Enhancing Flood Vulnerability Assessment: Integrating Flow Velocity, Duration, and Debris Flow into a Component-Level Framework

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ABSTRACT

Recent extreme flood events have highlighted the limitations of traditional flood vulnerability models that rely predominantly on inundation depth as the sole hazard intensity metric. Observations from events such as the July 2021 European floods and prolonged rainfall-induced flooding in recent years demonstrate that flow velocity, flood duration, and debris flow play a decisive role in driving structural damage and economic losses. This paper presents an enhanced flood vulnerability framework that explicitly integrates these additional hazard-intensity parameters into an engineering-based, component-level modeling approach. The framework introduces four flow-velocity classes, two flood-duration categories, and an explicit treatment of debris flow, resulting in twelve distinct hazard intensity combinations. Component-level damage functions are developed and then aggregated to create building mean damage ratios (MDRs) using floor-level cost distributions, allowing the model to explicitly capture hydrostatic and hydrodynamic forces, prolonged saturation effects, and debris-induced load amplification.

KEYWORDS: Flood vulnerability; component-level modeling; flow velocity; flood duration; debris flow; mean damage ratio; hydrodynamic forces; catastrophe modeling

1 INTRODUCTION

Flood catastrophe models have become essential tools for quantifying and managing flood risk across insurance, reinsurance, and public-sector applications. These models typically consist of four integrated modules: hazard, exposure, vulnerability, and financial modules. Each module contributes to the estimation of physical damage and economic loss. Traditional models generally categorize events into storm surge and precipitation-induced flooding, with the latter further divided into on-plain (fluvial) and off-plain (pluvial) flooding. Historically, for all types of flood events, flood vulnerability modules have relied almost exclusively on inundation depth as the primary determinant of damage. While depth remains the dominant factor in many flood scenarios, recent flood events have highlighted the limitations of depth-only representations for capturing the full range of flood-induced damage mechanisms.

Recent extreme events, such as the July 2021 Bernd flood in Germany and neighbouring European countries, were characterized by high flow velocities and substantial debris flow, leading to severe structural damage, bridge clogging, and rapid escalation of flood levels. Conversely, long-duration rainfall events, such as the April 2023 flooding in South Florida, demonstrated that prolonged exposure to relatively shallow water can also result in significant losses through prolonged wetting, material degradation, and delayed recovery. These contrasting event types underscore the need for vulnerability models that distinguish among fundamentally different flood processes rather than treating all floods as having equivalent depth–damage relationships.

In response to these challenges, Verisk has developed an enhanced flood vulnerability framework that extends hazard intensity parameters beyond inundation depth. Leveraging nearly two decades of probabilistic flood modeling experience across multiple regions, this framework integrates additional hazard parameters such as flood velocity, flood duration, and debris flow into a unified, component-level vulnerability methodology. The objective is to enhance the physical realism of damage estimates while maintaining consistency with observed insured loss experience and established engineering principles.

2 METHODOLOGY

2.1 Overview of the Vulnerability Framework

The enhanced vulnerability framework is embedded within a standard catastrophe modeling architecture and focuses on the engineering-based estimation of physical damage. Damage is expressed in terms of the mean damage ratio (MDR), defined as the ratio of repair cost to replacement value for a given asset (see Figure 1). Separate damage functions are developed for buildings and contents, with additional functions to support loss-of-use and business-interruption estimation.

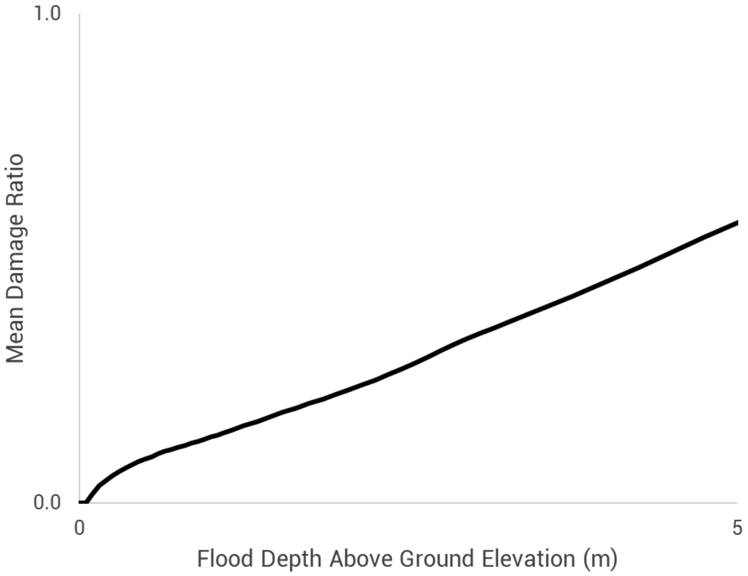


Figure 1: Sample flood damage function, showing the relationship between flood intensity and the mean damage ratio for a given building type

Unlike traditional depth-only approaches, the local flood intensity in this framework is defined by four parameters: inundation depth, flow velocity, flood duration, and the presence of debris flow. Damage functions are conditioned on combinations of these parameters and on a detailed representation of building characteristics.

2.2 Hazard Intensity Parameters

Flood Depth: The on-plain and off-plain depths are modeled for each event and location to account for the hydrostatic forces. On-floodplain flood depths are computed using a computational algorithm similar to the steady-state mode of HEC-RAS (HEC-RAS, 2002). To explicitly determine off-floodplain inundation depths, Verisk researchers developed a Graphics Processing Unit (GPU)-based 2D shallow-water wave model that uses 24-hour precipitation accumulation to compute inundation depths.

Flood Velocity: Flow and runoff velocity are explicitly modeled for each event and location to account for hydrodynamic forces exerted by moving water. As velocity increases, hydrodynamic forces acting on structural and non-structural components increase nonlinearly, increasing the potential for damage (FEMA, 2011). To represent this effect, flood velocity is classified into four discrete classes: low (0-0.5 m/s), normal (0.5-1.5 m/s), moderate (1.5-2.5 m/s), and high velocity (2.5 m/s or higher).

Flood Duration: Flood duration captures the length of time a structure remains exposed to inundation above a critical depth threshold. Duration is estimated using event-specific hydrographs and classified into two categories: short (less than 24 hours) and long-duration (24 hours or longer). Prolonged exposure increases the likelihood of water penetration, material saturation, mold growth, and damage to porous components, such as interior finishes and fixtures (Hall et al., 1984).

Debris Flow: Debris flow is the transport of solid materials such as sediment, soil, vegetation, and man-made objects by moving floodwater, which amplifies hydrostatic and hydrodynamic forces and increases structural damage beyond that caused by water depth and velocity alone. Its occurrence is driven by a combination of debris susceptibility (derived from slope/topography and land use/cover), event-level soil moisture, and flood velocity. Debris flow is applied only to moderate- and high-velocity classes, reflecting the minimum energy required to mobilize and transport debris.

The combination of four velocity classes, two duration classes, and the presence or absence of debris flow results in 12 distinct hazard-intensity combinations. Each combination is associated with a unique set of damage functions.

2.3 Component-Level Damage Functions

The framework employs a component-based approach to vulnerability modeling, in which buildings are decomposed into discrete physical components. The model considers ten key building components, plus clean-up and miscellaneous costs, to determine the total replacement cost (see Table 1).

Table 1: Building component breakdown

Component Name	Component Description
Foundation	The foundation forms part of the building that transmits the loads from the building to the ground below. The types of foundations used for residential buildings vary and may be in the form of a basement, crawlspace, slab, or others.
Structural Frame	The structural frame includes all load-carrying parts of the building, including the columns, beams, joists, and studs.
Exterior	The exterior forms the outer parts of a building, including the exterior walls and siding.
Openings	The opening includes the building's doors and windows.
Roof	The roof includes the roof frame, roof decking, and roof covering.
Interior	The interior component refers to walls inside the building (e.g., partition walls and drywall), flooring and floor coverings, and other interior finishes.
Fixtures	Fixture components of a house include items like light fixtures, faucets, sinks, toilets, built-in cabinets, door handles, window coverings, ceiling fans, and any other item permanently attached to the structure of the house, meaning they are considered part of the property.
Mechanical Systems	Mechanical systems typically include heating, ventilation, and air conditioning (HVAC), ducts, and elevators.
Electrical Systems	The electrical systems component includes electrical switchboards, meters, distribution panels, switches, circuit breakers, and control and utilization systems (e.g., lighting and wiring).
Plumbing Systems	Plumbing systems consist of water piping and sewage treatment and disposal systems, including septic tanks, bathroom drains, sinks, and interior pipes.
Clean-Up and Miscellaneous	This component includes remediation and other activities associated with repair and mold removal.

For each component, damage functions are developed as functions of flood depth relative to the floor level, conditioned on the applicable velocity and duration class (see Figure 2). To build the component damage functions, Verisk engineers used the results of studies conducted by the New Orleans District of the USACE, as well as other studies, on flood losses to single-family homes and commercial buildings (e.g., Babbitt et al., 2010; Dottori et al., 2016; FEMA, 2006; Kelman, I., 2003; Kelman, I., & Spence, R., 2004; Penning-Rowsell et al., 2005, 2005; Priest et al., 2021; Shrubsole et al., 1993; USACE, 1992; USACE, 2006). Velocity effects influence most components, primarily load-bearing and envelope components, while duration effects are most pronounced for porous interior components and fixtures (see Figure 3). The presence of debris flow is represented through an amplification factor applied at the building level.

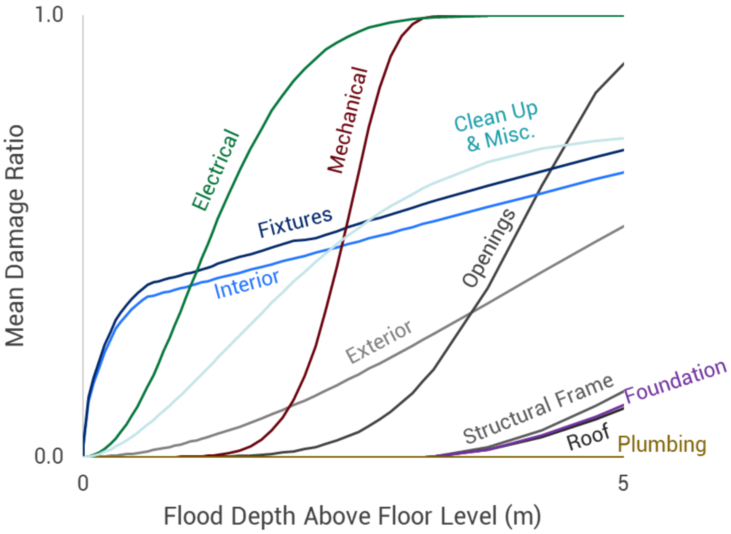


Figure 2: Sample component damage functions for a given building type, susceptible to a low velocity, short-duration flood event

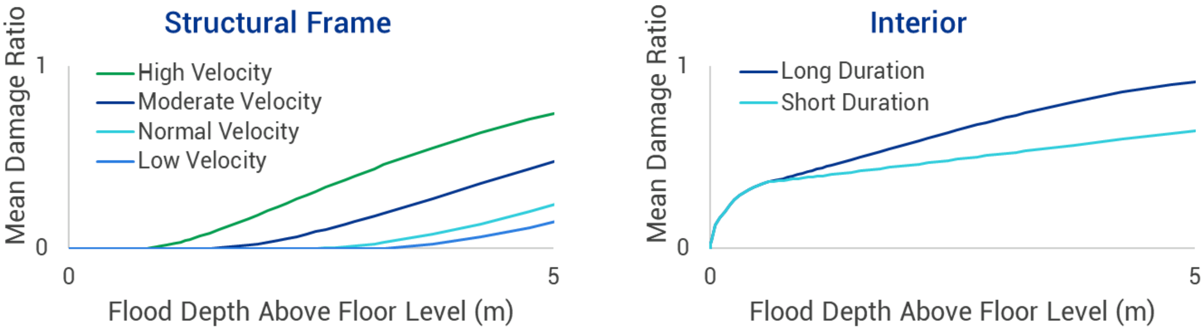


Figure 3: The effect of flow velocity and flood duration on different components

2.4 Aggregation to Building-Level Damage

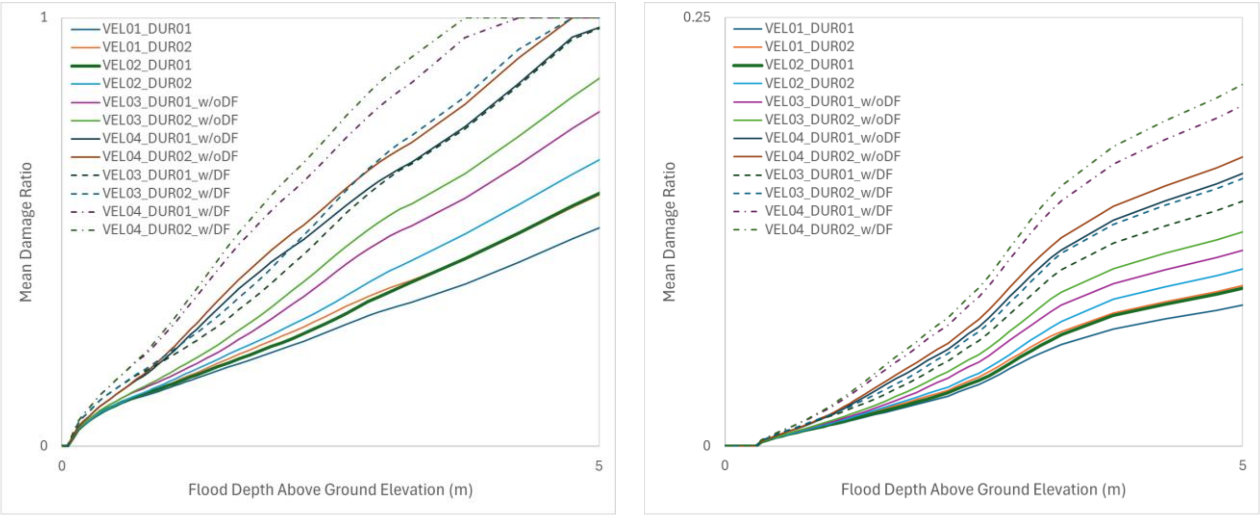
Component-level damage functions are aggregated to produce story-level damage functions using component cost ratios and vertical distribution factors (Ramanathan and Kafali, 2014). These story-level functions are then aggregated across the building's height to obtain an overall building damage function. The aggregation explicitly accounts for building height, number of stories, foundation type, and the vertical location of vulnerable components, such as mechanical and electrical systems. The mathematical formulation for the building damage function ($DF_{Building}$) is (1):

$$DF_{Building} = \sum_{j=1}^{N}\sum_{i=1}^{M}\alpha_i\beta_{i-j}DF_{component,i} \tag{1}$$

Where:

- N is the number of stories.
- M is the number of components.
- α_i is the $i-th$ component cost breakdown.
- β_{i-j} is the floor cost distribution factor for the $i-th$ component at the $j-th$ story.
- $DF_{component,i}$ is the $i-th$ component-level damage function.

Component cost ratios and floor cost distributions are informed by Verisk 360-Value (a subsidiary of Verisk) and local sources. This formulation enables the model to capture key vulnerability drivers, including the presence of a basement and the concentration of value in lower floors. For instance, in multi-story residential buildings, mechanical and electrical fittings are often located on lower floors, increasing their vulnerability. In such cases, the values of β_{i-j} will be higher in lower floors, exacerbating the vulnerability of such buildings. Figure 4 shows the resulting building-level MDR for a one-story masonry single-family home (see Figure 4-a) and a five-story office building (see Figure 4-b) expressed as a function of flood depth relative to ground level, ensuring compatibility with hazard outputs.



(a) (b)

Figure 4: Sample building level damage functions for twelve distinct hazard combinations, showing the range of damage for a given inundation depth depending on the velocity (VEL01-VEL04) and duration class (DUR01-DUR02), and the debris flow presence (without debris flow - w/oDF, and with debris flow - w/DF) for a one-story masonry single-family home (a) and a five-story concrete office building (b). The thicker line depicts the damage function for normal velocity (VEL02) and short duration (DUR01).

2.5 Building Characteristics and Unknown Attributes

Building vulnerability is conditioned by a set of primary risk characteristics, including occupancy, construction type, and height, as well as secondary characteristics such as foundation type and first-floor height. For the Verisk United Kingdom (UK) and Republic of Ireland (ROI) inland flood model, researchers utilized 142 occupancies, 129 construction types, and height classifications up to 30 stories to create hundreds of thousands of unique archetypes.

For cases where exposure attributes are missing, such as unknown construction types, the number of stories, or foundation type, the model employs CRESTA[1]-level weighted damage functions derived from industry exposure databases (IEDs) and proprietary datasets, such as the Verisk UKBuildings data, another subsidiary of Verisk. This approach preserves regional variability in vulnerability and avoids reliance on national-average assumptions.

Example: Building Height in the UK: The IED analysis shows distinct regional variations. As an example, London is characterized mainly by high-rise apartments, while Bath consists of low- and mid-rise buildings. Since vulnerability decreases as the number of stories increases (due to value distribution), applying a country-wide average would misrepresent the risk. By using CRESTA-level unknown-height damage functions, the model correctly identifies Bath as more vulnerable than London for undefined apartment risks (see Figure 5).

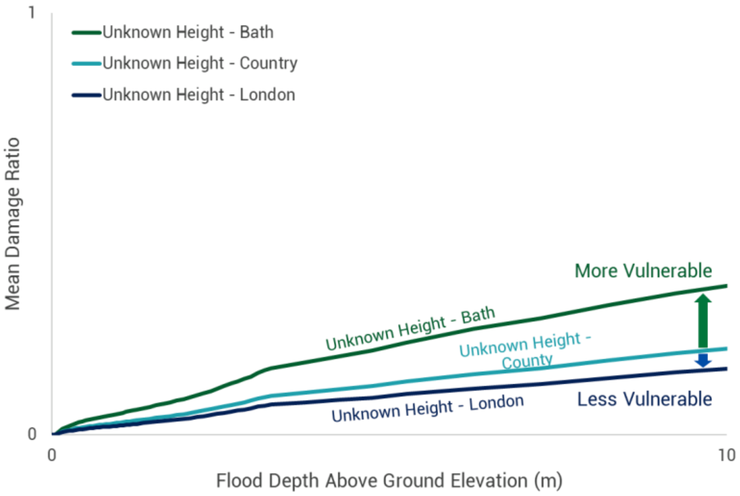


Figure 5: Verisk's UK industry exposure database informs highly granular assumptions on primary risk characteristics – building height in the UK

Example: Basements – Foundation Type: Basements significantly increase flood vulnerability. Using the UKBuildings Database, we determined the likelihood of basement presence based on occupancy, year built, height, and CRESTA, resulting in 72 specific combinations per CRESTA zone. For instance, buildings constructed before 1914 are significantly more likely to have a basement. Figure 6 shows the percentage of commercial mid-rise (4 to 7 stories) buildings with a basement constructed before 1914 (Figure 6-a) and after 1914 (Figure 6-b), per CRESTA.

For example, for CRESTA Leeds, the percentages of commercial mid-rise buildings with a basement constructed before and after 1914 are 83% and 38%, respectively. Using this CRESTA-year built-level information, we can develop known and unknown foundation damage functions per year-built class for 5-story commercial buildings susceptible to normal velocity and short-duration events in a sample CRESTA, Leeds, as shown in Figure 7.

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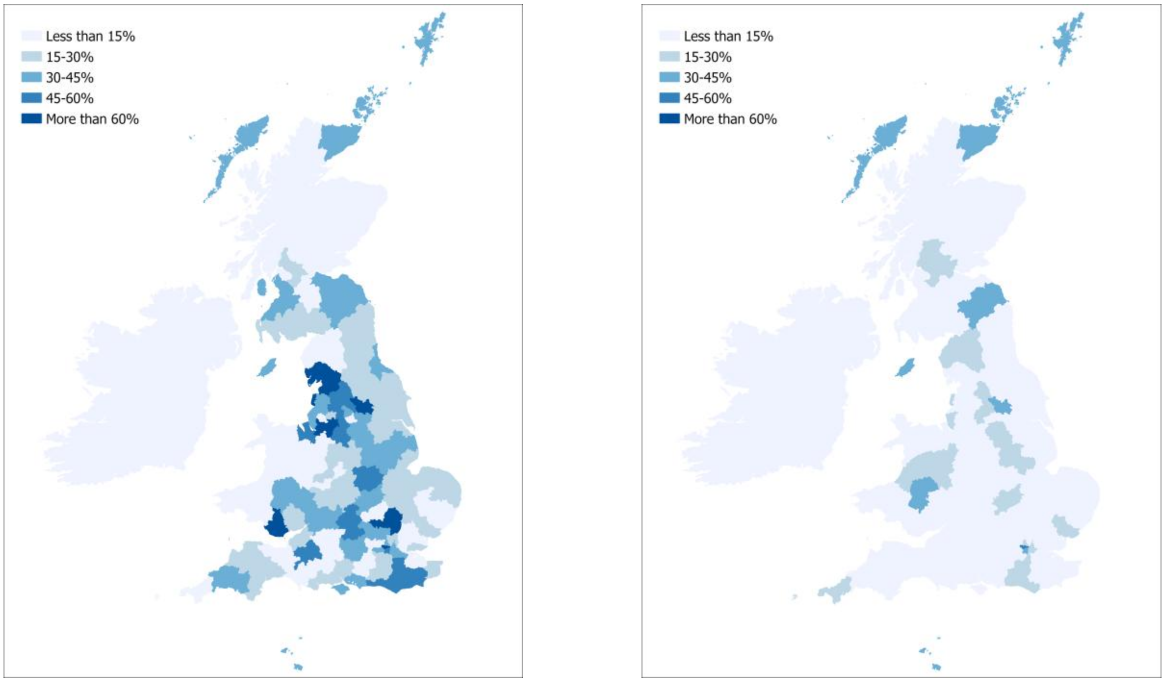
[1] A standardized geographic zoning system developed by the Catastrophe Risk Evaluating and Standardizing Target Accumulations initiative, used by the insurance industry to consistently aggregate and manage catastrophe risk exposure and losses at a subnational regional level.



(a) (b)

Figure 6: Verisk's UK Buildings database offers highly granular assumptions on the presence of basements. (a) shows the percentage of commercial mid-rise buildings constructed before 1914 with a basement per CRESTA, and (b) shows the percentage of commercial mid-rise buildings constructed after 1914 with a basement per CRESTA

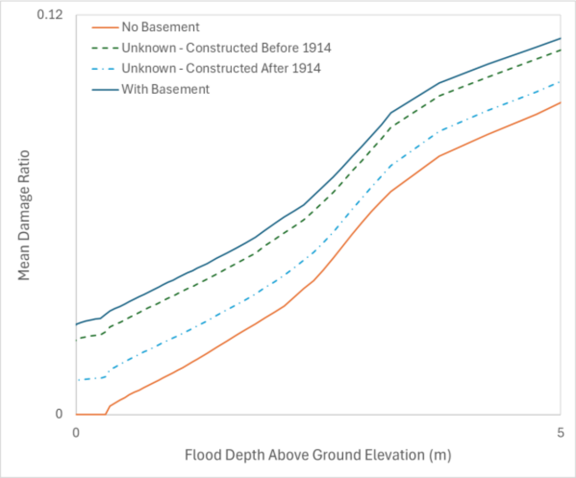


Figure 7: Basement, no basement, and unknown basement damage function for 5-story commercial buildings susceptible to normal velocity and short duration in CRESTA Leeds

2.6 Model Calibration and Validation

Validating the entire model, from hazard to vulnerability to loss, is essential. For our UK and ROI inland flood model, we validated our component-level damage functions against established external sources, including the Multi-Coloured Manual (MCM; Priest et al., 2021), INSYDE (Dottori et al., 2016), and various loss data sets.

Comparisons show that Verisk-derived damage functions closely mirror MCM functions, with expected deviations at lower depths, where our model accounts for uncertainties in building characteristics and hazard (see Figure 8).

While the framework does not explicitly model all secondary damage mechanisms (e.g., contamination or erosion), these effects are implicitly captured through calibration and validation.

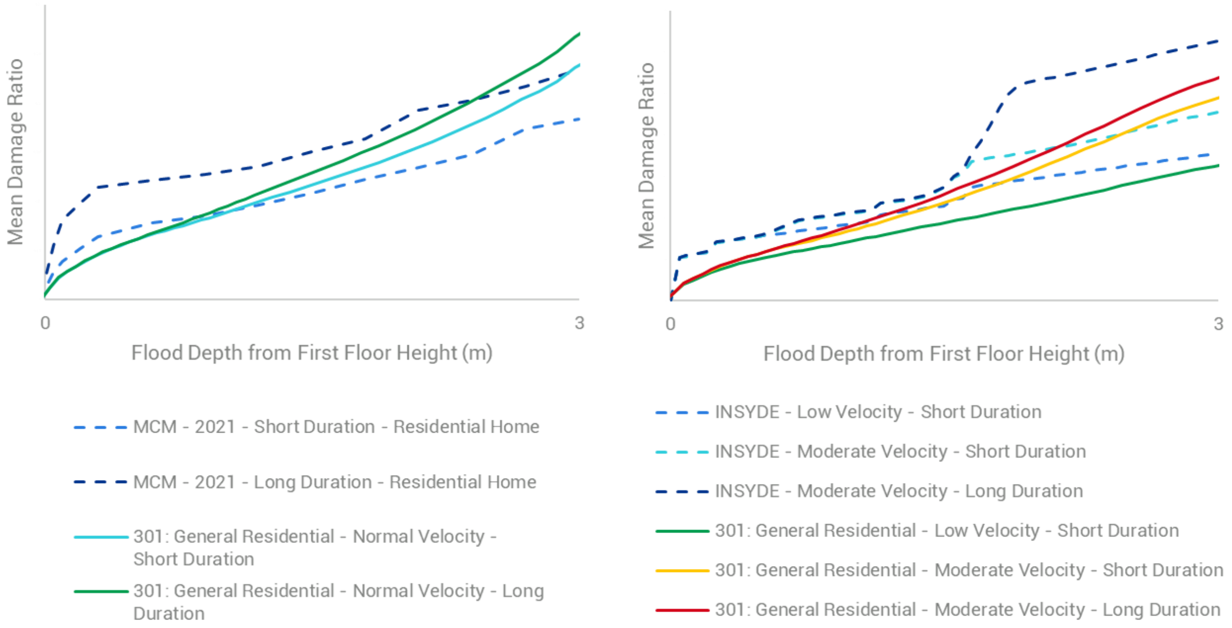


Figure 8: Comparison of Verisk flood damage functions (solid lines) with external sources (dashed lines)

3 RESULTS

The introduction of additional hazard intensity parameters substantially broadens the range of damage outcomes that can be represented at a given flood depth (see Figure 4). When averaged over depth, modeled MDRs for low-velocity, short-duration floods are approximately 5–10% lower than those associated with the baseline normal-velocity, short-duration case. In contrast, high-velocity, long-duration floods with debris flow can produce MDR increases on the order of 130–140% relative to the baseline.

These differences reflect the cumulative effects of hydrodynamic loading, prolonged wetting, and debris-induced force amplification. Notably, the framework enables consistent modeling of both slow-rising, long-duration floods and short-duration, high-energy flash floods within a single vulnerability modeling framework.

4 DISCUSSION

The enhanced vulnerability framework demonstrates that explicitly incorporating flood velocity, duration, and debris flow materially improves flood damage functions. By operating at the component level, the model effectively captures key primary characteristics, such as occupancy and number of stories, as well as secondary features, including foundation type and first-floor height. This approach enables differential sensitivity analysis across various building systems and facilitates a detailed understanding of how specific building features influence loss outcomes.

The use of highly granular exposure and building inventory data allows the model to move beyond an "average building" representation and instead reflect regional construction practices and exposure distributions. This capability is significant for flood risk, where slight differences in first-floor elevation, foundation type, or building height can result in substantial differences in damage.

5 CONCLUSION

This paper presents a component-level flood vulnerability framework that extends traditional depth-based modeling by incorporating flood velocity, duration, and debris flow as explicit parameters of hazard intensity. By defining twelve distinct hazard combinations and developing component-specific damage functions, the framework captures key physical processes that drive flood damage across diverse event types.

Application of the framework demonstrates significant variation in modeled damage outcomes at a given flood depth, highlighting the importance of distinguishing between slow-rising inundation and high-energy, debris-laden floods. The results suggest that vulnerability models incorporating these additional parameters can provide a more accurate and differentiated view of flood risk, supporting improved risk management, pricing, and resilience planning. The framework is designed to be extensible and suitable for application across regions, providing a robust foundation for future enhancements and potential journal-level extensions.

The inclusion of granular "unknown" damage functions further refines risk assessment for portfolios with incomplete data. We encourage the scientific community to continue researching the complexities of the flood peril to further refine these engineering frameworks.

6 ACKNOWLEDGEMENTS

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