November 2016

Costs of Doing Nothing: Economic Consequences of Not Adapting to Sea Level Rise in the Hampton Roads Region

Final Report

Prepared for

Virginia Coastal Policy Center
College of William & Mary Law School

Prepared by

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Executive Summary

The Hampton Roads region is a vital center of commerce and employment for Virginia and the Mid-Atlantic. However, because of its location, the region and its economy are particularly vulnerable to the effects of sea level rise. The combination of global climate change and relatively significant land subsidence in the region have already contributed to the highest rates of *relative* sea level rise along the U.S. East Coast. In the coming decades, sea levels are expected to continue rising, even at an accelerated pace. Projections by the Virginia Institute of Marine Science (VIMS) estimate increases of 1 to 2 meters by the end the century (Hershner & Mitchell, 2012).

Given these conditions, there is an increased urgency for developing and implementing adaptation strategies to protect coastal communities in Hampton Roads against the effects of sea level rise. One study ranked the Norfolk-Virginia Beach Metropolitan Area as 10th in the world in value of assets exposed to sea level rise (Nicholls et al., 2008). As sea levels rise and flooding events become more common in Hampton Roads, buildings and other structures in lower lying areas will become increasingly vulnerable to high water damages. The region already has a long history of floods caused by coastal storms. Unless measures are taken to adapt to rising sea levels, damages from these types of events can only be expected to increase. Adaptation approaches in coastal areas can vary widely from structural methods, such as beach nourishment and shoreline armoring, to proactive policies to discourage development in risky areas or efforts to conduct outreach for coastal evacuation during storm events. Choosing the appropriate strategies will require weighing these costs against their expected benefits.

As a first step in developing a firm understanding of how a community can benefit from adaptation, it is important to understand the potential costs and economic impacts of *not* acting. In other words, what types of damages are likely to occur if a "business as usual" approach is used? What if regional and local officials take no specific actions to moderate the negative impacts or strengthen the resiliency of coastal communities against the effects of sea level rise? In addition, how would the damages resulting from no action be expected to affect the performance of the local and regional economies? Decision makers can use estimates of these costs and impacts as an important reference point to evaluate the expected benefits of alternative adaptation strategies.

To contribute to this understanding and assist decision makers, this study analyzes the expected costs and economic impacts of sea level rise for Hampton Roads, under a scenario where no significant adaptation actions are undertaken. Based on VIMS projections, the analysis includes two main sea level rise scenarios—0.5 meters and 0.75 meters—which represent expected increases over the next 50 years.

Our analysis is divided into two main parts. The first focuses on residential properties in the Hampton Roads region and their vulnerability to coastal flooding under different sea level rise conditions. Even without sea level rise, coastal properties face risks from coastal storm surges. That is, there is always a chance of flooding, but the likelihood of major flood damage in any given year is relatively small without rising seas. Sea level rise will make these damaging events more likely. Using a risk-based (i.e., probabilistic) approach, we assess how rising seas will (1) affect the *probability* of experiencing different coastal storm surge levels and (2) increase *expected* flood damages in any given year.

For this analysis, we focus on damages to the existing housing stock, using available parcel level data for residential properties in 13 of the 16 counties and cities in the Hampton Roads region. For a scenario without sea level rise, we estimate relatively low expected annual damages of about $12 million. This value is small compared to the total value of the housing stock in these areas, but it stresses that in *most* years, particularly in the absence of sea level rise, damages due to coastal storm surges would not be expected to be very significant. In other words, the storm surges causing major damages and high costs are relatively infrequent.

With sea level rise, however, more damaging storm surges become more likely and the expected residential property damages increase substantially. With sea level rise of 0.5 meters, the total expected damages for the region increase by a factor of more than four, to over $52 million per year. An increase in sea levels of 0.75 meters further augments the expected damages by over 100 percent, to about $112 million.

Importantly, these estimates should be interpreted as lower bound estimates of the total expected residential damages to residential properties. To address data limitations and uncertainties, regarding for example the replacement costs and foundation heights of residential structures, we have taken a conservative approach in estimating these damages. Although they underestimate the actual expected damages, they nonetheless provide useful indicators of the potential magnifying effect of sea level rise on coastal storm damages. It is also important to note that this analysis does not account for the additional potential impacts from changes in future storm intensity or frequency due to climate change, because of the significant uncertainty associated with these projections. Instead, it assumes that historical storm patterns will continue, but these storms will be more damaging because of a higher sea level starting point.

For the second part of the study, we broaden the analysis to examine the implications of sea level rise impacts on the regional and state economy. Rather than focusing only on local and direct damages to residential structures, we use a multi-market macroeconomic model to estimate how flood damages to residential, industrial, and commercial structures would impose both direct and indirect costs on the broader economy. In other words, we examine how losing a portion of the region's physical capital stock would affect its productive capacity and would ripple through the region's markets for products, labor, and buildings and equipment.

In this case, to be able to include these additional dimensions, we also simplified the analysis by focusing on a specific magnitude storm event—a once per 100-year coastal storm surge—rather than applying a risk-based approach. We examine how sea level rise would affect the state and regional economic impacts resulting from such a single event. For each sea level rise scenario, we estimate the economic impacts for the single year in which the event takes place; therefore, longer-term impacts on the economy are not captured by this analysis.

Without sea level rise, we estimate that a 100-year storm event would reduce total household income in Hampton Roads in the year of the storm by $611 million ($944 per household), which is the equivalent of about 1 percent. Losses for individual income classes range from 0.1 percent for households making less than $10,000 per year to 1.2 percent for households making more than $150,000 per year. The variation in losses by income class is driven by underlying differences in the source of income. Low income households receive a majority of their income from labor while high income households tend to receive significant income from the ownership of equipment and buildings. As a result, high income households tend to bear more of the direct costs associated with damages to equipment and buildings and subsequent income losses.

In contrast, under a sea level rise scenario of 0.5 meters, we estimate that annual household income in Hampton Roads would fall by about twice as much—$1.14 billion ($1,760 per household). Under a sea level rise scenario of 0.75 meters, the impacts are almost four times as large, with annual household income in Hampton Roads estimated to fall by $2.18 billion ($3,366 per household).

In summary, using sea level rise scenarios based on the estimates by VIMS, and even with conservative assumptions, we find that sea level rise will significantly exacerbate the property damages and economic losses associated with coastal storm events and flooding.

1

Introduction

The Hampton Roads region in Virginia is a regional economic powerhouse with a significant population and valuable property, infrastructure, and ecosystems that face growing risks of flooding due to sea level rise. While global climate change causes sea levels to rise, local geologic processes are causing Southeastern Virginia to sink, resulting in the Hampton Roads region having the highest rates of relative sea level rise along the U.S. East Coast. Hampton Roads contains more than $100 billion worth of buildings, not including the vital infrastructure and strategic value of the region's defense industry and ports that drive the local economy and stimulate future growth and investment. One study ranked the Norfolk-Virginia Beach Metropolitan Area as 10th in the world in value of assets exposed to sea level rise (Nicholls et al., 2008).

Recent experiences demonstrate the damaging impacts that sea level rise can have when coupled with storm surges in coastal Virginia. Hurricane Isabel struck Hampton Roads in 2003 and caused $925 million in damage to insured properties. The hurricane produced a storm surge that was 21 percent lower than the infamous 1933 "Storm of the Century," but the maximum water levels of both storms was roughly the same due to the sea level rise during the 70 years between the two storms (Tompkins & DeConcini, 2014).

Given these types of impacts, there is increasing recognition that adaptation strategies will be essential for protecting coastal communities. Adaptation approaches in coastal areas can vary widely from structural methods, such as beach nourishment and shoreline armoring, to proactive policies to discourage development in risky areas or efforts to conduct outreach for coastal evacuation during storm events.

Virginia lawmakers are taking note of sea level rise and have begun to act. In 2015, the Virginia General Assembly passed Senate Bill 1443 requiring all localities in the Hampton Roads Planning District Commission to incorporate "strategies to combat projected sea level rise and current flooding" into their comprehensive planning processes. The bill was bipartisan and passed the Virginia House in February 2015 by a vote of 90 to 9.[12] Additionally, in 2016, the General Assembly passed House Bill 903 to create the Commonwealth Center for Recurrent Flooding Resiliency, which is a partnership between Old Dominion University, the Virginia Institute of Marine Science at the College of William & Mary, and the Virginia Coastal Policy Center at William & Mary Law School. The new center will support the Commonwealth state agencies, localities, and other entities by providing scientific and technical support furthering recurrent flooding resiliency.[13]

[12] SB 1443 Comprehensive plan; strategies to combat projected sea-level rise. 2015 Session. https://lis.virginia.gov/cgi-bin/legp604.exe?151+sum+SB1443

[13] HB 903 Recurrent Flooding Resiliency, Commonwealth Center for; at various educational institutions. 2016 Session. https://lis.virginia.gov/cgi-bin/legp604.exe?161+ful+CHAP0440.

As a first step in developing a firm understanding of how a community can benefit from adaptation, it is important to understand the potential costs and economic consequences of *not* acting. In other words, what types of damages are likely to occur if a "business as usual" approach is used? What if regional and local officials take no specific actions to moderate the negative impacts or strengthen the resiliency of coastal communities against the effects of sea level rise? In addition, how would the damages resulting from no action be expected to affect the performance of the local and regional economies? Decision makers can use estimates of these costs and impacts as an important reference point to evaluate the expected benefits of alternative adaptation strategies.

Therefore, the primary objective of this study is to analyze and estimate the expected costs and economic impacts of sea level rise over the next 50 years for the Hampton Roads region, under a scenario where no significant adaptation actions are undertaken. We begin in Section 2 by providing an overview of the Hampton Roads region and its economy and by describing sea level rise conditions and expectations for the area. In Section 3 we focus on the impacts that sea level rise will have on flood risks and damages to residential properties in the region. We apply a risk-based approach to assess how rising seas will affect the probability of experiencing different coastal storm surge levels and change expected flood damages in any given year. In Section 4, we examine the broader implications of sea level rise and associated flood damages on the regional (Hampton Roads) and state economy. Using a multi-market model, we estimate how damages to residential, industrial, and commercial structures associated with a large (100-year) flood event would impose both direct and indirect costs on the economy. We then estimate how different amounts of sea level rise would increase these regional and state-level costs. In Section 5, we summarize our findings and discuss some of the main implications and limitations of our analysis.

The Hampton Roads Region

2.1 Economy and Demographics

The Hampton Roads region has a large, diverse population and a thriving economy. People, houses, buildings, transportation infrastructure, and local businesses all face risks from flooding, which will steadily worsen over time with rising sea levels, along with associated tides and storm surges.

Hampton Roads consists of the 16 main jurisdictions[14] shown in **Figure 2-1**, including 10 cities and 6 counties, with a population of approximately 1.73 million and 625,540 households, forecasted to grow to 2.04 million and 773,200 by 2040 (see **Table 2-1**).[15] The median age is 35.3, more than 2 years younger than the national median age of 37.5. Relative to the rest of the country, a significant portion of the region's citizens are African American (30.7% in Hampton Roads compared to the national average of 12.6%; HRPDC, 2015). In 2013, per capita income in the Hampton Roads region was close to $45,000 and the economy produced goods and services worth $89 billion (Grootendorst & Clary, 2015). In all, the region represents approximately 20 percent of Virginia's total economy, income, and population.

Hampton Roads infrastructure has enormous private and public value that is susceptible to flooding. The fair market value of all buildings in Hampton Roads more than doubled to $106 billion in the 10-year period from 2000 to 2010.[16] New building permits give an indication of how many new structures investors plan on constructing each year. More than 5,000 single- and multifamily building permits were issued in 2011, with a preceding 10-year annual average of 7,300 permits.[17]

The Hampton Roads economy is anchored by the federal government, and particularly military spending, as well as major ports such as the Port of Virginia. These industries bring skilled, well-paid workers, which in turn leads to further investment and secondary growth. In addition to employment in military and federal civilian industries, Hampton Roads has high regional concentrations in industries such as real estate, accommodation and food services, construction, entertainment, and retail trade. Close to 24 percent of East Coast trade by weight passes through Hampton Roads, and 26,100 individuals work in the transportation and warehousing industries.

[14] The HRPDC includes the town of Smithfield, located within Isle of Wight County, as a 17th separate district.
[15] Although similar in population size and land area, the Hampton Roads region is distinct from the Virginia Beach-Norfolk-Newport News VA-NC Metropolitan Statistical Area, which does not include Southampton County, Surry County, or Franklin City, but does include Mathews County (VA) and Gates and Currituck Counties (NC).
[16] Data from Virginia Department of Taxation, accessed from http://www.hrpdcva.gov/page/data-book/.
[17] According to the most recent data reported by HRPDC, accessed from http://www.hrpdcva.gov/page/data-book/.

Figure 2-1. The Hampton Roads Region

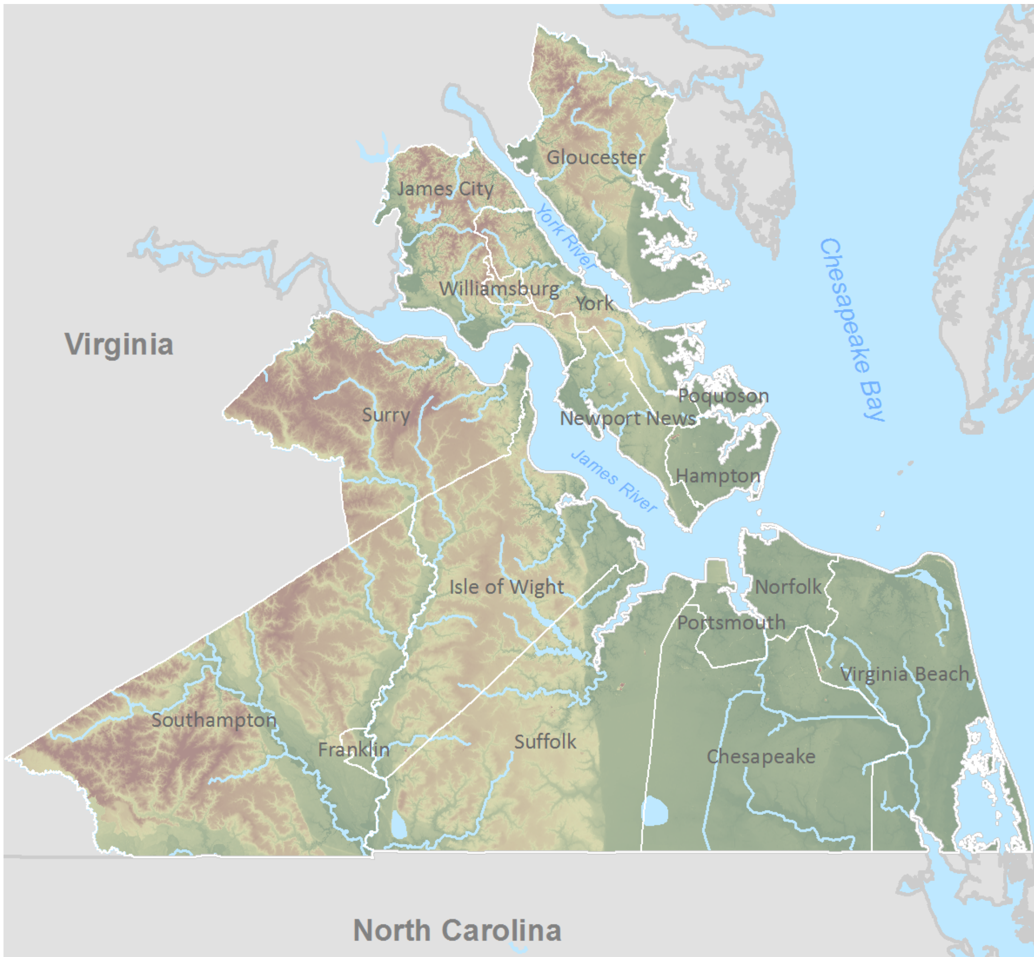


Table 2-1. Hampton Roads Population and Households

Jurisdiction	Population		Number of Households	
	2015	2040 Forecast	2010	2040 Forecast
Chesapeake City	238,283	314,600	79,574	114,300
Franklin City	8,535	10,800	3,530	4,500
Gloucester County	37,072	40,200	14,293	15,700
Hampton City	138,626	137,200	55,031	55,500
Isle of Wight County	36,438	62,800	13,713	24,700
James City County	73,325	104,200	26,860	42,300
Newport News City	183,454	189,100	70,664	74,700
Norfolk City	247,189	253,200	86,485	91,500
Poquoson City	12,359	12,400	4,525	4,700
Portsmouth City	96,874	98,200	37,324	38,700
Southampton County	18,551	25,500	6,719	9,500
Suffolk City	90,426	182,700	30,868	67,800
Surry County	6,819	8,700	2,826	3,500
Virginia Beach City	453,500	497,500	165,089	189,200
Williamsburg City	14,860	17,200	4,571	6,000
York County	69,466	82,700	24,006	30,600
Hampton Roads	**1,725,777**	**2,037,000**	**626,083**	**773,200**

Source: Hampton Roads Planning District Commission [HRPDC] (2013).

2.2 Sea Level Rise

Global sea levels have risen at a higher rate since the mid-19th century than during the previous two millennia, and this trend is expected to continue (IPCC, 2013). Although sea level rise is a global phenomenon, it can vary from region to region, making it important to use geographic-specific information for planning purposes. *Relative* sea level rise captures the relationship between sea level rise in a location and the elevation of the land, and better reflects how much sea level rise may be observed in an area where land is sinking or rising.

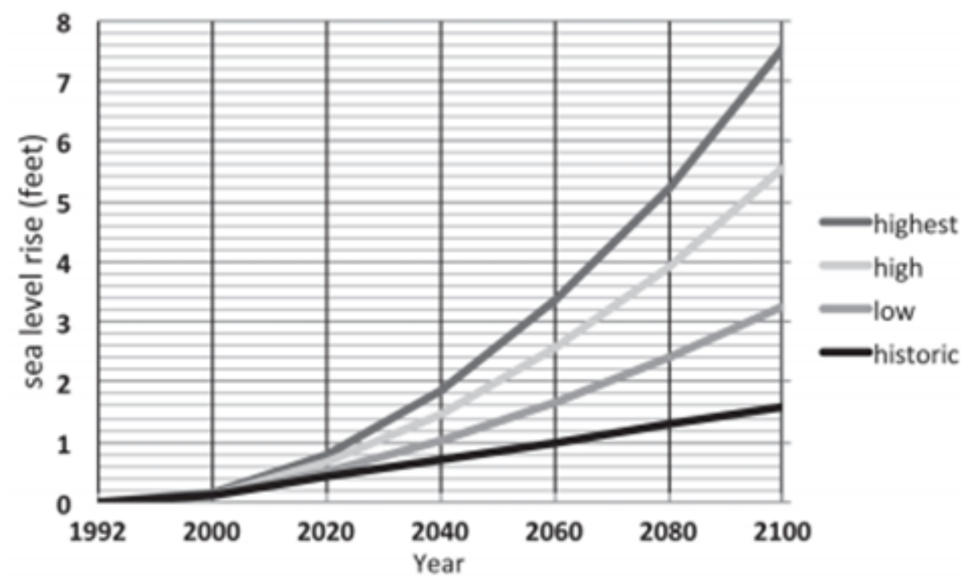
In the Chesapeake Bay, land has slowly been sinking for millions of years, primarily due to long-term geologic processes. In some localities, the land is sinking even faster due to groundwater extraction. With sea level rise and land subsidence taken together, the Chesapeake Bay experienced relative sea level rise of 3.9 mm per year during 1927–2006, which is more than double the estimated global sea level rise rate of 1.8 mm per year, and represents the highest rates of sea level rise on the Atlantic Coast of the

United States (Eggleston & Pope, 2013).[18] This could mean a 1.5 ft (0.46 m) increase in sea level by 2040.

In this study, we base our analysis on sea level rise risk projections calculated by the Virginia Institute of Marine Science (VIMS; Hershner & Mitchell, 2012). VIMS developed these risk projections based on four scenarios used in the National Climate Assessment with an adjustment that incorporates expected land subsidence. The scenarios range from a very low historic trend that extrapolates from historic average (historic) to a worst case scenario (highest) that assumes a rapid melting of all the Earth's glaciers and ice caps (see **Figure 2-2**).

Based on the mid-range ("high") estimates for the years 2040 and 2060 in Figure 2-2, we use two main sea level rise scenarios for our analysis: 0.5 m (roughly 1.5 ft.) and 0.75 m (roughly 2.5 ft.). These selected scenarios are consistent with the recommendations made by the Recurrent Flooding Sub-Panel to Virginia's Secure Commonwealth Panel regarding the sea level rise assumptions that coastal communities should use in their planning (Recurrent Flooding Sub-Panel, 2014)

Figure 2-2. Southeast Virginia Sea Level Rise Scenarios



Hershner and Mitchell (2012)

Among the primary concerns associated with sea level rise in the Hampton Roads region are potential damage to buildings and infrastructure and resulting impacts on the economy. Previous analysis has found that many physical assets in the region are vulnerable to rising seas (HRPDC, 2012); however, the risks that sea level rise pose are more complex than just physical exposure to flooding. Populations

[18] Historically, regional subsidence has represented about one half of the change in relative sea level, but the share is expected to decrease as subsidence rates remain constant while global rates of sea level rise increase (VIMS, 2013).

can be more or less vulnerable depending on the context and various economic, social, political, and environmental factors. Communities can also develop proactive adaptation strategies to reduce their vulnerability to sea level rise.

VIMS analyzed adaptation strategies for coastal Virginia according to three categories: management/retreat, accommodation, and protection. ***Management/retreat actions*** include policies to prevent or discourage development in high risk or flood-prone lands. Although these areas can be hard to identify, the study considers these to be the most practical and effective options to minimize risks and costs along the Virginia coastline. ***Accommodation actions*** help residents avoid damages by raising houses and buildings, establishing evacuation routes, developing early warning systems, and enhancing stormwater system capacity. These are currently the most common in the region, but they are also the most expensive and can encourage people to stay in increasingly hazardous areas. ***Protection actions*** typically employ engineering solutions, such as levees and storm surge barriers. These are also very expensive and can only protect a limited area.

3

Costs of Residential Property Damages with Sea Level Rise

As sea levels rise and flooding events become more common in Hampton Roads, buildings and other structures in lower lying areas will become increasingly vulnerable to damage from high water. The region already has a long history of floods caused by coastal storms. Unless measures are taken to adapt to rising sea levels, damages from these types of events can only be expected to increase.

Past experience with coastal flooding in the region also indicates that residential structures have been particularly hard hit, accounting for a large portion of the economic losses from these events. For this reason and because data describing these types of structures are relatively more available than for other types of structures, in this section we focus on residential property damages. We estimate how future sea level rise will increase the flood risks and expected damages to residential properties in the region, particularly if additional adaptive measures are not implemented.

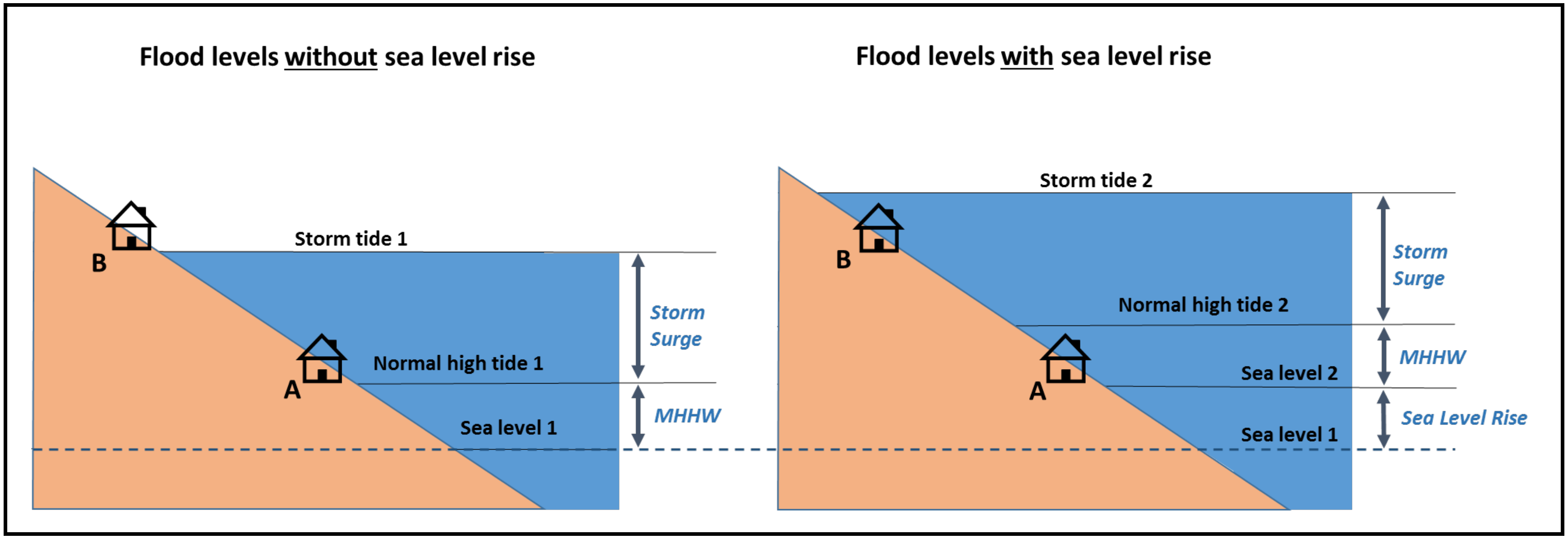
3.1 Risk-based Damage Assessment Approach

To assess the expected value of flood damages to residential properties under alternative sea level rise scenarios, we use a risk-based approach (Kirshen et al., 2012). This approach recognizes that the severity of coastal storms in any given year is not known with certainty; therefore, flood damages are uncertain. To address this uncertainty, we rely on our understanding of the probability of different sized storm events to estimate expected storm damages in any given year.

With a risk-based approach, we use historical data on storm events to observe how often storms of different sizes have occurred in the past. Assuming that these historical patterns will continue, we treat the past frequency of small and large storms (i.e., number of events per 100 years) as measures of their future probability of occurring. These probabilities act as “weights” in calculating expected flood damages for any given year in the future. The large damages associated with high impact storms are assigned relatively lower weights in the calculation because they are less likely to occur. The opposite is true of the more frequent lower impact storms with smaller damages.

For this analysis, we focus on three factors contributing to coastal flood levels, which are shown in **Figure 3-1**. The first factor is regular tidal patterns. High tides occur twice daily in the region and their levels vary from day to day in mostly predictable ways. By themselves, they are typically not a major source of flooding; however, when combined with the other two factors they can exacerbate flood damages. In Figure 3-1, they are represented by a “normal” (average) high tide level. In practice, this normal level is measured and reported by the National Oceanic and Atmospheric Administration (NOAA) as the mean higher high water (MHHW) level above sea level. The “higher high” refers to the higher of the two tides occurring each day, and the mean is the average of these measures over the monitored period.

Figure 3-1. Flood Risk Factors for Residential Structures: High Tides, Storm Surge, and Sea Level Rise



The second factor is coastal storm surges, which are associated with less frequent, less predictable, and more extreme weather events such as tropical storms and hurricanes. The height of these surges mainly depends on changes in atmospheric pressure and the associated wind speeds. These surges can cause widespread flooding in coastal areas, particularly when combined with high tide levels. As shown in Figure 3-1, the combination of storm surge and high tide levels is referred to as the storm tide level.

The third factor is sea level rise. The sources and characteristics of sea level rise in the region have been discussed in Section 2. The contribution of this factor to coastal flooding and damages is represented in Figure 3-1, by comparing conditions without sea level rise and with sea level rise. In the left-side panel, when sea levels remain at their initial level ("Sea level 1"), residential structures that are located above the normal high tide line are generally safe from tidal flooding. However, with the storm surge level shown in this figure, Structure A is assumed to be damaged or destroyed, whereas Structure B is unaffected because it is located above the combined effect of high tide and storm surge (i.e., "Storm tide 1"). In contrast, in the right-side panel, sea levels are assumed to rise to "Sea level 2." Under these conditions, Structure A now falls below the new normal high tide level ("Normal hide tide 2"). Unless specific actions are taken to protect this property, it is assumed to be a total loss. With sea level rise, Structure B is located below the new storm tide level ("Storm tide level 2") and is therefore either damaged or destroyed when the shown storm surge occurs.

For this analysis, we use a risk-based approach to address the annual uncertainty specifically associated with the second effect, storm surge. To address uncertainties associated with the other two factors, we do the following:

- Use NOAA measures of MHHW to represent the normal high tide levels in the region; and,
- As discussed previously, select two scenarios to represent sea level rise: 0.5 m and 0.75 m.

One factor not addressed in this approach is the additional effect of storm energy and wave forcing on coastal storm damages. Although water depth is a critical determinant of flood damages, the force of moving waters will cause additional damage, particularly for properties located closer to shore and more exposed to wave action. For this reason and others discussed in the report, our approach is likely to underestimate total damages from coastal storm events.

3.2 Measuring the Size and Probability of Storm Surges in the Region

To account for the effects of storm surge in our analysis, we rely on results reported by NOAA (2013) based on long-term historical water level data collected at four coastal stations in Hampton Roads. The locations of these four stations are shown in **Figure 3-2**.

Figure 3-2. Locations of NOAA Stations Measuring High Water Levels in Hampton Roads

Data from these stations provide several decades of high water observations, measured in meters above normal high tide (mean higher high water or MHHW). Based on statistical analyses of these data, NOAA reports annual exceedance probability curves for each station. For any selected high water level (X) at the station location, these curves answer the following question: ***What is the probability (in percentage terms) that the highest water level observed over a year will exceed X meters?***

The high water level corresponding to a 1 percent exceedance probability represents a storm surge event with a 100-year return period (i.e., a 100-year storm). In other words, a storm of this magnitude or greater has a 1 percent probability of occurring in any given year and therefore is only expected to occur once per 100 years or 1 percent of the time. Similarly, a 10 percent probability corresponds with a 10-year storm.

Table 3-1 reports the MHHW and the 10-year and 100-year storm tide elevations for the four NOAA stations. All elevations are reported relative to the commonly used reference standard for sea level, known as the North American Vertical Datum of 1988 (NAVD88). Without sea level rise, the normal high tides fall between 0.34 m and 0.4 m above NAVD88, and the 100-year storm tides fall between 1.64 m and 2.06 m. With sea level rise of 0.75 m, the highest 100-year storm tide elevation (at Sewells Point) increases to over 2.8 m.

Using the NOAA annual exceedance probability curves, it is also possible to estimate the probability of high water levels falling within any *range* of elevation (i.e., between X meters and Y meters above NAVD88). In other words, it can answer the following question: ***What is the probability that the highest water level over a year will be in the range between X meters and Y meters?***

Using the Sewells Point station as an example, **Figure 3-3** shows probabilities of different high water ranges (in 0.05 meter increments) under the different sea level rise assumptions. Based on historical patterns at this station, without sea level rise the most likely high water in a given year would be between 1.0 m and 1.05 m above NAVD88 (with an annual probability just of almost 11 percent). In contrast, there is a less than 2 percent chance that the interval will be between 1.4 m and 1.45 m and only about a 0.5 percent chance of being between 1.7 m and 1.75 m above NAVD88.

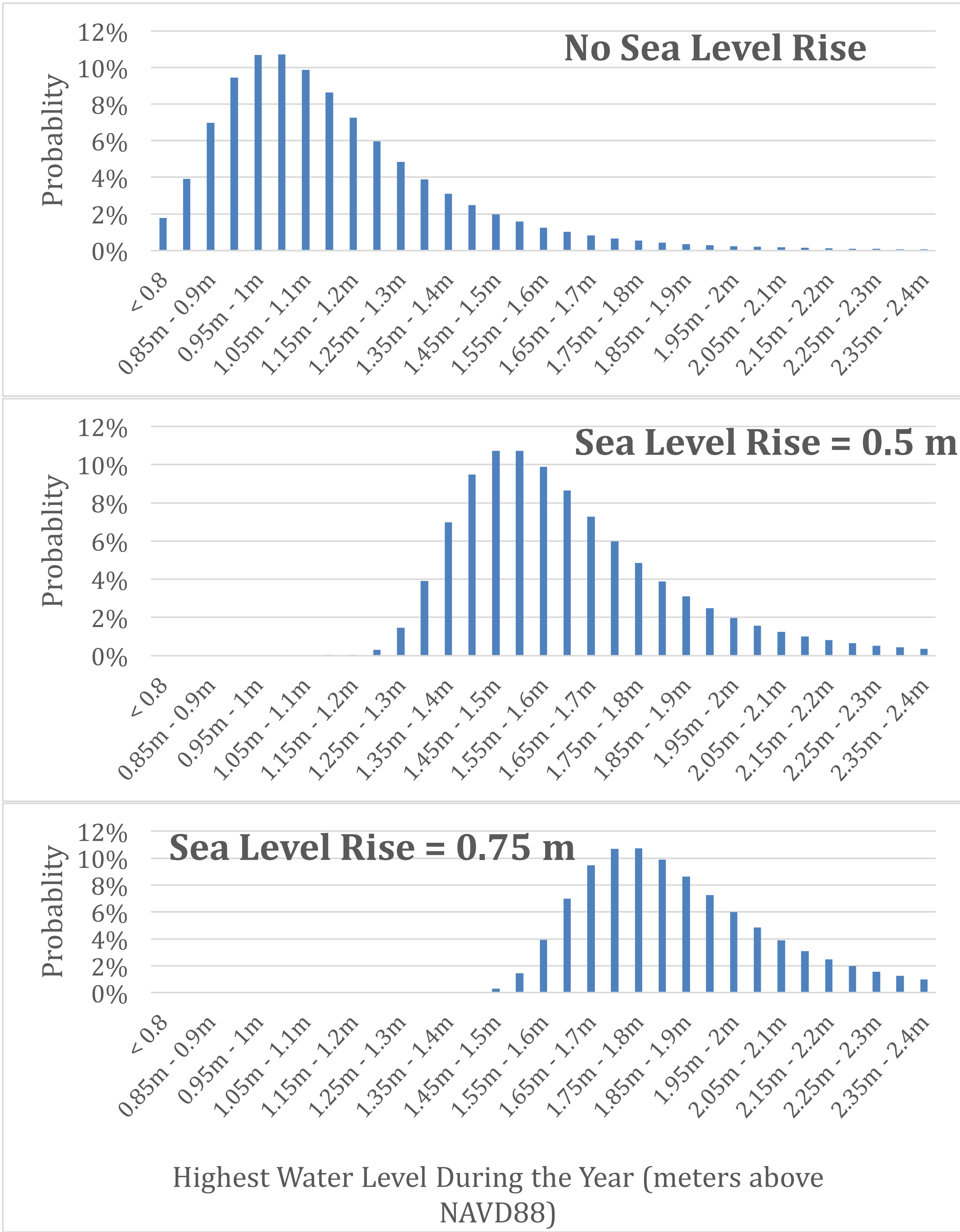
For our analysis, we account for sea level rise by shifting this probability distribution upwards to more elevated high water levels.[19] With 0.5 m of sea level rise, the most likely high water in a given year range increases from the 1.0–1.05 m range to the 1.5–1.55 m range. With 0.75 m of sea level rise, it increases to between 1.75 m and 1.8 m above NAVD88.

Table 3-1. High Water Levels at NOAA Stations in Hampton Roads (in meters above NAVD88)

	Sewells Point	Portsmouth	Chesapeake Bay Bridge-Tunnel	Gloucester
No Sea Level Rise				
100-yr storm tide	2.06	2.04	1.88	1.64
10-yr storm tide	1.46	1.52	1.39	1.25
Normal high tide (MHHW)	0.34	0.4	0.37	0.34
Sea Level Rise = 0.5 m				
100-yr storm tide	2.56	2.54	2.38	2.14
10-yr storm tide	1.96	2.02	1.89	1.75
Normal high tide (MHHW)	0.84	0.9	0.87	0.84
Sea Level Rise = 0.75 m				
100-yr storm tide	2.81	2.79	2.63	2.39
10-yr storm tide	2.21	2.27	2.14	2
Normal high tide (MHHW)	1.09	1.15	1.12	1.09

[19] More complex hydrodynamic modeling approaches would be needed to adapt this distribution to account for changes in tidal propagation through a flooding coastal plain.

Figure 3-3. Effect of Sea Level Rise on Annual High Water Probabilities (Sewells Point Station)



3.3 Identifying At-risk Residential Structures and Property Value

For any specific coastal storm event, the magnitude of flood damages to residential structures will depend on several factors, including

- the height of flood waters relative to the ground level elevation of the residential structures;
- the structural characteristics of the properties (e.g., number of stories and foundation type); and
- the value of the flood-affected structures and their contents.

To account for and measure these factors, we acquired parcel-level property tax assessment data from 13 of the 16 counties and cities in the Hampton Roads region.[20] Most importantly, these data identify the geographic location and assessed value of all residential structures in the respective districts. They also provide information regarding the type, size, and other features of structures; however, the amount and type of additional information provided for these structures varies significantly across counties. In addition, we acquired GIS data detailing the structural footprint of each parcel in the entire study area (except for Isle of Wight County).[21]

Using these data, we estimated the ground-level elevation (in meters above NAVD88) of the largest residential structure in each parcel. We estimated these elevations by overlaying the GIS shape files for each structure with georeferenced surface elevation data for the study region.[22] To assign a single elevation measure to each structure, we calculated the mean elevation of each structural footprint.[23]

Table 3-2 provides a summary overview of the potentially affected residential structures and their values. For the 13 counties and cities with available parcel data, values are reported for almost 445,000 residential properties.[24] The median value for these structures is $132,558, with a total value exceeding $73 billion. Virginia Beach accounts for almost one third of these structures and total value.

For each county, the residential structures reported in Table 3-2 are separated into three elevation zones based on the ground-level elevations of the structures. The lowest elevation range is below 1.2 m, which is roughly the sum of normal high tide plus 0.75 m of sea level rise. This range identifies the

[20] Three jurisdictions—Southampton County, Franklin, and Suffolk—were excluded from the analysis because parcel-level data containing property values were not available. The flood risks due to sea level rise are expected to be relatively small for Franklin and Southampton due to their relatively inland locations.

[21] This building footprint layer was downloaded from the Virginia GIS Clearinghouse (http://vgin.maps.arcgis.com/home/index.html).

[22] For surface elevation estimates, we acquired Digital Elevation Model (DEM) data from http://virginialidar.com/, which provides DEMs derived from Light Detection and Ranging (LiDAR) data at a 2.5-ft resolution for the entire study area

[23] Particularly for structures located on sloping terrain, using the mean rather than the maximum elevation of the structure may lead to underestimation of the first floor elevation and therefore flood damage. In the absence of structure footprint date for Isle of Wight County, we calculated and used mean parcel elevation as a proxy measure.

[24] This estimate excludes roughly 19,000 additional residential properties whose values are either missing or reported as zero in the data.

roughly 2,300 structures (with a value of about $329 million) that are most vulnerable to permanent sea level rise, even in the absence of periodic storm surges. The middle elevation range goes up to 2.8 m, which is roughly the sum of (1) normal high tide, (2) sea level rise of 0.75 m, and (3) the largest 100-year storm surge level in the region. This mid-range of vulnerability includes 68,400 structures (15% of total), with a total value of roughly $11.6 billion (16% of total). The remaining 83 percent of structures, with elevation above 2.8 m, are the least vulnerable to the combined effects of sea level rise and storm surge.

Table 3-2. Number and Value of Residential Structures in the Hampton Roads Region (by County and Elevation Range)

Jurisdiction	Number of Units[a]	Value of Structures[a]		
Ground-Level Elevation (above NAVD88)		Mean	Median	Total
Chesapeake	67,942	$174,613	$145,300	$11,862,344,100
Less than 1.2 m	202	$136,844	$117,450	$27,642,400
1.2 m to 2.8 m	9,900	$165,290	$146,200	$1,636,366,000
Greater than 2.8 meters	57,833	$176,341	$145,300	$10,198,335,700
Gloucester County	13,127	$155,248	$133,250	$2,037,934,029
Less than 1.2 m	292	$116,172	$86,160	$33,922,210
1.2 m to 2.8 m	2,046	$194,316	$146,515	$397,570,105
Greater than 2.8 m	10,789	$148,896	$132,580	$1,606,441,714
Hampton	43,693	$134,099	$106,000	$5,859,173,400
Less than 1.2 m	195	$125,870	$109,600	$24,544,700
1.2 m to 2.8 m	13,436	$139,672	$116,300	$1,876,634,800
Greater than 2.8 m	30,062	$131,661	$101,200	$2,136,815,400
Isle of Wight County	12,962	$172,514	$156,900	$2,236,124,900
Less than 1.2 m	55	$285,295	$291,500	$15,691,200
1.2 m to 2.8 m	333	$251,106	$241,700	$83,618,300
Greater than 2.8 m	12,574	$169,939	$154,450	$2,136,815,400
James City County	22,030	$266,190	$220,100	$5,864,162,000
Less than 1.2 m	11	$137,255	$117,500	$1,509,800
1.2 m to 2.8 m	522	$211,719	$172,350	$110,517,100
Greater than 2.8 m	21,497	$267,579	$221,300	$5,752,135,100
Newport News	46,360	$147,360	$110,400	$6,831,629,300
Less than 1.2 m	16	$58,781	$59,950	$940,500
1.2 m to 2.8 m	824	$87,378	$71,700	$71,999,500
Greater than 2.8 m	45,520	$148,477	$111,200	$6,758,689,300
Norfolk	53,374	$157,665	$112,400	$8,415,208,700
Less than 1.2 m	521	$152,620	$112,600	$79,515,000
1.2 m to 2.8 m	10,827	$223,304	$155,700	$2,417,708,600
Greater than 2.8 m	42,026	$140,817	$106,600	$5,917,985,100
Poquoson	4,437	$183,535	$161,500	$814,343,100
Less than 1.2 m	321	$125,425	$101,100	$40,261,400
1.2 m to 2.8 m	3,698	$180,618	$161,100	$667,924,100
Greater than 2.8 m	418	$253,966	$239,600	$106,157,600
Portsmouth	30,629	$118,653	$107,510	$3,634,214,380
Less than 1.2 m	146	$148,745	$148,590	$21,716,730
1.2 m to 2.8 m	6,273	$113,451	$100,920	$711,674,730
Greater than 2.8 m	24,210	$119,819	$109,140	$2,900,822,920
Surry	3,074	$118,920	$97,650	$365,561,100
Less than 1.2 m	36	$120,650	$121,500	$4,343,400
1.2 m to 2.8 m	46	$110,487	$79,300	$5,082,400
Greater than 2.8 m	2,992	$119,029	$97,700	$356,135,300

(continued)

Table 3-2. Number and Value of Residential Structures in the Hampton Roads Region (by County and Elevation Range) (continued)

Jurisdiction / Ground-Level Elevation (above NAVD88)	Number of Units[a]	Value of Structures[a] Mean	Median	Total
Virginia Beach	122,615	$171,455	$130,100	$20,156,262,290
Less than 1.2 m	463	$147,881	$117,500	$68,469,100
1.2 m to 2.8 m	17,672	$173,121	$131,450	$3,059,400,790
Greater than 2.8 m	99,425	$171,269	$129,900	$17,028,392,400
Williamsburg	2,854	$264,698	$173,300	$755,449,300
Less than 1.2 m	0	$-	$-	$-
1.2 m to 2.8 m	0	$-	$-	$-
Greater than 2.8 m	2,854	$264,698	$173,300	$755,449,300
York County	21,122	$208,230	$183,500	$4,398,224,400
Less than 1.2 m	67	$159,036	$135,500	$10,655,400
1.2 m to 2.8 m	2,818	$212,182	$185,600	$597,929,100
Greater than 2.8 m	18,237	$207,800	$183,200	$3,789,639,900
Hampton Roads 13 County/City Total	**444,219**	**$166,806**	**$132,558**	**$73,230,630,999**
Less than 1.2 m	**2,325**	**$141,597**	**$115,788**	**$329,211,840**
1.2 m to 2.8 m	**68,395**	**$170,136**	**$136,026**	**$11,636,425,525**
Greater than 2.8 m	**368,437**	**$166,283**	**$132,730**	**$61,264,993,634**

[a] Excludes structures with missing or $0 reported values.

3.4 Measuring Damages Due to Storm Events

As shown in Figure 3-3, the range of potential worst storm events in a given year (as measured by the highest water level) can vary widely. As a result, so can the range of damages to residential properties. To account for this uncertainty using a risk-based approach, we first generate separate damage estimates for selected high water conditions. We then weight each of these damage estimates according to their probability of occurring.

To estimate damages for a particular storm event, we assume that all residential structures whose base elevation lies at or below the storms' highest water level are at risk of damage. To estimate the extent of these damages, we use average depth-damage relationships developed by the U.S. Army Corps of Engineers (USACE) combined with estimates of the structures' foundation height.

Depth-damage relationships express damages as a percentage of a structure's total value. USACE has developed these relationships for a range of residential property types, which are characterized in particular by (1) the type of residence (e.g., single- vs. multiple-family dwellings), (2) the number of stories, and (3) the presence of a basement (USACE, 2000, 2003, 2006). They also provide separate damage estimates for the structures themselves and for the contents of residential properties. As shown in **Table 3-3**, using the example of single-family residential structures without basements, the percentage of damage increases with the flood depth. As a percentage of the structure's total value, damage is less for contents than for the structure itself, and it is less for buildings with more stories.[25]

Table 3-3. Example Depth-Damage Relationships: Single-Family Residential Structures Without a Basement

Flood Depth Relative to First Floor Elevation (feet)	Mean Damage (% of Structure Value)			
	Structure		Contents	
	One Story	Two Story	One Story	Two Story
−2	0.0	0.0	0.0	0.0
−1	2.5	3.0	2.4	1.0
0	13.4	9.3	8.1	5.0
1	23.3	15.2	13.3	8.7
2	32.1	20.9	17.9	12.2
3	40.1	26.3	22.0	15.5
4	47.1	31.4	25.7	18.5
5	53.2	36.2	28.8	21.3
6	58.6	40.7	31.5	23.9
7	63.2	44.9	33.8	26.3
8	67.2	48.8	35.7	28.4
9	70.5	52.4	37.2	30.3
10	73.2	55.7	38.4	32.0
11	75.4	58.7	39.2	33.4
12	77.2	61.4	39.7	34.7

Source: USACE (2003)

Because flood depth is expressed relative to the first floor elevation of the structure, it is important to also account for the foundation height of each affected structure, which is the difference between the ground level elevation of the structure (based on LIDAR data as described above) and the first floor elevation. Unfortunately, the acquired parcel-level data provide very little information regarding the type or height of foundations. To address this data gap we developed and applied average foundation height estimates based on information contained in the Federal Emergency Management Agency's (FEMA's) HAZUS-MH multi-hazard flood model.

[25] Data for all three of these structural characteristics were not always reported in the districts' parcel-level data. In these cases, we used information on the relative frequency or these characteristics in the other districts to construct weighted average depth-damage relationships.

HAZUS-MH provides average foundation height estimates for seven foundation types—pile, pier, solid wall, basement, crawl space, fill, and slab. These heights differ depending on the location and date of construction of the structure. First, they differ depending whether the structure is located in a riverine or coastal flooding area. HAZUS provides these assignments by census block. Second, for structures located in communities that have entered the National Flood Insurance Program and have Flood Insurance Rate Maps (FIRMs), foundation heights are assumed to be greater for those constructed *after* the entry date into the program. HAZUS reports the year of program entry by census block. To determine whether a structure was pre-FIRM or post-FIRM, we compared the date of construction (provided by most counties in their parcel-level data) with their block's entry date. Third, for post-FIRM structures in coastal areas, heights depend on proximity to the coast. HAZUS defines two types of post-FIRM coastal zones (A-Zone and V-Zone) and provides zone assignments by census block.

Using HAZUS-MH estimates of the average height and prevalence of each foundation type by zone for Virginia, we estimated the following average foundation heights by zone:

- Coastal PreFIRM = 3.84 ft
- Coastal PostFIRM A-Zone = 5.99 ft
- Coastal PostFIRM V-Zone = 7.82 ft
- Riverine PreFIRM = 2.39 ft
- Riverine PostFIRM = 2.74 ft.

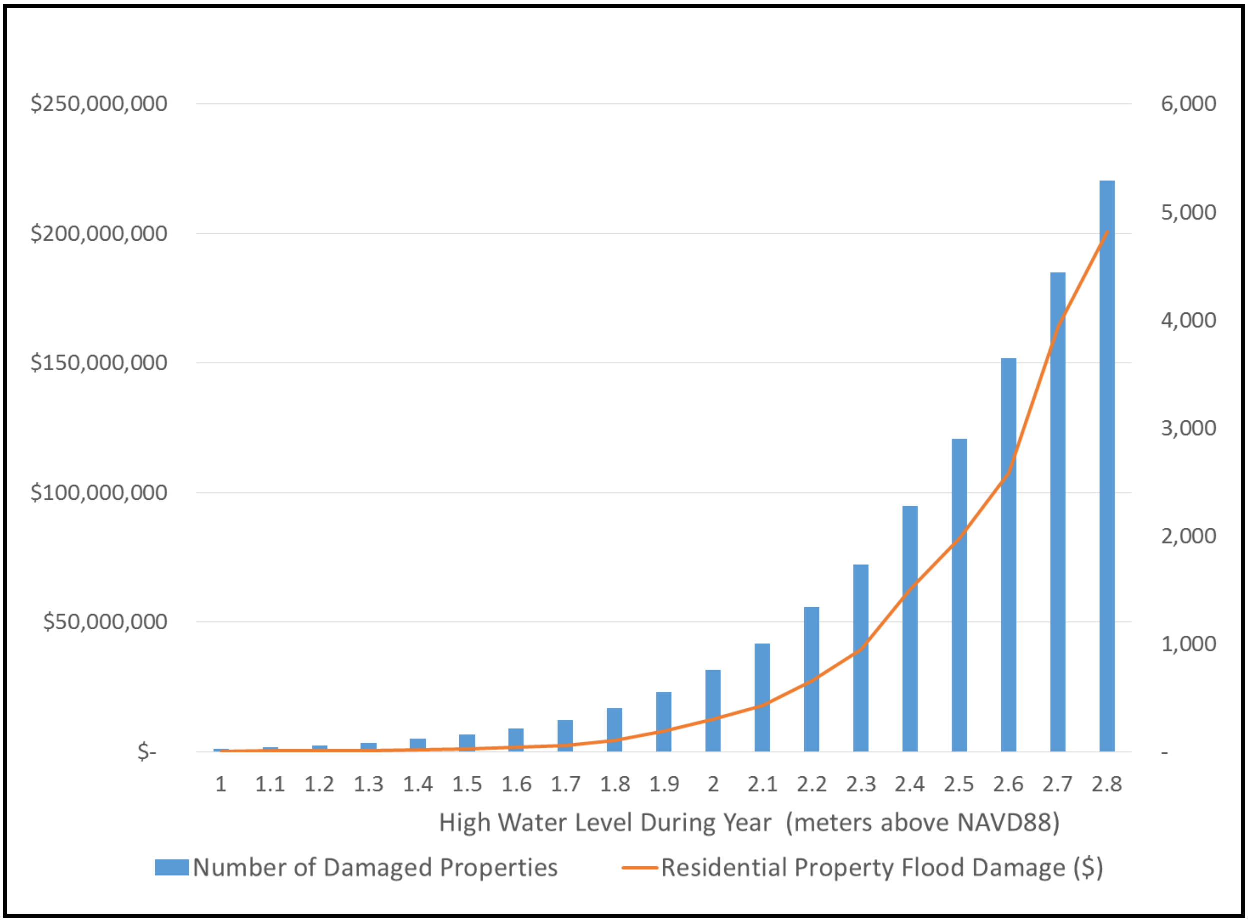
Applying the depth-damage relationships to the residential structures in our database, we then estimated total residential flood damages for a range of specific high water levels in each district. In particular, we examined the impacts of high water levels between 0.5 m and 3 m (in 0.1 m increments). For each property, we estimated the difference between the first floor elevation and the flood level, and then applied the depth-damage functions to estimate the loss in property value.[26] We then aggregated across properties to estimate a total loss per district. As an example, **Figure 3-4** reports these estimates for Norfolk. At a 2 m flood elevation, we estimate that there would be 760 damaged properties with a total loss in value of $12.4 million. The impacts increase to 2,900 affected properties and $82.5 million in damages with a 2.5 m high water level, and to 5,290 properties and over $200 million in damages with a 2.8 m level.

It is important to note that the use of tax assessment data to represent values for residential structures is likely to underestimate the value of property damages. In practice, the replacement cost of structures is considered a better indicator of value for calculating flood damages. However, parcel-specific data on replacement costs is not easily available for the region, nor is there a simple conversion factor, as there can be large variation in the relationship between these two measures. To gauge the extent of underestimation, we conducted a county-by-county comparison of average replacement values from

[26] Following methods used in HAZUS-MH, for structural damages exceeding 50 percent, we assume that the property is a total loss (in effect, a 100% loss).

HAZUS-MH data with average tax assessed values and found that replacements costs in the region are roughly twice as high as the tax values.

Figure 3-4. Effect of High Water Levels on Residential Flood Damage Estimates for Norfolk



3.5 Estimating Expected Annual Flood Damages Without Sea Level Rise

To estimate what we refer to as *expected* annual damages, we combine (1) the total damage estimates for the different high water levels (as shown in Figure 3-4) with (2) the respective probabilities of these high water levels occurring (as shown in Figure 3-3). For each high water level, we first multiply these two components and then add the results together. The result is a probability-weighted damage estimate, which gives less weight to the damages associated with lower probability events.

As a point of reference, we begin by estimating total expected damages assuming that there is no sea level rise. The results of this scenario assumption are shown in the second column of **Table 3-4**. Without sea level rise, the year-to-year flood damages could vary widely, but from a risk-based perspective, the *expected* annual damages are estimated to be about $12 million for the 13 county/city study area. The areas with the largest expected damages are Poquoson, Portsmouth, and Virginia Beach, where the estimated annual damages are, respectively, $3.5 million, $2.4 million, and $1.7 million.[27] This value is small compared to the total value of the housing stock in these areas, but it stresses that in *most* years, particularly in the absence of sea level rise, damages due to coastal storm surges may be somewhat limited. Storm surges causing major damages are relatively infrequent, but they become more likely with rising seas.

Table 3-4. Annual Expected Damages to Residential Structures from Coastal Storm Surges Under Alternative Sea Level Rise Scenarios

	Annual Expected Flood Damage ($/year)		
	No Sea Level Rise	**Sea Level Rise = 0.5 m**	**Sea Level Rise = 0.75 m**
Chesapeake	$1,140,192	$8,458,211	$21,434,528
Gloucester County	$539,623	$3,727,190	$7,456,131
Hampton	$1,092,171	$6,193,237	$14,610,496
Isle of Wight County	$176,019	$1,012,201	$2,129,931
James City County	$116,126	$482,371	$940,498
Newport News	$19,014	$146,446	$375,531
Norfolk	$1,185,899	$8,034,841	$19,401,040
Poquoson	$3,455,446	$7,364,925	$12,173,715
Portsmouth	$2,351,949	$6,986,100	$11,815,720
Surry County	$80,650	$280,895	$360,951
Virginia Beach	$1,667,350	$7,139,991	$14,602,494
Williamsburg	$-	$-	$-
York County	$322,605	$2,512,690	$6,429,584
Hampton Roads	**$12,147,044**	**$52,339,099**	**$111,730,620**

3.6 Estimating the Effects of Sea Level Rise on Expected Annual Flood Damages

To account for the effect of sea level rise on these expected damage estimates we make two main adjustments to the calculations. First, we revise the annual high water probability estimates to account for higher baseline sea levels. These adjustments, which were discussed in Section 3-1 (see Figure 3-3),

[27] The smallest expected damages are estimated for Newport News, even though it has the third highest number of residential properties after Virginia Beach and Norfolk. However, as shown in Table 3-2, a very small percentage of its residential structures with reported values are located in the lower elevation zones. Moreover, the parcel-level data from Newport News do not include information on presence of basements or number of stories; therefore, we apply an average depth-to-damage relationship, which may underestimate damages (see Section 5 for discussion of this issue).

account for the increased probability of more extreme high water events. Second, we adjust the property damage estimates to account for properties that are permanently affected by higher seas (see, for example, Structure A in Figure 3-1). In other words, rather than using the previously described depth-damage relationships, we assume a total loss in value for any structure whose ground level falls below the combination of normal high tide and sea level rise. We make this assumption because, under these conditions, the structure should be permanently, or at least routinely, flooded and, therefore, uninhabitable.

Table 3-4 shows how the expected residential property damages increase substantially with rising sea levels. With sea level rise of 0.5 m, the total expected damages for the region increase by a factor of more than four, to over $52 million per year. An increase to 0.75 m further augments the expected damages by over 100 percent, to about $112 million. Chesapeake, Virginia Beach, Norfolk, and Hampton together account for 57 percent (0.5 m scenario) and 63 percent (0.75 m scenario) of the total expected annual damages.

4

Regional Economic Impacts of Damages from Sea Level Rise

As discussed earlier, sea level rise and flooding events in Hampton Roads will damage buildings and other structures located in lower lying areas. Although the value of direct damages provides one metric of the costs of no action, the direct damages will influence the overall performance and growth of the local and regional economies. As Darwin and Tol (2001) state, "Direct cost does not reflect the total value of consumer goods and service foregone as a result of sea level rise, however, because it does not take account of the higher prices that would be generated by the relatively large loss of land and capital resources" (p: 121). The goal of this section is to provide a broader measure of the costs; one that accounts for indirect costs brought about by the changes in the prices of goods and services.

Our approach to estimating regional economic impacts of sea level rise is different in several respects from the one used in Section 3 to estimate expected damages to residential structures. First, we expand the analysis to include damage to commercial, industrial, and other types of buildings, in addition to residential structures. To accommodate this expanded scope, we apply the HAZUS-MH model, which contains building stock estimates for these additional sectors. Second, we expand the analysis to examine not only the direct damages to properties, but also the indirect ripple effects of these damages to other parts of the regional and state economy. Third, to feasibly add these two new dimensions to the modeling framework, it was also necessary to simplify other aspects of the framework. Therefore, rather than conducting a probability-based analysis that examines the full range of potential storm surge levels, we instead focus on the impacts of specific type of storm surge events—a 100-year storm—under alternative sea level rise conditions.

A common way of measuring the direct and indirect costs of sea level rise is the use of economy-wide computer models. These models trace costs as they ripple across a market economy. At least seven sea level rise studies have used economy-wide models and the existing results offer several lessons for this study (Bosello & De Cian, 2014):

- Local losses of equipment and buildings (i.e., physical capital stock) are one of the most important damage categories that induce secondary effects.
- Price increases resulting from damages provide households and producers with incentives to adapt. In other words, they seek out substitute opportunities to minimize losses.
- Direct damage estimates alone miss economically significant indirect costs to households brought about by price and income changes. For example, Darwin and Tol (2001) found that after accounting for price-induced ripple effects across the economy, estimates of total economic costs were 13 percent higher than direct cost damage estimates.

Using these lessons, we selected and used a computable general equilibrium (CGE) model of the Virginia economy, introduced estimated damages to the existing stock of equipment and buildings due to a specified high water level into the capital market, and estimated the resulting impacts on regional economic performance.

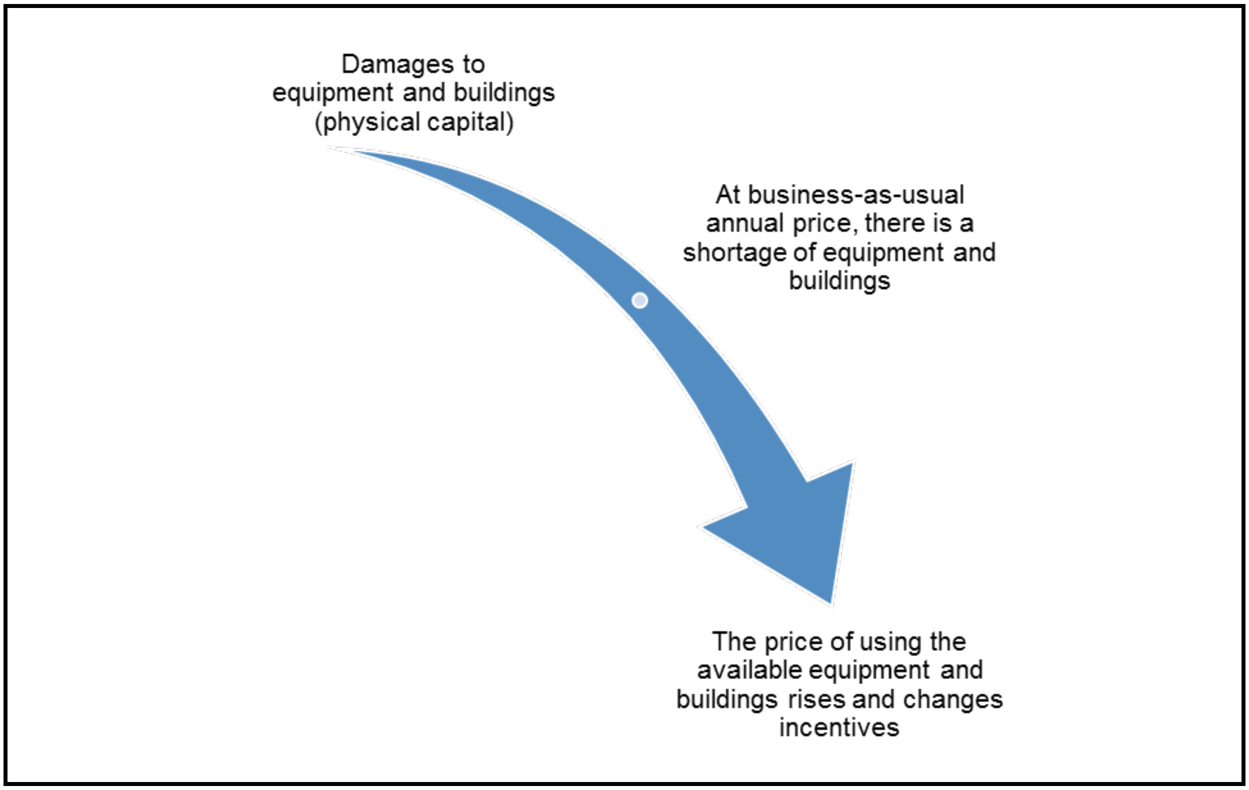
4.1 Economic Consequences in a Single Market: The Economy's Capital Market

The initial economic story begins with damages to the existing stock of capital (i.e., structures and equipment) in the economy as result of a 100-year storm surge. To estimate these damages, we applied the HAZUS-MH modeling system to 12 of the counties/cities in the Hampton Roads region.[28] As in the residential flood damage analysis described in Section 3, we linked each county to the nearest NOAA station. For each model run, we specified coastal flood depths that correspond to the 100-year storm tide levels reported in Table 3-1. Based on these specifications, HAZUS-MH provides estimates of direct damages to the capital stock, which are expressed as losses (in millions of dollars) to building structures, contents, and inventory for residential, commercial, industrial, and other sectors.

Damages to the existing stock of equipment and buildings restrict the economy's productive capacity and its ability to produce and provide goods and services. In the short run, these damages will cause the supply of capital to fall short of its demand. Given this shortage, how does a market economy coordinate the use of the remaining equipment and buildings? Economic principles suggest that buyers would compete for the use of structures and buildings (i.e., capital services) and bid up the annual price of using these services (see Figure 4-1). As the price of these services rises, households and businesses will be required to reassess the benefits and costs of using equipment and buildings in alternative uses. As a result, the remaining equipment and building would tend move to their highest valued uses.

[28] Due to their more inland locations, HAZUS-MH does not provide a coastal flooding module for Chesapeake, Franklin, Southampton, and Williamsburg.

Figure 4-1. Initial Economic Consequences in a Single Market: Shortage of Available Equipment and Buildings (i.e., Physical Capital)



4.2 Economy-Wide Effects across the All Regional Markets

The market for the use of existing equipment and buildings is important enough in the regional economy that a higher price for their use can have major and far-reaching ripple effects. As industries compete for the use of the remaining equipment and buildings after a coastal flood event, the direct effect is that the price of using this capital rises. This higher price then increases the cost of producing goods and services in the economy, which has the indirect effect of changing prices and incomes earned in the markets for these goods and services. In other words, the changes in available equipment and buildings ultimately influence prices, sales, and wage earnings in other markets. Buyers, faced with new income constraints and prices, then respond by seeking out substitute spending opportunities, which has additional impacts on these markets (**Figure 4-2**). Consequently, an analysis of sea level rise should consider all of these interconnected markets and determine how they would change together.

Figure 4-2. Ripple Effects Across the Economy

4.3 Overview of ARTIMAS® Economy-Wide Model for Virginia

ARTIMAS uses a CGE model, which is a special type of economy-wide model, to estimate the full economic hardships brought about by sea level rise. CGE models are similar in many ways to Input-Output (I/O) modeling frameworks, such as the Impact Analysis for Planning (IMPLAN) system, which are commonly used for regional economic analyses; however, CGE models overcome some of the limitations of these other frameworks because they consider how market price and income changes influence households and business choices. As Devarajan and Robinson (2002) wrote, the "CGE model provides the policy analyst with a simulation laboratory that supports individual, controlled experiments. Any empirical result from an applied model can be explained in terms of parameters, structural data, and behavioral specification" (p: 3). The central behavioral feature we are adding above and beyond the common I/O frameworks is the role that changing relative prices play in decision making within market economies.

In this analysis, we applied ARTIMAS to develop a two-region CGE model of the Virginia economy, which separately estimates economic impacts in the Hampton Roads region and in the rest of Virginia. The model is constructed using IMPLAN county-level data for Virginia for model year 2013, and the Hampton Roads region is defined as the 16 jurisdictions specified in Section 2. The model includes a statewide market for the use of equipment and buildings, which does not differentiate between effects associated with residential, industrial, and commercial use, and a statewide labor market that includes representative households by income classes.

With this model, we simulate the economic effects of a 100-year storm event *in a single year*. Therefore, our results are best interpreted as a "snapshot" comparison of the annual economy with and without the event, and in particular with and without the damaged capital stock. Longer-term transitory changes associated with investment and saving decisions or repair and replacement of the capital stock are not captured in the model.

4.4 Summary of Results

We estimated the economic impacts of a 100-year storm event under the same three sea level rise scenarios evaluated in Section 3—zero, 0.5, and 0.75 meters.[29] The economic performance indicators developed for each scenario include impacts on:

- equivalent income losses, divided into nine income classes,
- size of the regional economy and output (gross regional product),
- tax revenues,
- consumer prices, and
- annual wage and capital service prices.

Income Changes

Under a 100-year storm scenario without sea level rise, we estimated that total annual household income in Hampton Roads would fall by $611 million ($944 per household) (**Table 4-1**). Dividing this total income change by average household income, this is equivalent to a loss of almost 5,200 jobs to the Hampton Roads community. Although CGE models do not track the number of jobs, this metric helps clarify the size of the total income losses.

Examining the distribution of total income losses, there are important variations by income class (less than $1 million to $291 million), with households making less than $50,000 per year bearing about 9 percent of the losses. In percentage terms, these storm-related losses translate to a reduction in total annual household income of 0.8 percent. Total income losses for individual income classes range from less than 0.1 percent for households making less than $10,000 per year to 1.2 percent for households making more than $150,000 per year. The variation in losses by income class is driven by underlying differences in the source of income. Low income households receive a majority of their income from labor while high income households tend to receive significant capital income. As a result, high income households tend to bear more of the direct costs associated with capital damages and subsequent income losses.

Under a sea level rise scenario of 0.5 m, we estimated that total annual household income in Hampton Roads would fall by $1.139 billion ($1,760 per household) (**Table 4-1**). Dividing this total income change by average household income, this is equivalent to almost 9,700 jobs. Total income losses vary by income class ($1 million to $541 million). In percentage terms, total annual household income falls by 1.4 percent. Individual income class impacts range from 0.1 percent for households making less than $10,000 per year to 2.2 percent for households making more than $150,000 per year.

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[29] To be consistent with the analysis is Chapter 3, we specified the 100-year flood levels for each county using the 1 percent probability water levels from the nearest of the four NOAA stations shown in Figure 3-2, rather than using FEMA flood maps which would have provided more spatial resolution.

Table 4-1. Total Income Changes by Income Group in Hampton Roads: 100-Year Storm and No Sea Level Rise

Income Group	Change from Reference Conditions		
	No Sea Level Rise	Sea Level Rise = 0.5 Meters	Sea Level Rise = 0.75 Meters
	Change in Annual Income ($ million per year [% of group's income])		
≤ $10K	−$2 (<0.1%)	−$3 (0.2%)	−$6 (0.4%)
$10K–$15K	−$1 (0.1%)	−$1 (0.1%)	−$3 (0.3%)
$15K–$25K	−$8 (0.2%)	−$14 (0.4%)	−$27 (0.8%)
$25K–$35K	−$13 (0.3%)	−$24 (0.6%)	−$47 (1.1%)
$35K–$50K	−$29 (0.4%)	−$54 (0.8%)	−$104 (1.5%)
$50K–$75K	−$63 (0.5%)	−$117 (1.0%)	−$225 (1.9%)
$75K–$100K	−$71 (0.7%)	−$133 (1.3%)	−$254 (2.5%)
$100K–$150K	−$135 (0.8%)	−$251 (1.5%)	−$481 (3.0%)
≥ $150	−$291 (1.2%)	−$541 (2.2%)	−$1,031 (4.2%)
All Income Classes	**−$611** (0.8%)	**−$1,139 (1.4%)**	**−$2,180 (2.7%)**

Lastly, under a sea level rise scenario of 0.75 m, annual household income in Hampton Roads falls by $2.180 billion ($3,336 per household) (**Table 4-1**).[30] Dividing this total income change by average household income, this is equivalent to almost 18,500 jobs. Total income losses vary by income class ($3 million to $1,031 million). In percentage terms, annual household income falls by 2.7 percent. Individual income class impacts range from 0.4 percent for households making less than $10,000 per year to 4.2 percent for households making more than $150,000 per year.

To summarize the additional consequences of a 100-year storm with sea level rise, we report the differences in the total income losses (**Table 4-2**) and average household income losses (**Table 4-3**). As shown, a sea level rise scenario of 0.5 m increases total income losses by $528 million for Hampton Roads. The more severe sea level rise of 0.75 m increases total income losses by $1.6 billion. Averaged across households in the region, the income losses in the year of a 100-year storm event are estimated to increase from $944 per household with no sea level rise to $1,760 per household with 0.5 m sea level rise (i.e., an additional income loss of $816 per household). With 0.75 m sea level rise, average per household income loss in the year of the storm event would be $2,422 greater compared to a scenario without sea level rise.

[30] Economic effects spill outside of Hampton Roads to the rest of Virginia. However, in percentage terms, these total annual household income changes are small (less than 0.1%).

Table 4-2. Total Income Changes ($ million/year) in Hampton Roads: Comparison of Changes With and Without Sea Level Rise

Scenario	Total Income Changes ($ million/year)
No Sea Level Rise	−$611
Sea Level Rise = 0.5 m	−$1,139
Difference from No Sea Level Rise	**−$528**
Sea Level Rise = 0.75 m	−$2,180
Difference from No Sea Level Rise	**−$1,568**

Table 4-3. Average Household Income Changes ($/year per household) in Hampton Roads: Comparison of Changes With and Without Sea Level Rise

Scenario	Average Household Income Changes ($/year per household)
No Sea Level Rise	−$944
Sea Level Rise = 0.5 m	−$1,760
Difference from No Sea Level Rise	**−$816**
Sea Level Rise = 0.75 m	−$3,366
Difference from No Sea Level Rise	**−$2,422**

Average household income uses IMPLAN's estimate of the total number of households in the 16 jurisdictions (647,968).

Changes in the Size of the Economy, Tax Revenue, and Prices

In this section, we summarize and compare economic impacts related to changes in gross regional product (GRP), federal, state and local tax revenue from all sources, and changes in prices (consumer prices, wages and annual capital service prices) for the Hampton Roads region and for the rest of Virginia. As shown in **Table 4-4**, without sea level rise, flood damages in the Hampton Roads region from a 100-year storm would cause the regional economy to shrink by $611 million dollars in the year of the storm. These impacts would increase to $1,139 million with sea level rise of 0.5 m, and to $2,180 million with a sea level rise of 0.75 m. These are economically significant decreases for GRP, representing 1–2 percent reductions in annual product under the sea level rise scenarios.[31] The economic

[31] The GRP referenced here is for the 16 jurisdiction Hampton Roads study region, not the Virginia Beach-Norfolk-Newport News VA-NC Metropolitan Statistical Area. By assuming no change in government spending in the region, changes in GRP are the same as changes in total household income in the region.

effects of flood damages in the Hampton Roads region will also spill outside of the region, reducing GRP in the rest of Virginia; however, these secondary impacts are relatively small.[32] Under the sea level rise scenarios, the loss in GRP in the year of the storm would be between $38 million and $61 million, which is less than 0.1 percent of annual GRP in the rest of Virginia.

The economic contraction resulting from a 100-year storm would also reduce federal, state, and local tax collections from the Hampton Roads region in the year of the storm. In the scenario with no sea level rise, tax collections would decrease by $27 million. Under the 0.5 m and 0.75 m sea level rise scenarios, tax collection would fall by $95 million and $309 million respectively. In other words, sea level rise would lead to tax collection shortfalls in the event of a 100-year storm that are 3 to 10 times higher than would occur without sea level rise. Areas in Virginia outside Hampton Roads would also see reductions in federal, state, and local tax collections as the result of the contractions that occur throughout the state economy. In percentage terms, all of these reductions reflect approximately 0.3 percent of tax collections that would occur without a 100-year storm.

Table 4-4. Changes in the Size of the Economy and Total Tax Revenue from All Sources (Relative to 2013 Reference Conditions)

	Change from Reference Conditions		
	No Sea Level Rise	Sea Level Rise = 0.5 Meters	Sea Level Rise = 0.75 Meters
Real Gross Regional Product ($ million/year)			
Hampton Roads	−$611	−$1,139	−$2,180
Rest of Virginia	−$20	−$38	−$61
Federal, State, and Local Tax Revenue (All Sources) ($ million/year)			
Hampton Roads	−$27	−$95	−$309
Rest of Virginia	−$241	−$403	−$655

As noted earlier, one advantage of the CGE framework is that it considers how market price and income changes influence households and business choices and generate additional indirect costs throughout the economy (see Figure 4-2). We report several price metrics in **Table 4-5** to illustrate how the economy adjusts to the price and income changes brought about by damages to capital. As shown, the price of capital services, which is in essence the price of renting buildings and equipment, rises under all of the damage scenarios. With a sea level rise of 0.75 m, these prices rise by almost 0.8 percent. As these changes ripple through the economy, overall consumer prices rise by up to 0.1 percent and wages fall as

[32] All of the estimated economic impacts in Virginia are from flood damages that occur within the Hampton Roads region.

the economy contracts. The relative wage changes in the sea level rises is 2 to 4 times higher than the no sea level rise 100-year flood scenario.

Table 4-5. Changes in Selected Price Indices (Relative to 2013 Reference Conditions)

	Change from Reference Conditions		
	No Sea Level Rise	Sea Level Rise = 0.5 Meters	Sea Level Rise = 0.75 Meters
Consumer Price Index			
Hampton Roads	0.03%	0.06%	0.10%
Rest of Virginia	0.03%	0.05%	0.09%
Wage Index	−0.09%	−0.18%	−0.38%
Annual Capital Services Price Index	0.20%	0.39%	0.78%

5

Conclusion

The primary objective of this study has been to analyze and estimate the expected costs and economic impacts of sea level rise for the Hampton Roads region, under a scenario where no significant adaptation actions are undertaken.

Our analysis is divided into two main parts. The first part focuses specifically on residential properties in the Hampton Roads region and their vulnerability to coastal flooding under alternative sea level rise assumptions. For a scenario without sea level rise, we estimate relatively low *expected* annual damages of about $12 million. This value is small compared to the total value of the housing stock in these areas, but it stresses that in *most* years, particularly in the absence of sea level rise, damages due to coastal storm surges should not be very significant.

With sea level rise, however, the more damaging storm surges become more likely and the expected residential property damages increase substantially. With sea level rise of 0.5 m, the total expected damages for the region increase by a factor of more than four, to over $52 million per year. An increase to 0.75 m further augments the expected damages by over 100 percent, to about $112 million.

It is important to acknowledge the main limitations and uncertainties associated with the methods used to estimate residential damages and to consider how they affect the results. First, the analysis is based on parcel-level data, which in many cases is incomplete for the study area due in part to the following reasons:

- The analysis underestimates total damages by excluding three districts due to unavailable data—Suffolk, Franklin, and Southampton. Because of its proximity to the coast, the omission of Suffolk is expected to be most significant.

- For some of the counties, data on certain property characteristics—type (single or multi-family dwellings), number of stories, and presence of basement—are missing or not included. Because the depth-damage relationships depend on these characteristics, for cases with missing data we developed "composite" depth-damage relationships reflecting average percent damages across the missing characteristics. This averaging process reduces the variation in damages across properties, which most likely results in underestimation of damages for the lower range of high water levels.

- None of the parcel-level data provide estimates of the foundation height of the structures. To address this data limitation, we developed average height approximations based on statewide estimates, which depend on the construction date and location for the property (as described in Section 3). As in the previous cases, this averaging process reduces the variation in damages across properties, which most likely results in underestimation of damages for the lower range of high water levels.

- Damages are also underestimated because residential properties within the boundaries of Department of Defense (DOD) facilities are generally not included.

Second, the analysis relies on reported tax assessment values, which is likely to underestimate the value of property damages. In practice, the replacement cost of structures is arguably a better indicator of flood damages. Although there can be large variation in the relationship between these two measures, we conducted a county-by-county comparison of average replacement values from HAZUS-MH data with average tax assessed values and found that replacements costs in the region are roughly twice as high as the tax values.

Third, by focusing on the effects of water depth on flood damages, the analysis does not estimate the potential additional effects of storm energy and wave forcing on coastal storm damages. Although water depth is a critical determinant of flood damages, the force of moving waters will have additional negative impacts, particularly for properties located closer to shore and more exposed to wave action.

Finally, the analysis does not account for the additional potential impacts from changes in future storm intensity or frequency due to climate change, because of the significant uncertainty associated with these projections.

In sum, the expected damage values presented in this study should be interpreted as conservative or lower bound estimates of residential property damages due to sea level rise.

For the second part of the analysis, we examine the broader implications of sea level rise and associated flood damages on the regional and state economy. We estimated how damages to residential, industrial, and commercial structures associated with a 100-year flood event would impact the economy under different sea level rise scenarios.

Without sea level rise, we estimated that total annual household income in Hampton Roads would fall by $0.611 billion ($944 per household), which is the equivalent of about 1 percent. Losses for individual income classes range from 0.1 percent for households making less than $10,000 per year to 1.2 percent for households making more than $150,000 per year.

In contrast, under a sea level rise scenario of 0.5 m, we estimated that annual household income in Hampton Roads would fall by about twice as much—$1.139 billion ($1,760 per household). Under a sea level rise scenario of 0.75 m, the impacts are almost four times as large, with annual household income in Hampton Roads estimated to fall by $2.180 billion ($3,366 per household)

The economic effects of flood damages in Hampton Roads will also spill outside of the region to the rest of Virginia. However, in percentage terms, our estimates of these total annual household income changes are relatively small (less than 0.1%). As the result of price and income changes, the average household living in the rest of Virginia experience small income losses ranging from $6 per household under the no sea level rise scenario to $24 per household under the 0.75 m sea level rise scenario.

Key limitations and uncertainties associated with this part of the analysis include the following:

- We are using a single-period (1-year) CGE model, which does not capture or measure longer-term transitory changes associated with investment and saving decisions or with repair and replacement of the capital stock. As a result, our results are best interpreted as a "snapshot" comparison of the economy with and without a 100-year storm surge and sea level rise and, more specifically, with and without the damaged capital stock.

- The model includes a simplified representation of the market for capital services by combining residential, industrial, and commercial structures into a single market, rather than differentiating between them and representing each component separately.

- Due to data restrictions, impacts on structures and equipment located within the boundaries of DOD facilities are not included in the flood damage estimates generated with HAZUS-MH.

References

Bosello, F., & De Cian, E. (2014). Climate change, sea level rise, and coastal disasters. A review of modeling practices. *Energy Economics, 46,* 593–604. ISSN 0140-9883, http://dx.doi.org/10.1016/j.eneco.2013.09.002

Darwin, R. F., & Tol, R. S. J. (2001). Estimates of the economic effects of sea level rise. *Environmental and Resource Economics, 19*, 113–129.

Devarajan, S., & Robinson, S. (2002, May). *The impact of computable general equilibrium models on policy*. Paper presented at the Frontiers in Applied General Equilibrium Modeling conference, Yale University, New Haven, CT. Retrieved from https://www.pep-net.org/sites/pep-net.org/files/typo3doc/pdf/DevarajanRobinson.pdf

Eggleston, J., & Pope, J. (2013). Land subsidence and relative sea-level rise in the southern Chesapeake Bay region. *U.S. Geological Survey Circular* 1392, 30 p.

Grootendorst, G. and Clary, J. (2015). *Hampton Roads Regional Benchmarking Study 2015*. Hampton Roads Planning District Commission 10th Edition.

Hampton Roads Planning District Commission (HRPDC). (2012). *Climate Change in Hampton Roads: Phase III: Sea Level Rise in Hampton Roads, Virginia.* Retrieved from http://www.hrpdcva.gov/uploads/docs/HRPDC_ClimateChangeReport2012_Full_Reduced.pdf

Hampton Roads Planning District Commission (HRPDC). (2013). *Hampton Roads 2040 Socioeconomic Forecast*. Retrieved from http://www.hrpdcva.gov/uploads/docs/2040_Final_Forecast_Tables_for_HRPDC.pdf

Hampton Roads Planning District Commission (HRPDC). (2015). *Hampton Roads Regional Economic Development Strategy*. Retrieved from http://www.hrpdcva.gov/uploads/docs/09_Handout_Regional_Economic_Development_Strategy.pdf

Hershner, C., & Mitchell, M. (2012). Rising tides, sinking coast: How Virginia's coastal communities can adapt to surging sea levels. *Virginia Issues & Answers, 17*(2), 22–27. Retrieved from http://www.via.vt.edu/winter13/Rising-Tides-Sinking-Coast.pdf

Intergovernmental Panel on Climate Change (IPCC). (2013). Summary for policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Kirshen, P., Merrill, S., Slovinsky, P., & Richardson, N. (2012). Simplified method for scenario-based risk assessment adaptation planning in the coastal zone. *Climatic Change, 113*(3–4), 919–931.

National Oceanic and Atmospheric Administration (NOAA) (2013). *Extreme Water Levels of the United States 1893–2010*. NOAA Technical Report NOS CO-OPS 067.

Nicholls, R. J., Hanson, S., Herweijer, C., Patmore, N., Hallegatte, S., Corfee-Morlot, J., Château, J., & Muir-Wood, R. (2008). Ranking port cities with high exposure and vulnerability to climate extremes, exposure estimates. *Environmental Working Papers* No. 1. Organisation for Economic Co-operation and Development. Retrieved from http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=ENV/WKP(2007)1&doclanguage=en

Recurrent Flooding Sub-Panel. (2014). *Recommendations to the Secure Commonwealth Panel on the Issue of Sea Level Rise and Recurrent Flooding in Coastal Virginia*. Retrieved from http://ccrm.vims.edu/SCPRecommendationsReport_Sept2014.pdf

Tompkins, F. & DeConcini, C. (2014). *Sea-level Rise and its Impact on Virginia*. Fact Sheet. World Resources Institute. Retrieved from https://www.wri.org/sites/default/files/wri_factsheet_virginia_final.pdf

U.S. Army Corps of Engineers (USACE). (2000). *Economic Guidance Memorandum (EGM) 01–03, Generic Depth-Damage Relationships*. Retrieved from http://planning.usace.army.mil/toolbox/library/EGMs/egm01-03.pdf

U.S. Army Corps of Engineers (USACE). (2003). *Economic Guidance Memorandum (EGM) 04–01, Generic Depth-Damage Relationships for Residential Structures with Basements.* Retrieved from http://planning.usace.army.mil/toolbox/library/EGMs/egm04-01.pdf

U.S. Army Corps of Engineers (USACE). (2006). *Depth-Damage Relationships for Residential Structures, Contents, and Vehicles and Content-to Structure Value Ratios (CSVR) in Support of the Donaldsonville to the Gulf, Louisiana, Feasibility Study: Final Report.* New Orleans District. Prepared by Gulf Engineers and Consultants.

Virginia Institute of Marine Science (VIMS). (2013). *Recurrent Flooding Study for Tidewater Virginia* (SJR 76, 2012). Report to the Governor and the General Assembly of Virginia. Senate Document No. 3. Richmond VA.