MODELING OF THE POTENTIAL IMPACTS OF A HURRICANE STRIKING HAMPTON ROADS WITH INCREASED SEA LEVEL

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EXECUTIVE SUMMARY

Catastrophic hurricane events in other areas of the country often elicit our posing the question, "What if the storm had made landfall over my region?" Modeling of possible variants in storm track, intensity, and baseline environmental conditions can be used to broadly answer this question and to provide valuable information to emergency managers, elected officials, and the citizenry. As we strive to build more economically and socially resilient communities, understanding how sea-level rise amplifies the impact of a hurricane is paramount of planning, preparation, and mitigation efforts.

If mean sea level rises by 3 feet, which is the current prediction for the end of the century, physical damages would double from the current estimate, to over $40 billion.

Only days before Hurricane Florence's landfall at Wilmington, North Carolina in 2018, several models predicted the possibility of a direct landfall near Hampton Roads, Virginia. Fortunately, this did not transpire, yet predictive modeling of physical damages allows us to estimate the potential impacts as if the storm had come ashore in the Commonwealth. Furthermore, by altering the modeling environment to account for sea level rise we examine how flooding impacts could increase if a hurricane were to strike Hampton Roads in the future.

Modeling of a Florence-like Category 1 storm at present-day sea level making landfall near Virginia Beach and travelling westward through Hampton Roads predicted significant flooding and estimated physical damages, including impairment to critical emergency services, in excess of $20 billion. As sea level continues to rise, future storm surges will build upon an elevated platform. If the mean sea level rises by the predicted 1.5 feet by 2050, a storm similar to Florence making landfall in Hampton Roads would generate over $30 billion in physical damage, with a preponderance of damage due to flooding. If mean sea level rises by 3 feet, which is the current prediction for the end of the century, physical damages would double from the current estimate, to over $40 billion. Our modeling also revealed disparities amongst Hampton Roads localities in both dollar damage amounts and expected percentage increases in damage with rising sea level. Cities with the most exposed coastline and low-lying areas were predicted to have highest total cost in flood damages. Norfolk ranked first, suffering between $6 billion (present sea level) and $16 billion (+3 feet sea level) in damages.

These estimates consider only physical damages to infrastructure currently in place and are calculated in present-day $USD without adjustments for inflation. Additional in-depth economic analyses are necessary to develop a more complete picture of the total future costs of this storm's impact.

BACKGROUND

On the morning of Friday, September 14, 2018, Hurricane Florence made landfall as a Category 1 storm near Wilmington, North Carolina. Despite a reduction in wind speed, this wide and slow-moving storm dropped over 30 inches of rain in some parts of the state. Extreme precipitation in combination with storm surge resulted in widespread flooding that damaged or destroyed tens of thousands of structures.

What would have happened if Florence had made landfall directly at and through the major population centers and heavily developed areas of Hampton Roads?

In the aftermath of the storm, a detailed impacts assessment was provided by the North Carolina Office of State Budget and Management (OSBM). The NC OSBM concluded that Florence caused nearly $17 billion in total damage and loss, with a significant portion coming in the form of direct economic loss and property damage.[1] Of these losses, research firm CoreLogic concluded that actual insured flood losses for Florence totaled between $5 billion and $9 billion.[2]

Only days before landfall, on September 11th, Florence was a Major Category 4 hurricane with maximum sustained winds of 140 mph and was expected to strengthen.[3] The future path of the storm was still highly uncertain with several forecast model runs predicting landfall near Virginia Beach and the mouth of the Chesapeake Bay, directly impacting the Hampton Roads region on September 15-16. **FIGURE 1** illustrates possible Hurricane Florence tracks modeled on September 11, 2018.

In preparation for this potentially catastrophic possibility, many schools and businesses in Hampton Roads announced closures and municipal leaders began implementing pre-storm action plans. The decision by Virginia Governor Ralph Northam to order mandatory evacuation for approximately 250,000 residents living in Evacuation Zone A underscored the seriousness of the risk posed by the storm. Mobilization, action, and preparation were driven by the fundamental question, "What if Florence strikes our region?"

In the days following the storm, a collective sigh of relief was breathed in coastal Virginia as the aftermath of Florence's devastating winds, rainfall, and storm surge on the Carolinas became fully realized. This near-miss event prompted many in State and local governments to rephrase that fundamental question. What would have happened if Florence had made landfall directly at and through the major population centers and heavily developed areas of Hampton Roads?

In a recently published report entitled "An Analysis of the Potential Costs and Consequences of a Hurricane Impacting the Virginia Beach-Norfolk-Newport News Metropolitan Area" researchers

1. https://files.nc.gov/ncosbm/documents/files/Florence_Report_Full_rev20181016v10.pdf
2. https://www.corelogic.com/insights-download/storm-surge-report.aspx
3. https://www.nhc.noaa.gov/archive/2018/al06/al062018.public.048.shtml?

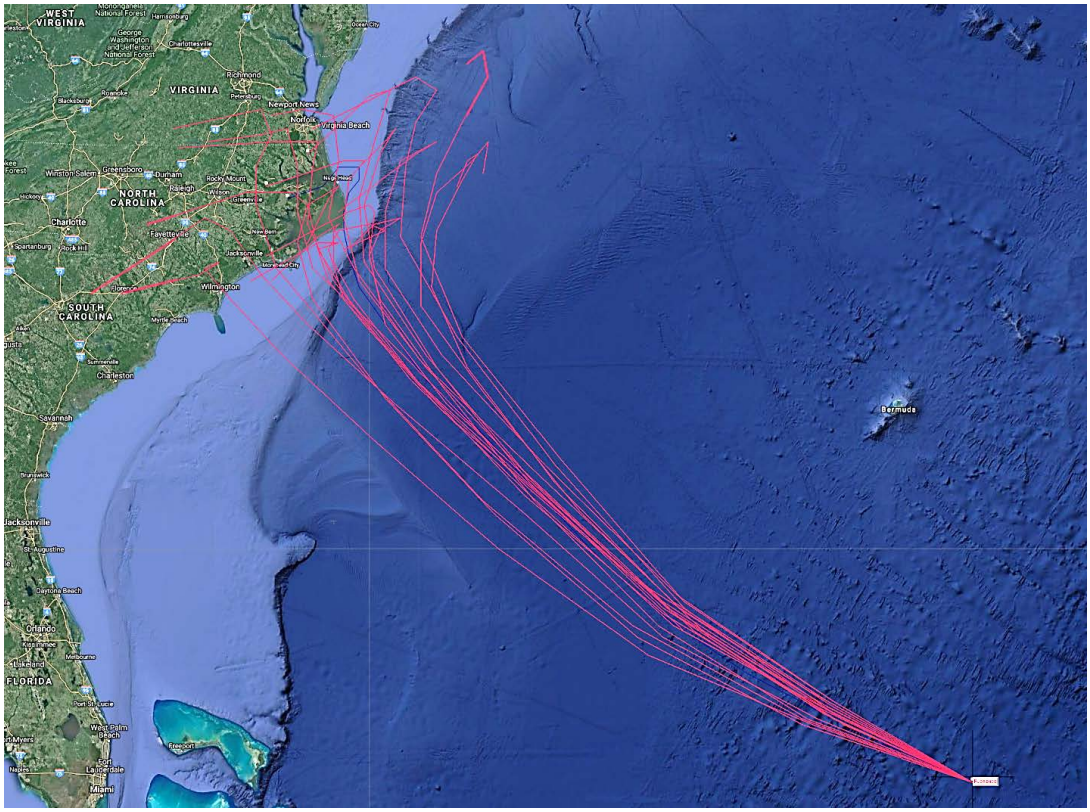
posed that very question and estimated that physical damages resulting from a Florence type hurricane striking Hampton Roads would approach $18 billion.[4] Model calculations revealed that approximately 38,000 structures in Hampton Roads would be damaged, 2.4 million tons of debris would be generated, and over 200,000 people would be immediately displaced following the storm.

Calculations of physical damages only represented a portion of the total impact on the economy. Impacts such as inability to work, reduction or closure of businesses, and impairment of major transportation infrastructure (i.e. highways, ports, railways) would ripple through the economy, resulting in an estimated total impact in excess of $25 billion.[4] Damage of this magnitude would make Florence by far the costliest hurricane to impact the Commonwealth, exceeding by ten-fold the $2.5 billion total of Isabel (2003).

However, it is important to realize that these damage estimates represent a single snapshot in time for a hurricane occurring with present-day sea level. It is critical for us to endeavor to understand the potential future impacts of a similar storm as sea level continues to rise in Hampton Roads.

FIGURE 1

Plot of GEFS Forecast Data for Hurricane Florence Track Valid at September 11, 2018, at 00 UTC



Source: NOAA – Hurricane Forecast Improvement System. https://ruc.noaa.gov/tracks/

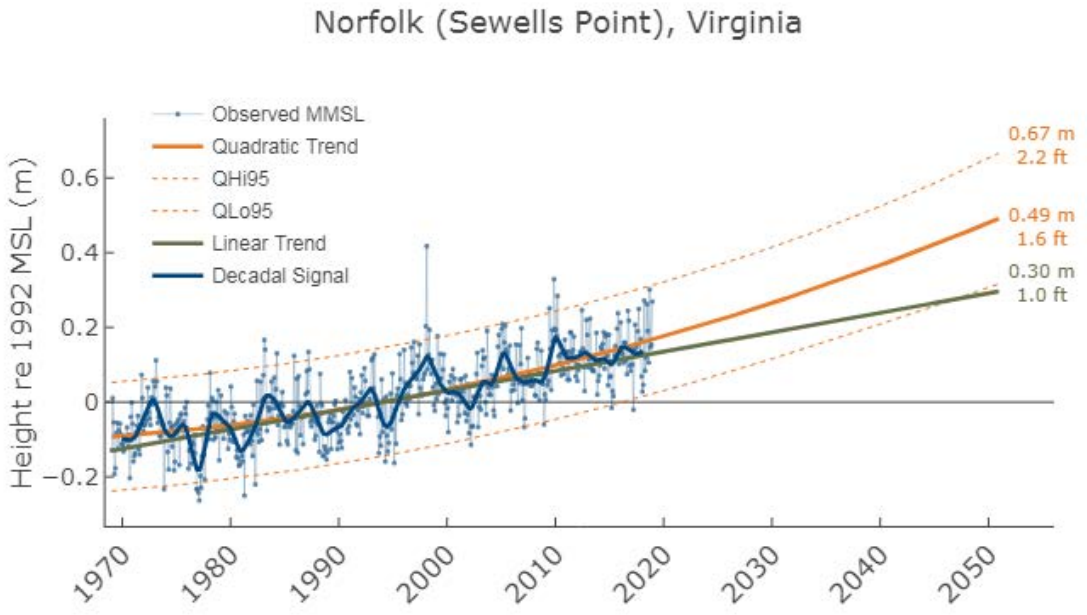
4. McNab, R., Argarwal, V., Komerek, T., Blake, B., McLeod, G., Hutt, S., and E. Steinhilber. 2019. An Analysis of the Potential Costs and Consequences of a Hurricane Impacting the Virginia Beach-Norfolk-Newport News Metropolitan Area. Commonwealth Center for Recurrent Flooding Resiliency Report 9. 42pp. https://www.floodingresiliency.org/Florence/

SEA LEVEL RISE

The Hampton Roads region is a hotspot for sea level rise, increasing at approximately double the estimated rate of global sea level rise.[5] The rate of sea level rise in the mid-Atlantic is higher for several reasons including: local subsidence from groundwater withdrawal and settling of sub-structural fill, regional subsidence resulting from glacial isostatic rebound, and changes in ocean surface elevation related to ocean circulation dynamics and weakening of the Gulf Stream current.[6] **FIGURE 2** details the latest projections of sea level change for the Sewells Point tide station in Norfolk, VA.[7]

FIGURE 2

Sea Level Rise Prediction of 1.6 ft (0.49m) for Norfolk, VA by 2050



Source: Virginia Institute of Marine Science, College of William and Mary. https://doi.org/10.21220/V5T17T

5. Ezer, T., and L. P. Atkinson (2014), Accelerated flooding along the U.S. East Coast: On the impact of sea-level rise, tides, storms, the Gulf Stream, and the North Atlantic Oscillations, Earth's Future, 2, 362–382, doi:10.1002/2014EF000252.

6. Atkinson, L., Ezer, T., and E. Smith. 2013. Sea Level Rise and Flooding Risk in Virginia. Sea Grant Law and Policy Journal, 5(2), 3-14.

7. Boon, J. D., Mitchell, M., Loftis, J. D., & Malmquist, D. M. (2018) Anthropocene Sea Level Change: A History of Recent Trends Observed in the U.S. East, Gulf, and West Coast Regions. Special Report in Applied Marine Science and Ocean Engineering (SRAMSOE) No. 467. Virginia Institute of Marine Science, College of William and Mary. https://doi.org/10.21220/V5T17T

As early as 2008, state officials were taking notice of this trend. The Governor's Panel on Climate Change recognized the serious threats posed to coastal Virginia from sea level rise and inundation including wetland and habitat loss, incapacitation of critical military installations and impairment of national defense readiness.[8] In Norfolk and throughout Hampton Roads, Mitchel et al. (2013) reported that increases in sea level, precipitation, and storm frequency would likely result in increased severity of flooding events.[9]

Hampton Roads location at the convergence of the Atlantic Ocean, Chesapeake Bay, and several rivers and bordered on the south by Back Bay/Currituck/ Albemarle Sounds makes the region especially vulnerable to changes in sea level. There is very little natural slope and large contiguous areas are uniformly elevated. These characteristics are critical in that they allow for potential wide-spread flooding of both residential and commercial areas when sea level and storm surges reach certain heights.

A recent report by CoreLogic identified the Virginia Beach metropolitan area (Hampton Roads) as 5th in the nation for storm surge risk posed to single-family homes and 10th in the nation for storm-surge exposure for multi-family dwellings.[10] Recognizing that vulnerability to storm surge increases as the "platform" of sea level is elevated leads us to explore the impacts of a hurricane such as Florence under future sea level conditions. Accordingly, we have replicated modeling of the direct physical impacts of Hurricane Florence on Hampton Roads with an additional 1.5 feet and 3 feet of future sea level rise.

8. Bryant, L. 2008. Governor's Commission on Climate Change, Final Report: A Climate Change Action Plan. 156pp.

9. Molly Mitchell et al. 2013. Recurrent Flooding Study for Tidewater Virginia, Virginia Sensate Document No. 3. 141pp.

10. https://www.corelogic.com/insights-download/storm-surge-report.aspx

HURRICANE IMPACTS MODELING

As with our prior modeling of Florence's impact with present-day sea level, we again employed the HAZUS model to generate the damage estimates for our simulated storm making landfall over Hampton Roads with the addition of sea level rise. The HAZUS model is a GIS-based regional multi-hazard model, developed by the Federal Emergency Management Agency (FEMA) and the National Institute of Building Sciences (NIBS) to "assist in risk-informed decision-making efforts by estimating potential losses from earthquakes, floods, hurricanes, and tsunamis and visualizing the effects of such hazards."[11]

HAZUS modeling represents possible future scenarios which are based on state-of-the-art scientific and engineering knowledge and software architecture.

Actual historical data for Florence were used as input parameters for impacts modeling. Wind speed, pressure, track geometry, time of storms location, and radius of maximum winds all remained unchanged from the original storm. **FIGURE 3** displays a GOES-16 infrared satellite image of the position of the storm (Category 4) on September 12, 2018.

The storm track was modified towards the north (+3° latitude) to result in Hurricane Florence making landfall in southern Virginia Beach and directly impacting the Hampton Roads area. **FIGURE 4** illustrates the adjusted track.

Loss estimates caused by wind and flood which are generated by HAZUS include:

- Physical damage – damage to various building stock
- Economic loss – incorporates loss associated with damages to businesses, estimated workforce losses due to damages to buildings that prevent employees from returning to work, etc.
- Social impacts – societal impacts due to individuals being displaced based on the amount of damage caused by a storm

The methods within the HAZUS Flood Model are commonly used by federal, state, and local agencies for planning studies and are considered "reasonable." Uncertainties are inherent in any loss estimation methodology and may arise from incomplete scientific knowledge concerning floods and their effects upon buildings and facilities, or from approximations that are necessary for comprehensive analyses.[12]

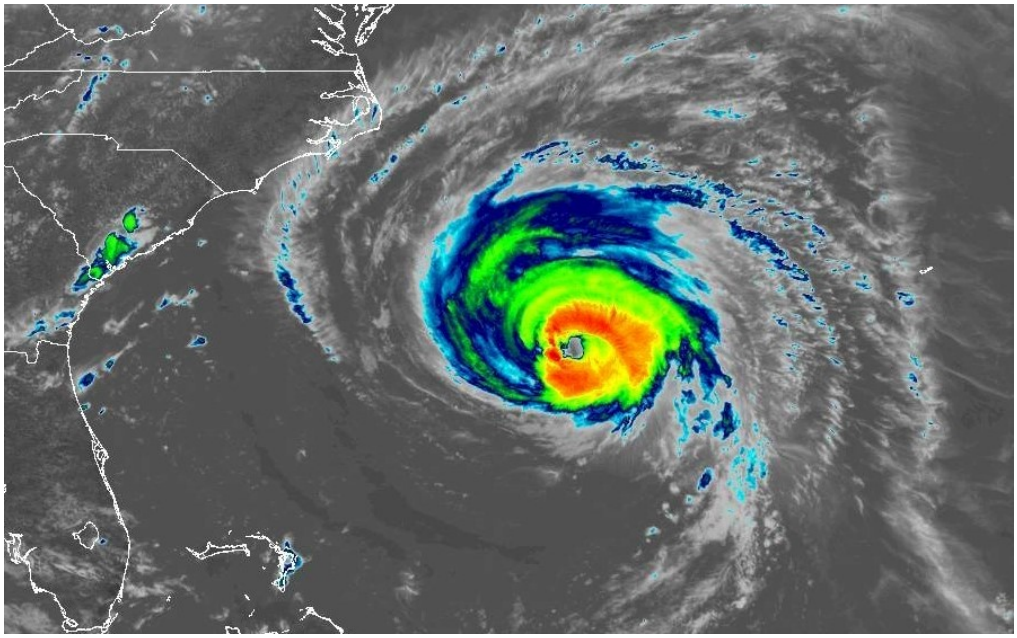
HAZUS modeling represents possible future scenarios which are based on state-of-the-art scientific and engineering knowledge and software architecture. These estimates are most valuable when used in concert with expert knowledge and related information as the basis for developing mitigation plans and policies, emergency preparedness and response, and recovery planning, and to inform other synergistic research efforts.

11. https://www.fema.gov/hazus-detail

12. https://www.fema.gov/media-library-data/20130726-1820-25045-8814/hzmh2_1_fl_um.pdf

FIGURE 3

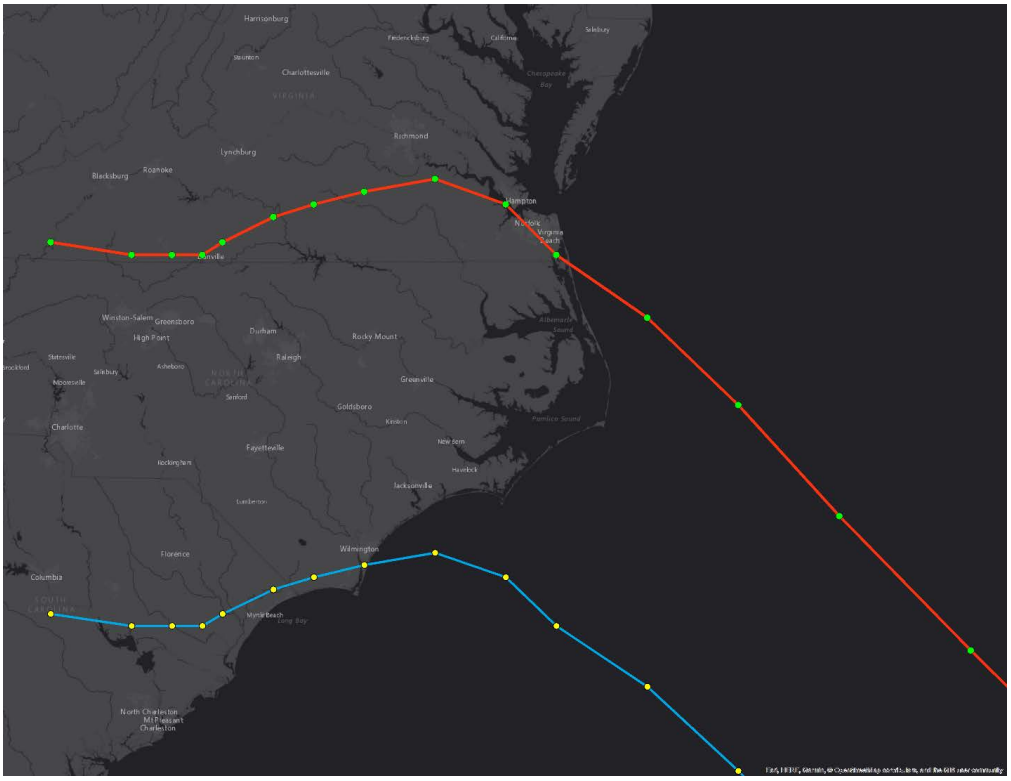
Infared Image of Florence Captured by GOES-16 on September 12, 2018



Source: NOAA

FIGURE 4

Original Path of Florence (blue) Shown with Modified Path (red) Making Landfall at the Virginia Coast



WIND DAMAGE

As we did not modify the strength or category of the storm for this analysis, the HAZUS model holds the wind damages constant for all sea level scenarios. If Florence were to have made landfall in southeastern Virginia, approximately 107,260 or 18% of all buildings in Hampton Roads would suffer some form of wind damage. This figure includes an estimated 2502 buildings that would be either severely damaged or completely destroyed. Building-related economic losses are estimated to total nearly $5 billion (**TABLE 1**). Approximately 91% of theses losses are in the form of direct property damage with the remainder being business interruption-related costs.

If Florence were to have made landfall in southeastern Virginia, approximately 107,260 or 18% of all buildings in Hampton Roads would suffer some form of wind damage.

TABLE 1

Building-Related Economic Loss Estimates from HAZUS Hurricane Model

Category	Residential	Commercial	Industrial	Others	Total
Property Damage					
Building	3,132,647,680	145,555,030	42,377,080	38,595,530	3,359,174,320
Content	996,107,790	50,136,380	29,453,780	12,883,350	1,088,581,310
Inventory	0	1,260,420	5,445,120	297,480	7,003,020
Subtotal	**4,128,754,470**	**196,951,830**	**77,275,980**	**51,776,360**	**4,454,758,650**
Business Interruption					
Income	130,410	18,849,060	584,680	4,004,140	23,568,290
Relocation	211,432,000	3,052,800	3,155,360	7,837,180	252,953,340
Rental Income	98,693,710	16,303,940	494,660	788,360	116,280,660
Lost Wages	305,380	18,998,010	970,510	18,800,100	39,074,000
Subtotal	**310,561,500**	**84,679,820**	**5,205,200**	**31,429,790**	**431,876,300**
Total	**4,439,315,970**	**281,631,650**	**82,481,180**	**83,206,150**	**4,886,634,950**

Source: HAZUS (2019). Figures may not sum exactly to totals due to rounding.

Losses were predicted for every locality in Hampton Roads, with many totaling in the hundreds of millions or billions (Virginia Beach) of dollars. When considering these losses as a percentage of the building stock for each municipality, the impact of Florence's winds was the strongest in Virginia Beach (2.95%), Chesapeake (1.8%), Norfolk (1.5%), and Portsmouth (1.43%), with others trailing closely behind. **TABLE 2** details the direct economic losses resulting from wind damages related to buildings for each municipality in the region. Capital Stock losses include building and contents damage as well as inventory loss. Income losses include relocation expense, lost capital, lost wages, and rental income loss.

TABLE 2

Direct Economic Losses Caused by Wind Damage for Buildings by Municipality

Locality	Capital Stock Losses	Loss Ratio	Income Losses	Total Loss
Chesapeake	669,295,000	1.8	57,075,000	726,370,000
Franklin	6,653,000	0.57	392,000	7,045,000
Gloucester	78,313,000	1.09	3,082,000	81,395,000
Hampton	192,212,000	0.87	8,458,000	200,670,000
Isle of Wight	20,845,000	0.35	789,000	21,634,000
James City County	107,719,000	0.73	3,137,000	110,856,000
Newport News	133,610,000	0.53	10,057,000	143,667,000
Norfolk	544,955,000	1.51	69,961,000	614,916,000
Poquoson	23,857,000	0.94	618,000	24,475,000
Portsmouth	175,812,000	1.43	21,994,000	197,806,000
Southampton	16,789,000	0.68	568,000	17,357,000
Suffolk	69,411,000	0.56	3,262,000	72,673,000
Surry	6,695,000	0.65	232,000	6,927,000
Virginia Beach	2,287,843,000	2.95	248,559,000	2,536,402,000
Williamsburg	10,037,000	0.41	502,000	10,539,000
York	110,714,000	0.79	3,188,000	113,902,000
Total	**4,454,758,000**	**1.6**	**431,876,000**	**4,886,634,000**

Source: HAZUS (2019). Figures may not sum exactly to totals due to rounding

WATER DAMAGE WITH INCREASED SEA LEVEL

Flooding-related damages occur mostly adjacent to the ocean, bays, rivers, and other low-lying flood-prone areas. As would be expected, HAZUS modeling predicts that flooding from a Florence-like hurricane would progressively increase with sea level rise. The estimates compare three scenarios given current infrastructure and building stock. Scenario 1 is Florence tracking over Hampton Roads. Scenario 2 is Scenario 1 plus 1.5 feet of sea level rise. Scenario 3 is Scenario 1 plus 3 feet of sea level rise.

At present-day sea level, it was estimated that flooding from Hurricane Florence in Hampton Roads would cause approximately $16 billion in economic losses directly related to building damages.

The estimates generated by the model for Scenario 2 and Scenario 3 are to compare how the damage estimates from a major storm increase significantly with sea level rise and, given that Hampton Roads is at greater risk of sea level rise, that the vulnerability of the region will increase more quickly than many other communities in the United States.

TABLE 3 provides an accounting of the number of parcels for each municipality and the entire region which are predicted to experience flooding at present day, +1.5 feet, and +3 feet sea levels.

According to these estimates, the Hampton Roads region as a whole could expect to experience an increase in flood-impacted parcels of approximately 53% with 1.5 feet of sea level rise and 106% with 3 feet of sea level rise. These data also reveal that storm-flooding impacts will not be uniform throughout the region. The cities of Franklin, Williamsburg, Smithfield and Southampton County are minimally impacted by surge-related flooding even as sea level rises. Conversely, localities with more coastline show a trend of sharply increasing flooding with increasing sea level.

Examination of predicted flooding for the City of Norfolk provides ample evidence of this trend. Approximately 31% (21,305) of all parcels (68,403) in Norfolk would have been partially or entirely inundated if Florence had made initial landfall at current sea level. With 1.5 feet and 3 feet of sea level rise, the percentage of impacted parcels would climb to 50% and 74%, respectively. **FIGURES 5-7** illustrate this progression for the Ocean View–Willoughby area of Norfolk by highlighting the extent of inundation and the impacted parcels.

While a larger number of buildings experience wind damage than flood damage, loss estimates reveal that the impacts of storm surge and flooding are far costlier on a per building basis. At present-day sea level, it was estimated that flooding from Hurricane Florence in Hampton Roads would cause approximately $16 billion in economic losses directly related to building damages.

TABLE 3

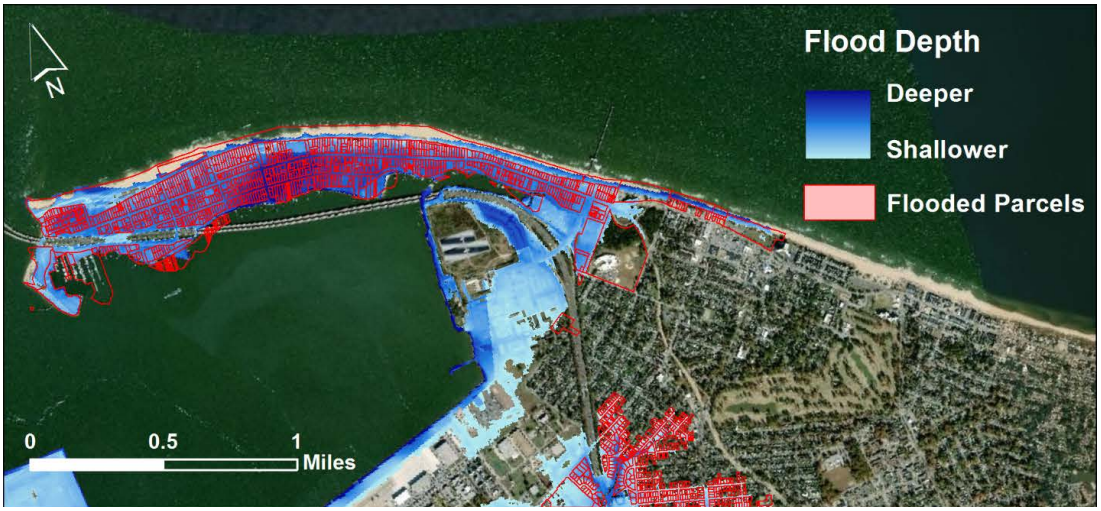
Percentage of Flooded Parcels Predicted at Present Day, +1.5 feet, and +3 feet Sea Level

Municipality	# of Parcels Total	% of Parcels Flooded, No Sea Level Rise	% of Parcels Flooded, +1.5 feet sea Level	% of Parcels Flooded, +3 feet sea Level
Chesapeake	88,725	3	13	21
Franklin	5,029	0	0	0
Gloucester	27,334	28	28	29
Hampton	51,347	45	55	61
Isle of Wight	17,308	4	4	4
James City	35,054	2	2	2
Newport News	54,087	1	4	5
Norfolk	68,570	31	50	74
Poquoson	37	100	100	100
Portsmouth	36,513	33	40	68
Smithfield	4,222	0	0	0
Southampton	15,245	0	0	0
Suffolk	40,774	2	3	3
Surry	6,676	4	4	4
Virginia Beach	161,669	5	12	17
Williamsburg	4,752	0	0	0
York	27,247	21	22	22
Total	**644,589**	**13**	**20**	**27**

Source: HAZUS (2019) – inundation. HRGEO – parcels data[13]

FIGURE 5

Flooded Areas and Impacted Parcels in Ocean View/Willoughby with Present-Day Sea Level



13. http://www.hrgeo.org/pages/regional-parcels

Modeling of Florence's flooding with increasing sea level reveals that damage estimates will naturally increase as the base water level increases. An additional 1.5 feet of sea level rise escalates direct economic loss revealed by flood damage modeling to approximately $26.3 billion. According to Virginia Institute of Marine Science forecasts, we should expect to the +1.5 feet sea level scenario to be our present-day reality near the year 2050.[7]

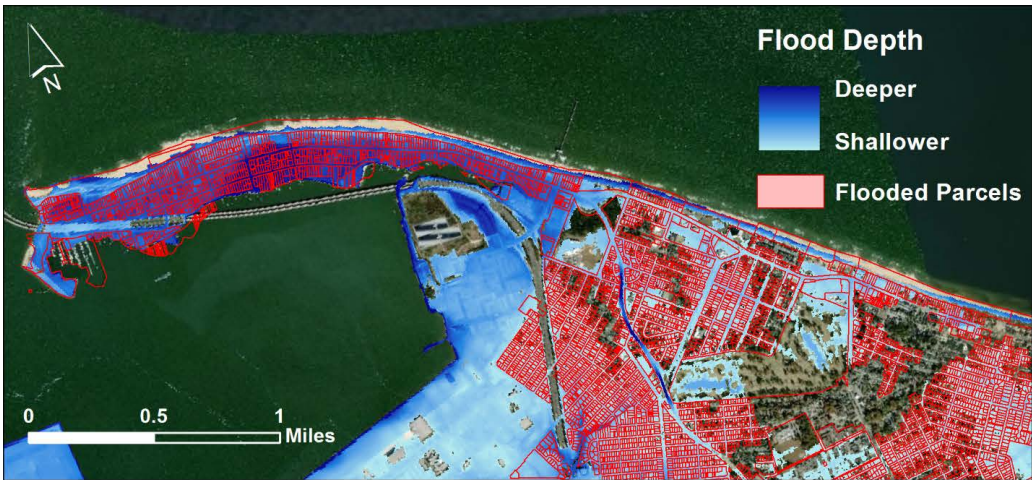
Amplification of sea level to +3 feet above today's level inflates modeled flood damages for a Florence-like storm by another $10.3 billion, to approximately $36.6 billion. **TABLE 4** provides a comparison of these direct economic loss at each increment of sea level (0 feet, +1.5 feet, +3feet).

FIGURE 6

Flooded Areas and Impacted Parcels in Ocean View/Willoughby with +1.5 feet of Sea Level Rise

FIGURE 7

Flooded Areas and Impacted Parcels in Ocean View/Willoughby with +3 feet of Sea Level Rise



7. Boon, J. D., Mitchell, M., Loftis, J. D., & Malmquist, D. M. (2018) Anthropocene Sea Level Change: A History of Recent Trends Observed in the U.S. East, Gulf, and West Coast Regions. Special Report in Applied Marine Science and Ocean Engineering (SRAMSOE) No. 467. Virginia Institute of Marine Science, College of William and Mary. https://doi.org/10.21220/V5T17T

TABLE 4

Direct Economic Loss Estimates for Flood Damage with Increasing Sea Level

Category	Present Sea Level	+1.5 Feet Sea Level	+3 Feet Sea Level
Property Damage			
Building	5,356,673,000	9,002,668,000	13,007,361,000
Content	5,125,881,000	8,476,029,000	12,135,917,000
Inventory	69,465,000	110,257,000	168,974,000
Subtotal	**10,552,019,000**	**17,588,954,000**	**25,312,252,000**
Business Interruption			
Income	1,227,714,000	2,073,942,000	2,812,123,000
Relocation	1,306,987,000	1,848,060,000	2,451,746,000
Rental	815,612,000	3,619,334,000	4,529,337,000
Wage	2,507,853,000	1,189,033,000	1,547,936,000
Subtotal	**5,858,166,000**	**8,730,369,000**	**11,341,142,000**
Total	**16,410,185,000**	**26,319,323,000**	**36,653,394,000**

Source: HAZUS (2019). Figures may not sum exactly to totals due to rounding

In addition to direct economic losses resulting from building damage, an array of related impacts would be experienced. Among those most acutely felt would be the loss of emergency infrastructure such as, police, fire, hospitals, and shelters.

TABLE 5 details the expected loss of such facilities and services as a result of a Florence-like storm directly impacting Hampton Roads with increasing sea level.

TABLE 5

Emergency Infrastructure at Least Moderately Damaged by Flooding with Increasing Sea Level

		# Facilities Impacted		
Facility Type	**Total Count**	**Present Sea Level**	**+1.5 Feet Sea Level**	**+3 Feet Sea Level**
Emergency Operations Centers	4	1	1	1
Fire Stations	63	10	12	15
Hospitals	26	4	5	8
Police Stations	63	12	15	18
Schools	561	56	103	146

Source: HAZUS (2019)

Furthermore, a hurricane of this scope will displace a significant number of households and require tens of thousands of individuals to seek short-term shelter during the storm and longer-term temporary residences afterwards. Demand for shelter of this magnitude is certain to strain the resources available to potential Hampton Roads evacuees. The Commonwealth's Annual Report on Emergency Shelter Capabilities and Readiness, released in 2018, identified a capacity to shelter 93,275 individuals in the Hampton Roads region.[14]

However, this accounting includes many facilities which may not be suitable or may be inoperable in high-wind and/or storm surge events. The report concluded that the Commonwealth would be unable to meet the shelter needs of 10,595 people during a CAT 2 storm, 45,000 people during a CAT 3 storm, and 96,000 during a CAT 4 storm.[14] **TABLE 5** details HAZUS model estimates showing a pattern of escalating displacement and shelter needs commensurate with hurricane impacts with rising sea level.

TABLE 6

Household Displacement and Shelter Requirements caused by Flooding with Increasing Sea Level

Shelter Requirements	Present Sea Level	+1.5 Feet Sea Level	+3 Feet Sea Level
Displaced Households	69,542	108,249	147,133
Shelter Required (# people)	15,821	25,309	35,279

Also noteworthy is the fact that the flooding impacts of a Florence-like storm would not be felt equally throughout the region. Municipalities having more shoreline exposure to water bodies and/or higher percentages of low-lying land areas show greater and more rapidly increasing damage estimates as sea level increases. Actual dollar damages for the City of Norfolk are predicted to be the greatest of any Hampton Roads municipality. However, economic losses for Newport News and Chesapeake are predicted to dramatically increase with sea level. **TABLE 6** ranks the top 5 Hampton Roads cities by rate of increase of predicted direct economic loss from flooding as a result of a Florence-like hurricane with sea level rise.

TABLE 7

Top 5 Hampton Roads Localities Ranked by % Increase in Hurricane Flood Damage with SLR

Locality	Flood Damages ($) Present Sea Level	Flood Damages ($) +1.5 feet Sea Level	Flood Damages ($) +3 feet Sea Level	% Increase from Present to +3 feet Sea Level
Newport News	14,713,000	256,742,000	288,932,000	1864
Chesapeake	242,306,000	2,414,828,000	4,255,419,000	1656
Virginia Beach	850,437,000	2,636,480,000	4,164,771,000	390
Portsmouth	1,948,081,000	2,746,035,000	5,286,229,000	171
Norfolk	6,556,167,000	10,507,936,000	15,705,385,000	140

14. https://rga.lis.virginia.gov/Published/2018/RD1/PDF

CONCLUDING REMARKS

Combined wind and flood physical damage losses of over $20 billion for a Hurricane Florence-like storm directly striking Hampton Roads would rank the storm among the top ten costliest hurricanes to ever strike the continental United States, even with no increase in sea level.[15] Furthermore, analysis of storm-related and ancillary impacts over the first year after landfall by McNab et al. (2019) revealed that the total impact could approach or exceed $40 billion.[4]

Modeling of potential physical damages and tightly coupled economic analysis and forecasting are invaluable for developing a clear picture of the risks posed to Hampton Roads by a major hurricane.

Increasing sea level will only exacerbate the impact of such a devastating storm, resulting in total physical damages estimated at over $30 billion with 1.5 feet of sea level rise predicted by 2050 and $40 billion with 3 feet of sea level rise by the end of the century. These damages are calculated in present-day $USD without inflation and consider neither new infrastructure nor mitigation solutions which may be developed in the coming decades. While these and other variables will determine the actual cost of storm-inflicted damages, it remains clear that rising sea level will dramatically increase the region's risk from storm flooding. Given the rapid increase in sea level in coastal Virginia relative to other communities in the United States, the consequences associated with a major hurricane making landfall are increasing. In essence, we are observing increasing risk at an increasing rate.

Modeling of potential physical damages and tightly coupled economic analysis and forecasting are invaluable for developing a clear picture of the risks posed to Hampton Roads by a major hurricane. Valuating risks at the region-scale is a must for ensuring that sufficient resources are allocated for mitigation, adaptation, and recovery efforts. Moreover, "big picture" analyses of this type often provide key insight into smaller-scale areas of vulnerability. The results of regional modeling should be used to target smaller geographic regions, such as watersheds or neighborhoods, which exhibit the highest vulnerability to the impacts of hurricane surge and flooding for further analysis. The coupling of HAZUS damage estimates with other information, such as real estate records, transportation features, utilities, and economic and business data can be invaluable for highlighting which areas and potentially critical potential failures must be addressed before a major hurricane directly strikes southeastern Virginia.

4. McNab, R., Argarwal, V., Komerek, T., Blake, B., McLeod, G., Hutt, S., and E. Steinhilber. 2019. An Analysis of the Potential Costs and Consequences of a Hurricane Impacting the Virginia Beach-Norfolk-Newport News Metropolitan Area. Commonwealth Center for Recurrent Flooding Resiliency Report 9. 42pp. https://www.floodingresiliency.org/Florence/

15. https://www.nhc.noaa.gov/news/UpdatedCostliest.pdf

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