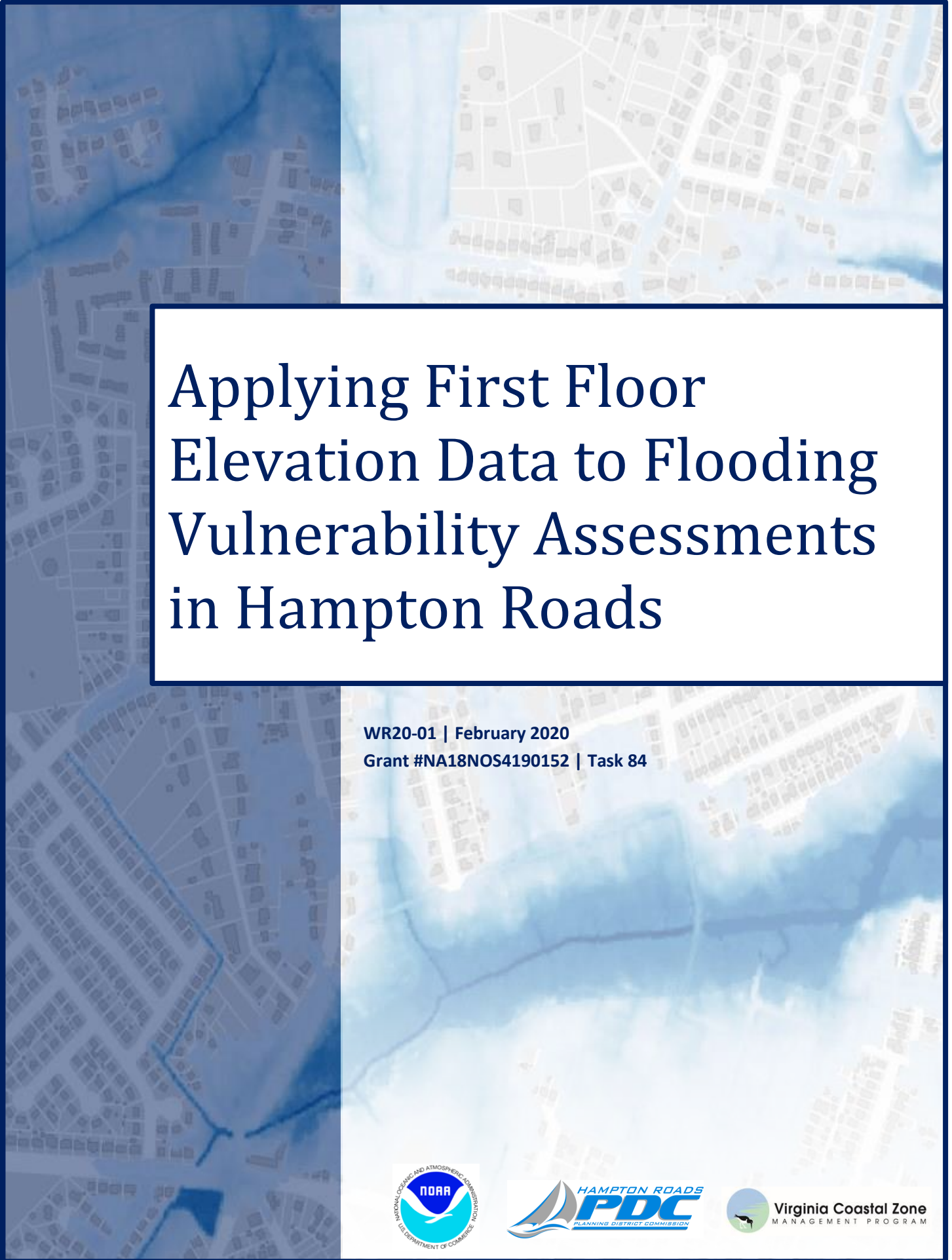




Applying First Floor Elevation Data to Flooding Vulnerability Assessments in Hampton Roads

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APPLYING FIRST FLOOR ELEVATION DATA TO FLOODING VULNERABILITY ASSESSMENTS IN HAMPTON ROADS

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Prepared by the staff of the
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ABSTRACT

This report documents the second phase of the regional first floor elevation database initiative. Building upon methodology developed in the first phase, the regional elevation certificate inventory was expanded and used to support the development of a statistical model that predicts building first floor height in York County, Virginia. Additional first floor height estimation methods based on imagery were also evaluated and applied. Flooding vulnerability assessments were conducted for the 1% annual chance floodplain in three pilot communities, the City of Chesapeake, City of Hampton, and York County. The results of this analysis highlight that flooding damage estimates are highly sensitive to first floor height, and where feasible, individual structure locations should be used. A vulnerability assessment approach that considers a range of first floor heights and associated probabilities was also explored and warrants further research. Developing local and regional databases of first floor height data will likely require the application of multiple methods to support community floodplain management and hazard mitigation planning.

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Glossary of Acronyms

Term	Acronym	Definition
First Floor Elevation	FFE	Elevation of a structure's first finished floor elevation, recorded in feet relative to the vertical datum.
First Floor Height	FFH	Height of first floor above the ground elevation (calculated as FFE – LAG), reported in feet.
Flood Assessment Structure Tool	FAST	FEMA Natural Hazards Risk Assessment Program open-source tool that analyzes site-specific flood losses (FAST, 2019).
Flood Insurance Rate Map	FIRM	Official map delineating the flood zones within a community. (FEMA, 2019b)
General Building Stock	GBS	Census block level structural inventory provided in the FEMA Hazus software. (FEMA, 2017)
Hampton Roads Hazard Mitigation Plan	HMP	2017 Regional hazard mitigation plan including flooding vulnerability analysis for Hampton Roads.
Lowest Adjacent Grade	LAG	Lowest land elevation adjacent to the structure, recorded in feet relative to the vertical datum.
Single-Family Residential Structure	RES1	Single-family residential structures with one or multiple stories. RES1 represents the code used by the FEMA Hazus software. (FEMA, 2017)
Special Flood Hazard Area	SFHA	Area corresponding to the 100-year, or 1% annual chance, flood event and where the National Flood Insurance Program regulations must be enforced. (FEMA, 2019d)
User-Defined Facilities	UDF	Individual structure inventory with attributes compatible for input to FEMA's Hazus software. (FEMA, 2017)

Executive Summary

Identifying structures vulnerable to flooding improves understanding of community flood risk and supports local government mitigation efforts. Previous flooding vulnerability assessments conducted by the Hampton Roads Planning District Commission (HRPDC) have defined structural damage based on the extent of flooding. Accounting for the depth of flooding relative to a structure's elevation can further improve vulnerability assessments. By comparing a structure's first finished floor elevation (FFE) to the depth of water, the water level within the structure can be determined and translated to estimated damage. The FEMA Hazus-MH software provides estimates of flooding damage at the census block or individual structure-level with the appropriate user-supplied data. A required attribute is building first floor height (FFH), calculated as the difference between the FFE and lowest adjacent grade.

Elevation certificates are the primary source of FFE measurements. However, less than 1% of structures in Hampton Roads have elevation certificates. This report builds upon the first phase of a multi-year initiative to develop a regional FFE database that addresses this data gap. In Phase 1 of the regional FFE initiative, information was recorded from over 2,000 elevation certificates, provided as digital copies from ten Hampton Roads localities, and joined with parcel and building footprints in a GIS data format (available at HRGEO.org). The resulting dataset was applied in two case study communities to pilot the development of a predictive statistical model. The model uses FFHs based on elevation certificates and building attributes to estimate FFH for structures without elevation certificates.

This report documents Phase 2 of the regional FFE initiative, which supports the following objectives: (1) expand the spatial database of elevation certificate data and predictive modeling to additional Hampton Roads localities, (2) assess alternative FFH estimation approaches based on imagery, and (3) evaluate the sensitivity of damage estimates to a range of estimated FFHs. For Phase 2, three pilot communities, Chesapeake, Hampton, and York County, were selected.

First Floor Elevation Data Collection, Assessment, and Analysis

The elevation certificate information GIS database was updated in October 2019 with new elevation certificates completed since the previous data call and additional York County elevation certificates. The statistical model developed for York County indicated building foundation type was the most important variable for predicting FFH, which corresponds with findings from Phase 1.

Since the modeling approach required a significant number of elevation certificates, additional methodologies for estimating FFH were also explored. These included: (1) measuring FFH using Google Street View and Google Earth imagery (Needham and McIntyre, 2018), (2) counting the number of stairs leading to the first floor and assuming a stair height of 7.5 inches, and (3) adjusting the stair count FFH estimate based on the land elevation of the stairs relative to the structure's lowest adjacent grade. The elevation adjusted stair counting approach resulted in the lowest absolute average error (0.5ft) relative to the observed elevation certificate values, although all three methods had an average error of less than one foot. The stair counting approach without adjusting for land elevation (method 2) was estimated to take less than one minute per structure. The most time intensive approach was measuring FFH from imagery (method 1), which generally took about 10 minutes per structure.

Coastal Hazard Vulnerability Assessments

The FFH estimates for the three pilot communities were applied in evaluating vulnerability assessment approaches. Three different vulnerability analysis methods were tested: (1) a census block scale analysis using default Hazus inventory data, (2) individual structure level analysis with default Hazus FFH values (default FFH method), and (3) individual structure level analysis with custom FFH values from local data and model predictions (custom FFH method). The census block scale analysis was conducted using FEMA's Hazus software, and the individual structure level analysis for both the default and custom FFH approach was completed using the new FEMA open-source Flood Assessment Structure Tool. Building damages for the 1% annual chance flood event were compared across methods.

In each community, the census block scale analysis resulted in building damages that were at least three times greater than the dollar value of damages estimated at the individual structure scale. This is likely attributed to incorrect assumptions on building location and a higher percentage of basement and slab structure foundation types in the default Hazus inventory than what is observed in the community. At the individual structure scale, the default FFH values resulted in greater estimated building losses by tens of millions of dollars compared to the custom FFH estimates. This is the result of model predicted FFHs tending to be higher than the default Hazus FFH values. It is important to note a limited number of elevation certificates for certain classes of foundation types, such as slab, may affect the accuracy of model FFH estimates. For example, the model may inflate FFH estimates for slab structures in older neighborhoods because the slab elevation certificate sample is biased towards more recent raised slab development. Altering the FFH by less than one foot changed the estimated damage by hundreds of structures and millions of dollars in each community.

Given the uncertainty of FFH estimation approaches and the sensitivity of damage estimates to the FFH input, a vulnerability assessment approach that considers a range of FFH values for a given structure would help capture the variability. Adapting a methodology developed by Parson and Onufrychuk (2019), damages for a range of FFH values, weighted by the probability of occurrence, were calculated for individual structures. Using Hampton as a pilot community, separate FFH ranges and corresponding probabilities were developed for slab foundation and Pre-FIRM and Post-FIRM crawlspace foundation structures. The building losses estimated with this approach were slightly greater than the range of damages observed from the single-value custom FFH and default FFH approaches. This method warrants further research in other pilot communities and at the regional scale.

Conclusions and Next Steps

Developing a regional database of FFH information will likely require the application of multiple methods, including imagery-based estimation and survey data where available. The statistical modeling and imagery-based analysis estimation approaches compared in this analysis have different data and time requirements. The predictive modeling approach developed in Phase 1 and 2 of the regional FFE initiative has the advantage of producing estimates for thousands of structures relatively quickly, but is limited by the availability of elevation certificates that represent the community building stock. While the imagery-based methods do not require building attribute data, they are more labor intensive given each structure must be reviewed individually. The evaluation of vulnerability assessment methods illustrates the need for accurate FFH data, given that resulting flood damage estimates are highly sensitive to changes in the FFH input. Where feasible, localities should utilize individual structure-level analyses to improve the accuracy of flooding vulnerability assessments. When reporting damage estimates for simulated flooding scenarios, it is also important to consider the potential sources of error and present losses as a range of values to better capture uncertainty.

To build upon the findings of this analysis, the third phase of the regional FFE Initiative will include continued expansion of the FFE database across the region and coordination with entities conducting research related to FFEs and coastal hazards. In addition to the current 1% annual chance flood, future vulnerability assessments could also incorporate sea level rise. Phase 3 will document methods and research findings for other entities interested in developing and applying FFEs in vulnerability assessments and will help support regional and individual locality hazard mitigation planning efforts.

I. Introduction

The Hampton Roads region of southeastern Virginia is exposed to a variety of coastal hazards, including recurrent flooding, sea level rise, and storm surge. With over \$1.1 billion of projects under design and \$1.2 billion of projects proposed, local governments of the Hampton Roads region¹ are actively planning and implementing projects to mitigate current and future flood risk (HRPDC, 2019b). Vulnerability assessments support local governments in identifying areas most at risk from flood hazards within the community. By quantifying potential dollar losses, project benefits can be compared to project costs in terms of losses avoided.

The HRPDC previously conducted regional vulnerability assessments related to storm surge and sea level rise (McFarlane, 2012). Metrics used to assess vulnerability included area, population, the number of businesses and personnel employed, linear miles of roads, and critical infrastructure exposed to storm surge (McFarlane, 2011). The results of these analyses indicated the Hampton Roads region is highly exposed to storm surge and sea level rise and provided justification for localities to integrate climate change considerations into planning and decision-making processes (McFarlane, 2012).

While the methods applied previously by the HRPDC defined impacts based on the extent of flooding, the depth of flooding relative to a structure's elevation is also an important consideration. Since the completion of these analyses, the Hampton Roads region has acquired improved elevation data (high-resolution LiDAR) to support three-dimensional vulnerability analyses (McFarlane, 2015). Finished first floor elevations (FFE) are a critical data set for assessing structural vulnerability to flooding. To determine the depth of flooding within the structure, the finished first floor height (FFH), or difference between the building's FFE and lowest adjacent grade, can be compared to flood water depth. For example, a structure with a FFH of 1ft at a location with a 2ft flood depth would experience 1ft of flooding within the structure. The flood depth within the structure can be translated into dollar losses using a depth-damage function, which relates a percent of the structure's total value or replacement cost to flood depth.

¹ The Hampton Roads region includes seventeen localities in southeastern Virginia: Chesapeake, Franklin, Gloucester County, Hampton, Isle of Wight County, James City County, Newport News, Norfolk, Poquoson, Portsmouth, Southampton County, Suffolk, Surry County, Town of Smithfield, Virginia Beach, Williamsburg, and York County.

The Federal Emergency Management Agency (FEMA) Hazus software applies depth-damage functions to estimate losses from simulated flooding events (FEMA, 2017). Flood hazard analysis in Hazus can be conducted at the census block or individual structure scale (FEMA, 2017). The Hazus software includes a default building inventory aggregated at the census block level, referred to as the general building stock (GBS) (FEMA, 2017). The user can apply the GBS without any modifications to conduct a basic flooding analysis (Pluss et al., 2018). The GBS analysis assumes structures are evenly distributed across the census block. For example, if 25% of the census block area is inundated with 3ft of water, Hazus assumes the depth of water is 3ft for 25% of single-family dwellings within the census block (Figure 1). This can lead to the over- or under-estimation of losses by incorrectly assuming the location of structures. To help address this source of error, census block shapes within the flood model inventory have been modified to exclude undeveloped areas, such as wetlands and forests. Satellite and land-use data from the 2011 National Land Cover Dataset were used to distinguish developed areas when developing the modified census block inventory, referred to as dasymetric (FEMA, 2019a). Although the equal distribution assumption of the GBS still applies, the dasymetric inventory helps reduce error by limiting the area of the census block to only developed areas. Given the coarse scale of analysis and higher level of uncertainty in structure location, the Hazus program recommends an analysis using only the default inventory with no modifications serve primarily as a baseline for additional research (Pluss et al., 2018).

The location of structures within the GBS cannot be modified. However, actual structure locations can be incorporated into Hazus as user-defined facilities (UDF) (Pluss et al., 2018). The UDF dataset must represent structure locations as points and contain a suite of attributes for each structure, including building FFH. While the UDF analysis requires a greater time investment in data preparation than the default GBS analysis, it offers the advantage of producing damage estimates for each individual structure. Users can also substitute default depth damage functions with custom parameters given detailed engineering data is available (Pluss et al., 2018). FEMA's Natural Hazard Risk Assessment Program encourages Hazus users to modify the default data with local data when available for more accurate results in support of mitigation planning (Pluss et al., 2018).

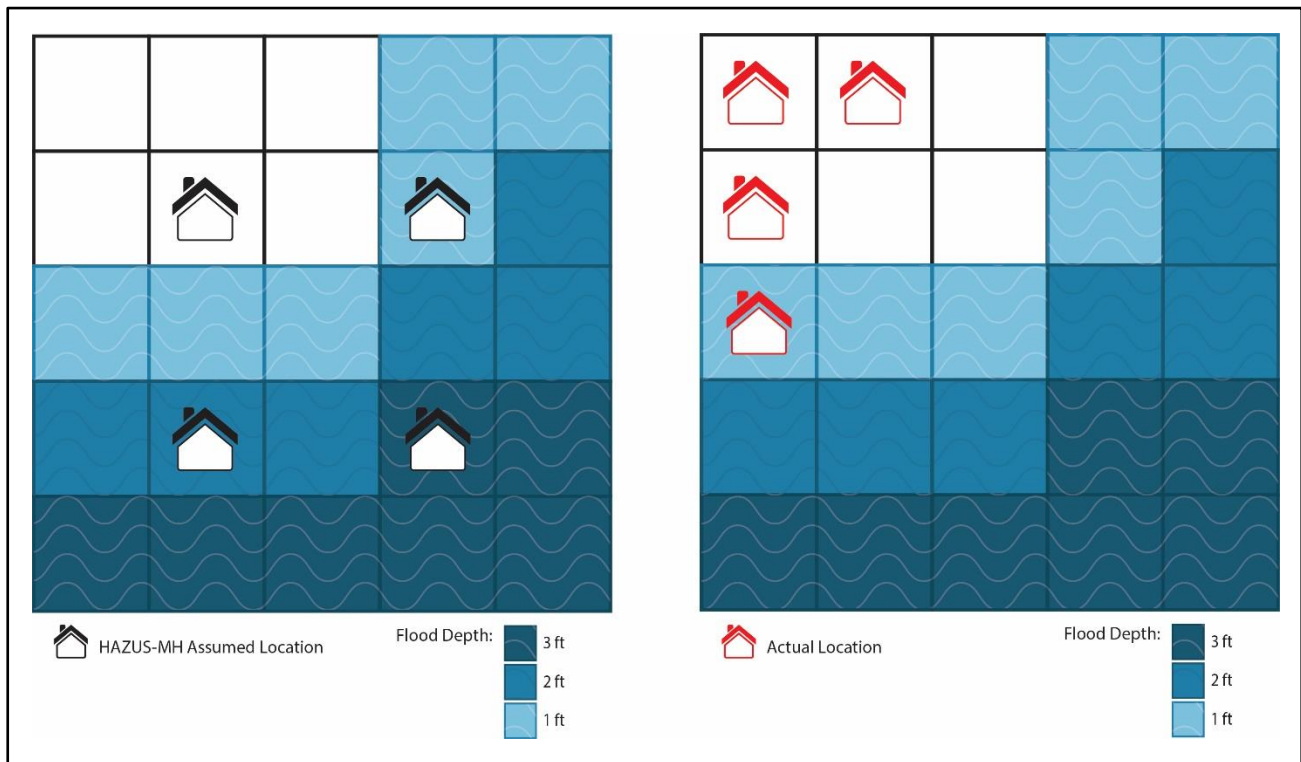


Figure 1: Hazus building distribution assumption (left) compared to actual structure locations within a given census block (right). Adapted from FEMA E0172: Hazus for Floods Student Manual (FEMA, 2019a).

As part of the regional 2017 Hampton Roads Hazard Mitigation Plan (HMP), a UDF Hazus analysis was conducted for the 1% annual chance flood event (HMP, 2017). In previous hazard mitigation plans, the Hazus analysis was conducted at the census block scale, resulting in greater damage estimates than what was reported by the UDF analysis (HMP, 2017). The UDF inventory incorporated available local assessor data for structural attributes; however, due to a lack of surveyed FFH data, the local FFH values were based on reference tables provided in the Hazus flood technical manual (HMP, 2017). Hazus provides default FFH values based on foundation type, Flood Insurance Rate Map (FIRM) status, and riverine or coastal flood zone (FEMA, 2017). For example, a Post-FIRM crawlspace structure would have a default FFH of 4ft (FEMA, 2017). The HMP recommended incorporating local FFH data into future vulnerability assessments to improve accuracy (HMP, 2017).

To address the existing FFE/FFH data gap, the HRPDC piloted a methodology for predicting the FFH of residential structures in Phase 1 of the regional first floor elevation initiative (Gordon and McFarlane, 2019). Phase 1 consisted of two primary objectives: (1) building a regional spatial database of information from elevation certificates, and (2) applying information from the elevation certificates to develop a predictive statistical model for estimating the FFH of structures without elevation certificates.

To build the regional spatial database, the HRPDC collected over 2,000 digital elevation certificate copies from ten Hampton Roads localities. Building elevation measurements and relevant attributes were recorded from the elevation certificates and joined with parcels and building footprints where available in a spatial GIS format. This database is now available for download by searching “elevation certificates” on the Hampton Roads Geospatial Exchange Online at HRGEO.org (HRGEO, 2019a). Based on the availability of elevation certificates, the cities of Hampton and Chesapeake were selected as pilot communities to develop the predictive statistical model for estimating FFH. Using a Random Forest methodology, building attributes, including foundation type, year built, current flood zone, difference in grade (highest adjacent grade minus lowest adjacent grade), and land elevation, were used to predict FFH. Foundation type was identified as the most important predictor in both models. The models showed an improvement in FFH estimation accuracy as compared to applying default Hazus foundation codes (Gordon and McFarlane, 2019).

This report documents the second phase of the regional FFE initiative. The first objective of this phase is to expand the spatial database of elevation certificate information and predictive modeling approach to additional Hampton Roads localities. The second objective is to assess alternative FFH estimation approaches based on imagery. The third objective is to evaluate the sensitivity of flooding damage estimates to a range of estimated FFHs in pilot communities. Three approaches to assess residential structural vulnerability were selected: (1) a census block scale analysis with default data, (2) an individual structure level analysis with default Hazus FFH values, and (3) an individual structure level analysis with custom FFH values estimated from local data. These options were assessed in terms of time commitment for data preparation and accuracy. Understanding the tradeoffs between time and accuracy in vulnerability assessments is important given limited resource availability for coastal hazard planning.

This report includes four main sections:

- (1) *First Floor Elevation Data Collection, Assessment, and Analysis* – Reviews the development of a predictive statistical model for estimating FFH in York County, which was selected as a pilot community based on the availability of additional elevation certificate data. This section also includes a comparison of imagery-based FFH estimation methods, including stair counting and photographic measurements.

- (2) *Coastal Hazard Vulnerability Assessments*: Describes the selected vulnerability analysis methods and results for the 1% annual chance flood event in three pilot communities: Chesapeake, Hampton, and York County.
- (3) *Alternative Vulnerability Assessment Approaches*: Demonstrates an alternative approach to flood vulnerability assessment that does not require assigning a single FFH estimate to a structure. The damage estimate for each structure is based on a probability-weighted sum of damages for a range of FFH values.
- (4) *Conclusions and Next Steps*: Reviews key findings of the Phase 2 analysis and recommends next steps for Phase 3 of the regional FFE initiative, including expanding FFH estimates and coastal hazard vulnerability assessments across the Hampton Roads region.

II. First Floor Elevation Data Collection, Assessment, and Analysis

Regional Elevation Certificate Database Update

The regional elevation certificate database created in Phase 1 had 2,065 elevation certificates. This database is available on the regional GIS portal, HRGEO.org (HRGEO, 2019a). Information recorded from the elevation certificates included all measurements reported in Section C, as well as property and flood zone information (Table 1).

Table 1: Information recorded from FEMA Elevation Certificate, 2015 edition (FEMA, 2015a).

Elevation Certificate Section	Attributes Recorded
A) Property Information	Address Building Use Building Diagram
B) Flood Insurance Rate Map Information	NFIP Community Number Effective FIRM Panel Date Flood Zone Base Flood Elevation
C) Building Elevation Information	Elevation Datum All Structural Elevations (a-h), including Lowest and Highest Adjacent Grade
D) Survey, Engineer, or Architect Certification	Surveyor Signature Date

Four separate GIS layers are available containing elevation certificate information: (1) parcel polygons with elevation measurements reported in the original vertical datum (NGVD 1929 or NAVD 1988), (2) parcel polygons with elevation measurements converted to NAVD 1988, (3) building footprints with elevation measurements reported in the original vertical datum, and (4) building footprints with elevation measurements converted to NAVD 1988.

To update the regional elevation certificate inventory, HRPDC staff contacted Hampton Roads localities in August 2019 requesting digital copies of new elevation certificates. A total of 504 finished construction elevation certificates were received and entered into GIS (Table 2). Included in this count

are additional historic elevation certificates provided by York County to complete their inventory. The updated inventory was published on HRGEO.org in October 2019 (HRGEO, 2019a).

Table 2: Distribution of elevation certificates collected by locality during Phase 2 of the regional FFE initiative. All elevation certificates are for finished construction.

Locality	Total Elevation Certificates	Elevation Certificates Added in October 2019
Chesapeake	636	43
Franklin	171	2
Hampton	688	37
James City County	187	10
Newport News	6	2
Norfolk	123	54
Portsmouth	90	15
Southampton County	33	1
Suffolk	3	3
Virginia Beach	200	38
York County*	432	299
TOTAL	2,569	504

*The York County inventory includes historic elevation certificate copies that were not available digitally during Phase 1 of the regional FFE initiative. The inventory is now complete for the County.

Case Study: York County Model Development and Results

In Phase 1 of the regional FFE initiative, a methodology to predict FFH for residential structures based on elevation certificate observations was piloted for the cities of Hampton and Chesapeake. These localities were selected due to an abundance of over 500 elevation certificates in each community. The modeling approach, referred to as Random Forest, generates and averages hundreds of regression trees to predict FFH based on building attributes (Liaw and Wiener, 2002). The Random Forest approach is best suited for sample sizes that include several hundred features (Esri, 2018a).

Following Phase 1, York County provided 299 elevation certificates in addition to the 133 previously collected, establishing a sufficient sample size for Random Forest analysis. Of the 432 elevation certificates within the inventory, 366 residential certificates were suitable for use in model development and evaluation. Elevation certificates for accessory structures and non-residential buildings were excluded from the analysis. Given only seven structures outside the current Special Flood Hazard Area (SFHA) and Shaded-X flood zones had elevation certificates, the Random Forest model was applicable to structures only within the SFHA or Shaded-X flood zone. The elevation certificate data was randomly partitioned into a training data set of 293 observations (80%) and testing data set for model validation of 73 observations (20%) (Figure 2). The York County model included the same five predictor variables used previously for the Chesapeake and Hampton case studies, as well as a sixth predictor variable, total property value. The predictor variables are as follows:

- (1) Foundation type – Building FFH can vary by several feet between foundation types. For example, the Hazus technical manual assigns a 4ft foundation height to Post-FIRM structures with a crawlspace foundation, and a height of 1ft to slab structures (FEMA, 2017).
- (2) Year built – Given structures must comply with local floodplain ordinances, trends in FFH may vary based on when the community joined the FEMA National Flood Insurance Program and local policy changes. For example, in 2014 York County implemented a 3ft freeboard standard for structures in the SFHA, with an additional 1ft of freeboard for Coastal A and VE zones (York County, 2015).
- (3) Current Flood Zone – Structures built since the adoption of the most recent flood maps must comply with the building standards of the flood zone.
- (4) Difference in grade - Defined as the difference between a structure's highest adjacent grade and lowest adjacent grade (LAG), difference in grade was applied as a predictor because sloping ground may result in a greater FFH.
- (5) Digital Elevation Model (DEM) value - The land elevation, or DEM value, at the structure location provides a spatial predictor that also reflects differences in risk within a flood zone. For example, structures built at a lower elevation in the SFHA may be required to have a larger FFH to comply with local floodplain regulations.
- (6) Total property value - Plotting FFH by total property value, including the combined assessed value of the land and structure, revealed a modest positive linear correlation between the two variables, meaning as property value increases, FFH also tends to increase (Pearson correlation coefficient of 0.18, $p < 0.001$).

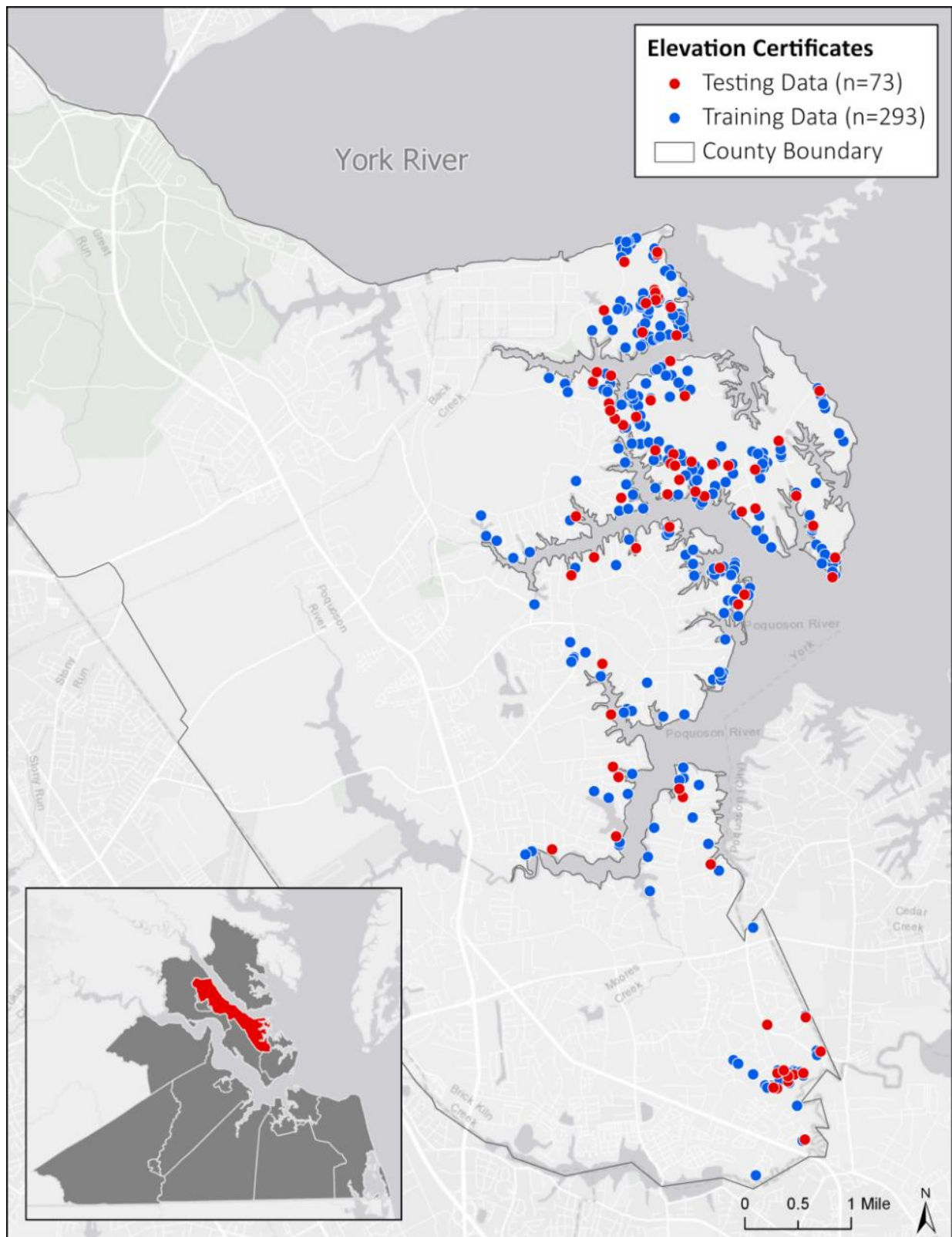


Figure 2: Distribution of elevation certificate locations used to support predictive model development in York County.

The predictive model was developed directly in ArcGIS Pro (v 2.2.0) using the Forest-based Classification and Regression tool (Esri, 2018a). The resulting explanatory variable importance scores reflect the frequency of a decision in the regression tree, or split, based on that variable and the relative impact of that split divided by the number of trees (Esri, 2018b). The most important predictor variable was foundation type, with a score representing 52% of all variable importance, followed by the DEM value (20%) and total property value (11%) (Table 3).

Table 3: Summary of variable importance for explanatory variables included in the York County Random Forest model.

<i>Explanatory Variable</i>	<i>Importance</i>	<i>Percent Importance</i>
Foundation Type	1,132.20	52%
DEM Value	434.06	20%
Total Property Value	235.32	11%
Year Built	200.54	9%
Difference in Grade	156.39	7%
Flood Zone	15.94	1%

To assess model accuracy, the Forest-based Classification and Regression tool provides Out of Bag (OOB) statistics, which are calculated iteratively and averaged using training data that is absent from a subset of the hundreds of regression trees (Esri, 2018b). The OOB Mean Squared Error (MSE) and percent of variation explained are based on the ability of the model to accurately predict FFH for the subset of structures, and therefore are not based on the entire “forest” of regression trees (Esri, 2018b). The lower the MSE and higher percent of variation explained, the better the model performance. The results indicated the model explained 74.5% of the sample variance with an MSE of 2.02. Taking the square root of the MSE allows for interpretation of the result in the linear unit of the response variable. The Random Forest model on average produces FFH estimates that are within 1.42ft of the actual measured FFH.

By applying the model to generate predictions for the reserved 73 testing data set features, the model performance for the entire forest of regression trees can be evaluated. Using the absolute value

of difference between the observed and predicted FFH (average absolute error), 45.2% of the predicted FFHs were within half a foot of the observed FFH (Table 4). All features in the testing data set were also assigned a default FFH based on Hazus reference tables provided in Appendix A. 38.4% of the FFHs estimated using Hazus default values were within half a foot of the observed value (Table 4). The average absolute errors were 0.83ft and 1.25ft for the Random Forest and Hazus estimation approaches respectively. Overall, the Random Forest prediction approach resulted in a 33.6% reduction in average error relative to the Hazus default assignment method (Figure 3).

Table 4: Summary of absolute average errors for the York County Random Forest Model and Hazus default value estimates.

<i>Estimation Approach</i>	<i>Within +/- 0.5 ft</i>	<i>Within +/- 1 ft</i>
Random Forest Model	45.2% (33/73)	72.6% (53/73)
Hazus Default Value	38.4% (28/73)	53.4% (39/73)

The Pearson correlation coefficient ² was 0.90 (p<0.001) when comparing the Random Forest predictions to the observed testing data FFH and 0.86 (p<0.001) when comparing the Hazus estimation approach to the observed FFH (Figure 4). Given that a value of one indicates perfect correlation between observed and predicted values, the Pearson correlation coefficients further support that the Random Forest model improved prediction performance relative to the default Hazus values. In the Figure 4 scatterplot, points left of the diagonal reference line represent overestimates of the observed FFH and points right of the diagonal line indicate underestimated values. The Hazus value assignment predicted FFHs of lower value than that reported on the elevation certificate for 72.6% of the testing data set, whereas the Random Forest approach underpredicted 56.2% observations.

² The Pearson correlation coefficient measures the degree of linear association between two variables. A Pearson correlation coefficient of 1 indicates perfect positive correlation between observed and predicted values. A p-value less than 0.05 indicates the two variables are statistically significantly linearly related. (Hughes, 2013)

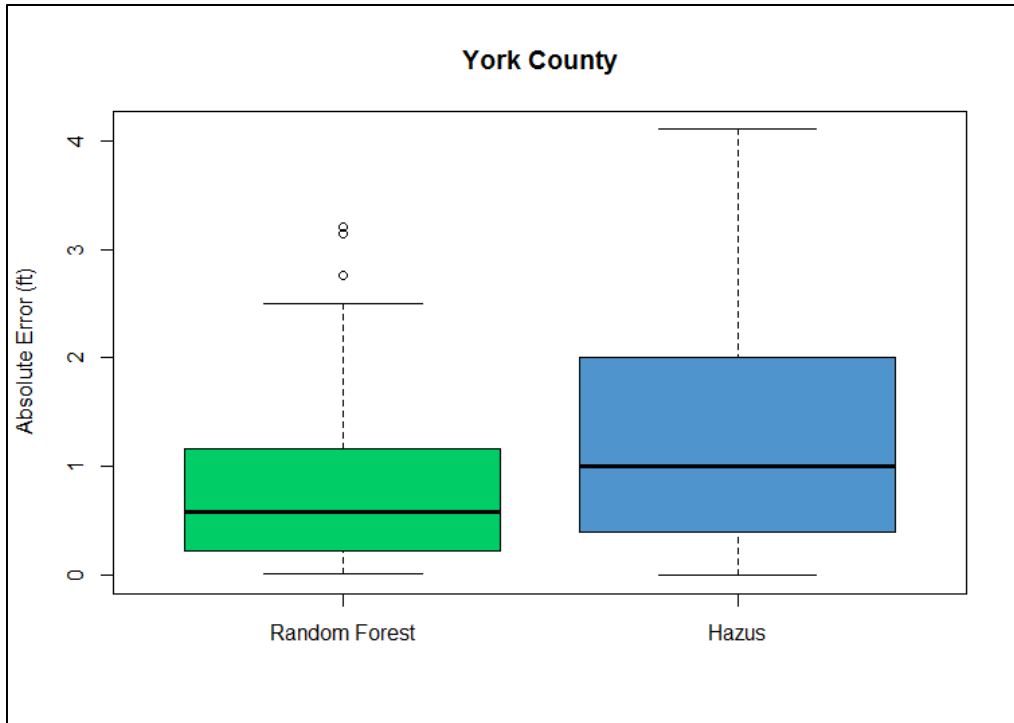


Figure 3: Comparison of absolute error (Observed Elevation Certificate FFH – Estimated FFH) distribution for the York County Random Forest model estimated FFH and Hazus default assignment method.

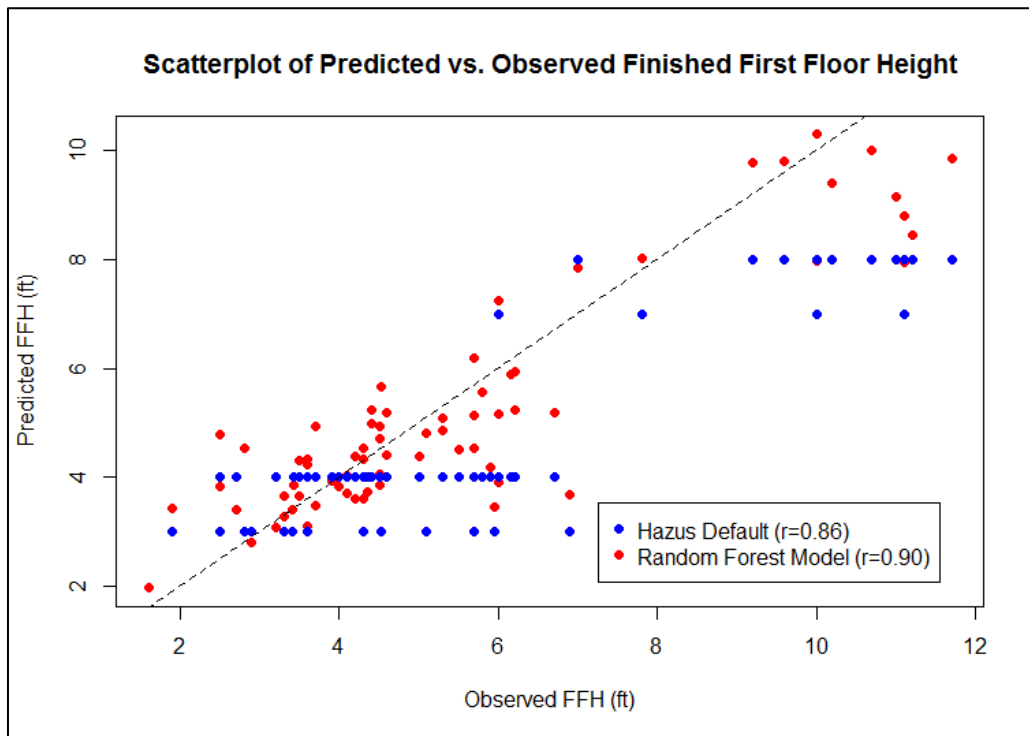


Figure 4: Comparison of absolute errors (Observed Elevation Certificate FFH – Estimated FFH) for the York County Random Forest model and Hazus default methods.

Given the difference of several feet between an elevated first floor above storage foundation (referred to as solid wall) and crawlspace foundation, it is important to note how the model performs for different foundation types. The following foundation types used by the York County assessor's office were included in the model: crawlspace (CRAWL), slab (SLAB), elevated (ELEV), and garage under living space (GAR/U). Solid wall structures can be classified as either ELEV or GAR/U depending on the use of the enclosure. For both crawlspace and solid wall structures, the absolute average error was greater when using the Hazus default method rather than the Random Forest method (Table 5). The Hazus default estimates underpredicted FFH for 69% of crawlspace structures and 86% of solid wall foundation types. The Random Forest approach only underpredicted FFH for 57% of crawlspace and solid wall foundation types. Given only one slab foundation structure was present in the testing data set, statistics for this foundation type were not calculated. Predictions for slab foundation type may be biased given the limited sample of slab structures (n=6) in the training data set likely does not reflect the true distribution of values.

Table 5: Summary of absolute average errors for the York County Random Forest Model and Hazus default estimation methods by foundation type.

<i>Estimation Approach</i>	<i>Crawlspace Avg. Error (n = 58)</i>	<i>Solid Wall Avg. Error (n=14)</i>
Random Forest Model	0.71 ft	1.34 ft
Hazus Default Value	1.00 ft	2.33 ft

Overall the York County predictive model had a slightly higher absolute average error than what was observed for Chesapeake and Hampton (Table 6). However, it is important to note the range of observed values was greater in York County; therefore, the model considered a larger range of possible FFH values. The larger FFH values correspond with structures that have an elevated living space above an enclosure. These structure types were excluded from the Chesapeake and Hampton models because the assessor foundation codes did not distinguish them. The percent variation explained by the model and reduction in error relative to the Hazus FFH values were highest for the York County model relative to the other pilot communities (Table 6). Foundation type was the most important predictor in all three case study localities (Table 6).

Table 6: Comparison of Random Forest model performance by case study community.

Model Results	Chesapeake	Hampton	York County
% Variation Explained	69.5%	62.0%	74.5%
MSE (RMSE ft)	0.47 (0.69 ft)	1.03 (1.02 ft)	2.02 (1.42 ft)
Absolute Average Error (ft)	0.45 ft	0.80 ft	0.83 ft
Most Important Predictor (% Importance)	Foundation (53%)	Foundation (38%)	Foundation (52%)
% Reduction in Error Relative to Hazus default	19.6%	4.8%	33.6%

Evaluation and Application of Imagery-Based Estimation Approaches

Given the constraints of data availability and model accuracy, developing a regional database of FFH information will likely require the application of multiple estimation methods. Visual review of a community's building stock through imagery supports several different approaches for estimating FFH. Street-level panoramic images are widely available online through products such as Bing Maps or Google Street View, and available for download through Google API. Imagery-based methods to estimate FFH have been implemented in Hampton Roads and other regions. The following section provides a review of these methodologies and associated accuracy when compared to elevation certificate observations.

In Galveston, Texas, researchers developed a methodology for measuring FFH using a combination of Google Street View and Google Earth imagery (Needham and McIntyre, 2018). The methodology involves three measurements: (1) the vertical distance in pixels from the ground to the first floor, (2) the horizontal distance in pixels of a roof line in the same plane as the vertical distance measurement, and (3) the horizontal distance in inches of the roof line (Needham and McIntyre, 2018). The pixel measurements are recorded from Google Street View imagery and the roof line inches measurement is completed in Google Earth (Figure 5).

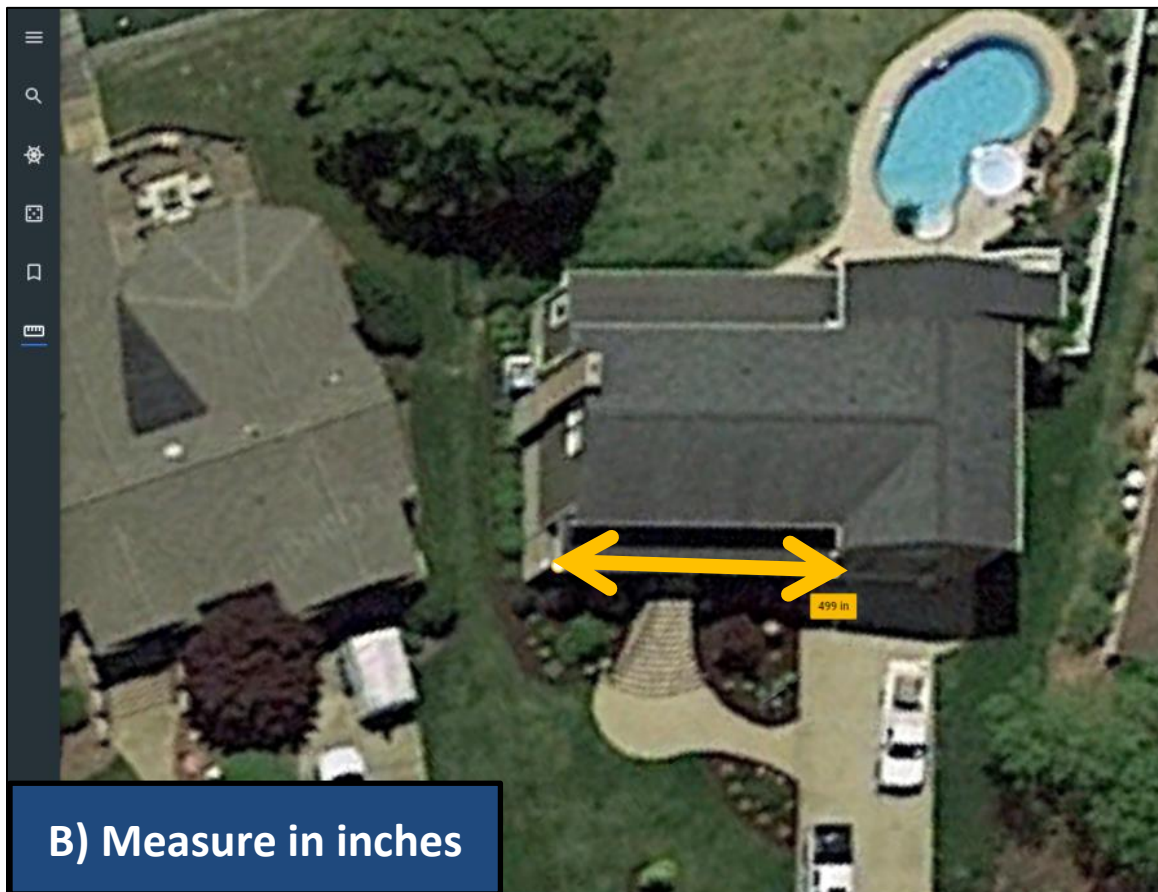
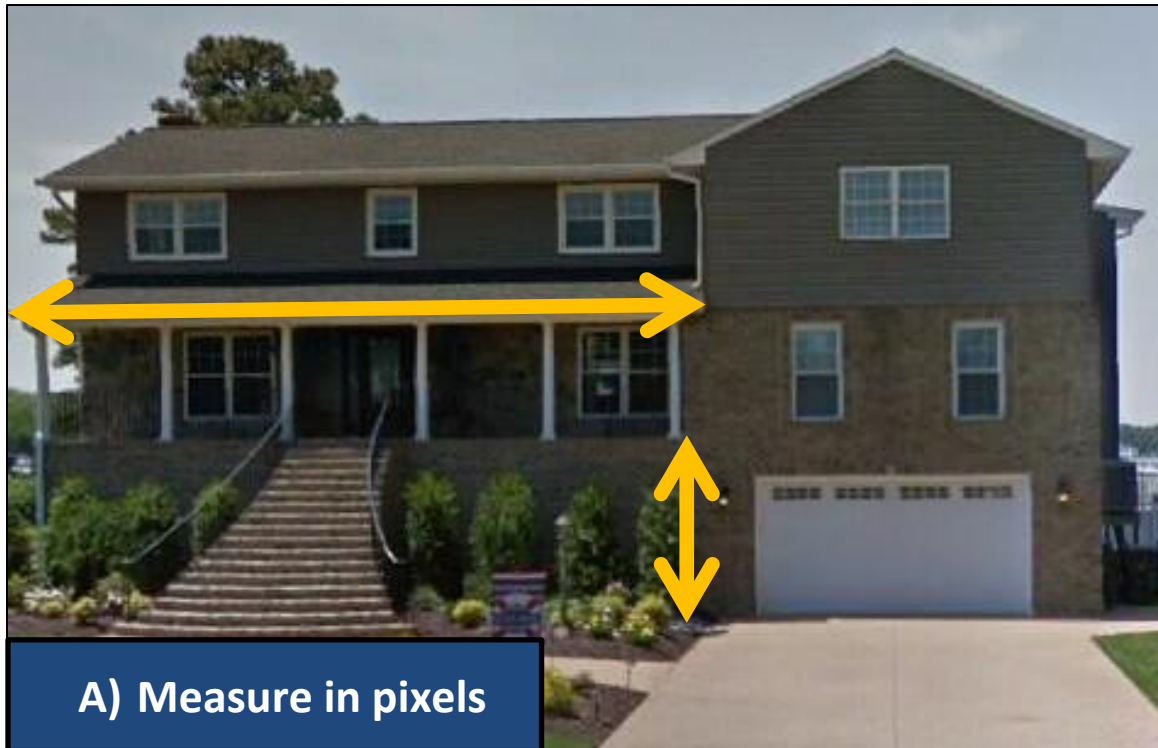


Figure 5: Measurements recorded to estimate FFH using (A) Google Street View and (B) Google Earth.

To report the structure's FFH in inches, the Google imagery measurements can be applied in the following equation (adapted from Needham and McIntyre, 2018):

$$\text{FFH} = (\text{Roof line inches} / \text{Roof line pixels}) * \text{vertical distance to first floor in pixels}$$

To evaluate the feasibility and accuracy of this approach in the Hampton Roads region, measurements were completed on a sample of 100 structures with corresponding elevation certificates. Structures were selected based on the best available imagery within four different communities and covered three general foundation types (Table 7).

Table 7: Summary of structures selected for Google measurement by locality and foundation type.

<i>Locality</i>	<i>Slab</i>	<i>Crawlspace</i>	<i>Solid Wall</i>	<i>Total</i>
Chesapeake	11	19	---	30
Hampton	10	13	7	30
James City County	---	10	---	10
York County	---	13	17	30
Total	21	55	24	100

Google Street View Images were collected through Google API. Using Google API offers the benefit of controlling the camera pitch, or upward or downward angle, to ensure it is set to 0 (Wen, 2019). However, more time and effort are required to position the camera perpendicular to the front of the structure by adjusting the camera heading value than if using a screen capture approach. The specific latitude and longitude coordinates and heading of the camera must be manually provided when accessing the API. A Python script outlining the steps is provided in Appendix B.

For each structure in the above sample, the FFH measurement was subtracted from the observed elevation certificate FFH to calculate the error. The absolute average error across all foundation types was 0.63ft, with a range of 0.01ft to 5.34ft. The structure with the maximum error has a difference in grade of nearly 6ft. To account for larger differences in grade, the difference between the land elevation at the location of the vertical measurement and the structure's LAG could be added to the FFH estimate. The average error reported from the Galveston study for the Google measurement approach was 0.33ft based on a sample of 22 field observations (Needham and McIntyre, 2018).

Although this average error estimate is lower than what was observed in this analysis, 48% of FFH estimates were within +/- 0.33 ft of the elevation certificate observation.

While the Google measurement approach produced reasonably accurate results, the process can be time consuming and is not applicable to all structures. If imagery is available that provides a clear view of stairs, the number of stairs can be used to approximate FFH. This method was also applied in the Galveston vulnerability analysis, with a default stair height of 7.5 in (0.625 ft) (Needham and McIntyre, 2018). Within Hampton Roads, the U.S. Army Corps of Engineers has applied a stair counting approach to estimate FFH for Pre-FIRM structures within the cities of Portsmouth and Norfolk. To directly compare the accuracy of this method to the Google measurement approach, stair counts were recorded for the same sample of 100 residential structures used in the measurement analysis. A value of 7.5 in was used to approximate the height of each stair. Across all foundation types, the absolute average error was 0.85ft when compared to elevation certificate FFH values. The stair estimated FFH underestimated the elevation certificate FFH value for 88% of the observations. This is likely the result of the stairs beginning at a higher land elevation than the building's LAG.

To account for the difference in land elevation, the ground elevation at the approximate location of the stairs was determined in GIS using the DEM. The difference between the stairs ground elevation and the LAG was then added to the estimate of FFH based on the count of stairs (Equation 1).

$$\text{FFH} = (\text{Number of stairs} * 0.625 \text{ ft}) + (\text{Ground elevation of stairs} - \text{LAG})$$

When comparing the elevation adjusted stair count FFH to the elevation certificate FFH, the absolute average error was reduced to 0.51ft. This value is 40% lower than what was observed prior to the stair elevation adjustment.

Hazus default values based on foundation type were also assigned to each of the 100 sample structures. Structures with a foundation coded as "None" were assigned as slab or solid wall based on imagery review. The Hazus default FFH assignments resulted in the largest absolute average error when compared to the elevation certificates. Figure 6 provides a comparison of the overall distribution of the absolute average errors for each estimation method, and Table 8 summarizes the absolute average errors for each FFH estimation approach by foundation type.

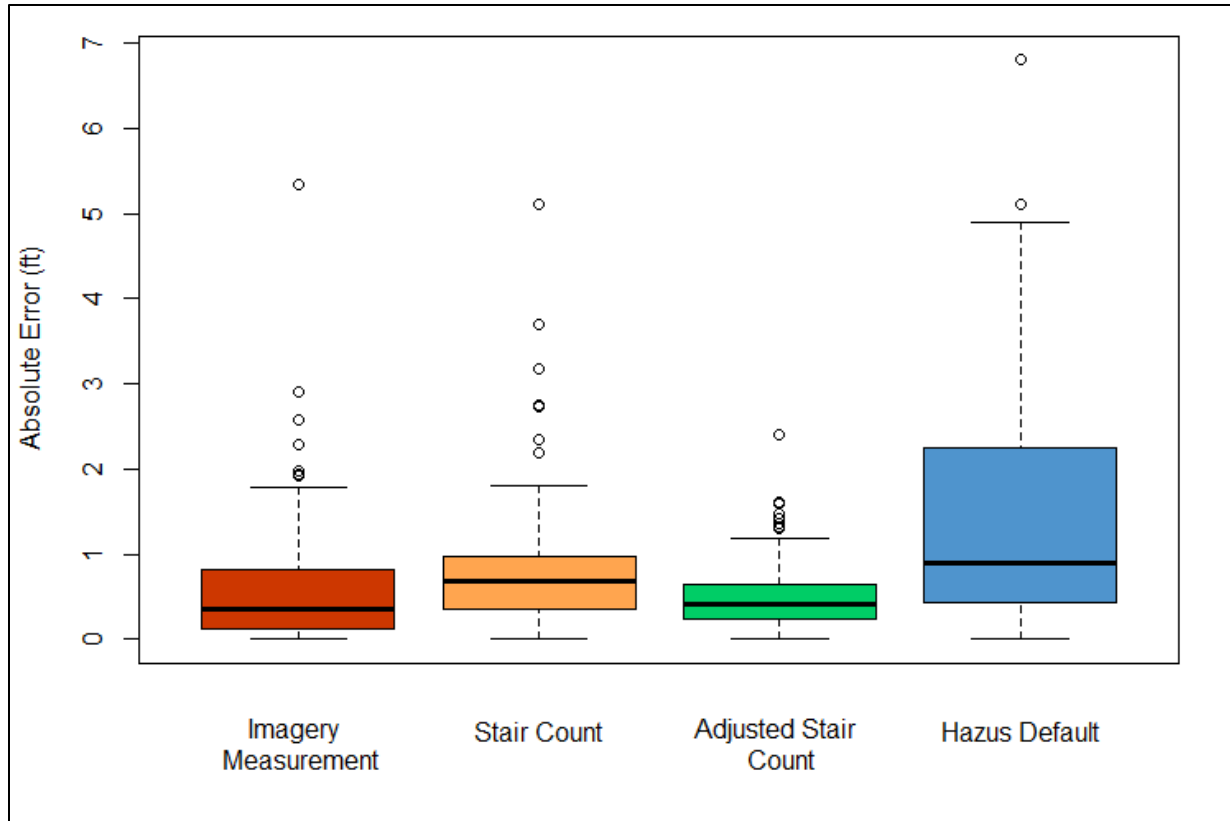


Figure 6: Comparison of absolute error associated with each FFH estimation approach by comparing FFH estimates to elevation certificate values.

Table 8: Summary of absolute error associated with each FFH estimation approach by foundation type.

<i>Foundation Type</i>	<i>Measurement</i>	<i>Stair Count</i>	<i>Adjusted Stair Count</i>	<i>Hazus Default</i>
Slab	0.36 ft	0.47 ft	0.40 ft	0.50 ft
Crawlspace	0.68 ft	1.04 ft	0.47 ft	1.32 ft
Solid Wall	0.75 ft	0.74 ft	0.68 ft	2.61 ft
Overall Average Error	0.63 ft	0.85 ft	0.51 ft	1.46 ft

In addition to the level of accuracy, it is important to note the relative time investment involved with each FFH estimation approach. The FFH for thousands of structures can be assigned at once using the Hazus default or Random Forest analysis approach because the estimates are based on structure attributes (Table 9). The second fastest estimation method is stair counting, where recording the count of stairs can take less than one minutes per structure (Table 9). Adjusting for the elevation of the location of the stairs increases the time to roughly 1-2 minutes per structure, requiring manual point

placement in GIS to extract the land elevation from the DEM (Table 9). The Google Street View/Google Earth measurement approach is the most time intensive. While locating a given structure and correctly positioning the camera through Google API alone can take several minutes, the actual measurements also require a couple minutes. The Galveston study which developed the measurement methodology estimated an average of 4 hours per city block, with most city blocks containing more than 24 structures (Needham and McIntyre, 2018). This results in an average of around 10 minutes per structure. Therefore, the elevation adjusted Google stairs approach is roughly at least 5 times faster with comparable accuracy.

Table 9: Comparison of time and data requirements for different FFH estimation methods.

FFH Estimation Method	Data Required	Estimated Time per Structure
Measurement	Google Street View imagery, Google Earth imagery	10 Minutes
Stair Count	Street-level imagery	< 1 Minute
Adjusted Stair Count	Street-level imagery, Digital Elevation Model	1-2 Minutes
Hazus Default	Foundation Type, Pre/Post-FIRM construction, Flood Zone	< 1 Minute

The 100 structures used in this accuracy assessment satisfied the image quality required for both the stair counting and measurement approach. However, obstructions such as trees and cars, as well as difficulty obtaining a roofline measurement in the same plane as the vertical measurement, hinder the imagery methodologies. Over 300 structures with elevation certificate were reviewed to select the final sample of 100, resulting in a success rate of roughly 29% for structures that could be measured with both imagery-based approaches (Table 10). However, this figure may underestimate the true success rate for imagery analysis within the community given that it was based on only structures with available elevation certificates and was not a completely random sample.

Table 10: Summary of structures reviewed and structures that were not used due to obstructed imagery or lack of imagery. Percent unmeasurable represents $1 - (\text{the number of structures measured} / \text{the number of structures reviewed})$.

<i>Locality</i>	<i>Structures Measured</i>	<i>Structures Reviewed</i>	<i>Obstructed/Not in Same Plane</i>	<i>No Street View Imagery</i>	<i>Percent Unmeasurable</i>
Chesapeake	30	96	13	53	68.8%
Hampton	30	63	16	17	52.4%
James City County	10	119	21	88	91.6%
York County	30	69	13	26	56.5%
Total	100	347	63	184	71.2%

Given that the elevation adjusted stair count approach produces the relatively lowest error and requires less time than the Google measurement approach, this method was applied to structures within the flooding vulnerability case study communities where the Random Forest predictions appeared inaccurate. Suspect model predictions were identified for Chesapeake and Hampton by visually reviewing structures within close proximity (~0.1 mile radius) of elevation certificates reporting structures with an elevated living space (elevation certificate building diagram 5) or structures with storage enclosures under the living space (elevation certificate building diagram 6 and 7). In Hampton, the FFH of 88 structures with the “None” foundation code was estimated using stair counting after determining through imagery that the structures had an elevated living space, often over a garage (Table 11). Within York County, structures with foundation codes not included in model development due to insufficient sample size (i.e. pier, piling, raised slab, basement) were also estimated with the adjusted stair counting approach (Table 11). Hazus default FFH assignments were made for any remaining structures where the imagery and modeling approach were not suitable. Following completion of the imagery review and model development, FFH estimates were assigned to all single-family residential structures within the 1% and 0.2% annual chance floodplains in the case study communities. Single-family residential structures were selected because a majority of the elevation certificates correspond with this occupancy type.

Table 11: Summary of FFH estimation methods applied to develop the building inventory for single-family residential structures within the 1% and 0.2% annual chance floodplains. Hazus default values were applied to structures where the following three FFH estimation approaches were not suitable.

<i>Locality</i>	<i>Total Number of Residential Buildings in the 1% and 0.2% annual chance floodplain</i>	<i>First Floor Height Estimation Method</i>		
		<i>Elevation Certificates</i>	<i>Random Forest Model</i>	<i>Imagery Stair Count</i>
Chesapeake	8,647	549 (6.3%)	8,093 (93.6%)	5 (0.06%)
Hampton	13,625	605 (4.4%)	12,926 (94.9%)	88 (0.6%)
York County	2,814	381 (13.5%)	2,384 (84.7%)	31 (1.1%)

This assessment demonstrates the utility of combining multiple approaches depending on the availability of observational data and building attribute data. Table 12 summarizes the data requirements, advantages, and disadvantages of the various FFH estimation methods.

Table 12: Summary and comparison of select FFH estimation methods.

	Default Hazus Data	Statistical Model	Imagery Analysis
Data Requirements	Structure foundation type, Pre/Post-FIRM construction, and flood zone.	Building attributes and flood zones for structures.	Street-level imagery required at a minimum. FFH estimates can be further refined by identifying the elevation of the stairs with a Digital Elevation Model, or conducting measurements using Google Street View and Google Earth.
Processing Time	Generates FFH estimates for thousands of structures within minutes.	Generates FFH estimates for thousands of structures within minutes.	<i>Stair Counting:</i> <1 minute per structure <i>Elevation Adjusted Stair Counting:</i> 1-2 minutes per structure <i>Google Measurements:</i> Around 10 minutes per structure
Advantages	Requires less time to prepare data than the statistical modeling approach.	Reflects local FFH value range, which may differ from the Hazus default. Incorporates additional factors beyond the Hazus default approach that may influence FFH.	Requires no local assessor information. Only structure address is required.
Disadvantages	Local assessor foundation codes may not be detailed enough to identify the correct Hazus foundation type code. Default FFH values may not reflect local conditions.	Requires sample size of several hundred elevation certificates or survey observations that represent the range of structures. Data preparation for model development can be time intensive.	Time intensive process given each structure must be assessed individually. Average stair height may not reflect actual stair height conditions.

III. Coastal Hazard Vulnerability Assessments

Vulnerability Assessment Methods

Several vulnerability assessment methods were applied to each case study community to identify benefits and challenges. A single flooding scenario, the 1% annual chance flood, was applied for each assessment to offer consistency between the different methodologies. Two primary inputs were required for each analysis method: (1) a flood depth grid, and (2) the building inventory. Three flooding vulnerability assessment methods were applied for each case study community (Figure 7).

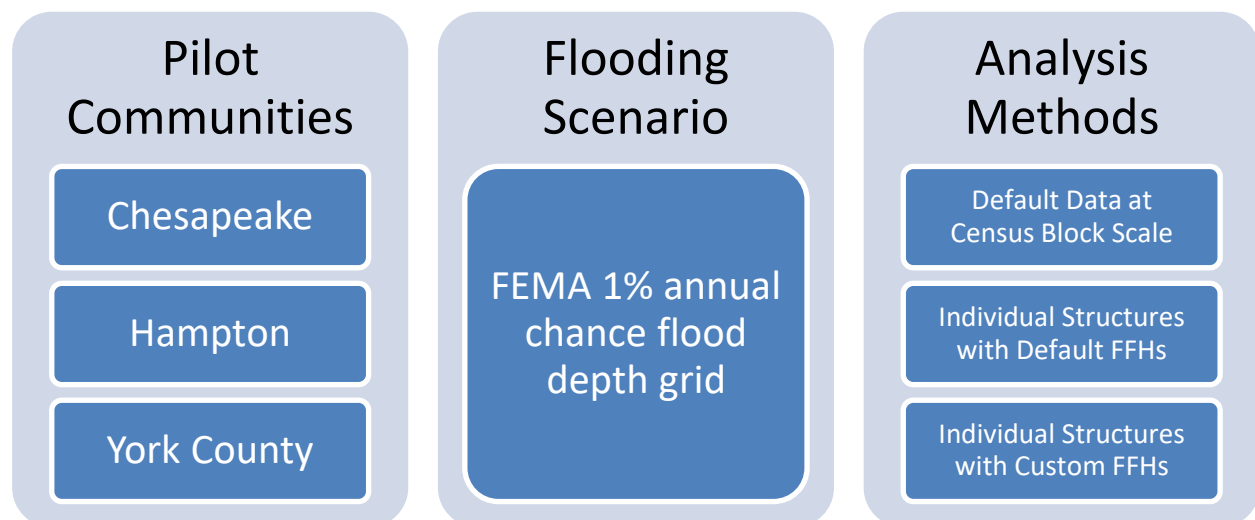


Figure 7: Vulnerability assessment scenarios evaluated for each case study community. Default FFH refers to the values associated with foundation type in the Hazus technical manual (FEMA, 2017). Custom FFH refers to elevation certificate information and FFH estimates from predictive statistical modeling.

For each case study community, FEMA has developed a Flood Risk Database through the Risk Mapping, Assessment, and Planning (Risk MAP) program (FEMA, 2019c). The Flood Risk Databases are available for download from the FEMA Flood Map Service Center and include a water surface elevation grid and flood depth grid (FEMA Risk MAP, 2015a, 2015b, 2016). The water surface elevation grid provides flood water heights for the 1% annual chance flood event reported in the same vertical datum as the land elevation (FEMA Risk MAP, 2015a, 2015b, 2016). The flood depth grid is calculated by subtracting the elevation of the land (DEM) from the predicted water surface elevation (FEMA Risk MAP,

2015a, 2015b, 2016). For example, a predicted flood elevation of 8ft over a land elevation of 6ft results in a flood depth of 2ft. Through the vulnerability analysis, the flood depth is compared to the structure's FFH to calculate the depth of water within the structure.

Three vulnerability methods were selected to compare the sensitivity of damage estimates to the scale of analysis and FFH input. These methods included: (1) census block scale analysis using default Hazus inventory data, (2) individual structure level analysis with default Hazus FFH values (default FFH method), and (3) individual structure level analysis with custom FFH values from local data and model predictions (custom FFH method). For the census block level analysis, the default Hazus GBS was applied to establish a baseline damage estimate that required minimal data preparation. For each census block within a selected community, default distributions of building square footage, occupancy type, building type, dollar exposure (replacement cost), foundation type, and first floor heights are provided. To create the flood scenario, the FEMA 1% annual chance flood depth grid from each community's Flood Risk Database was imported into Hazus (FEMA Risk MAP, 2015a, 2015b, 2016).

To estimate dollar losses for a given flooding scenario, Hazus applies a suite of depth-damage functions that vary based on the number of stories, presence of a basement, and occupancy type. The depth-damage functions are compiled from several sources, including the Federal Insurance and Mitigation Administration (formerly FIA) and U.S. Army Corps of Engineers (USACE) (FEMA, 2017). The FIA damage functions were developed through credibility analyses that combine available flood insurance claims data and theoretical base tables into weighted curves (FEMA, 2017). USACE depth-damage functions have been developed for several districts, and the USACE Institute for Water Resources (USACE IWR) has developed national depth-damage functions for single-family residential structures without basements based on flood damage surveys (FEMA, 2017). Figure 8 displays default depth damage functions from Hazus reference tables for single-family residential structures with one, two, or three stories and no basement. The increase in percent damage per foot of water is not uniform across structure types. For example, a \$300,000 home with one-story would have an increase in damage of \$30,000 from 0ft to 1ft of water within the structure, whereas a two-story or three-story home would have an increase of less than \$10,000 damage. This illustrates that damage estimates for single-story structures are more sensitive to changes in FFH than two-story or three-story structures.

Depth-damage functions also differ between coastal and riverine flood hazards. The coastal flood hazard corresponds to areas within velocity zones subject to three-foot wave action under the 1% annual chance flood event (FEMA, 2017). The coastal depth-damage functions are relevant to structures

within the VE flood zone in Hampton Roads communities. Riverine depth damage functions are applicable to structures within the SFHA that are outside of VE flood zones, such as the AE flood zone, in coastal communities. Currently unique depth-damage functions are not established for Coastal A zones. The default coastal depth damage function for one-story single-family residential structures increases more rapidly than the riverine function. For example, at 4ft water depth, the coastal function estimates 100% structural damage, whereas the riverine function reports only 47% structural damage. Therefore, distinguishing between structures within coastal VE zones and riverine flood zones significantly influences damage estimates.

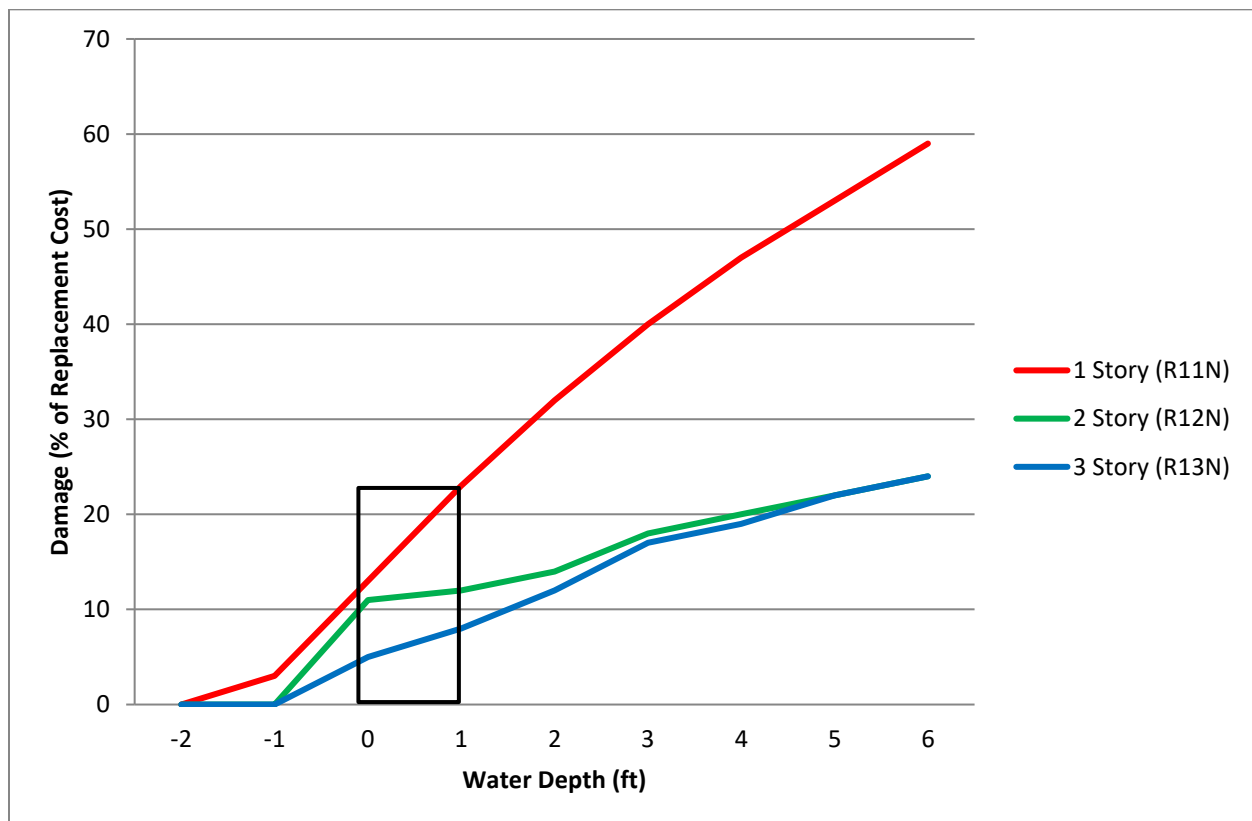


Figure 8: Depth damage function values provided in the Hazus software for one, two, and three-story single-family residential homes with no basement. Curves have been truncated from the full range of values (-4ft to 24ft). The single-story depth-damage function was developed by USACE IWR, and the two-story and three-story functions were produced by FIA.

For an individual structure analysis, Hazus applies the appropriate depth-damage function to each structure based on the building's attributes (FEMA, 2017). Incorporating individual structures into the Hazus software currently requires use of the Comprehensive Data Management System (CDMS)

(FEMA, 2017). To streamline the application of UDF data and reduce processing time, the Hazus program has developed a new open-source tool, referred to as the Flood Assessment Structure Tool (FAST) (FEMA NHRAP-Hazus, 2019). FAST requires the UDF inventory to be formatted as a comma-separated values (CSV) file and the flood depth grid to be formatted as a .tif file. The Hazus software and ArcGIS do not have to be installed to run FAST. The tool is able to process 10,000 structures per second, which drastically reduces processing time from the traditional Hazus UDF analysis. As in Hazus, the FAST output includes building and contents percent damage and dollar losses. (FEMA NHRAP-Hazus, 2019)

For the individual structure vulnerability analysis, the FAST tool was applied for two scenarios: (1) default FFH based on Hazus reference tables, and (2) custom FFH based on elevation certificates, model predictions, and imagery analysis estimates.

Table 13 lists the required building attributes for the FAST analysis. The steps for data preparation and analysis were as follows:

- (1) Information from local assessor data was adapted to the required occupancy class and foundation type codes.
- (2) Building replacement cost was calculated in GIS using the methodology applied by Hazus based on square footage. The appropriate R.S. Means value, or dollar value per square foot, was determined using building attributes and the census block income ratios identified by Hazus (FEMA, 2017). Appendix C provides the detailed methodology and reference values for calculating replacement cost.
- (3) The latitude and longitude for each structure location was based on the structure's LAG, or maximum flood depth if the structure's LAG

Figure 9: FEMA Flood Assessment Structure Tool user-interface. Attributes highlighted in green indicate required fields.

did not overlap with the depth grid. Discrepancies between the LAG and maximum depth are likely the result of different underlying DEMs between the LAG analysis and FEMA depth grid development. Appendix D describes the GIS methodology for assigning points to the building's LAG.

- (4) Once all attributes were completed, the inventory was divided into structures located within the coastal VE flood zone and all other structures in the SFHA and output from GIS to a CSV file format.
- (5) The FAST tool was run separately for coastal VE structures and other buildings in the SFHA. 'Coastal V' was selected as the flooding attribute for structures within the VE flood zone, and 'Riverine' was selected for all other structures (Figure 9). The FEMA 1% annual chance flood depth grid was loaded as a .tif file (Figure 9). The analysis results were transferred into GIS by joining the output CSV with the existing spatial inventory.

Table 13: Required user inputs for the FEMA FAST tool and the corresponding source of each attribute.

Attribute	Description	Source
User Defined Flty Id	Structure unique identifier	Local parcel ID
Occupancy Class	Hazus occupancy class code	Classified based on local assessor data
Building Cost	Replacement cost	Calculated using square footage from assessor data and R.S. Means values
Building Area	Square footage of structure	Local assessor data
Number of Stories	Number of stories rounded up to nearest whole number	Local assessor data
Foundation Type	Corresponding Hazus foundation type reported as an integer	Classified based on local assessor data
First Floor Height	Height of FFH above grade, reported in feet	Determined using elevation certificates, model estimates, imagery estimates, or default Hazus values based on foundation type

Case Study Results: City of Chesapeake

Within the City of Chesapeake, approximately 4,524 single-family residential structures (RES1) intersected the FEMA 1% annual chance flood depth grid, with a total exposure value of \$1.5 billion. The total exposure value represents the sum of all RES1 replacement costs within the 1% annual chance floodplain. The census block analysis estimated \$219.2M (14.5% of total exposure value) in flood losses for 3,826 damaged RES1 structures, representing the largest damage estimate of the three scenarios (Figure 10). The individual structure level analysis using default foundation type FFH estimates resulted in 1,822 damaged structures, totaling \$39.0M (2.6% of total exposure value) in RES1 losses (Figure 10). When using custom model predictions, elevation certificate, and stair-based values, the number of damaged structures was reduced to 1,443, totaling \$17.1M (1.1% of total exposure value) in RES1 losses (Figure 10).

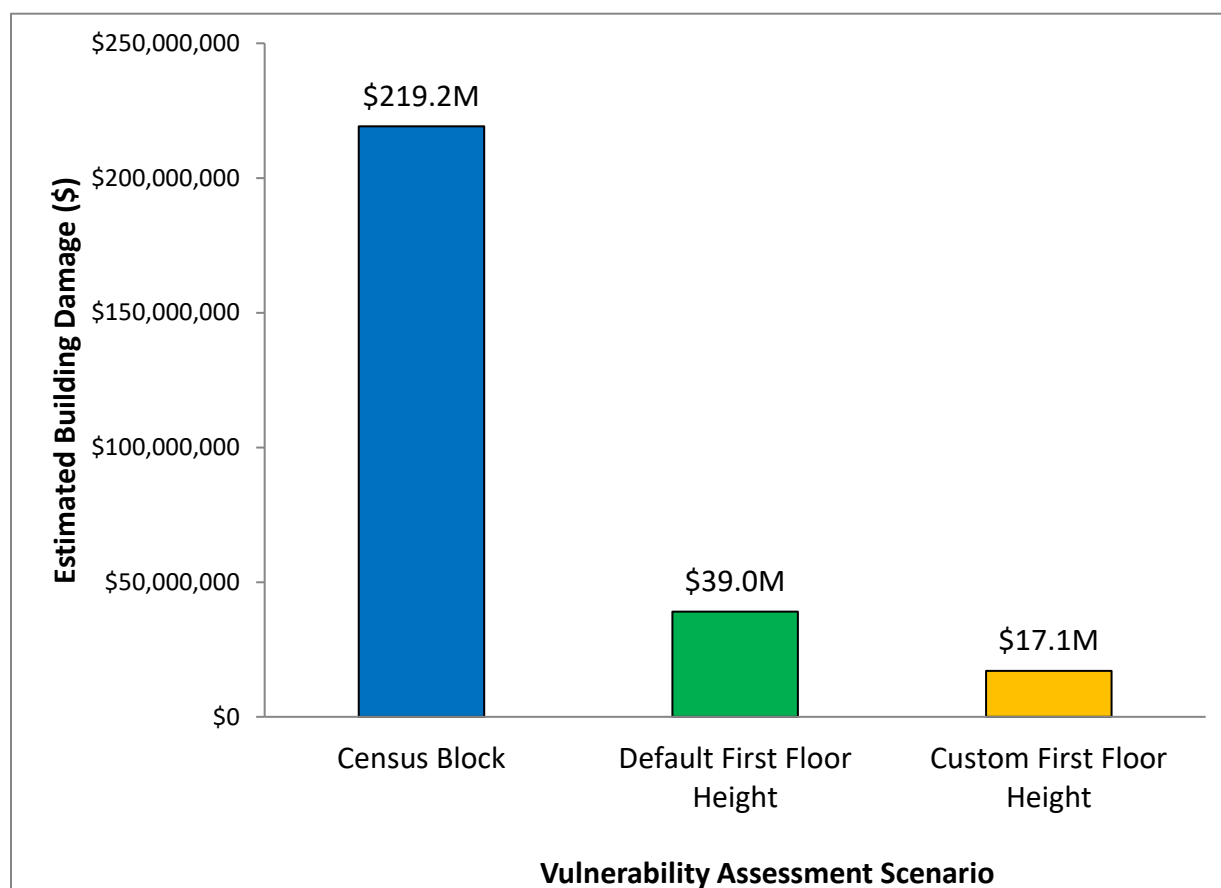


Figure 10: Comparison of estimated dollar losses resulting from the 1% annual chance flood event for Chesapeake by FFH input. Default FFH refers to the values associated with foundation type in the Hazus technical manual (FEMA, 2017). Custom FFH includes elevation certificate information and FFH estimates from predictive statistical modeling and Google imagery.

The two primary foundation types for RES1 structures in the Chesapeake 1% annual chance floodplain are crawlspace (84.5% of structures) and slab (15.1% of structures). When applying custom FFH values, the estimated flood losses decreased by 38% for RES1 crawlspace structures and 77% for slab structures relative to the default damage estimates (Figure 11). The substantial decrease in slab structure losses is attributed to the default method resulting in an average lower FFH estimate (1.0ft) for slab structures than the custom method (2.3ft). The custom method average FFH is higher due to the inclusion of raised slab structures in the elevation certificate sample. The default scenario resulted in an additional 325 slab structures and 194 crawlspace structures damaged than the custom scenario.

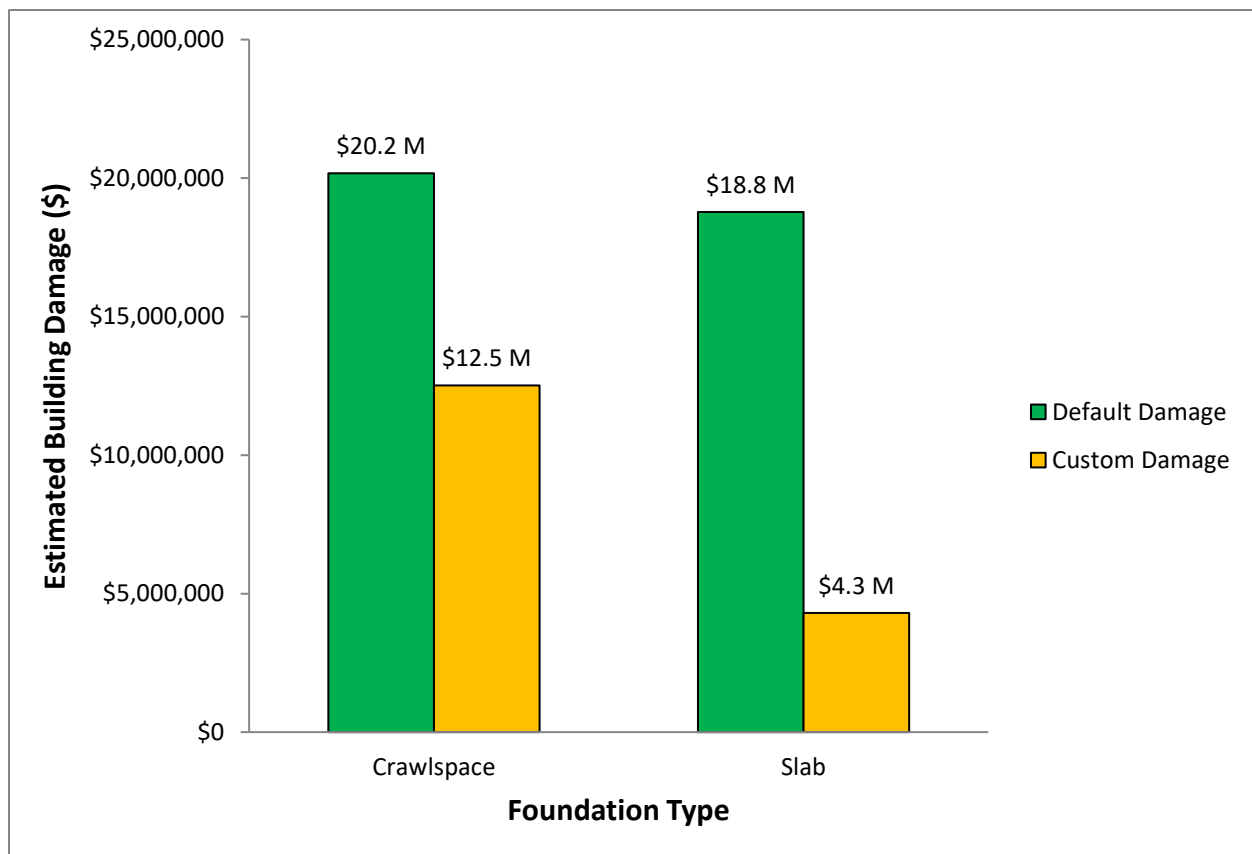


Figure 11: Comparison of estimated dollar losses resulting from the 1% annual chance flood event for Chesapeake by FFH input for crawlspace and slab foundation type.

Of the structures which intersected the depth grid, 432 structures had corresponding elevation certificates. By using only the sample of structures with elevation certificates, the sensitivity of damage estimates to changes in FFH can be evaluated without introducing error from the model predictions. While the total estimated losses differed by less than 2% for crawlspace structures between default FFH

and elevation certificate FFH methods, the damages for slab structures were nearly twice as large when using default FFH values (Table 14). This is likely because raised slab structures were included in the elevation certificate sample. Approximately 71% of slab structures with elevation certificates included in the analysis were of building diagram 1B, or raised slab, with an average first floor height of 1.86ft. It is important to note that in the elevation certificate sample used to build the predictive model, 99% of slab structures were built between 2007 and 2018, and 43% were built in 2013 or later following the enactment of a 16in freeboard standard in the SFHA (City of Chesapeake, 2013). Therefore, the model may inflate slab FFH estimates for older structures because the elevation certificate sample used to train the model was biased towards more recent slab construction. In the SFHA, 71% of slab structures were built before 2007, which is outside of the range of the training data. Further review of slab structures within the SFHA using Google Street View imagery would help determine if the default FFH estimate of 1ft may be more appropriate for older slab structures.

Table 14: Estimated building losses from the 1% annual chance flood event for Chesapeake when using recorded elevation certificate FFH values and default FFH values.

<i>FFH Method</i>	<i>Crawlspace FFH Total Damage</i>	<i>Slab FFH Total Damage</i>
Default	\$1,632,912	\$3,847,049
Elevation Certificate	\$1,606,290	\$1,961,371

Figure 12 displays the census blocks by level of flood damage, with the maximum census block building flood loss value of \$9.8M. Figure 13 displays the density of individual damaged structures, weighted by loss value, for both the default and custom FFH scenarios. The number of structures experiencing a moderate level of damage was higher under the default FFH scenario than the custom (Table 15). The Hampton Roads HMP (2017) defines moderately damaged as 15-49% of total structural value, and substantially damaged as greater than 49%. The repetitive loss areas mapped for the regional HMP (2017) were also overlaid with individual structure point locations. Although the conditions under which repetitive flood loss structures experienced damage may not correspond with the 1% annual chance flood event, this comparison shows that generally the areas that are estimated to experience the greatest losses under the 1% annual chance flood overlap with areas that have repeatedly experienced flooding.

Table 15: Summary of individual structures damaged under the 1% annual chance flood event using the default and custom FFH estimation methods for Chesapeake. Values are displayed as number of structures damaged and percent of total structures damaged under that scenario.

<i>FFH Method</i>	<i>Buildings Moderately Damaged</i>	<i>Buildings Substantially Damaged</i>
Default	223 (12.2%)	1 (<1%)
Custom	51 (3.5%)	1 (<1%)

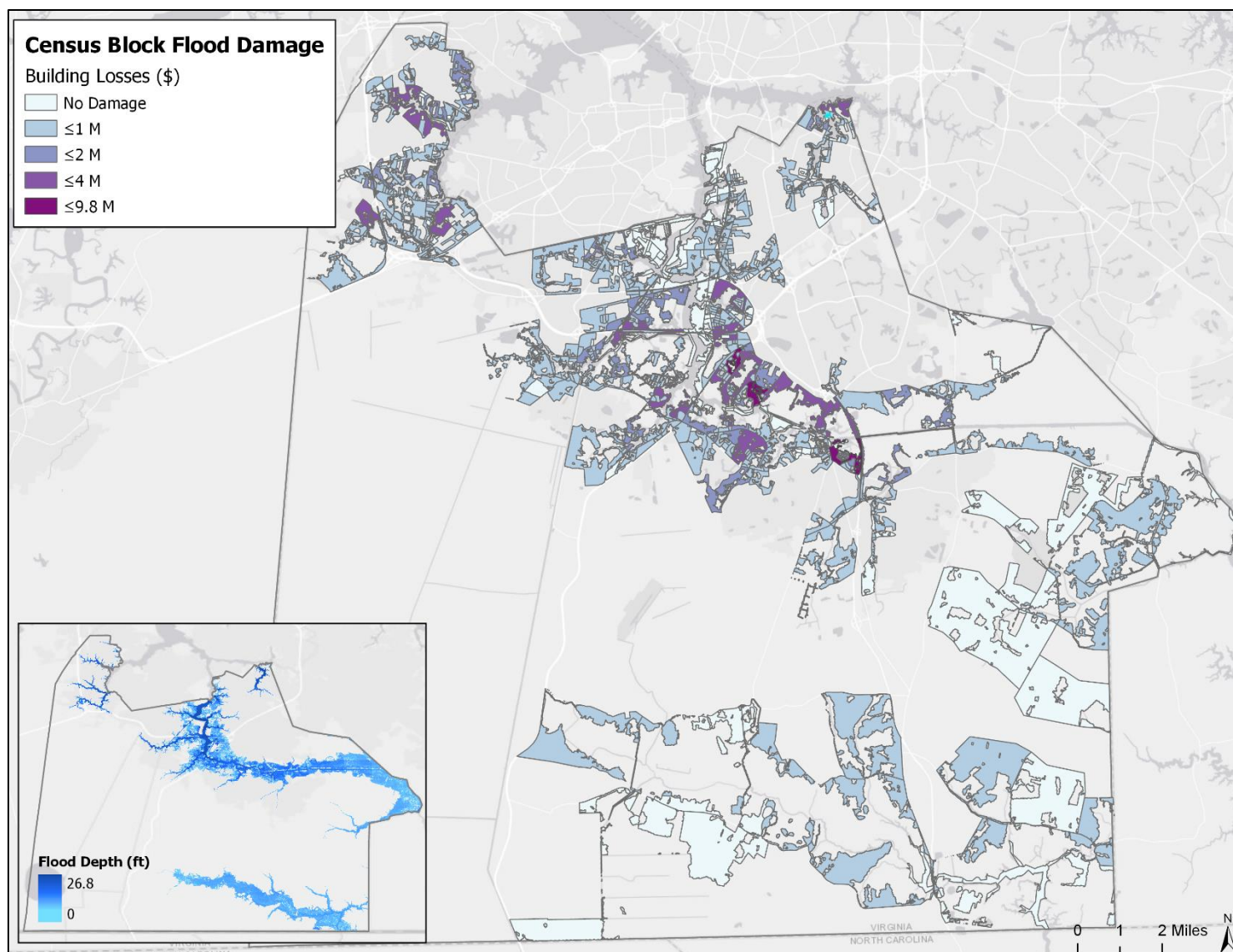


Figure 12: Census blocks included in the Hazus Analysis coded by estimated building losses from the 1% annual chance flood event for Chesapeake. The depth grid used in the analysis is provided as an inset map.

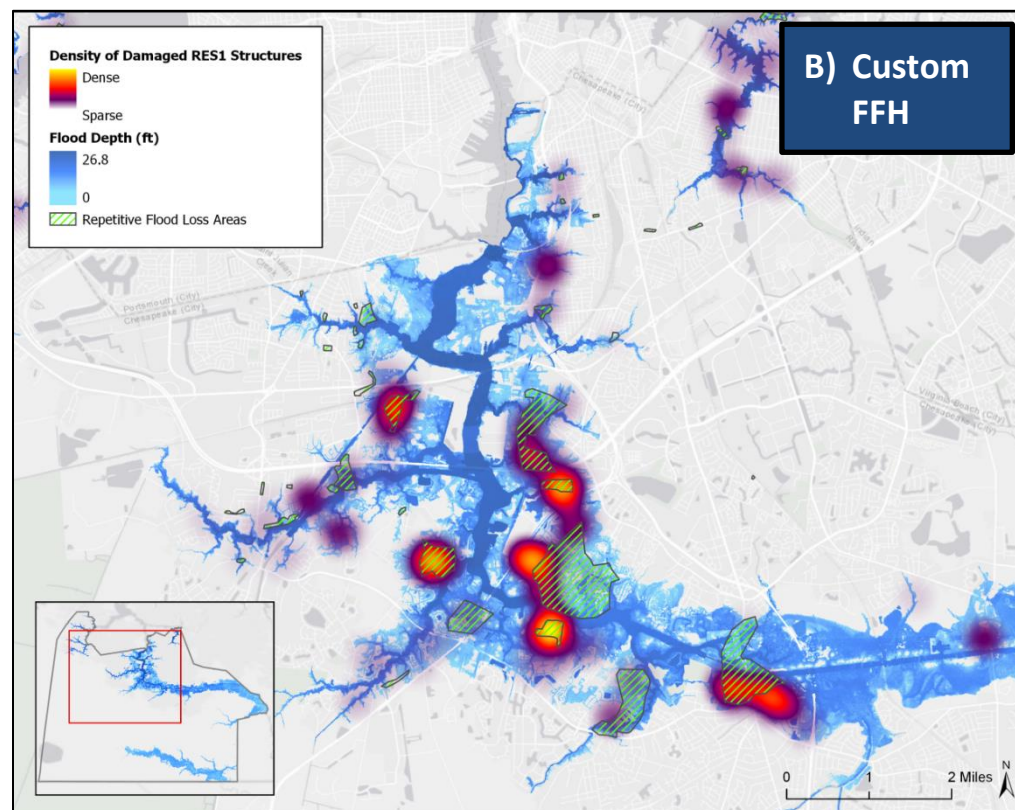
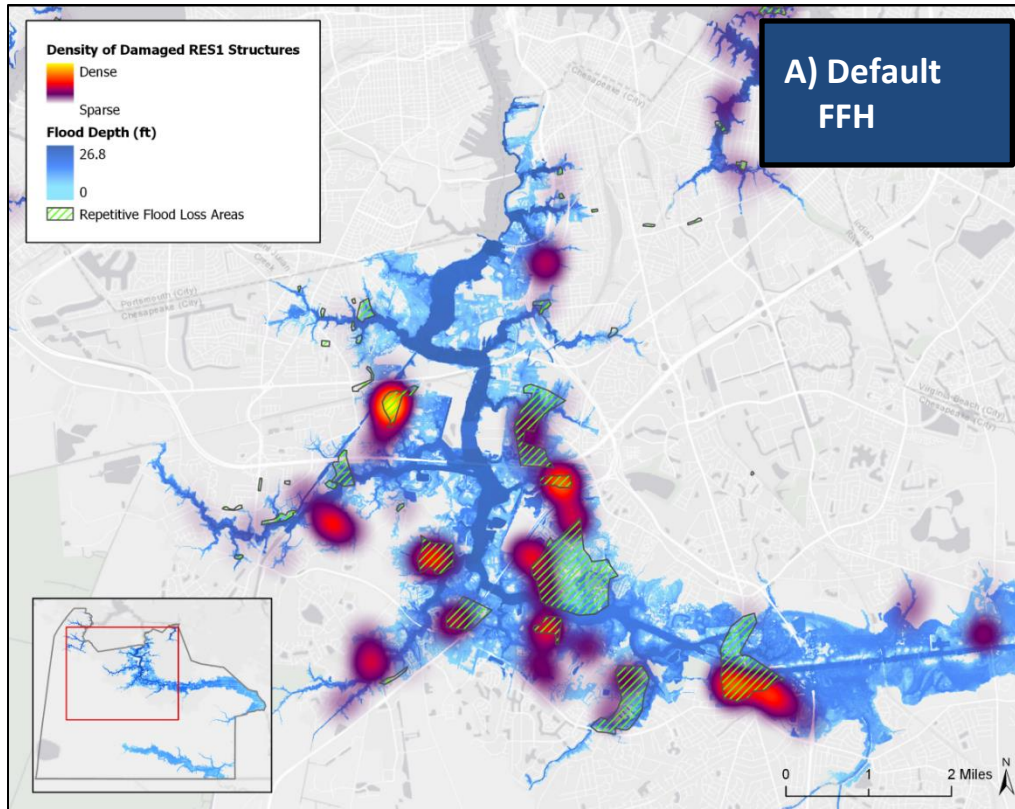


Figure 13: Distribution of individual structures with estimated flood damage weighted by the value of the loss for the 1% annual chance flood event in Chesapeake. Yellow indicates dense areas of high value losses.

Case Study Results: City of Hampton

Approximately 7,106 RES1 structures intersected the FEMA 1% annual chance flood depth grid in the City of Hampton, with a total exposure value of \$1.9 billion. The census block analysis resulted in the largest building damage estimate of the three scenarios, with \$295.4M in estimated losses for 5,879 damaged RES1 structures (26.9% of total exposure value) (Figure 14). The individual structure level analysis using default foundation type FFH estimates resulted in \$96.2M in RES1 losses (5.1% of total exposure value) (Figure 14). The estimated RES1 losses decreased to \$86.5M (4.6% of total exposure value) when replacing default FFH estimates with custom FFH estimates, despite an increase from 3,785 to 4,144 structures that experienced damage (Figure 14). Approximately 63.5% of structures that experienced damage in both the default and custom FFH scenarios had a higher loss value under the default scenario.

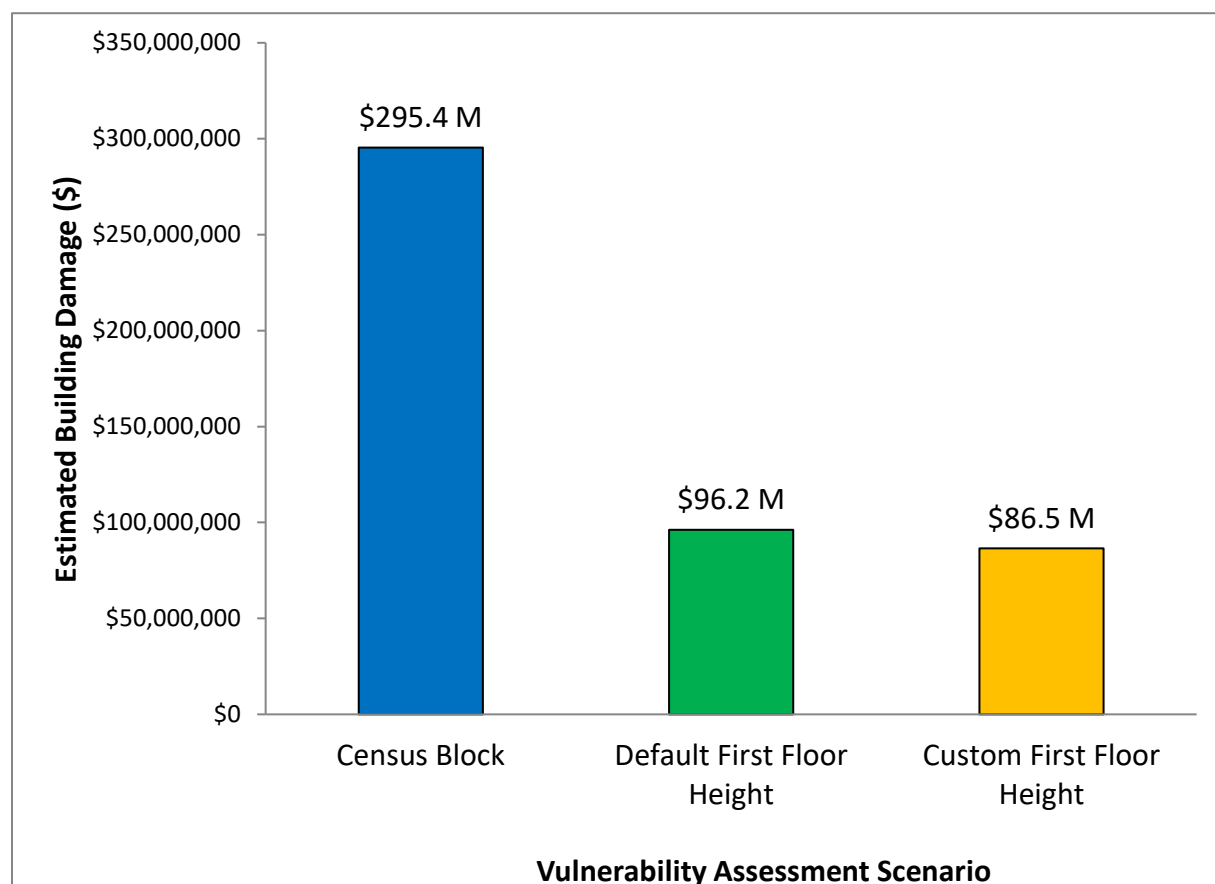


Figure 14: Comparison of estimated dollar losses resulting from the 1% annual chance flood event for Hampton by FFH input. Default FFH refers to the values associated with foundation type in the Hazus technical manual (FEMA, 2017). Custom FFH includes elevation certificate information and FFH estimates from predictive statistical modeling and Google imagery.

The three primary foundation types for RES1 structures in the Hampton 1% annual chance floodplain are crawlspace (5,524, 77.7% of structures), slab (1,382, 19.4% of structures), and solid wall (112, 1.6% of structures). Crawlspace and slab structures experienced greater losses under the default FFH scenario than the custom FFH scenario (Figure 15).

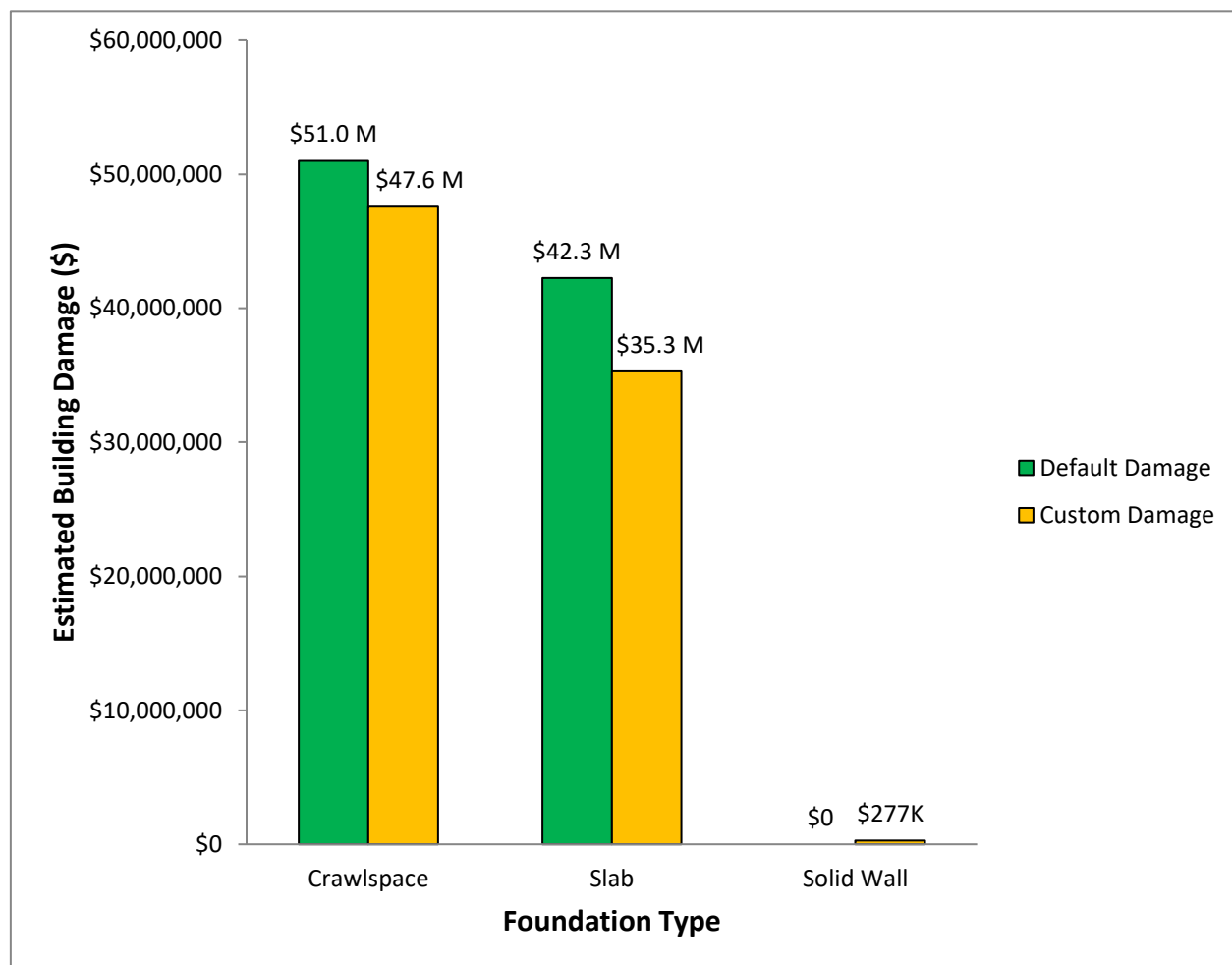


Figure 15: Comparison of estimated dollar losses resulting from the 1% annual chance flood event for Hampton by FFH input for crawlspace and slab foundation type.

Elevation certificates were available for 465 structures that intersected the 1% annual chance flood depth grid. Table 16 compares the total reported damage by crawlspace, solid wall, and slab foundation type for structures with elevation certificates. The average crawlspace elevation for Pre- and Post-FIRM structures with elevation certificates was 3.4ft and 4.4ft respectively. These averages are only around 0.4ft greater than the default FFH of 3 and 4ft; however, an overall decrease in damages of \$1.4M (24%) was observed (Table 16). Four structures with an elevated living space, or solid wall

foundation type, were damaged in the 1% annual chance flood analysis when using the elevation certificate reported FFH. While the default FFH value of 7ft or 8ft was higher than the observed FFH for these select structures, the average FFH for structures with an elevated living space was 9.4ft based on elevation certificate data. Therefore, more damage was observed for solid wall structures in comparison to the default data set as a result of several abnormally low FFH values.

Table 16: Summary of individual structures damaged under the 1% annual chance flood event using the default and elevation certificate FFH estimation methods for Hampton.

<i>FFH Method</i>	<i>Crawlspace FFH Total Damage</i>	<i>Solid Wall FFH Total Damage</i>	<i>Slab FFH Total Damage</i>
Default	\$ 6,138,899	\$ 0	\$2,728,677
Elevation Certificate	\$ 4,673,758	\$ 277,130	\$2,183,963

When creating the custom FFH dataset for Hampton, structures with a foundation type of “None” within close proximity of known elevated living space structures were reviewed using Google Street View imagery to determine if a slab or solid wall foundation code was appropriate. To assess the impact of these structures on the damage estimates, a vulnerability analysis was run with all “None” structures classified as slab foundation type. Therefore, rather than having a default FFH value of 7ft or 8ft, the structures were assigned a FFH value of 1ft. Figure 16 compares the reported damages for slab and solid wall structures specifically. Under the Slab FFH, “None” Foundation scenario, all “None” foundation type structures have a value of 1ft. The Default FFH, Slab or Solid Wall Foundation scenario includes the reclassification of “None” foundation types to “Solid Wall” where necessary, with a default FFH value of 7ft or 8ft assigned. The third scenario includes the same foundation types as the previous but replaces default FFH estimates with values based on stair counts or elevation certificates. An additional 76 structures were damaged, resulting in an increase of \$6.7M in losses, when the FFH value was changed but the foundation type was held constant. An additional 112 structures were damaged, resulting in an increase of \$6.0M in losses, when assuming all structures were slab. The visual review of

structures to confirm slab or elevated living space foundation type thus avoided an overestimation of damage by \$6.0M.

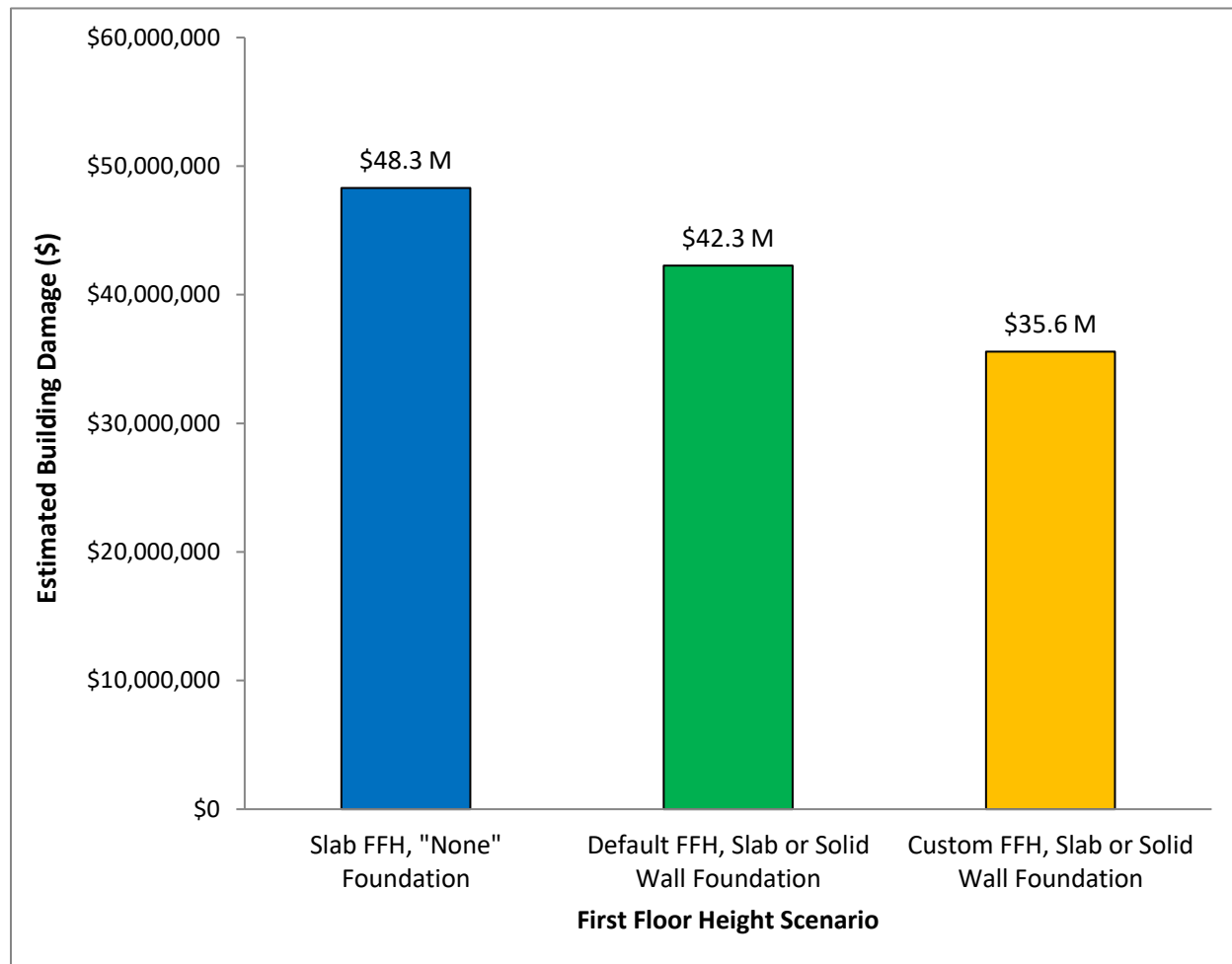


Figure 16: Comparison of damage estimates before and after adjusting foundation codes and FFH estimates for structures identified through Google imagery as having an elevated first floor living space. The far-left scenario assumes all structures of “None” foundation type are slab. The middle scenario reclassifies structures with an elevated living space as solid wall, with an FFH of 7ft or 8ft. The far-right scenario replaces default FFH values with custom FFH values.

Figure 17 displays the census blocks categorized by flood losses, with the maximum building flood loss value of \$11.9M. The density of damaged structures, weighted by loss value, for both the default and custom FFH scenarios are displayed in Figure 18. The number of structures experiencing moderate (15-49%) or substantial (>49%) damage was higher under the default FFH scenario than the custom (Table 17). To identify areas of overlap between damaged structures and areas that repeatedly flood, the repetitive loss areas created for the regional HMP (2017) were also mapped with damaged

individual structure point locations. Although the conditions under which repetitive flood loss structures experienced damage may not correspond with the 1% annual chance flood, the areas experiencing damage under the 1% annual chance flood generally fall within the repetitive flood loss areas, with the exception of an area of slab foundation structures near the southwest branch of Back River (Figure 18).

Table 17: Summary of individual structures damaged under the 1% annual chance flood event using the default and custom FFH estimation methods for Hampton. Values are displayed as number of structures damaged and percent of total structure damaged.

<i>FFH Method</i>	<i>Buildings Moderately Damaged</i>	<i>Buildings Substantially Damaged</i>
Default	752 (19.9%)	11 (0.3%)
Custom	504 (12.2%)	8 (0.2%)

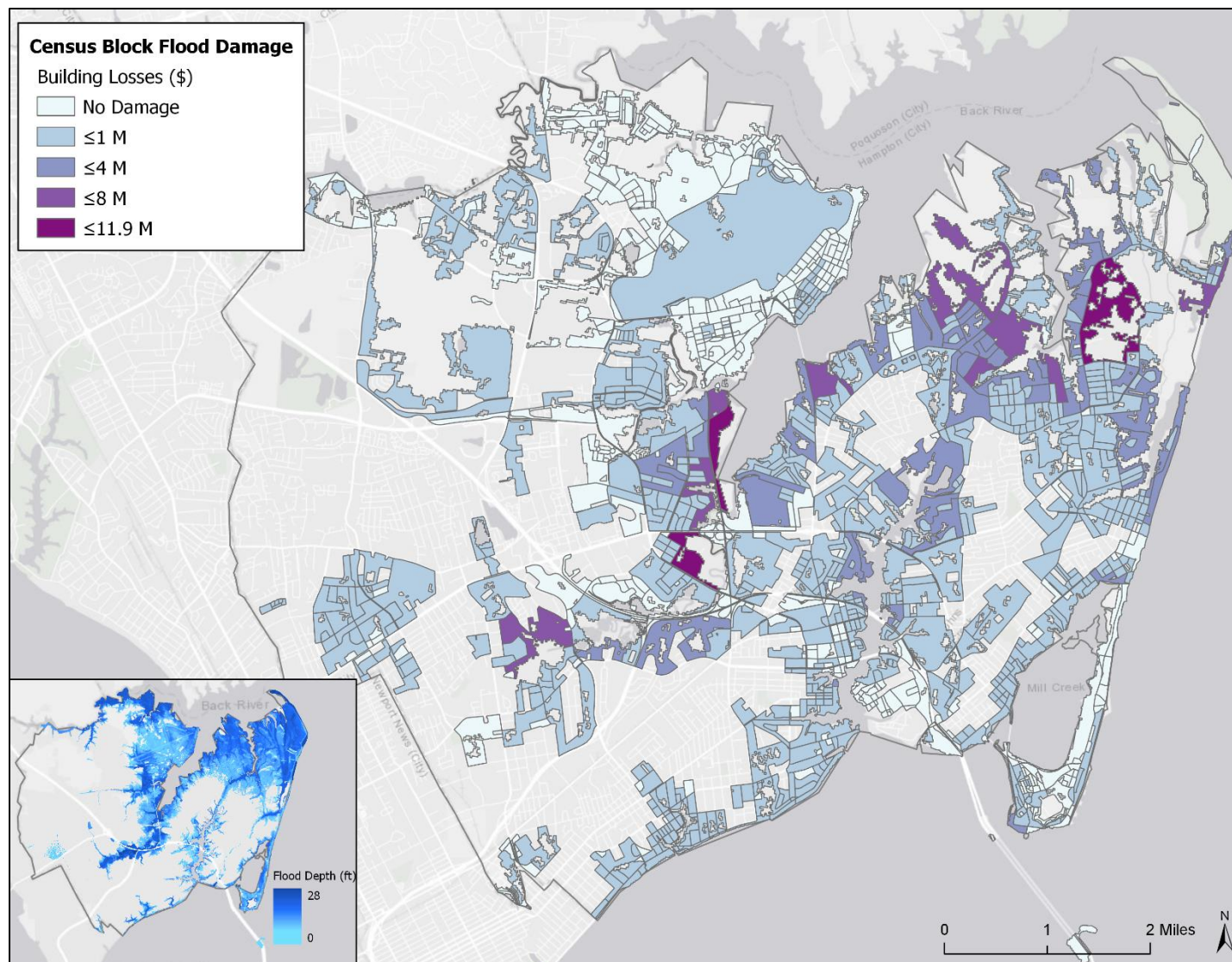


Figure 17: Census Blocks included in the Hazus Analysis coded by estimated building losses from the 1% annual chance flood event for Hampton.

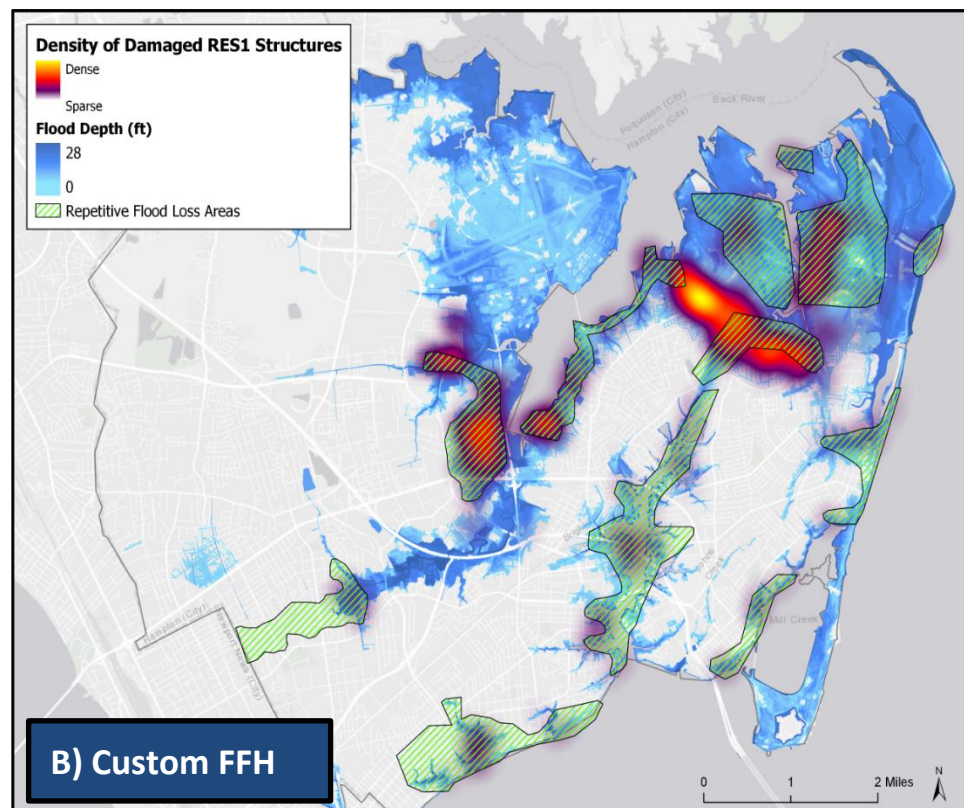
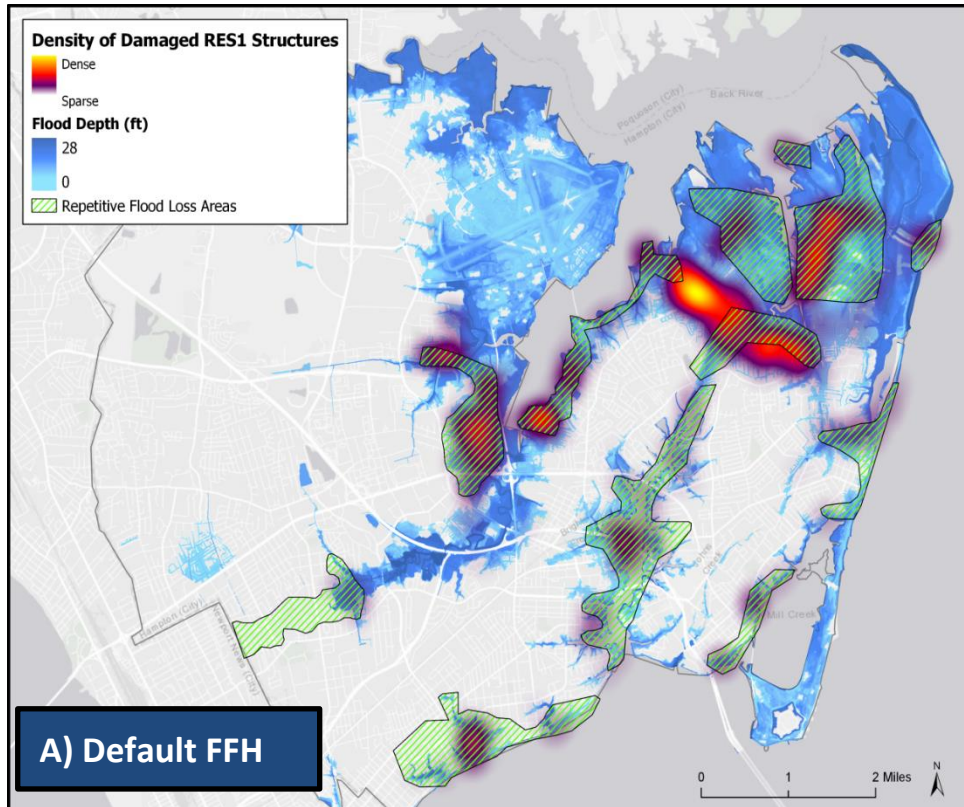


Figure 18: Distribution of individual structures with estimated flood damage weighted by the loss value for the 1% annual chance flood event in Hampton. Yellow indicates dense areas of high value losses.

Case Study Results: York County

Within York County, approximately 1,634 RES1 structures intersected the FEMA 1% annual chance flood depth grid, with a total exposure value of \$659.8M. The census block analysis resulted in \$77.9M in estimated losses for 951 damaged RES1 structures (11.8% of total exposure value), the largest damage estimate of the three scenarios (Figure 19). The individual structure level analysis using default foundation type FFH estimates resulted in 657 damaged structures, totaling \$19.9M in RES1 losses (3.0% of total exposure value) (Figure 19). The estimated number of structures damaged decreased to 283, totaling \$5.5M in losses (0.8% of total exposure value), when replacing default FFH estimates with custom model predictions, elevation certificate, and stair-based values (Figure 19).

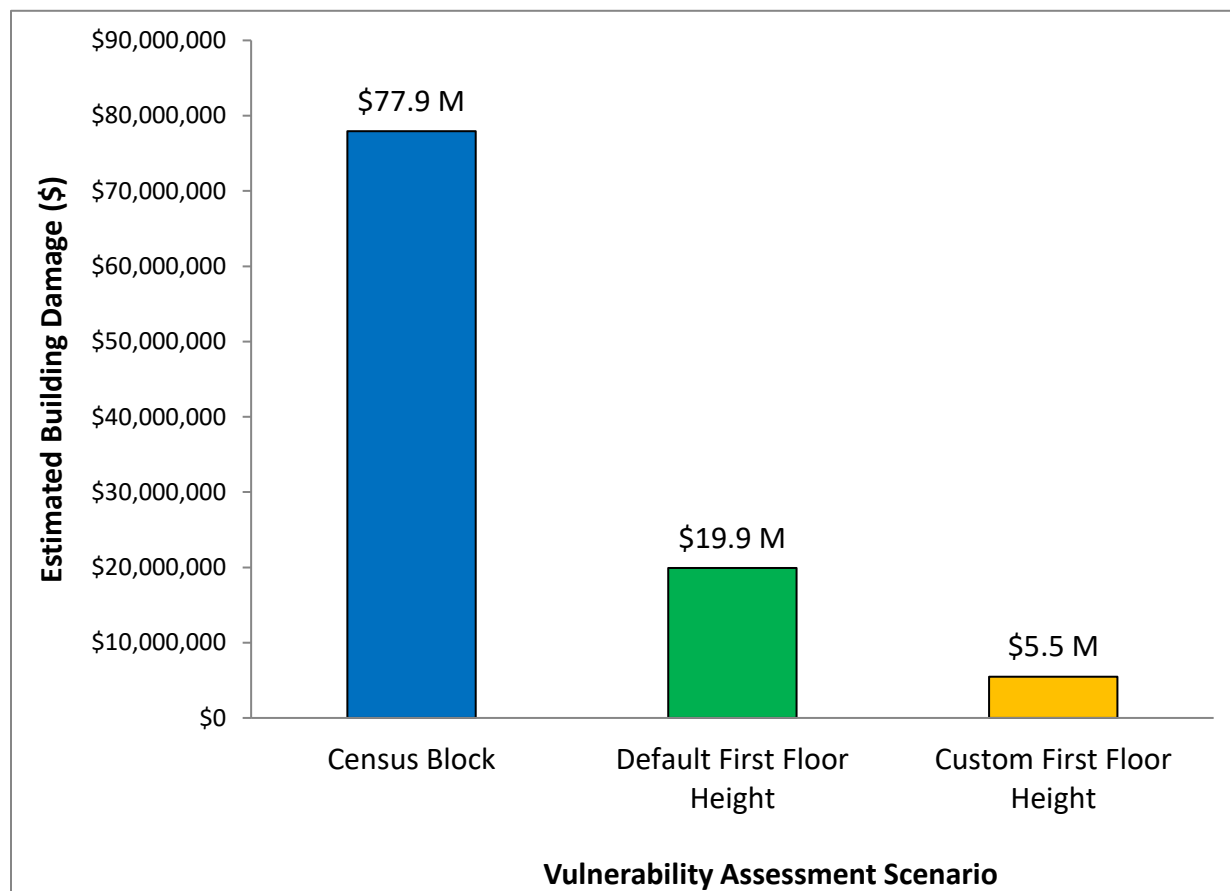


Figure 19: Comparison of estimated dollar losses resulting from the 1% annual chance flood event for York County by FFH input. Default FFH refers to the values associated with foundation type in the Hazus technical manual (FEMA, 2017). Custom FFH includes elevation certificate information and FFH estimates from predictive statistical modeling and Google imagery.

The three primary foundation types for RES1 structures in the York County 1% annual chance floodplain are crawlspace (1,374, 84.1% of structures), solid wall (146, 8.9% of structures), and slab (71, 4.3% of structures) (Figure 20). Estimated flood losses decreased by 74% for RES1 crawlspace structures when custom FFH values were used rather than the default losses. Similarly, for RES1 slab structures, estimated flood losses decreased by 85% when applying custom FFH values. A decrease in losses is attributed to higher FFHs under the custom scenario than the default. For structures within the 1% annual chance depth grid, the average FFH for Pre- and Post-FIRM crawlspace estimates of 4.0ft and 4.6ft respectively exceeded the default crawlspace FFH values of 3ft and 4ft. Likewise, custom slab structures had an average predicted FFH of 2.9ft, whereas the default value was 1ft. However, it is important to note that the sample size of elevation certificates for slab structures used to develop the predictive model included only six structures. This limited sample may not be representative of the 71 slab structures present within the SFHA. As a result, the model predictions may overestimate the true FFH for slab structures, particularly those built Pre-FIRM (39% of slab structures). Visual review of slab structures using Google Street View imagery would help identify structures where the model may be over-predicting FFH.

Of the structures which intersected the depth grid, 325 structures had corresponding elevation certificates. The flood losses reported under the default scenario were over double the losses reported when using only the elevation certificate FFH values for crawlspace foundation types (Table 18). Based on this sample, the default FFH values for the crawlspace foundation type tend to underestimate the observed FFH from elevation certificates. The elevation certificate average crawlspace FFH are 3.8ft and 4.5ft for Pre- and Post-FIRM structures respectively. Although more damage was observed for solid wall structures in comparison to the default data set, this can be attributed to several abnormally low values (Table 18). While the default FFH value of 7ft or 8ft over-predicted FFH for 10 structures, the average FFH for structures with an elevated living space was 9.8ft based on elevation certificate data for 80 structures. A comparison of damage for slab structures is not presented given the limited sample size of three slab structures with elevation certificates in the SFHA.

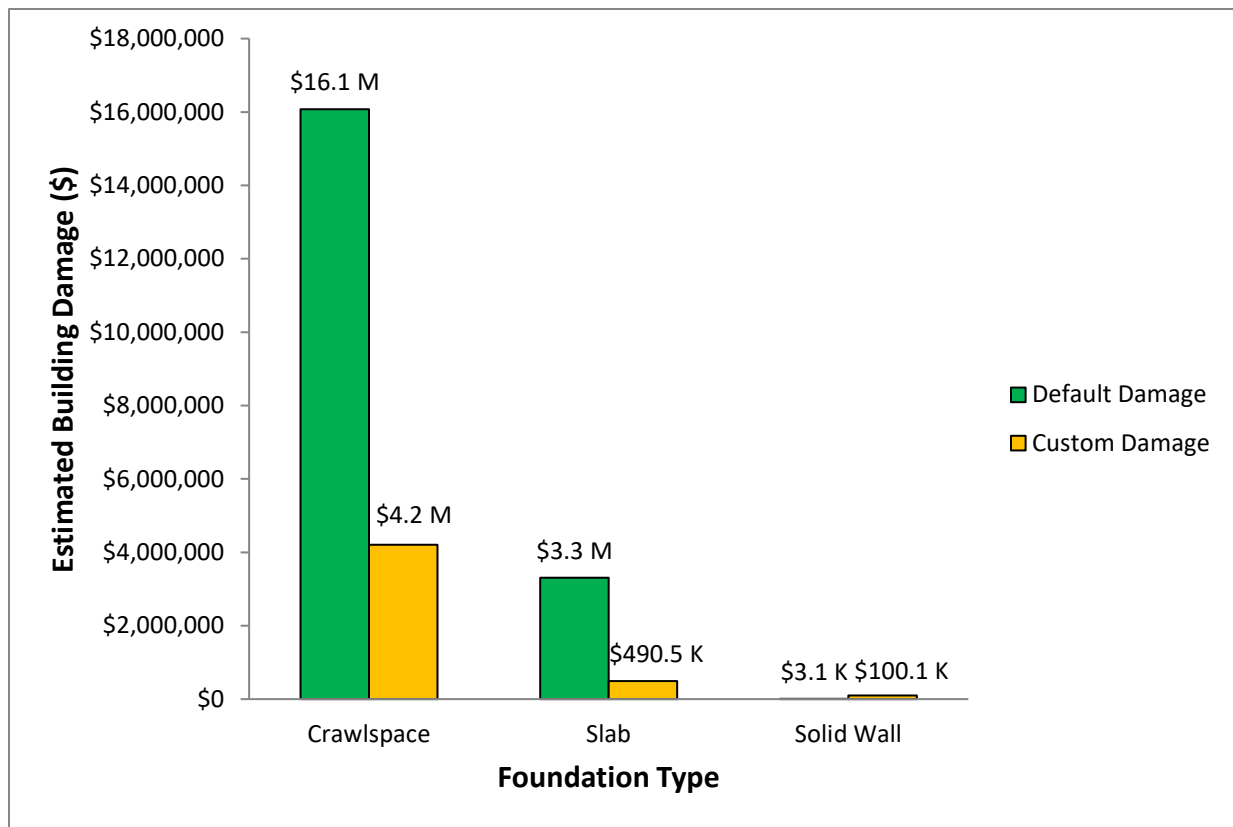


Figure 20: Comparison of estimated dollar losses resulting from the 1% annual chance flood event for York County by FFH input. Default FFH refers to the values associated with foundation type in the Hazus technical manual (FEMA, 2017). Custom FFH includes elevation certificate information and FFH estimates from predictive statistical modeling and Google imagery.

Table 18: Summary of individual structures damaged under the 1% annual chance flood event using the default and custom FFH estimation methods for York County.

<i>FFH Method</i>	<i>Crawlspace FFH</i>	<i>Solid Wall</i>
	<i>Total Damage</i>	<i>FFH Total Damage</i>
Default	\$2,961,076	\$0
Elevation Certificate	\$1,235,313	\$100,081

The maximum flood loss for a census block is \$6.1M (Figure 21). Figure 22 displays the density of damaged structures, weighted by loss value, for both the default and custom FFH scenarios. The number of structures experiencing a moderate (15-49%) level of damage was higher under the default FFH scenario than the custom (Table 19). The repetitive loss areas created for the regional HMP (2017) were also overlaid with the damaged individual structure point locations. Although the conditions under which repetitive flood loss structures experienced damage may be different, this comparison shows that generally areas that are estimated to experience the greatest losses under the 1% annual chance flood event correspond with areas that have repeatedly experienced flooding.

Table 19: Summary of individual structures damaged under the 1% annual chance flood event using the default and custom FFH estimation methods for York County. Values are displayed as number of structures damaged and percent of total structures damaged for the given FFH estimation method.

<i>FFH Method</i>	<i>Buildings Moderately Damaged</i>	<i>Buildings Substantially Damaged</i>
Default	93 (14.2%)	0 (0%)
Custom	17 (6.0 %)	0 (0%)

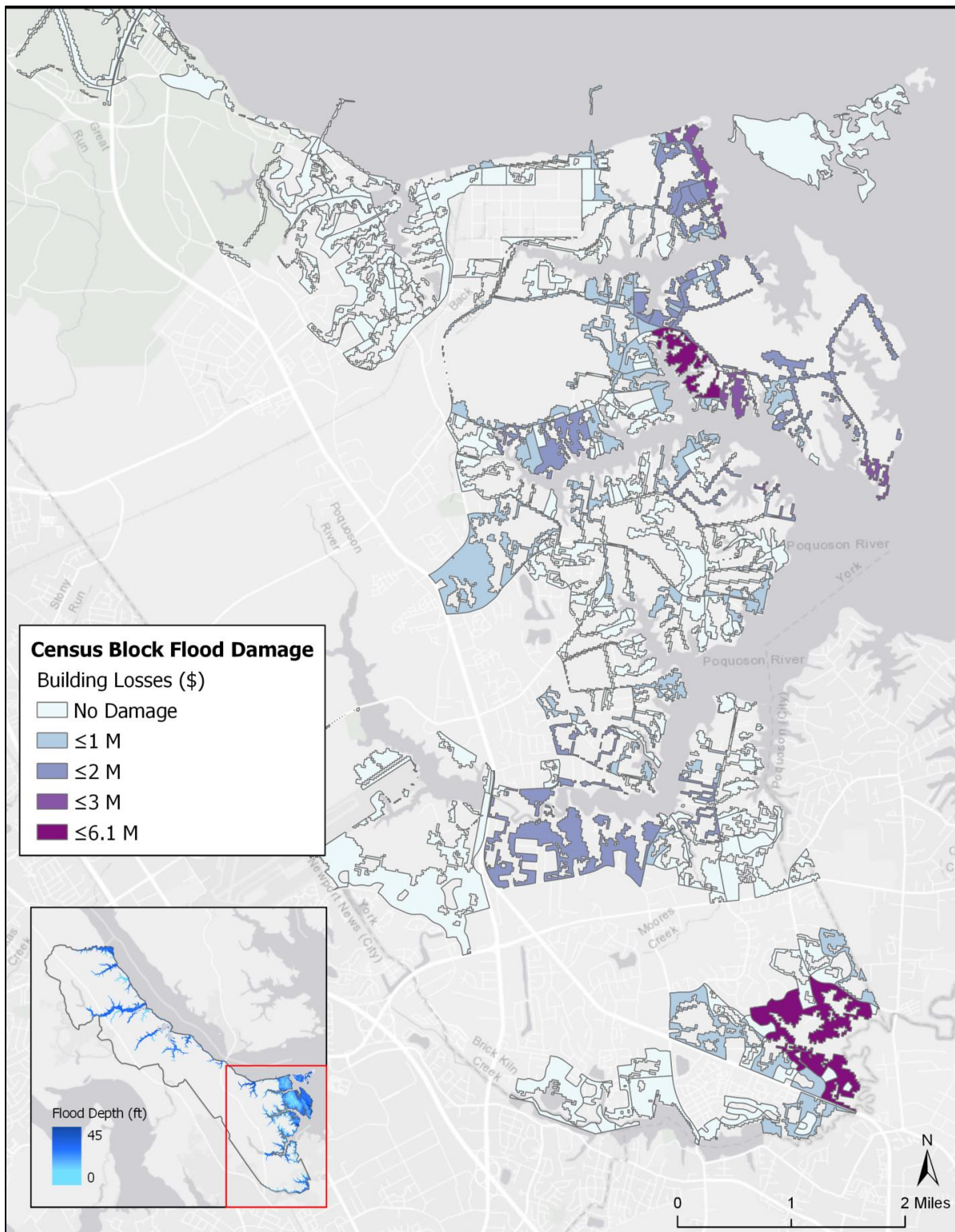


Figure 21: Census blocks included in the Hazus Analysis coded by estimated building losses from the 1% annual chance flood event for York County. The depth grid used in the analysis is provided as an inset map.

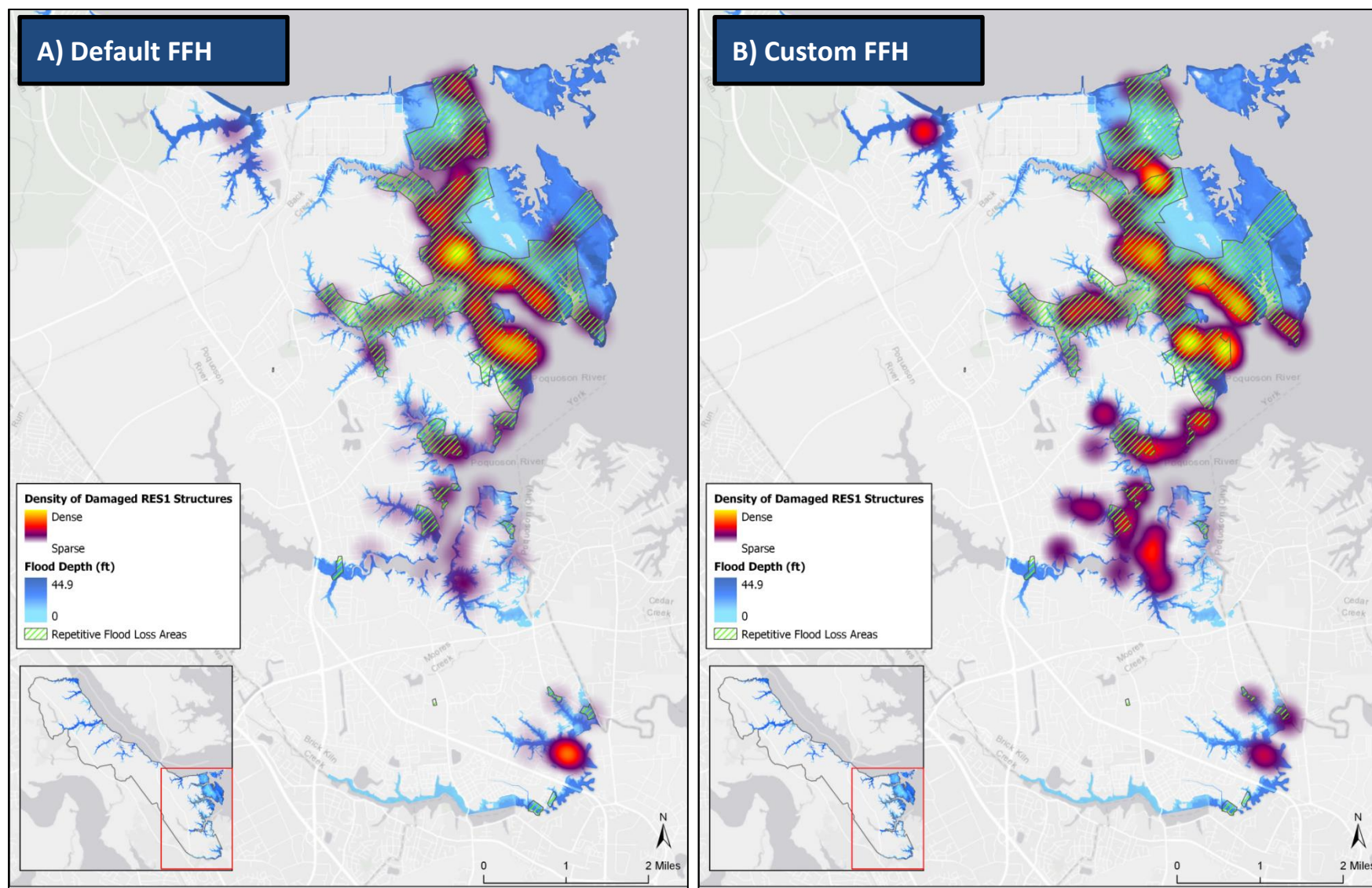


Figure 22: Distribution of individual structures with estimated flood damage weighted by the value of the loss for the 1% annual chance flood event in York County. Yellow indicates dense areas of high value losses.

Case Study Comparisons and Limitations

Within each case study community, the estimated dollar losses from flood damage were highly sensitive to changes in FFH. Estimated dollar losses were highest at the census block analysis scale and lowest when using custom FFH estimates at the individual structure level (Table 20).

Table 20: Summary of losses for each FFH scenario under the 1% annual chance flood event in each community. Values are displayed as total estimated dollar loss and as a percent of total structure exposure replacement value.

Case Study Community	Census Block Building Losses	Default FFH Building Losses	Custom FFH Building Losses
Chesapeake	\$219.2 M (14.5%)	\$ 39.0 M (2.6%)	\$ 17.1 M (1.1%)
Hampton	\$295.4 M (15.6%)	\$ 96.2 M (5.1%)	\$ 86.5 M (4.6%)
York County	\$ 77.9 M (11.8%)	\$ 19.9 M (3.0%)	\$ 5.5 M (0.8%)

The Hazus assumption of equal distribution of structures across the census block likely contributes to inflated building losses relative to the individual structure analysis. For example, within a given census block in Chesapeake, the Hazus estimated building losses were \$4.4M using the GBS inventory; however, the losses were only estimated to be \$164K in the individual structure custom FFH analysis and \$1.03 M in the default FFH analysis. Several structures were positioned just outside the SFHA, thus avoiding damage under the 1% annual chance flood scenario (Figure 23). It is important to note that the census block in Figure 23 also has a portion of the middle area removed. The Hazus flood model inventory includes dasymetric census blocks, in which the boundaries are modified to remove areas that are not developed. This decreases the overall area of the census block and helps reduce error associated with the

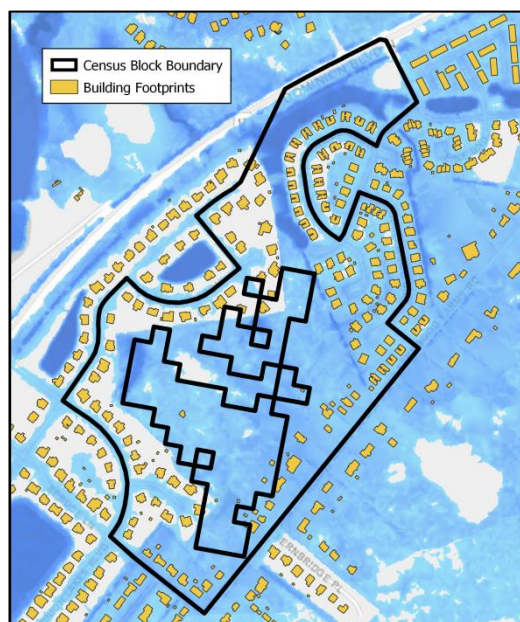


Figure 23: Example census block with uneven distribution of buildings.

equal distribution assumption. However, given the census block analysis does not include precise building locations, the assumptions of building location may still contribute to an overestimation, or in some cases underestimation, of damage compared to an individual structure level analysis.

Another important attribute of the census block analysis that contributes to higher damage estimates is the default foundation type distribution. For census blocks in the riverine floodplain, Hazus assumes a foundation distribution for RES1 structures of 23% basements, 35% crawlspace, and 42% slab structures (FEMA, 2017) (Table 21). This assumes a higher percentage of basements and slab structures within the riverine SFHA than what is observed in the Hampton Roads pilot communities (Table 21). Reducing the percent of basement foundation types would likely result in lower census block damage estimates. The foundation distribution can be adjusted in Hazus based on local assessor data. Rather than modifying the census block foundation distributions in this analysis, the individual structure level analysis was selected to more accurately reflect structure attributes and locations.

Table 21: Foundation type distribution of single-family residential structures within the riverine flood zones of the Special Flood Hazard Area for each pilot community compared to the default Hazus foundation distribution. Locality foundation distributions were based on assessor data.

Foundation Type	Hazus Foundation Distribution	Chesapeake Foundation Distribution	Hampton Foundation Distribution	York County Foundation Distribution
Pile	0%	0%	<1%	<1%
Pier	0%	<1%	<1%	1%
Solid Wall	0%	<1%	2%	9%
Basement	23%	0%	1%	1%
Crawl	35%	85%	78%	84%
Fill	0%	0%	0%	0%
Slab	42%	15%	20%	4%

Comparing the damage estimates between Hazus default and custom FFH values for only structures where elevation certificates were available provided a sensitivity analysis that excludes predictive model error. The total dollar losses were higher when using the default values rather than the elevation certificate values for each community (Table 20). This implies the default FFH assignment method may underestimate the FFH of structures in the pilot communities and consequently inflate damage estimates. It is important to note, however, that the elevation certificate sample is not random and may not reflect the true distribution of structure FFHs across the community, especially if the sample is skewed towards more recent construction. Across all three case study communities, there were several hundred elevation certificates available for crawlspace structures to support model development. Hampton had the largest abundance of Pre-FIRM elevation certificates, and also had the smallest difference in losses between the default and custom FFH losses. In Chesapeake, the number of Pre-FIRM crawlspace structures was very limited (n=12). Only one Pre-FIRM slab elevation certificate was available for Chesapeake, and only six slab structures overall were available in York County's model training data set. Based on this sampling distribution, the model FFH predictions for Pre-FIRM slab structures in Chesapeake and York County are likely higher than what is observed because the sample is biased towards new construction.

To capture the uncertainty in predictive model FFH estimates, it is important to consider the damage estimates if assuming the model overestimated or underestimated structural FFH. Table 22 reports the Random Forest predictive model absolute average error observed for each case study community. The rate of model predictions overestimating and underestimating FFH was fairly balanced across the three case study communities. The model predicted FFH underestimated the elevation certificate FFH for 48% to 56% of testing observations across the pilot communities. To assess the maximum damage within the range of average model error for each community, the average error was subtracted from each FFH estimate. Conversely, the average error was also added to each FFH estimate to assess the minimum damage estimate. Within each case study community, altering the FFH by less than one foot changes the damage estimates by hundreds of structures and millions of dollars (Table 22). This emphasizes the importance of FFH estimation accuracy. It also provides justification for exploring a range of probable FFH values and damage estimates when conducting vulnerability assessments to better account for uncertainty. It is also important to note that only building losses are presented in this report. Content losses can also be calculated through Hazus and the FAST tool. Given the focus of this analysis was on modifying the FFH input, only building losses were presented for simplicity of comparison.

Table 22: Comparison of predictive model error across case study communities. The minimum number of structures damaged and building losses represents the results when adding the average error to each FFH estimate. The maximum number of structures damaged and building losses represents the results when subtracting the average error from each FFH estimate.

Case Study Community	Testing Absolute Average Error	Custom FFH Building Losses (\$)	Range of Number of Structures Damaged	Range of Building Losses (\$)
Chesapeake	0.45 ft	\$17.1 M	977 – 1,979	\$10.7M - \$ 28.6M
Hampton	0.80 ft	\$86.5 M	2,681 – 5,516	\$42.0M - \$150.0M
York County	0.83 ft	\$5.5 M	148 – 590	\$ 3.1M - \$ 12.2M

IV. Alternative Vulnerability Assessment Approaches

Given the uncertainty associated with estimating FFH and the sensitivity of resulting damage estimates to the FFH input, a vulnerability assessment approach that considers a range of FFH values for a given structure may better capture the variability in damage estimates. The consulting firm AECOM developed a vulnerability assessment methodology that weights estimated damages for a range of FFH values by the likelihood of that FFH value occurring (Parson and Onufrychuk, 2019). For example, a crawlspace structure may have a 20% probability of having a FFH of 4ft, and only a 1% probability of having a FFH of 1ft. The respective probabilities are determined by fitting a probability density function to a distribution of observed FFH for a given structure type (Parson and Onufrychuk, 2019). For a specific flooding scenario, the losses associated with each possible FFH value are estimated for a given structure and then multiplied by the associated probability (Parson and Onufrychuk, 2019). By adding the weighted loss values, a cumulative damage estimate is produced that captures a range of possible FFH values (Parson and Onufrychuk, 2019).

To evaluate the feasibility of this approach within the Hampton Roads region, FFH distributions were developed using the City of Hampton’s elevation certificates. Hampton was selected among the case-study communities because of the robust sample of elevation certificates that includes an abundance of both Pre- and Post-FIRM structures. In the Random Forest model analysis for Hampton,

foundation type and year built had the highest variable importance scores among the evaluated predictor variables. Based on this result, FFH distributions were developed for three classes of structures that encompassed most (96.2%) of the Hampton elevation certificate data: (1) Slab foundation, (2) Pre-FIRM crawlspace foundation, and (3) Post-FIRM crawlspace foundation (Figure 24). The same training data sample applied in Random Forest model development was used to build density distributions, representing 80% of the available elevation certificates. The remaining 20% was reserved for comparing results to the estimated damages when using elevation certificate FFH values. Slab structures were not divided into Pre- and Post-FIRM given the narrower range of FFH values.

Intervals of 0.5ft were selected to capture a range of FFH values. A kernel density estimate was developed for each subset of data using normal distribution kernels³. The probability of a value falling within each FFH interval was calculated as the area under the kernel density function. A complete R script for formatting the data and calculating the probability values is available in Appendix E. The FFH values and associated probabilities were applied to the testing data set for each distribution category and output to a .CSV file for application in the FEMA FAST tool. The FAST tool calculated the associated building dollar losses for each value. Each dollar loss was then multiplied by the corresponding FFH probability to determine the weighted dollar loss, as presented in Table 23, for an individual slab foundation structure.

The estimated losses for the Hampton testing data set resulting from the probability-based approach were compared to the losses if using the FFH value from the elevation certificate. The total probabilistic estimated losses were \$367K greater than the losses calculated from the elevation certificate values (Table 24). This difference is attributed to larger loss estimates specifically in the Post-FIRM and slab categories. The losses for the testing data set were also calculated using the values predicted by the Hampton Random Forest model and the default Hazus FFH foundation types. The Random Forest predictive method overestimated losses by approximately \$3K, and the default values overestimated damage by approximately \$346K, relative to the elevation certificate damages (Table 24).

³ A kernel density estimate is the result of aggregating individual kernels, such as the normal distribution, centered on each individual data point. This creates a smoother and more detailed representation of the data structure than a histogram (Hughes, 2013).

Table 23: A summary of estimated building losses for FFH ranging from 0 to 3ft for a given slab structure. Note that the most likely value of 1ft has the highest associated probability. The weighted loss is a product of the building loss multiplied by the associated probability.

First Floor Height (ft)	Building Losses	Probability (%)	Weighted Loss
0	\$ 33,898	2.8	\$ 949
0.5	\$ 32,437	15.9	\$5,158
1	\$ 19,287	31.5	\$6,075
1.5	\$ 3,215	23.8	\$ 765
2	\$ 0	16.2	\$ 0
2.5	\$ 0	6.2	\$ 0
3	\$ 0	1.9	\$ 0
Total Damage			\$12,947

Table 24: Comparison of estimated losses for the structures with elevation certificates reserved for the Hampton testing data set (n=107) by FFH estimation method.

FFH Estimation Method	Post-FIRM Crawlspace	Pre-FIRM Crawlspace	Slab	Total
Elevation Certificate	\$ 244,690	\$ 586,177	\$257,160	\$1,088,027
Random Forest Analysis	\$ 378,851	\$ 463,398	\$248,887	\$1,091,136
Probabilistic Estimation	\$ 542,572	\$ 581,648	\$330,716	\$1,454,936
Default Value	\$ 461,735	\$ 567,804	\$404,808	\$1,434,347

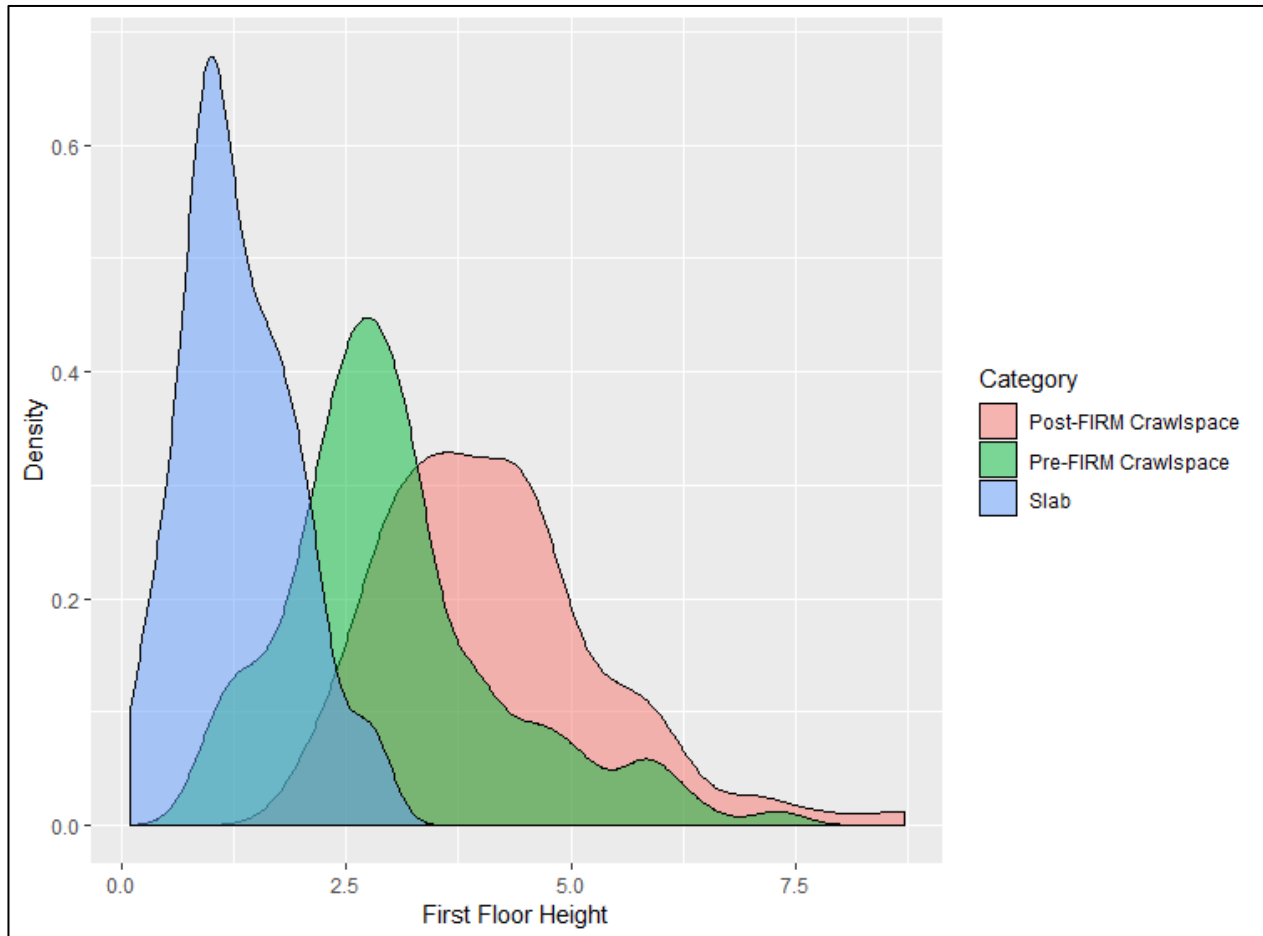


Figure 24: Distribution of FFH values from elevation certificates for three structure categories: (1) slab foundation, (2) Pre-FIRM crawlspace foundation, and (3) Post-FIRM crawlspace foundation. Fitted curves were developed through kernel density estimation.

Given the limited size of the testing data set, the estimated losses were also calculated using the probability-based approach for all RES1 structures of the appropriate foundation types in the SFHA. The custom value estimate corresponds with the Hampton result in the Coastal Hazard Vulnerability Assessments section of the report and includes FFH estimates from elevation certificates, Random Forest analysis, and Google imagery. The default value estimate also corresponds with the previously reported Hampton result where FFH estimates from Hazus reference tables were applied. For structures with different foundation types from selected crawlspace and slab categories (2.8% of observations), the custom value losses were used. The probabilistic flood loss estimate of \$98.5M is greater than both the custom and default FFH value flood losses (Table 25). Although it is difficult to determine which of the three flood loss estimates is most accurate without additional observational data, including the

probabilistic approach suggests that the range of flood building losses for the 1% annual chance flood event for RES1 structures within the Hampton SFHA is likely between \$86.5M and \$98.5M.

Table 25: Estimated building losses for single-family residential structures within the Hampton Special Flood Hazard Area using three different FFH estimation methods.

FFH Estimation Method	Building Losses	Difference Relative to Custom Values
Custom Value	\$ 86,518,587	---
Default Value	\$ 96,188,582	\$ 9,669,995
Probabilistic Estimation	\$ 98,494,364	\$ 11,975,777

To apply a probabilistic approach in other communities, distribution functions could be developed for similar categories of structures, as well as additional categories, such as structures with a garage under the living space for York County. Another consideration that may improve the probability estimates is to shift the distributions based on location. Within the Random Forest analysis, land elevation (DEM) value was also a relatively important predictor. Future research could include grouping buildings by foundation type, year built, and land elevation given a sufficient sample size for probability distribution development. While this methodology was tested in a single locality, regional distributions combining data from multiple localities could also be developed and compared to individual locality distributions to determine if the analysis could be implemented at a larger scale.

The FFH distributions developed by Parson and Onufrychuk (2019) were based on stair count observations. For communities with more limited samples of elevation certificates, FFH data could be supplemented with stair counts to develop distributions. Although the probabilistic approach will not result in the assignment of a specific FFH for development of the regional FFH database, the ability to capture a suite of possible FFH values in the damage estimate helps to estimate the likely range of building losses.

V. Conclusions and Next Steps

Flooding vulnerability assessments support local hazard mitigation planning and projects to improve community resiliency. Building FFH is a key input in flood vulnerability analysis that directly impacts the estimated flood losses. This analysis used elevation certificates to inform development of statistical models that estimate FFH. When compared to observed FFH values, the FFH model predictions result in lower estimation error than the default FFH estimates derived from FEMA's Hazus reference tables.

Although the modeling approach offers the advantage of generating FFH estimates for thousands of structures within minutes, it is limited by the availability of elevation certificates that represent the community building stock. Most communities do not have comprehensive observational FFH data. Developing local and regional databases of FFH information will likely require the application of multiple methods. While the imagery-based methods evaluated in this report do not require building attribute data, they are more labor intensive given each structure must be reviewed individually. Of the alternative imagery-based methods evaluated, counting stairs appeared to be more efficient in terms of time and accuracy than imagery measurements. The FFH estimation methods can help inform a more strategic sampling approach if resources become available for additional field data collection.

Flood damage estimates are highly sensitive to FFH and other flood vulnerability assessment assumptions. In addition to evaluating FFH estimation methods, this study also evaluated vulnerability analysis approaches that differed in terms of scale and data requirements. The three different vulnerability methods tested included: (1) a census block scale analysis using default Hazus inventory data, (2) individual structure level analysis with default Hazus FFH values (default FFH method), and (3) individual structure level analysis with custom FFH values from local data and model predictions (custom FFH method). Estimated flooding damages were highest at the census block analysis scale and lowest when using custom FFH estimates at the individual structure level. Where feasible, localities should utilize individual structure analysis to provide a more accurate assessment of flooding vulnerability. In addition, building damage estimates were higher when using default FFH estimates than custom FFH estimates. While the custom FFH model estimates may more accurately estimate the FFH for structures similar to those in the elevation certificate sample, the model predictions are less reliable for structure types not represented in the elevation certificate sample. Additional data gathering could increase the accuracy of the modeling approach. The vulnerability assessment methods comparison found that

changing FFH by less than a foot can increase or decrease flood damage estimates by hundreds of structures and millions of dollars across the community. Using a probability-based method that considers a range of FFHs could help account for the uncertainty in FFH values and variability in resulting flood loss estimates.

Vulnerability analyses support prioritization and design of flood mitigation projects at the local level and can assist communities in conducting benefit-cost analysis required for some competitive grant applications. Local government staff can also use FFE data for a variety of applications, such as identifying vulnerable structures, developing project proposals, or evaluating potential policy changes. While the 1% annual chance flood event was selected as the hazard scenario for this analysis, the methodologies evaluated in this study can be applied to other coastal hazard scenarios, including storm surge and sea level rise.

This report documents the second phase of a three-year regional FFE initiative. Within the third phase, the FFE dataset will continue to be expanded across the region and best practices will be documented for other entities interested in applying similar FFE estimation or vulnerability assessment approaches. Coordination with entities conducting research related to FFE and coastal hazards will support the development of complimentary products. Continued research and innovation in FFE data development and vulnerability assessment techniques will provide support for the upcoming Hampton Roads regional all-hazards mitigation plan update and local government resiliency efforts.

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VIII. Appendices

Appendix A: FEMA Hazus First Floor Height Reference Tables

The following table summarizes the Hazus default FFH values, reported in feet, by foundation type, flood zone, and FIRM-status. This table is adapted from FEMA's Multi-hazard Loss Estimation Methodology Flood Model Hazus-MH Technical Manual (Table 3.11 and Table 3.14, FEMA, 2017).

<i>Foundation Type</i>	<i>Pre-Firm FFH</i>	<i>Post-FIRM FFH (Riverine)</i>	<i>Post-FIRM FFH (Coastal A zone)</i>	<i>Post-FIRM FFH (Coastal V zone)</i>
Pile	7	8	8	8
Pier/Post/Beam	5	6	6	8
Solid Wall	7	8	8	8
Basement/Garden Level	4	4	4	4
Crawlspace	3	4	4	4
Fill	2	2	2	2
Slab	1	1	1	1

Appendix B: Python Script for Collecting Google Street View Imagery

```
#Script to download and save Google Street View images through Google API. Please note an individual
#Google API key is required.
#Resources
#Letchford, A. (2018). Streetview. https://github.com/robolyst/streetview
#Martin, A.W. (2017) SimpleGoogleStreetView2.pyde
#https://github.com/awmartin/spatialpixel/blob/master/Sketches/Intro/SimpleGoogleStreetView2/SimpleGoogleStreetView2.pyde
#Wen, R. (2019). Google-streetview 1.2.9 https://pypi.org/project/google-streetview/

#Import google_streetview for the api module
import os
import google_streetview.api #Wen, R. (2019).

#Define parameters for street view api

params = [{

    'size': '640x640', #max 640X640 pixels
    'location': ' ', #Enter coordinates in decimal degrees.
    'heading': '0',
    'fov': '60',
    'pitch': '0',
    'key': ' ' #Enter unique Google API Key.

}]

#Create a results object
results = google_streetview.api.results(params)

#Download images to specified directory 'downloads'
results.download_links(' ')#Provide local directory name.

#Download metadata
results.save_metadata('metadata.json')
```

Appendix C: Replacement Cost Calculation for Residential Structures

The structural replacement cost in Hazus is based on published R.S. Means Values for industry-standard cost-estimation (FEMA, 2017). For single-family residential structures, socio-economic data from the Census is applied to identify construction classes and associated replacement cost models (FEMA, 2017). Buildings are classified as Economy, Average, Custom, or Luxury based on the census block income ratio (I_k) as shown in Table 26.

Table 26: Income ratio ranges for selecting and weighting R.S. Means building classifications. Values correspond with the weight applied to the R.S. Means cost per square foot when calculating replacement cost. Adapted from Hazus Technical Manual (Table 14.5, pg 14-15. FEMA, 2017).

Income Ratio (I_k)	Luxury	Custom	Average	Economy
$I_k < 0.5$				1
$0.5 \leq I_k < 0.85$			.25	.75
$0.85 \leq I_k < 1.25$		.25	.75	
$1.25 \leq I_k < 2.0$		1		
$I_k \geq 2.0$	1			

The Hazus software includes reference tables for identifying R.S. Means values of cost per square foot. The R.S. Means values vary by construction classification, number of stories, and the presence of a basement (Table 27). These average national values are further adjusted by a regional factor provided in the Hazus software (Table 28).

Using values from the above reference tables, the structure replacement cost is calculated using the following formula (FEMA Risk Map CDS, 2016):

$$\text{BLDG_SQFT} * \text{RS_Means} * \text{Reg_Factor}$$

- BLDG_SQFT: Building Square Footage as reported in the assessor's database.
- RS_Means: 2018 RS Means Cost per square foot, weighted by income class for single-family residential structures.
- Reg_Factor: Regional adjustment factor for replacement cost calculation.

For example, the replacement cost for a \$2,000 square foot, two-story, single-family residential home with an income ratio between 0.85 and 1.25 located in Chesapeake would be calculated as follows:

$$2,000\text{ft} * (\$163.95/\text{ft} * 0.25) + (\$122.75/\text{ft} * 0.75)) * 0.95 = \$252,795 \text{ replacement cost value.}$$

For structures with a basement, an additive adjustment of additional cost per square foot of the structure is applied because the R.S. Means values do not consider basements in the base cost of the structure (FEMA, 2017). For structures with a partial basement, the basement additional cost was only applied to the corresponding square footage (i.e. half of structure's square footage for a half basement foundation type). Unless otherwise specified in the assessor data, all basements were assumed to be unfinished.

An additional adjustment can be made for structures with attached and detached garages. Given limited data on the type of garage in the assessor database and a different FFH for a garage compared to the main structure, garage replacement costs were not accounted for in this analysis.

Table 27: R.S. Means values representing cost per square foot for estimating structure replacement cost. Values copied from Hazus software reference tables.

Description	Height Class	Average Base Cost	Finished Basement Cost	Unfinished Basement Cost
Economy	1 story	97.61	26.45	9.55
Economy	2 story	104.04	15.20	6.30
Economy	3 story	104.04	15.20	6.30
Economy	Split level	96.69	15.20	6.30
Average	1 story	116.66	32.80	11.25
Average	2 story	122.75	21.05	7.40
Average	3 story	127.94	16.65	5.80
Average	Split level	113.66	21.05	7.40
Custom	1 story	159.51	53.65	21.65
Custom	2 story	163.95	30.90	12.90
Custom	3 story	168.69	22.50	9.60
Custom	Split level	153.15	30.90	12.90
Luxury	1 story	188.84	59.00	22.65
Luxury	2 story	194.94	34.55	13.85
Luxury	3 story	201.09	25.50	10.40
Luxury	Split level	181.61	34.55	13.85

Table 28: Regional location factors for adjusting R.S. Means values by community.

Locality	Regional Factor
Chesapeake	0.95
Hampton	0.95
York County	0.96

Appendix D: Methodology for Assigning Building Point Locations for Flood Vulnerability Analyses

The following steps outline the GIS methodology for assigning points to the Lowest Adjacent Grade (LAG) of a building for application in the flood vulnerability analysis. This analysis was adapted from Esri guidance (2019) and applied in ArcGIS Pro (v 2.2.0).

1. Convert building footprint polygons to lines using the Feature to Line tool.
2. Run Zonal Stats (Spatial Analyst Toolbox) with the statistic set to minimum and the zone set to a unique identifier for the building footprint lines.
3. Apply the resulting Zonal Stats output raster and the Digital Elevation Model (DEM) in the Raster Calculator tool with the following command:

- a. `Con (DEM == LAG, DEM)`

If a cell in the DEM raster equals the LAG value, the cell is retained. Otherwise, the cell is replaced with No Data.

4. Apply the resulting Raster Calculator output raster in the Raster to Point tool. This converts raster cells to point value, retaining the original DEM elevation value.
5. Run a Spatial Join of the resulting points and building footprints using “closest” to add necessary attributes for the flood vulnerability analysis.
6. To confirm that all building footprints which intersect the Special Flood Hazard Area (SFHA) have a point located within the SFHA boundary, run an Intersect function between the building footprints and SFHA polygon.

For structures where the LAG point location did not intersect the SFHA, but another portion of the building footprint does, the point was relocated to the maximum flood depth value using the same workflow as above with the depth grid substituted for the DEM. The maximum value was selected to identify maximum flood depth. The final point layer for the flooding vulnerability analysis is a combination of the LAG locations and locations adjusted for maximum depth where necessary.

Appendix E: Methodology for Probabilistic Vulnerability Assessment in R

```
#Script to determine probabilities and format dataset for probabilistic vulnerability assessment approach.  
#Hampton selected as case study community because of large abundance of Pre/Post-FIRM Structures.  
#Develop separate probability density functions for crawlspace Pre-firm structures, crawlspace Post-firm  
#structures, and slab structures.
```

```
#References:
```

```
#Brownlee, Jason. A Gentle Introduction to Probability Density Estimation.  
#https://machinelearningmastery.com/probability-density-estimation/
```

```
#Moss, Jonas and Tveten, Martin. Package 'kdensity'.  
#https://cran.rproject.org/web/packages/kdensity/kdensity.pdf
```

```
#Moss, Jonas. Tutorial for kdensity. https://cran.r-project.org/web/packages/kdensity/vignettes/tutorial.html
```

```
#Stack overflow. Repeat rows of a data.frame. https://stackoverflow.com/questions/11121385/repeat-rows-of-a-data-frame
```

```
#Statistical tools for high-throughput data analysis (STHDA). qplot: Quick plot with ggplot2-R software and data  
visualization.http://www.sthda.com/english/wiki/qplot-quick-plot-with-ggplot2-r-software-and-data-visualization
```

```
#Load necessary packages
```

```
library(arcgisbinding)  
arc.check_product()  
library(kdensity)  
library(EQL)  
library(dplyr)  
library(ggplot2)
```

```
#Load Hampton Training Data
```

```
gis_TrainHA <- arc.open(path =  
'K:/PHYS/PROJECTS/FFE/Hampton/HamptonFFEgdb.gdb/HA_TRAIN_NEW_FINAL_DEM')
```

```
#Save as data frame
```

```
TrainHA <- arc.select(gis_TrainHA)
```

```
#-----Slab Distribution Development-----
```

```
#Subset by category slab
```

```
attach(TrainHA)  
Slab_TrainHA <- TrainHA[which(Category=='Slab'),]  
detach(TrainHA)
```

#Build a probability density function for the continuous variable Finished First Floor Height.

#Steps:

1) Review the density of observations in the sample with a simple histogram

2) Use a kernel density estimator to fit a density function with the kdensity R package. Take the area under the curve using the integrate function to estimate the probability of a structure's FFH falling within that range of values.

#Step 1:

```
attach(Slab_TrainHA)
```

```
h<-hist(Finished_FirstFloorHeight, breaks=16)
```

#Check normality

```
qqnorm(Finished_FirstFloorHeight)
```

```
qqline(Finished_FirstFloorHeight)
```

#Step 2:

```
kdeSlab <- kdensity(Finished_FirstFloorHeight, kernel='gaussian')
```

```
plot(kdeSlab)
```

```
lines(kdeSlab,col='red')
```

#Determine the probabilities at appropriate 0.5ft intervals ranging from 0 to 3.

```
integrate(kdeSlab,0,0.25)
```

```
integrate(kdeSlab,0.25,0.75)
```

```
integrate(kdeSlab,0.75,1.25)
```

```
integrate(kdeSlab,1.25,1.75)
```

```
integrate(kdeSlab,1.75,2.25)
```

```
integrate(kdeSlab,2.25,2.75)
```

```
integrate(kdeSlab,2.75,3)
```

```
detach(Slab_TrainHA)
```

#Create vectors of the desired FFH values and associated probabilities.

```
hSlab <- c(0,0.5,1,1.5,2,2.5,3)
```

#Probability vector with values from integrate functions above.

```
pSlab<-c(0.028,0.159,0.315,0.238,0.162,0.062,0.019)
```

#-----Pre-FIRM Crawlspace Distribution Development-----

#Step 1:

```
attach(TrainHA)
```

```
PreCrawl_TrainHA<- TrainHA[which(Category=='Pre-FIRM Crawlspace'),]
```

```
detach(TrainHA)
```

```
attach(PreCrawl_TrainHA)
```

```
h<-hist(Finished_FirstFloorHeight, breaks=16)
```

#Check normality

```
qqnorm(Finished_FirstFloorHeight)
```

```
qqline(Finished_FirstFloorHeight)
```

#Step 2:

```
kdePreCrawl <- kdensity(Finished_FirstFloorHeight, kernel='gaussian')  
plot(kdePreCrawl)  
lines(kdePreCrawl, col='red')
```

#Determine the probabilities at appropriate 0.5ft intervals ranging from 1 to 7.5.

```
integrate(kdePreCrawl, 1, 1.25)  
integrate(kdePreCrawl, 1.25, 1.75)  
integrate(kdePreCrawl, 1.75, 2.25)  
integrate(kdePreCrawl, 2.25, 2.75)  
integrate(kdePreCrawl, 2.75, 3.25)  
integrate(kdePreCrawl, 3.25, 3.75)  
integrate(kdePreCrawl, 3.75, 4.25)  
integrate(kdePreCrawl, 4.25, 4.75)  
integrate(kdePreCrawl, 4.75, 5.25)  
integrate(kdePreCrawl, 5.25, 5.75)  
integrate(kdePreCrawl, 5.75, 6.25)  
integrate(kdePreCrawl, 6.25, 6.75)  
integrate(kdePreCrawl, 6.75, 7.25)  
integrate(kdePreCrawl, 7.25, 7.5)
```

```
detach(PreCrawl_TrainHA)
```

#Create vectors of the desired FFH values and associated probabilities.

```
hPreCrawl <- c(1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5)
```

#Probability vector with values from integrate functions above.

```
pPreCrawl <- c(0.029, 0.074, 0.126, 0.206, 0.204, 0.117, 0.066, 0.047, 0.036, 0.026, 0.026, 0.01, 0.004, 0.003)
```

#---Post-FIRM Crawlspace Distribution Development-----

#Step 1:

```
attach(TrainHA)  
PostCrawl_TrainHA <- TrainHA[which(Category == 'Post-FIRM Crawlspace'),]  
detach(TrainHA)
```

```
attach(PostCrawl_TrainHA)
```

```
h <- hist(Finished_FirstFloorHeight, breaks=16)
```

#Check normality

```
qqnorm(Finished_FirstFloorHeight)  
qqline(Finished_FirstFloorHeight)
```

#Step 2:

```
kdePostCrawl <- kdensity(Finished_FirstFloorHeight, kernel='gaussian')  
plot(kdePostCrawl)  
lines(kdePostCrawl, col='red')
```

#Determine the probabilities at appropriate 0.5ft intervals ranging from 2 to 8.5.

```
integrate(kdePostCrawl,1.75,2.25)
integrate(kdePostCrawl,2.25,2.75)
integrate(kdePostCrawl,2.75,3.25)
integrate(kdePostCrawl,3.25,3.75)
integrate(kdePostCrawl,3.75,4.25)
integrate(kdePostCrawl,4.25,4.75)
integrate(kdePostCrawl,4.75,5.25)
integrate(kdePostCrawl,5.25,5.75)
integrate(kdePostCrawl,5.75,6.25)
integrate(kdePostCrawl,6.25,6.75)
integrate(kdePostCrawl,6.75,7.25)
integrate(kdePostCrawl,7.25,7.75)
integrate(kdePostCrawl,7.75,8.25)
integrate(kdePostCrawl,8.25,8.75)
```

```
detach(PostCrawl_TrainHA)
```

#Create vectors of the desired FFH values and associated probabilities.

```
hPostCrawl <- c(2,2.5,3,3.5,4,4.5,5,5.5,6,6.5,7,7.5,8,8.5)
```

#Probability vector with values from integrate functions above.

```
pPostCrawl<-c(0.031,0.081,0.139,0.162,0.162,0.151,0.098,0.064,0.047,0.021,0.013,0.009,0.005,0.006)
```

#-----Create and Export Data for Vulnerability Analysis-----

#Overlay plots of the kernel density distributions from the training data for each of the categories.

#Remove outlier values

```
attach(TrainHA)
```

```
plotTrainHA<- TrainHA[which(Category!='Outlier'),]
```

```
detach(TrainHA)
```

```
attach(plotTrainHA)
```

```
qplot(Finished_FirstFloorHeight, data=plotTrainHA, geom='density', kernel='gaussian', fill=Category, alpha=I(0.5),
xlab="First Floor Height", ylab="Density")
```

```
detach(plotTrainHA)
```

#Load Hampton data for SFHA structures that will be applied in vulnerability assessments.

```
gis_HARES1 <- arc.open(path =
'K:/PHYS/PROJECTS/FFE/Hampton/HazusdataFINAL.gdb/Hampton_UDF_RES1_Custom_Default_FINAL_LatLon')
```

#Save as data frame

```
HA_RES1 <-arc.select(gis_HARES1)
```

#Subset data by category: Pre-FIRM Crawl, Post-FIRM Crawl, and Slab

```
attach(HA_RES1)
```

```
SlabHA<- HA_RES1[which(Category=='Slab'),]
```

```

PostCrawlHA<- HA_RES1[which(Category=='Post Crawl'),]
PreCrawlHA<- HA_RES1[which(Category=='Pre Crawl'),]

detach(HA_RES1)

#Create multiples of the original dataset. Each = number of FFH values in distribution for that foundation type.
dfSlab<-SlabHA %>% slice(rep(1:n(), each=7))
dfPostCrawl<- PostCrawlHA %>% slice(rep(1:n(), each=14))
dfPreCrawl<-PreCrawlHA %>% slice(rep(1:n(), each=14))

#Duplicate values in the vector by the number of structures of that foundation type.

hSlabR<-rep(hSlab,2910)
pSlabR<-rep(pSlab,2910)

hPostCrawlR<-rep(hPostCrawl,3697)
pPostCrawlR<-rep(pPostCrawl,3697)

hPreCrawlR<-rep(hPreCrawl,6773)
pPreCrawlR <- rep(pPreCrawl,6773)

#Create a new column using mutate that assigns a new FFH value to each row.

attach(dfSlab)
dfProbSlab<-dfSlab %>% mutate(FirstFloorHt=hSlabR, Probability=pSlabR)
detach(dfSlab)

attach(dfPreCrawl)
dfProbPreCrawl<-dfPreCrawl %>% mutate(FirstFloorHt=hPreCrawlR, Probability=pPreCrawlR)
detach(dfPreCrawl)

attach(dfPostCrawl)
dfProbPostCrawl<-dfPostCrawl %>% mutate(FirstFloorHt=hPostCrawlR, Probability=pPostCrawlR)
detach(dfPostCrawl)

#Write output to a CSV for use in vulnerability analysis tool.

write.csv(dfProbSlab,file="C:\\OpenHazarus_POC_demo\\ProbMethodData\\Hampton_Probability_Slab.csv")
write.csv(dfProbPreCrawl,file="C:\\OpenHazarus_POC_demo\\ProbMethodData\\Hampton_Probability_PreCrawl.csv")
write.csv(dfProbPostCrawl,file="C:\\OpenHazarus_POC_demo\\ProbMethodData\\Hampton_Probability_PostCrawl.csv")

```