Paperless Gypsum Board is a material used for wet flood proofing, which can stay in place and dry after flooding. See Federal Emergency Management Agency (FEMA), (2008).*

*It was assumed paper-faced gypsum on the ceiling is completely damaged once water reaches ceiling height.*

*Insulation (other than closed-cell foam) is assumed to be damaged 100% when water touches the insulation (i.e., at a ceiling height of 2.4 m).*

*Roof sheathing is assumed to need replacement as it is inundated, since typical sheathing material warps when soaked with water.*

**FIGURE 1** Example component depth–damage function
| Component | Floor depth relative to first floor (m) | 0.3  | 0.2  | 0    | 0.3  | 0.5  | 0.6  | 0.9  | 1.2  | 1.5  | 1.8  | 2.1  | 2.4  | 2.7  | 3    | 3.4  | 3.7  | 4.0  | 4.3  | 4.6  |
|-----------|----------------------------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Gypsum board | Wall paper-faced | 0 | 0 | 25 | 25 | 25 | 50 | 50 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Gypsum board | Wall paperless | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Gypsum board | Ceiling paper-faced | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 |
| Gypsum board | Ceiling paperless | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bottom cabinets | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Upper cabinets | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Countertops | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Water heater | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Insulation | Floor insulation closed-cell foam | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Insulation | Floor insulation all other types | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Insulation | Wall insulation closed-cell foam | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Insulation | Wall insulation all other types | 0 | 0 | 25 | 25 | 25 | 50 | 50 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Insulation | Ceiling insulation closed-cell foam | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Insulation | Ceiling insulation all other types | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Subflooring | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Base moulding | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Paint/wallpaper | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Wainscoting | 0 | 0 | 0 | 12.5 | 25 | 37.5 | 50 | 75 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Electrical | Electrical—floor receptacles | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Electrical | Electrical—wall receptacles | 0 | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Electrical | Electrical—switches | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Electrical | Electrical—fixtures | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Built-in appliances | Dishwasher | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Built-in appliances | Clothes dryer | 0 | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Built-in appliances | Clothes washer | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Built-in appliances | Kitchen Hood | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
It should be noted that in developing the damage assumptions, thought was given not just to the actual direct physical damage, but also to actions taken by construction professionals while restoring damaged homes. For example, if only a portion of a roof were flooded, it was assumed that all shingles were replaced since color matching might be difficult when replacing only a portion of the roof. Also, in cases where removing one item would lead to the removal of another item (e.g., kitchen cabinets and countertops), both items were assumed to be completely damaged simultaneously even when one item might not be flooded.

Using these component-level damage assumptions, the component-level, depth-damage functions were then developed. As with the flood depths in Table 1, the flood depths for the functions are also referenced to the top of the first-floor elevation. As an example, Figure 1 shows the component damage function for paper-faced gypsum board that was developed from the damage assumptions. The functions were modelled as step functions, to represent typical repair/replacement recommendations. For example, with paper-faced gypsum for any flood depth starting at zero and up to 0.6 m, it is recommended a homeowner replace up to 0.6 m (25%) of gypsum board to account for the wicking of moisture into paper above the waterline. Within the 0.6–0.9 m flood depth range, 1.2 m (50%) of gypsum would be replaced. Any flood depths 1.2 m or higher, requires total replacement.

For some of the components, the component percent damage functions were directly taken from the GEC tables (exterior siding, foundation, structural frame, roof, stairs, and fireplace) (Gulf Engineers & Consultants (GEC), 2006). For GEC components where multiple functions were calculated based on the building type and flood duration, similar functions were averaged to reduce the number of functions per component.

For one component, roof sheathing, there was not enough description from GEC or the SDE Manual to determine the percent damage (Gulf Engineers & Consultants (GEC), 2006; Federal Emergency Management Agency (FEMA), 2014). While GEC provides damage estimates for the roof from which functions could be developed, it was determined because GEC had to assume a roof configuration to make the estimates (Gulf Engineers & Consultants (GEC), 2006), the results from these functions might not match other roof configurations. It was decided that roof damage would be calculated based on the assumption that only inundated sheathing would require replacement. To determine the percent of roof sheathing that would need to be replaced, Equation (2) was utilised.

\[
\% \text{Damaged sheathing} = \frac{\text{Area of inundated sheathing}}{\text{Total area of sheathing}} \times 100
\]
| Component                  | Floor depth relative to first floor (m) |
|----------------------------|-----------------------------------------|
|                            | −0.3 −0.2 0 0.2 0.3 0.5 0.9 1.2 1.5 1.8 2.1 2.4 2.7 3 3.4 3.7 4.0 4.3 4.6 |
| Gypsum board               |                                          |
| Wall, paper-faced          | 0 0 0 0 0 0 0 0 0 0 0 0 25 25 50 50 100 100 100 |
| Wall, paperless            | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| Ceiling, paper-faced       | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| Ceiling, paperless         | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| Bottom cabinets            | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 100 100 100 100 100 |
| Top cabinets               | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 100 100 100 100 100 |
| Countertops                | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 100 100 100 100 100 |
| Plumbing fixtures (WH)     | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 100 100 100 100 100 |
| Wall insulation CCF        | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| Wall insulation (other)    | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 25 25 50 50 100 100 100 |
| Ceiling insulation CCF     | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| Ceiling insulation (other) | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| Subflooring               | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 100 100 100 100 100 |
| Base moulding              | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 100 100 100 100 100 |
| Paint/wallpaper            | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 100 100 100 100 100 |
| Wainscoting                | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 25 50 75 100 100 100 |
| Electrical                 |                                          |
| Floor receptacles          | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 100 100 100 100 100 |
| Wall receptacles           | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 100 100 100 100 100 |
| Switches                   | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 100 |
| Fixtures                   | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 100 |
| Built-in appliances         |                                          |
| Dishwasher                 | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 100 100 100 100 100 |
| Clothes dryer              | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 100 100 100 100 100 |
| Clothes washer             | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 100 |
| Hood                       | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 100 |
| Windows and doors          |                                          |
| Floor level                | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 100 100 100 100 100 |
| Sill height                | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 100 |
Also, to account for variation in the design of components at the first- and second-flow (i.e., attic of a two-story) of a SFR building, all components except for six were separated into two sets of depth-damage functions for the first and second floor levels. Only exterior siding, foundation, structural frame, roof, stairs, and fireplace depth damage functions include all the floors combined. These components were not separated by story because there was not enough information from GEC or the SDE Manual to split damage percentage by building level (Gulf Engineers & Consultants (GEC), 2006; Federal Emergency Management Agency (FEMA), 2014). The first-floor, second-floor, and combined depth damage functions can be found in Tables 2–4).

To utilize the tables for a specific building, the first-floor, second-floor, and combined functions that are applicable to the specific design in question are identified. As an example, for a one-story building, most applicable functions will be taken from Tables 2 and 4. If the equipment is located in the attic (e.g., ductwork, heating unit, and water heater) then functions from Table 4 may also be applicable to a one-story building since this equipment is located at the second-story level.

The carbon footprint to repair each component is calculated according to Equation (3):

$$CF_{i,j} = \frac{TCO_2 i \times PD_{i,j}}{100}$$

where, $CF_{i,j}$ is the carbon footprint of repairs to component $i$ at flood depth $j$, $TCO_2 i$ is the total carbon footprint to replace component $i$, and $PD_{i,j}$ is the percent damage for component $i$ at flood depth $j$. Repeating this for all components, the result is a table of carbon footprint repair values for all components over the full range of flood depth. Finally, the component carbon footprint values are summed at each flood depths. The summed carbon footprint values represent the total carbon footprint for building repairs as a function of flood depth. TCO2 values can be derived from literature, which is further demonstrated in following section. Since TCO2 values for individual materials can have a range of estimated values, an uncertainty analysis should be carried out to investigate the variability in the carbon footprint curves produced.

The uncertainty analysis is carried out investigating both the variability in carbon footprint values and materials quantities. Variability in carbon footprint values were characterized by utilising the maximum and minimum carbon footprint values for individual materials derived from literature. By applying the maximum and minimum values to the curve development methodology, maximum and minimum carbon footprint curves base on
### Table 4  First and second floor combined depth damage functions

| Component          | Floor depth relative to first floor (meters) | −0.3 | −0.2 | 0 | 0.2 | 0.3 | 0.5 | 0.6 | 0.9 | 1.2 | 1.5 | 1.8 | 2.1 | 2.4 | 2.7 | 3 | 3.4 | 3.7 | 4.0 | 4.3 | 4.6 |
|--------------------|---------------------------------------------|------|------|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|---|-----|-----|-----|-----|-----|
| Exterior wall/siding |                                             |      |      |   |     |     |     |     |     |     |     |     |     |     |     |   |     |     |     |     |     |
| One-story, S.D.³   |                                             | 0    | 0    | 2 | 12.5| 13.2| 16.1| 16.6| 19.9| 21.8| 24.1| 24.5| 26.8| 27.2| 28.3| 28.7| 29.2| 29.7| 30.1| 30.6|
| One-story, L.D.³   |                                             | 0    | 0    | 0 | 15.4| 27.6| 35.9| 41.1| 42.2| 45.5| 54.7| 58.1| 58.6| 60.8| 61.3| 62.4| 62.8| 63.3| 63.7| 64.2| 64.6|
| Two-story, S.D.     |                                             | 0    | 0    | 0 | 1.3 | 7.8 | 7.8 | 11  | 11  | 16.1| 16.5| 18.3| 18.3| 19.8| 19.8| 20.1| 22.6| 22.6| 27.1| 27.1| 27.1| 27.1|
| Two-story, L.D.     |                                             | 0    | 0    | 0 | 1.9 | 13.7| 15.5| 21.8| 22.1| 29.6| 30.8| 33.2| 34  | 38.3| 46.3| 46.3| 48.8| 50.1| 55.1| 56.8| 59.4|      |
| Brick/stone siding |                                             | 0    | 0    | 0 | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |      |
| Foundation          |                                             |      |      |   |     |     |     |     |     |     |     |     |     |     |     |     |   |     |     |     |     |     |
| Pier               |                                             | 0.7  | 1.1  | 3.2| 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 |      |
| Slab               |                                             | 0    | 0    | 0 | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |      |
| Structural frame    |                                             | 0    | 0    | 0 | 2.3 | 3.2 | 3.2 | 3.7 | 4.1 | 4.7 | 5.2 | 5.4 | 5.4 | 6   | 6.3 | 6.3 | 6.3 | 6.3 | 6.3 | 6.3 | 6.3 |      |
| Soffits/fascia, one-story |                               | 0    | 0    | 0 | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |      |
| Soffits/fascia, two-story |                              | 0    | 0    | 0 | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |      |
| Stairs—pier foundation |                                         | 0    | 0    | 0 | 7.7 | 31.6| 44.9| 63.4| 67.6| 69.1| 77.6| 79  | 80.4| 82  | 82.6| 82.6| 82.6| 82.6| 82.6| 82.6| 82.6| 82.6|
| Stairs—slab foundation |                                     | 0    | 0    | 0 | 5.5 | 16.6| 24.5| 25.9| 44.3| 46.4| 56.2| 58.8| 60.2| 61.6| 62.9| 62.9| 62.9| 62.9| 62.9| 62.9| 62.9| 62.9|
| Fireplace—two-story, S.D. |                                   | 0    | 0    | 0 | 18.4| 38.5| 45.3| 47.3| 47.3| 47.3| 47.3| 47.3| 47.3| 47.3| 47.3| 52.3| 52.3| 52.3| 52.3| 52.3| 52.3| 52.3|
| Fireplace—Two-story, L.D. |                               | 0    | 0    | 0 | 21.9| 51.7| 61.9| 65.9| 65.9| 65.9| 65.9| 65.9| 65.9| 70.9| 70.9| 70.9| 70.9| 70.9| 70.9| 70.9| 70.9| 70.9|

³S.D., short-duration flooding; L.D., long-duration flooding.
| Design component         | Units | Quantity | Min TCO₂ (kg CO₂ Eq. × 10³) | Mean TCO₂ (kg CO₂ Eq. × 10³) | Max TCO₂ (kg CO₂ Eq. × 10³) | TCO₂ data sources                                      |
|--------------------------|-------|----------|------------------------------|------------------------------|----------------------------|------------------------------------------------------|
| Gypsum board—walls       | S.M.  | 363.8 b  | 8.27 b                       | 8.27 b                       | National Institute of Standards and Technology (NIST), 2018 |
| Gypsum board—ceiling     | S.M.  | 191 b    | 4.34 b                       | 4.34 b                       | National Institute of Standards and Technology (NIST), 2018 |
| Bottom cabinets          | L.M.  | 7.2 0.145 | 0.155 0.162                  | Ashby, 2009                  |
| Upper cabinets           | L.M.  | 7.3 0.103 | 0.108 0.112                  | Ashby, 2009                  |
| Countertops              | S.M.  | 9.1 0.087 | 0.118 0.122                  | Ashby, 2009                  |
| Hot water heater         | Each  | 1 0.108  | 0.126 0.136                  | Ashby, 2009                  |
| Insulation—walls         | S.M.  | 146.7 0.384 | 0.292 0.417                  | National Institute of Standards and Technology (NIST), 2018 |
| Insulation—ceiling       | S.M.  | 191 0.384 | 0.736 1.09                    | National Institute of Standards and Technology (NIST), 2018 |
| Wood siding              | S.M.  | 146.7 b  | 0.335 b                      | National Institute of Standards and Technology (NIST), 2018 |
| Exterior wall sheathing  | S.M.  | 146.7 b  | 0.644 b                      | National Institute of Standards and Technology (NIST), 2018 |
| Base moulding            | S.M.  | 13.2 0.096 | 0.102 0.106                  | Ashby, 2009                  |
| Paint/wall coverings     | S.M.  | 411.2 b  | 0.984 b                      | National Institute of Standards and Technology (NIST), 2018 |
| Electrical outlets       | Each  | 24 0.003  | 0.003 0.003                  | Ashby, 2009                  |
| Electrical switches      | Each  | 19 0.006  | 0.007 0.007                  | Ashby, 2009                  |
| Electrical fixtures      | Each  | 26 a     | a a a                        | Ashby, 2009                  |
| Dishwasher               | Each  | 1 0.260  | 0.265 0.269                  | Ashby, 2009                  |
| Clothes washer           | Each  | 1 0.340  | 0.360 0.375                  | Ashby, 2009                  |
| Clothes dryer            | Each  | 1 0.303  | 0.318 0.330                  | Ashby, 2009                  |
| Kitchen Hood             | Each  | 1 a      | a a a                        | Ashby, 2009                  |
| Heating unit†            | Each  | 1 0.483  | 0.539 0.595                  | Ashby, 2009                  |
| Slab                     | S.M.  | 161.3 5.77 | 6.46 7.15                    | National Institute of Standards and Technology (NIST), 2018 |
| Wall and roof framing    | Kg    | 7,725 4.19 | 4.47 4.74                    | Ashby, 2009                  |
| Sill height windows      | S.M.  | 3.3 0.116 | 0.131 0.146                  | Ashby, 2009                  |
| High windows             | S.M.  | 9 0.312  | 0.352 0.392                  | Ashby, 2009                  |
| Interior doors           | S.M.  | 10.9 0.058 | 0.061 0.064                  | Ashby, 2009                  |
| Exterior doors           | S.M.  | 14.2 0.111 | 0.120 0.129                  | Ashby, 2009                  |
| Wood flooring            | S.M.  | 49.2 0.392 | 0.409 0.425                  | Ashby, 2009                  |
| Carpet                   | S.M.  | 50.3 0.463 | 0.821 2.06                   | National Institute of Standards and Technology (NIST), 2018 |
| Ceramic flooring         | S.M.  | 35.9 b  | 0.792 b                      | National Institute of Standards and Technology (NIST), 2018 |
Variability in carbon footprint were developed. Variability in material quantities due to errors in estimation were simulated by adding and subtracting 10% to the estimated quantity for each material component. Minimum and maximum carbon footprint curves were then created incorporating both the minimum and maximum carbon footprint value with the minus and plus 10% material variation, respectively. These curves help to demonstrate the potential variability of curve development based on both variations in carbon footprint values and material estimations.

### 3 | CASE STUDY

The following case study illustrates how the component depth–damage functions can be utilised for individual building designs to develop design-specific, whole-building functions for estimating carbon footprint impacts of repairs. A one-story, slab-on-grade, wood-framed, hipped roof SFR structure with three bedrooms and two baths was used for this case study. The home is typical of coastal, southeastern construction in Saint Petersburg, Florida (Matthews et al., 2016), and flooding was assumed to be of short-duration, fresh, or saltwater flooding.

Table 5 shows the material quantities and total carbon footprint for each component in the case study house. It was assumed that there was no difference between the carbon footprint of the new installation and the repair of each component. While there might be carbon emissions associated with the removal of damaged materials, it was assumed differences in carbon footprint between new installation and repairs was negligible.

Table 5 (Continued)

| Design component | Units | Quantity | Min TCO$_2$ (kg CO$_2$ Eq. x $10^3$) | Mean TCO$_2$ (kg CO$_2$ Eq. x $10^3$) | Max TCO$_2$ (kg CO$_2$ Eq. x $10^3$) | TCO$_2$ data sources |
|------------------|-------|----------|---------------------------------|---------------------------------|---------------------------------|---------------------|
| Roof cover       | S.M.  | 291.9    | 4.515                           | 4.515                           | 4.515                           | National Institute of Standards and Technology (NIST), 2018 |
| Roof sheathing   | S.M.  | 291.9    | 1.280                           | 1.280                           | 1.280                           | National Institute of Standards and Technology (NIST), 2018 |
| Fascia           | S.M.  | 10.7     | 0.057                           | 0.063                           | 0.065                           | Ashby, 2009         |
| Soffits          | S.M.  | 53.3     | 0.101                           | 0.111                           | 0.113                           | Ashby, 2009         |
| AC condensing unit | Each | 1        | 0.623                           | 0.688                           | 0.752                           | Ashby, 2009         |
| Ductwork         | Per story | 1 | 0.395                           | 0.441                           | 0.487                           | Ashby, 2009         |
| **Total**        |       |          | 36.24                           | 38.41                           | 41.42                           |                     |

aData not available.

bMinimum and maximum data same as mean; limited data available to develop range of data values.

Includes furnace and fan coil unit.
**TABLE 6**  Case study calculations for carbon footprint (−0.3 to 4.5 m)

| Component                     | Floor depth relative to first floor (m) | TCO₂ (kg CO₂ Eq. x 10³) |
|-------------------------------|-----------------------------------------|--------------------------|
|                               | −0.3 − 0.2 0 0.2 0.3 0.5 0.6 0.9 1.2 1.5 1.8 2.1 2.4 2.7 3 3.4 3.7 4.0 4.3 4.6 |                          |
| First floor Wall, paper-faced |                                         | 8.27                     |
| Ceiling, paper-faced          |                                         | 4.34                     |
| Bottom cabinets               |                                         | 0.155                    |
| Upper cabinets                |                                         | 0.108                    |
| Countertops                   |                                         | 0.118                    |
| Water heater                  |                                         | 0.126                    |
| Wall insulation               |                                         | 0.292                    |
| Ceiling insulation            |                                         | 0.736                    |
| Base moulding                 |                                         | 0.102                    |
| Paint/ wallpaper              |                                         | 0.984                    |
| Wall receptacles              |                                         | 0.003                    |
| Switches                      |                                         | 0.007                    |
| Fixtures                      |                                         |                           |
| Dishwasher                    |                                         | 0.265                    |
| Clothes washer                |                                         | 0.360                    |
| Clothes dryer                 |                                         | 0.318                    |
| Hood                          |                                         |                           |
| Sill height                   |                                         | 0.131                    |
| High windows                  |                                         | 0.352                    |
| Interior doors                |                                         | 0.061                    |
| Exterior doors                |                                         | 0.120                    |
| Wood flooring (slab)          |                                         | 0.409                    |
| Carpet (slab)                 |                                         | 0.821                    |
| Ceramic (slab)                |                                         | 0.792                    |
| AC condenser unit             |                                         | 0.688                    |
| Second floor Fixtures         |                                         |                           |
| Roof covering                 |                                         | 4.515                    |
| Roof's heating                |                                         | 1.280                    |
| Heating unit (attic)          |                                         | 0.599                    |
| Ductwork (attic)              |                                         | 0.441                    |
| Combined Siding               |                                         | 0.335                    |
| Exterior Wall sheathing       |                                         | 0.644                    |
| Foundation—slab               |                                         | 6.46                     |
| Structural frame              |                                         | 4.47                     |
| Roof—Soffits/ fascia          |                                         | 0.174                    |
| Sum                           |                                         | 36.24                    |

Note: The table provides detailed calculations for the carbon footprint of various building components at different floor depths relative to the first floor.
need to be replaced, at 1.2 m most interior materials below 2.4 m would be damaged and at 2.4 m roof and ceiling materials would need to be repaired. For a one-story building, once floodwater exceeds 2.4 m, most material damage in the building has occurred, which explains the flattening of the curve for higher flood depths. The flattening of the curve between 1.22 and 2.44 m is also expected since only additional damage to interior and exterior wall finishes and sheathing would be damaged.

The case study demonstrates how the customizable depth–damage functions developed in this study can be used to estimate the environmental impacts of damage repairs over a range of flood depths. While this study used carbon footprint to measure environmental impact, other environmental impact indicators could also be utilised (e.g., embodied energy, water consumptions).

These functions can be used by benefit–cost analysts when quantifying the effectiveness of designs to mitigate impacts beyond economic loss. This metric, when added to benefit cost analysis, enables a more holistic approach to sustainable construction practice that ideally should consider all economic, social and environmental impacts. For example, the Federal Emergency Management Agency already utilizes some limited environmental benefits to quantify the overall benefit of Hazard Mitigation Grant Program projects to determine feasibility for funding (Federal Emergency Management Agency (FEMA), 2013). By applying monetary values to reductions in carbon footprint associated with avoided flood losses, these benefits could be easily be integrated into the current environmental benefits utilised in FEMA cost–benefit methodologies. Customizable curves could also be integrated into cost–benefit approaches such as the one presented in Hennequin et al. (2018), which analysed whether constructing flood protection structures were more environmentally beneficial than repairing flood damages associated with the potentially protected buildings. These are just some examples of how developing carbon footprint curves for specific buildings can be utilised for analysis related to specific projects.

4  |  UNCERTAINTY ANALYSIS

The same calculations shown in Table 6 were also carried out for the minimum and maximum values. The range of total carbon footprint is shown in Figure 3. The minimum and maximum curves follow the same trend as the mean curve. The greatest percent difference between minimum and maximum values exist at flood depths between 0 and
1.2 \text{ m} with differences of 35–23\%, respectively. At depths 
1.2 \text{ m} or greater the percent difference between minimum 
and maximum values fall between 13 and 16\%.

When taking into account both variability in carbon 
footprint and material quantity variation (±10\%), the 
range of total carbon footprint increases (Figure 4). The 
greatest percent difference between minimum and maximum 
values range from 54 to 43\% between 0 and 1.2 \text{ m}, 
respectively. At depths greater than 1.2 \text{ m} the percent 
difference between minimum and maximum values fall 
between 32 and 36\%. For both Figures 3 and 4, as depth 
increases from 0 \text{ m} the percent difference between mini-
mum and maximum carbon footprint decreases.

5 | CONCLUSION

A set of component-level, synthetic depth–damage func-
tions for SFR type structures were developed and applied 
to case study building. These functions, while traditionally 
used to quantify damage in dollars, were applied to 
quantify the environmental impact of an individual 
building as demonstrated by the case study provided. The 
functions presented in the study target the most conven-
tional type of SFR construction (i.e., wood-framed). 
Inundation-only, nonvelocity flooding is considered in 
the development of these functions. The functions are 
applicable to both one-story and two-story SFR building 
designs, and flexible enough to account for variations in 
most SFR designs. The case study includes a wood-frame 
SFR building design typical of coastal, southeastern 
United States. The depth-damage functions were applied 
to the case study building to calculate the carbon foot-
print of flood damage over a range of flood depths. An 
uncertainty analysis of carbon footprint values was also 
completed to show the range (minimum and maximum) 
of possible carbon footprint values for flood depths −0.3 
to 4.6 \text{ m}. When accounting for variation in carbon foot-
print values, the percent difference between minimum 
and maximum curves ranged from 13 to 35\% from 4.6 to 
0 \text{ m}, respectively. When taking into account both varia-
tion in carbon footprint values and materials quantities 
the percent difference between minimum and maximum 
curves ranged from 32 to 54\% from 4.6 to 0 \text{ m}, respec-
tively. The greatest percent difference in both cases 
occurred at lower flood depths (0–1.2 \text{ m}). The customiz-
able component functions presented in this article serve 
as a tool for creating depth–damage carbon-footprint 
building functions specific to individual designs.

6 | LIMITATIONS AND FUTURE 
STUDY

The methodology in this study is limited to cases with 
inundation-only, nonvelocity flooding. The functions are 
only applicable to both one-story and two-story SFR 
wood-frame building designs. Moveable objects and con-
tents of buildings were not included. Due to need to for 
detailed materials component quantities, this methodol-
ogy is more easily applied to cases where only one or a 
few buildings are of interest. While this approach can be 
applied to quantify other environmental impacts, the case 
study presented is limited to quantifying carbon foot-
print. Recommended future studies include quantifying 
other environmental impact factors and investigating the 
incorporation of this analysis into cost–benefit studies for 
flood mitigation strategies. This could include applying a 
monetary value to reductions in carbon footprint associ-
ated with avoided flood losses, so that additional environ-
mental benefit can be incorporate into the FEMA 
benefit–cost analysis approach. Furthermore, since quan-
tifying material quantities for large groups of buildings is 
difficult, it would also be beneficial to investigate 
approaches for utilising LCA approaches for estimating 
the environmental impacts of flood damage case studies 
utilising large groups of buildings.

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No conflict of interest has been declared by the authors.

DATA AVAILABILITY STATEMENT
Data sharing is not applicable to this article as no new 
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