NORFOLK, VIRGINIA, SEA LEVEL RISE ANALYSIS REPORT

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U.S. DEPARTMENT OF HOMELAND SECURITY

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OFFICE OF CYBER AND INFRASTRUCTURE ANALYSIS

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EXECUTIVE SUMMARY

The rise in observed sea level is a result of several factors including ocean thermal expansion, glacier melting, Greenland and West Antarctica ice loss, and local land subsidence. Collectively, these changes contribute to an evolving threat referred to as sea level rise. The assumption is that as storm frequency and intensity increase, these changes will compound sea level rise impacts to critical infrastructure. These impacts are concerns for federal, state, and particularly local infrastructure stakeholders and planners. The increase in storm frequency and intensity presents a clear risk to population and critical infrastructure. Understanding the potential impact from the increase of storm frequency and intensity to the critical infrastructure of the East Coast and Gulf Coast regions is crucial to the long-term planning cycle to mitigate the risks associated with sea level rise.

The U.S. Department of Homeland Security (DHS)/Office of Cyber and Infrastructure Analysis (OCIA) manages the advanced modeling, simulation, and analysis capabilities of the National Infrastructure Simulation and Analysis Center (NISAC) in support of the DHS critical infrastructure security and resilience mission. OCIA, through NISAC, analyzed the impacts of flooding caused by sea level rise only and the impacts of flooding caused by sea level rise combined with a Category 3 hurricane storm surge on the population and critical infrastructure in the Hampton Roads, Virginia, area. OCIA estimated sea level rise at 20 years and 50 years. A hurricane combined with local sea level rise is a worst-case scenario because of the potential for increased surge-induced flooding.

With this analysis, OCIA intends to provide stakeholders, including regional infrastructure owner-operators and policy makers at all levels of government, with information that supports the development of flood mitigation strategies and preparedness measures and increased awareness of the nature and scope of sea level rise on coastal communities. These analytic results support DHS and National Infrastructure Protection Plan security partners with timely and defensible consequence modeling and analysis.

KEY FINDINGS

- **Sea level rise will inundate some urban areas in Hampton Roads in the next 50 years. The expected total population at risk from sea level rise flooding in 20 years is slightly less than 30,000 people, but increases to 42,000 to 85,000 people in 50 years. Sea level rise will amplify the effect of flooding on the population during hurricanes. For the Category 3 hurricane scenario in this report, the population at risk from flooding is 731,000 (baseline); by 2065, that number will increase to 815,600 to 898,700.**
- **Sea level rise will inundate a small number of electric power substations in the Hampton Roads area during the next 50 years. One substation will be at risk within 20 years, and two to five substations will be at risk in 50 years.**
- **Sea level rise will amplify the effect of flooding on electric power substations during hurricanes. For the Category 3 hurricane scenario in this report, three additional substations are at risk of flooding in 20 years, and 8–12 additional substations are at risk of flooding in 50 years. This represents a 20-percent and 29- to 37-percent increase in population served by flooded substations in 20 and 50 years, respectively.**
- **Sea level rise alone is unlikely to flood drinking water treatment or wastewater treatment facilities within the next 50 years. However, increased nuisance floods for low-lying facilities are possible.**
- **Sea level rise will increase the vulnerability of some water and wastewater infrastructure during hurricanes. For the Category 3 hurricane scenario in this report, one additional wastewater treatment plant will be flooded within 20 years, and one additional water treatment plant and one wastewater treatment plant will be flooded within 50 years.**

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INTRODUCTION

The intensity, frequency, and duration of North Atlantic hurricanes, as well as the frequency of Categories 4 and 5 hurricanes, have increased since the early 1980s.[1] Increased sea level rise coupled with increased hurricane frequency and intensity presents a clear threat to critical infrastructure along coastal regions and creates a unique set of planning, mitigation, and resiliency challenges for federal, state, and local planners. The U.S. Department of Homeland Security (DHS)/Office of Cyber and Infrastructure Analysis (OCIA) recognizes that an understanding of the potential risks to critical infrastructure along coastal regions resulting from sea level rise is crucial to long-term planning cycles.[2]

Hampton Roads is a highly urbanized coastal area of southeastern Virginia that encompasses nine cities, including Norfolk, Chesapeake, Newport News, Hampton, Portsmouth, Suffolk, Poquoson, Williamsburg, and Virginia Beach. The total estimated population in the Hampton Roads area is 1.6 million people.[3] The area is extremely low-lying, with a gentle increase in elevation moving inland and to the west. The highest point in the Hampton Roads area is less than 150 feet above mean sea level, the average height of the surface of the sea for all tide stages over a 19-year period. The low-lying nature of the area and its development around coastal waters, including the confluence of the Elizabeth, James, and Nansemond Rivers into the Chesapeake Bay near the Atlantic Ocean, make the region vulnerable to flooding from extreme storm events and changes in the local sea level.

The Hampton Roads area is important for the regional economy because of the Port of Virginia and its strong tourism industry. In addition, the area is important from a national security perspective with the presence of several military installations, including Naval Station Norfolk in Norfolk and Joint Base Langley-Eustis in Hampton.[4]

Flooding is not a new threat in the Hampton Roads area. Because of its coastal location and low-lying geography, extreme weather events have resulted in coastal flooding in the past. These floods resulted from events including the 1933 Chesapeake-Potomac Hurricane, which had nearly 90-mile-per-hour (mph) winds and a high tide of almost 10 feet above mean lower low water (a tide measurement that is the mean of the lower low water heights of each tidal day during a specified 19-year period) in Norfolk.[5] In 2003, Hurricane Isabel brought 75-mph winds and tides that measured almost 8 feet above mean lower low water. Hurricane Isabel resulted in more than $625 million in damage and 20 deaths.[6] However, flooding in the Hampton Roads area is not limited to extreme, relatively infrequent storm events. Recent studies have highlighted more frequently occurring, minor flooding events commonly referred to as nuisance floods. The National Oceanic and Atmospheric Administration (NOAA) found that regional nuisance flooding in U.S. coastal areas has increased between 300 and 925 percent since 1960. In Norfolk, a 325-percent increase has occurred since 1960, representing an increase from 1.7 days of flooding to 7.3 days of flooding per year.[7] NOAA has attributed the change in frequency of these minor flooding events to local sea level rise, largely a combination of sea level height increase and local land subsidence.[8]

Because of the low-lying topography in the Hampton Roads area, it is important to understand the vulnerabilities of its critical infrastructure to flooding and quantify how these vulnerabilities change under projected climate scenarios. Several studies have been conducted to understand the impacts of storm surge and sea level rise on social, economic, and infrastructure systems in the area. One study in 2007 investigated the impact of storm surge flooding, combined with varying levels of sea level rise, in the Hampton Roads area to understand the evolving

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[1] Melillo, J. M., Richmond,T.C., and Yohe, G.W. "Climate Change Impacts in the United States: The Third National Climate Assessment," US Global Change Research Program (2014), http://nca2014.globalchange.gov/, accessed 14 May 2015.

[2] For an-depth description of the lifeline critical infrastructure sectors—Communications, Energy, Transportation Systems, and Water and Wastewater Services Sectors—refer to the Department of Homeland Security, *National Infrastructure Protection Plan (NIPP) 2013: Partnering for Critical Infrastructure Security and Resilience* (Washington, D.C.: Secretary of the Department of Homeland Security, 2013) p. 17 and 43.

[3] U.S. Census Bureau, www.census.gov/population/www/cen2010/cph-t/CPH-T-2.pdf, accessed 14 May 2015.

[4] Military Installations, www.militaryinstallations.dod.mil, accessed 31 October 2015.

[5] National Oceanic and Atmospheric Administration, "The Hurricanes of the 1930s in Virginia and North Carolina," www.erh.noaa.gov/akq/Hur30s.htm, accessed 14 May 2015.

[6] National Oceanic and Atmospheric Administration, "The Hurricane History of Central and Eastern Virginia," www.erh.noaa.gov/akq/adobe_pdf/Hurrhist.pdf, accessed 14 May 2015.

[7] National Oceanic and Atmospheric Administration, "Sea level rise and nuisance flood frequency changes around the United States," *NOAA Technical Report NOS CO-OPS 073*, June 2014, http://tidesandcurrents.noaa.gov/publications/NOAA_Technical_Report_NOS_COOPS_073.pdf, accessed 14 May 2015.

[8] Ibid.

threat to population and infrastructure.[9] The study evaluated hurricane Categories 1 through 5 using NOAA's Sea, Lake, and Overland Surge from Hurricanes maximum data in combination with 30, 60, and 90 centimeters (cm) of sea level rise. Accounting for local land subsidence, the study assumed sea level rise of 60 cm for the year 2100 baseline estimate, using 30 and 90 cm to bound low and high estimates, respectively. The study results indicate that changes in sea level rise generally had a more significant impact on the percentage of infrastructure facilities vulnerable to flooding from smaller hurricanes than larger hurricanes. The study found that the number of infrastructure facilities presently considered vulnerable to a Category 4 or 5 hurricane does not significantly change with increases in sea level during the next 100 years, but it did not identify specific infrastructure impacts or the impacts of disruption to flooded infrastructure.

In 2015, the U.S. Army Engineer Research and Development Center modeled 25 combinations of storm surge and projected sea level rise to quantitatively assess the risk of critical military infrastructure at Naval Station Norfolk.[10] This study used 0.5-meter (1.6 feet) increments of sea level rise up to 2 meters to represent local sea level in the next century. This analysis combines estimates of sea level rise with five storm intensities, ranging from a 1-year recurrence interval to 100-year recurrence interval. Although the specific focus of the study was the military installation, the U.S. Army Engineer Research and Development Center developed geospatial flood hazard layers for the Hampton Roads area. This study concluded that sea level rise is a significant threat multiplier relative to mission sustainability and that sea level rise increases the failure risk of the infrastructure on the military installation.

SCOPE

One of the potential impacts of climate change is global sea level rise. Increased storm frequency and intensity, combined with sea level rise, are concerns for federal, state, and particularly local response and recovery planners. The combined threat of intensifying storms with sea level rise presents a clear risk to the population and critical infrastructure.

The city of Norfolk indicated its concern regarding potential risks to military bases and the Energy, Water and Wastewater Systems, and Transportation Systems Sectors in the face of sea level rise. OCIA conducted analysis for the larger Hampton Roads area based on evaluations of the impacts of sea level rise, impacts from hurricanes, impacts from a combination of sea level rise and hurricane storm surge. A hurricane scenario combined with sea level rise provides a worst-case scenario because of the potential for increased surge-induced flooding caused by changes in local sea level. The analysis in this report focuses on impacts to infrastructure systems during a 20- to 50-year timeframe, consistent with typical infrastructure design-life and planning criteria. OCIA used the following questions to help frame this analysis:

- What are the impacts to critical infrastructure from sea level rise, coastal inundation, flooding, and storm surge in Hampton Roads from sea level rise, a Category 3 hurricane, or from the combined effects of sea level rise and a Category 3 hurricane?
- What are the near-coastal critical infrastructure vulnerabilities relative to climate change, including local sea level changes; and changes in frequency, intensity, and duration of storm events?
- How is the Hampton Roads area organized to respond to coastal inundation, flooding, and storm surge, and what long-term planning decisions are local stakeholders exploring regarding mitigation measures that enhance critical infrastructure resilience in response to sea level rise, a Category 3 hurricane, or the combined effects of sea level rise and the Category 3 hurricane?
- What short- and long-term mitigation and adaptation responses can stakeholders adopt to ensure critical infrastructure resilience during long-term planning and management periods for impacts from sea level rise, hurricanes, and combined effects of sea level rise and a Category 3 hurricane?

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[9] Kleinosky, L.R., Yarnal, B., Fisher, A., "Vulnerability of Hampton Roads, Virginia, to Storm-Surge Flooding and Sea Level Rise," *Natural Hazards*, 40(2007): pp. 43-70.

[10] Burks-Copes, K.A., Russo, E.J., "Risk quantification for sustaining coastal military installation assets and mission capabilities, final technical report, 2014" Prepared by the U.S. Army Engineer Research and Development Center (ERDC), Environmental Laboratory, https://serdp-estcp.org/Program-Areas/Resource-Conservation-and-Climate-Change/Climate-Change/Vulnerability-and-Impact-Assessment/RC-1701, accessed 15 May 2015.

The primary assumption for this analysis is that critical infrastructure stakeholders in the Hampton Roads area do not implement any mitigation strategies during a 20- to 50-year timeframe. This business-as-usual assumption results in a worst-case scenario. Mitigation strategies would alter the combined effects of sea level rise and storm surge on the population, infrastructure, and economy.

OCIA intends the results of this analysis to increase awareness of the nature and scope of sea level rise on coastal communities. Specifically, OCIA intends the analytic results to provide stakeholders, including regional infrastructure owner-operators and policy makers at all levels of government, with information that supports the development of flood hazard mitigation strategies and preparedness planning measures. Further, OCIA intends the analytic results to support DHS and National Infrastructure Protection Plan security partners with timely and defensible consequence modeling and analysis.

OCIA coordinated this report with DHS/National Protection and Programs Division (NPPD)/Office of Infrastructure Protection (IP)/Sector Outreach and Programs Division, DHS/NPPD/IP/Protective Security Coordination Division/Protective Security Advisor-Region III, Emergency Planners from the City of Norfolk, Dominion Power, City of Norfolk Water, and Hampton Roads Sanitation District.

SCENARIOS

To determine the impacts of combined surge and sea level rise, this study evaluated a hurricane scenario that begins as a strong Category 4 storm at sea with winds of 130 mph, 6 hours before landfall. As the hurricane makes landfall near Virginia Beach, it decreases to a Category 3 storm and moves north toward the Chesapeake Bay area (Figure 1). The storm's basic characteristics at landfall are as follows:

- Category 3 hurricane
- Maximum wind intensity: 120 miles per hour
- Forward speed: 11.8 miles per hour
- Landfall: 36.87 °N, 75.98 °W (Virginia Beach)
- Radius of maximum winds: 29 miles

The hurricane scenario coincides with high tides. This study uses a 2-foot tide, referenced to the North Atlantic Vertical Datum 88.[11]

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[11] Tides for this study were taken from the Sewells Point, VA, tide gage, http://tidesandcurrents.noaa.gov/stationhome.html?id=8638610.

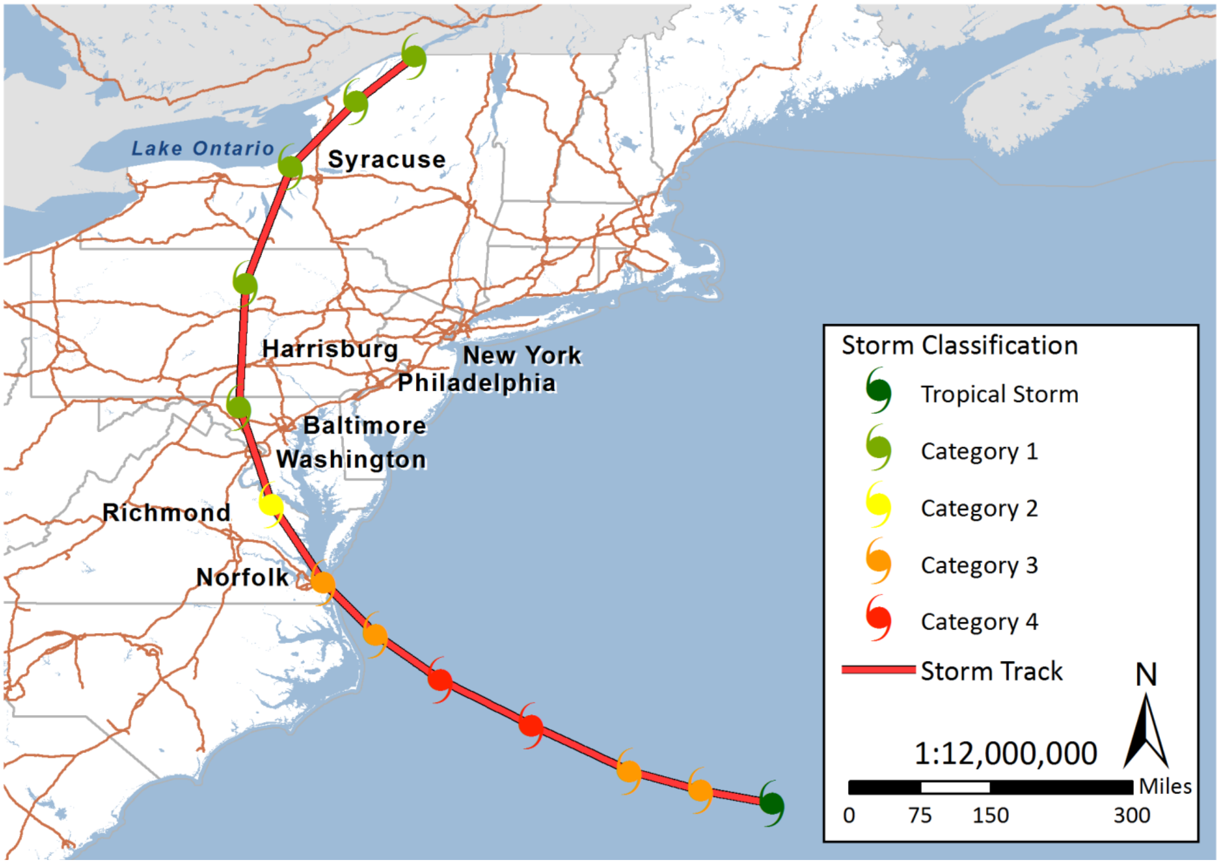

FIGURE 1—SCENARIO HURRICANE TRACK

Table 1 lists the scenarios and includes their specific characteristics throughout this report. The scenarios are developed so that the impacts of sea level rise, storm surge, and a combination of sea level rise and storm surge can be independently evaluated to determine the sensitivity to each effect. Combining hurricane storm surge with sea level rise projections produces worst-case scenarios for flooding. Appendix A provides a technical discussion of the sea level rise scenario development.

TABLE 1—FLOOD HAZARD SCENARIOS

Scenario	Sea Level Rise (feet)	Tide (feet)	Combined Sea Level Rise + Tide (feet)	Year	Storm Surge
Scenario 0	0	2	2	2015	No
Sea Level Rise Only					
Scenario 1	0.49	2	2.49	2035 (Mean)	No
Scenario 2	1.37	2	3.37	2065 (Mean)	No
Scenario 3	2.03	2	4.03	2065 (95%)	No
Scenario 4	2.49	2	4.49	2065 (99%)	No
Hurricane Scenarios					
Scenario 0S	0	2	2	2015	Yes
Scenario 1S	0.49	2	2.49	2035 (Mean)	Yes
Scenario 2S	1.37	2	3.37	2065 (Mean)	Yes
Scenario 3S	2.03	2	4.03	2065 (95%)	Yes
Scenario 4S	2.49	2	4.49	2065 (99%)	Yes

Table 2 lists specific estimates of sea level rise used to generate scenarios for this study. These projections were relative to mean sea level in 2015.

TABLE 2—PROJECTED SEA LEVEL RISE

Period	Sea Level Rise (feet)
2015	0.00
2035 (Mean)	0.49
2065 (Mean)	1.37
2065 (95%)	2.03
2065 (99%)	2.49

RESULTS

POPULATION IMPACTS

Flooding in the sea level rise only scenarios (Scenarios 1–4) in the Hampton Roads area affects a relatively small, urban area within the total area at risk of flooding (Table 3).[12] The results show that flooding in Scenarios 0S (storm surge only) through 4S (sea level rise with storm surge) increased the total inundated area and flooded population. For the Category 3 hurricane scenario, OCIA–NISAC anticipated that 731,900 people are at risk of flooding. The population at risk of flooding from a similar hurricane increases 7 percent in 20 years and 11–23 percent in 50 years. For the scenarios studied in the Hampton Roads area, sea level rise can significantly amplify the effect of the storm surge for flooding impact on population.

TABLE 3—FLOOD RISK IN THE HAMPTON ROADS AREA

Scenario	Flooded Area (square miles)	Developed Flooded Area (square miles)	Population
Scenario 0	0	0	0
Sea Level Rise Only			
Scenario 1	691	5	29,600
Scenario 2	811	6	42,200
Scenario 3	907	8	57,100
Scenario 4	980	11	85,400
Sea Level Rise Only			
Scenario 0S	1,378	85	731,900
Scenario 1S	1,463	91	787,100
Scenario 2S	1,629	102	815,600
Scenario 3S	1,737	109	845,900
Scenario 4S	2,344	120	898,700

ELECTRIC POWER

The analysis shows a relatively small population impact from flooding, in the Hampton Roads area, in the sea level rise only scenarios because of the small-developed area within the total area at risk of flooding. Sea level rise only impacts to electric power infrastructure represent a longer-term infrastructure mitigation challenge.

Sea level rise will amplify the effect of flooding on the population during hurricanes in the Hampton Roads area, particularly on electric power substations during hurricanes. For the Category 3 hurricane scenario in this report, three additional substations are at risk of flooding by 2035, and 8–12 additional substations are at risk of flooding by 2065.

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[12] Urbanized areas were classified as areas in which imperviousness is measured between 20 and 75 percent.

Community resilience is often based on the functionality of basic services across multiple infrastructure sectors. All lifeline infrastructure Sectors depend on Energy-Electric Power for operation. Lifeline Sectors and Subsectors include Water and Wastewater Systems; Healthcare and Public Health; Energy-Electric Power, Oil, and Natural Gas; Communications-Telecommunications; and Transportation Systems. For example, water distribution systems rely on electric power for pumping of water from low to high elevations. Without power, many additional community services will be disrupted, including communications, healthcare, and transportation. Understanding the vulnerability of electric power infrastructure to a changing climate is important to understanding community resilience. OCIA–NISAC used the Homeland Security Infrastructure Program electric power database to identify electric power assets that may be vulnerable to flooding within the next 20 and 50 years under all scenarios.[13]

Sea level rise-only impacts relative to electric power infrastructure represent a longer-term infrastructure mitigation challenge. The options to mitigate damage include relocating affected substations, raising base elevation, and creating flood defense mitigations. Table 4 shows the number of substations in the study area that are at risk from sea level rise only (Scenarios 1–4) and the populations they serve. The flood depth in these substations is below 4 feet, but utilities will need to apply some measure of mitigation to avoid water collecting permanently in the substations.

TABLE 4—SUBSTATIONS AT RISK FROM SEA LEVEL RISE WITHOUT STORM SURGE

Scenario	Substations at Risk	Population Served
Scenario 1	1	4,300
Scenario 2	2	6,800
Scenario 3	2	6,800
Scenario 4	5	27,200

Hurricanes present multiple hazards to electric power infrastructure. Wind, debris, and flooding all have the potential to disrupt all aspects of the Electricity Subsector. Wind damage primarily affects the distribution network components, that is, the utility poles and attached wires. In contrast, flooding and inundation primarily affect substations. In this analysis, OCIA–NISAC treats flooding and wind as independent processes. Because OCIA-NISAC considered the same hurricane scenario for all cases, the electric power outages from wind remain unchanged despite changes in sea level rise. The main difference in damage between the two cases is the relative impacts flood and winds have on substations and how it affects electric power restoration. The damage to individual substations from flood will generally be greater than from wind and result in longer restoration and recovery time. Therefore, it is important to understand the relative change in substations at risk of flooding during future hurricane events.

If forecasts predict that a hurricane will make landfall, a utility may place sandbags around a substation control house, the most vulnerable element in the substation during flooding. If a utility expects deeper inundation, it will remove substations from service to minimize component damage. For safety considerations, utilities commonly deenergize vulnerable facilities based on the potential for flooding. Table 5 shows the number of substations at risk of inundation by hurricane storm surge under the storm surge scenarios. Results shown in Table 5 indicate the number of substations likely to be inundated during the Category 3 scenario hurricane.

TABLE 5—NUMBER OF INUNDATED ELECTRIC POWER SUBSTATIONS, STORM SURGE SCENARIOS

Scenario With Storm Surge	Substations at Risk	Population Served
Scenario 0S	23	581,200
Scenario 1S	26	691,600
Scenario 2S	31	751,100
Scenario 3S	33	781,500
Scenario 4S	35	795,300

OICA-NISAC has assessed the amount of time it takes to bring an inundated substation back into service based on conversations with utilities. After the surge water recedes, utility crews must clean components immersed in

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[13] Los Alamos National Laboratory proprietary database.

seawater to remove salt deposits from bushings, transformers, insulators, bus bars, etc. The deeper the inundation, the longer it takes to bring a substation back into service. In addition, an area that is inundated by storm surge may not be habitable; in which case, no attempts at restoration may be made until major clean-up efforts are accomplished and rebuilding can begin. This was the case for parts of New Jersey and Long Island following Hurricane Sandy in 2012.

ROAD TRANSPORTATION

The analysis shows a relatively small population impact from flooding, in the Hampton Roads area, in the sea level rise only scenarios because of the small-developed area within the total area at risk of flooding. Sea level rise only impacts to electric power infrastructure represent a longer-term infrastructure mitigation challenge. No water or wastewater treatment plants in the Hampton Roads area are at risk of flooding from sea level rise only by 2065.

Sea level rise will amplify the effect of flooding on the population during hurricanes in the Hampton Roads area, particularly on electric power substations during hurricanes. Sea level rise conditions at the time of the storm surge from the Category 3 hurricane will disrupt roadways to a greater degree by 2065.

Because of the low-lying geography of the Hampton Roads area, the transportation infrastructure is vulnerable to disruption from flooding. The region experiences periodic flooding during lunar tides and minor storm events that affect transportation to some coastal areas, which will potentially increase with sea level rise. Storm surge, rainfall, flood, and debris from a Category 3 hurricane are likely to significantly affect roads and evacuation routes in the Hampton Roads area. OCIA–NISAC examined the impacts to roads under two scenarios representing the best and worst cases of sea level rise plus surge estimates. Scenario 0S establishes a base case and Scenario 4S determines the worst case. For this study, all roadways are divided into segments, typically a few tenths of a mile in length. Appendix D discusses the methodology used for the road transportation analysis.

BASE STORM SURGE ROADWAY DISRUPTIONS

Hampton Roads area roadways are expected to be disrupted from storm surge flooding. Road segments experiencing higher than 2 feet of inundation are assumed impassable until conditions allow the water to recede and debris is cleared. Under Scenario 0S, approximately 1,600 of almost 40,000 road segments in the entire study area are completely disrupted by the hurricane surge. About 18,000 road segments (45 percent) experience significantly altered traffic loads, primarily from the surge or the altered traffic patterns resulting from the surge.

The flooded road segments that normally carry the largest traffic loads are likely to cause the greatest disruption in traffic volumes and patterns as traffic is rerouted. The traffic flow on many of these roadways listed in Table 6 is disrupted at several locations along their route. The table lists the points on these routes only where the traffic flow rates are highest, and thus present the greatest challenge in rerouting the traffic to maintain commuter, commercial, military, emergency, and repair vehicle movement.

TABLE 6—NORMAL FLOW RATES ON HIGHLY AFFECTED ROADWAYS, SCENARIO 0S

Interrupted Roadway	Normal Flow (vehicles per hour)
I–64 (Hampton Roads Beltway), south of I–264 interchange	4,970
U.S. 13 (South Military Highway), south of I–264 interchange	4,590
Tidewater Drive (VA 168), near Barraud Park	4,120
Great Bridge Boulevard (VA 190), south of U.S. 17 interchange	3,680
Oak Grove Connector (VA 168), south of U.S. 17 interchange	3,650
U.S. 17, east of Great Bridge Boulevard (VA 190)	3,460
Little Florida Road (VA 171), east of Wythe Creek Road (VA 172)	3,380
U.S. 258 (West Mercury Boulevard), east of VA 167 interchange	3,310
U.S. 58 (West Brambleton Avenue), south of VA 337	3,050
Midtown Tunnel Expressway (VA 337), north of U.S. 58	2,800

WORST-CASE SCENARIO 4S STORM SURGE ROADWAY DISRUPTIONS

Under Scenario 4S, roadways in the Hampton Roads area are expected to be disrupted to a greater degree than the base case because of sea level rise conditions at the time of the surge from the Category 3 hurricane. The conditions are worse near coastal roadway locations and are assumed to disrupt travel on road segments experiencing 1-foot surge levels or more. OCIA–NISAC used this more stringent condition because the sea level rise conditions, although made worse by the storm surge, will not subside with the passing of a storm. The traffic flow of approximately 2,750 road segments is expected to be completely disrupted by the combination of storm surge and sea level rise. As a result, more than 18,700 road segments (48 percent) experience significantly altered traffic volumes.

Table 7 lists the roadways sustaining damage, with the highest normal traffic volumes for this scenario. The table lists the points on these routes where the flow rates are highest and thus present the greatest challenge in rerouting the flow to maintain required traffic movements.

TABLE 7—NORMAL FLOW RATES ON HIGHLY AFFECTED ROADWAYS, SCENARIO 4S

Interrupted Roadway	Normal Flow (vehicles per hour)
Midtown Tunnel Expressway (U.S. 58), north of tunnel	11,700
I–264 (north of Berkley Bridge)	7,400
East Virginia Beach Boulevard (U.S. 58), east of U.S. 13 interchange	7,350
Hampton Roads Beltway (I–64), north of VA 409 (Providence Road)	4,970
South Military Highway (U.S. 13), south of I–264 interchange	4,590
Mount Pleasant Road (VA 165), north of Fentress Airfield Road	4,280
Tidewater Drive (VA 168), north of Lindenwood Avenue	4,120
Great Bridge Boulevard (VA 190), south of U.S. 17	3,680
Oak Grove Connector (VA 168), south of I–64	3,650
U.S. 17 (east of Great Bridge Boulevard (VA 190)	3,460
Little Florida Road (VA 171), near Wythe Creek Road (VA 172)	3,380
West Mercury Boulevard (U.S. 258), east of LaSalle Avenue (VA 167)	3,310
Suffolk Northern Bypass (U.S. 13), east of Wilroy Road (VA 642)	3,140

The Midtown Tunnel Expressway is among the top 10 disrupted roadways in terms of normal flow rates for both the least disruptive (scenario 0S, a Category 3 hurricane with no sea level rise) and most disruptive (scenario 4S, a Category 3 hurricane with 2.49 sea level rise) cases examined in this report. However, the roadway disruption in the worst-case scenario (4S) occurs further south along U.S. 58 (closer to the water) where several routes converge, resulting in higher interrupted flows.

Table 8 lists some of the alternative routes expected to experience the most significant traffic changes. In the first example listed (U.S. 460 south of I–264), the traffic volume is expected to be a little more than double the normal volume during the disruption. Travel time along this stretch is expected to take almost 20 times longer than under normal conditions. Note that some of the smaller roads serving diverted traffic encounter large delays because they are single- or double-lane roads not designed to handle heavy traffic. The altered traffic patterns will cause significant delays for commuter, commercial, military, emergency, and repair vehicle movement.

TABLE 8—CHANGES IN AREA TRAFFIC ON KEY AFFECTED ALTERNATIVE ROUTES, SCENARIO 4S

Alternative Route	Traffic Flow Higher Than Normal[14]	Volume to Capacity Ratio[15]	Travel Time More Than Normal
New Campostella Bridge (U.S. 460), south of I–264	2.1	2.1	18.8
East Brambleton Avenue (U.S. 460), south of I–264	2.1	2.2	16.9
South Military Highway (U.S. 13), west of VA 166	1.8	1.8	10.3
George Washington Highway North (U.S. 17), east of Mill Creek Parkway	1.9	1.9	10.0
Bainbridge Boulevard (VA 166), north of I–64	4.9	4.8	9.3
Dominion Boulevard North (U.S. 17), near VA 166	2.0	2.1	11.5
Campostella Road (U.S. 460), near Arlington Avenue	2.2	2.2	19.6
Centerville Turnpike, near Butts Station Road	2.6	2.6	29.0
Canal Drive, south of South Military Drive (U.S. 13)	3.3	3.3	22.0
Hawks Bill Drive, south of Indian River Road	5.7	5.4	52.9
Poindexter Street (22nd St.), south of Berkley Avenue	2.3	2.2	3.2
Wilson Road (U.S. 460), near Berkley Avenue	2.1	2.1	4.1
Creek Lane, west of River Walk Parkway	5.4	5.4	49.3
Pepperwood Drive, west of Marina Reach	5.4	5.4	48.3
Bayberry Drive, north of River Edge Road	6.4	5.6	34.7

Figure 2 shows a map of disruptions near Harbor Park, depicting altered traffic patterns. The map shows the affected roadway segments indicated by the segments colored in dotted orange lines. The impact of the disruption as measured by the ratio of road traffic volume to capacity is shown using color codes. Green road segments correspond to normal levels (volume to capacity ratios less than or equal to 1), increasing to yellow and orange at volume to capacity ratios between 2 and 3, and into red at volume to capacity ratios greater than 4, meaning that these roadway segments are likely to experience 4 times their normal capacity, volume to capacity ratios exceeding 5 are shown in black. The thickness of the lines represents the flow rates along the roads (thicker represents higher flow rates). Note that this particular disruption near Harbor Park diverts a great deal of traffic along U.S. 460 and roads feeding into and out of U.S. 460 from the south (VA 168), east (I–264), and north (VA 166), significantly affecting Montclair Avenue, Kimball Terrace, and other smaller roads in the area.

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[14] Traffic Higher than Normal is defined as the relative ratio of traffic volume during disruptive events compared with normal daily traffic volume.

[15] Volume to Capacity Ratio is the ratio of traffic volume during a disruptive event and the design capacity (e.g., expected normal volume) of the roadway.

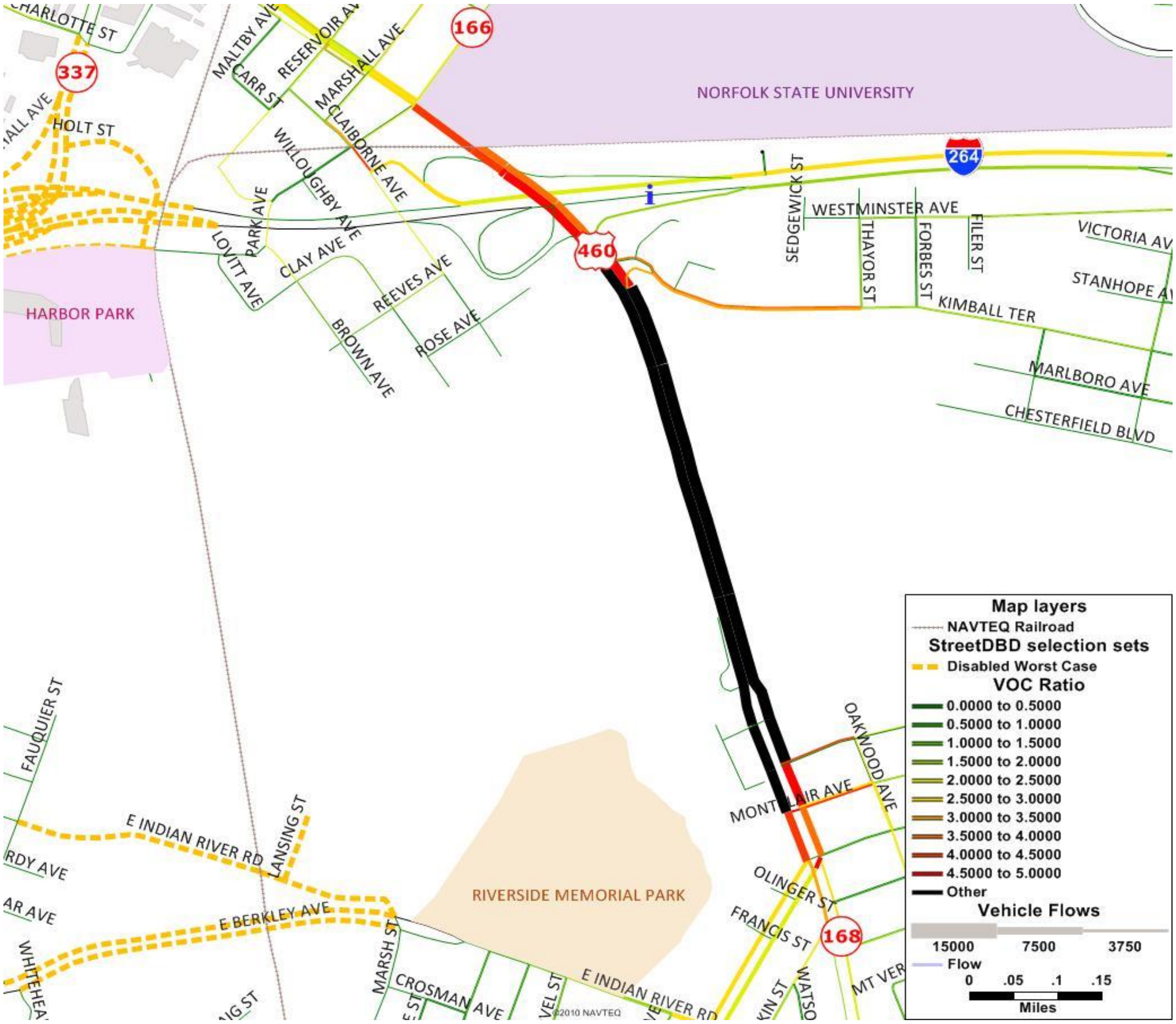

FIGURE 2—ALTERED TRAFFIC FROM DISRUPTION NEAR HARBOR PARK (I–264)

WATER AND WASTEWATER

DRINKING WATER

Clean, reliable drinking water is essential for community resilience. To develop mitigation strategies that protect water infrastructure, it is important to understand what could disrupt its operation. Climate change, including sea level rise, could affect water infrastructure. The Hampton Roads area has more than 40 community water systems. The Water and Wastewater Systems Sector infrastructure in the region is most succinctly described within three distinct subregions—Peninsula, Southside, and Western. The Western area is largely classified as rural, with individual wells providing drinking water. These were not explicitly accounted for in this analysis. Figure 3 shows the community water systems and service territories.

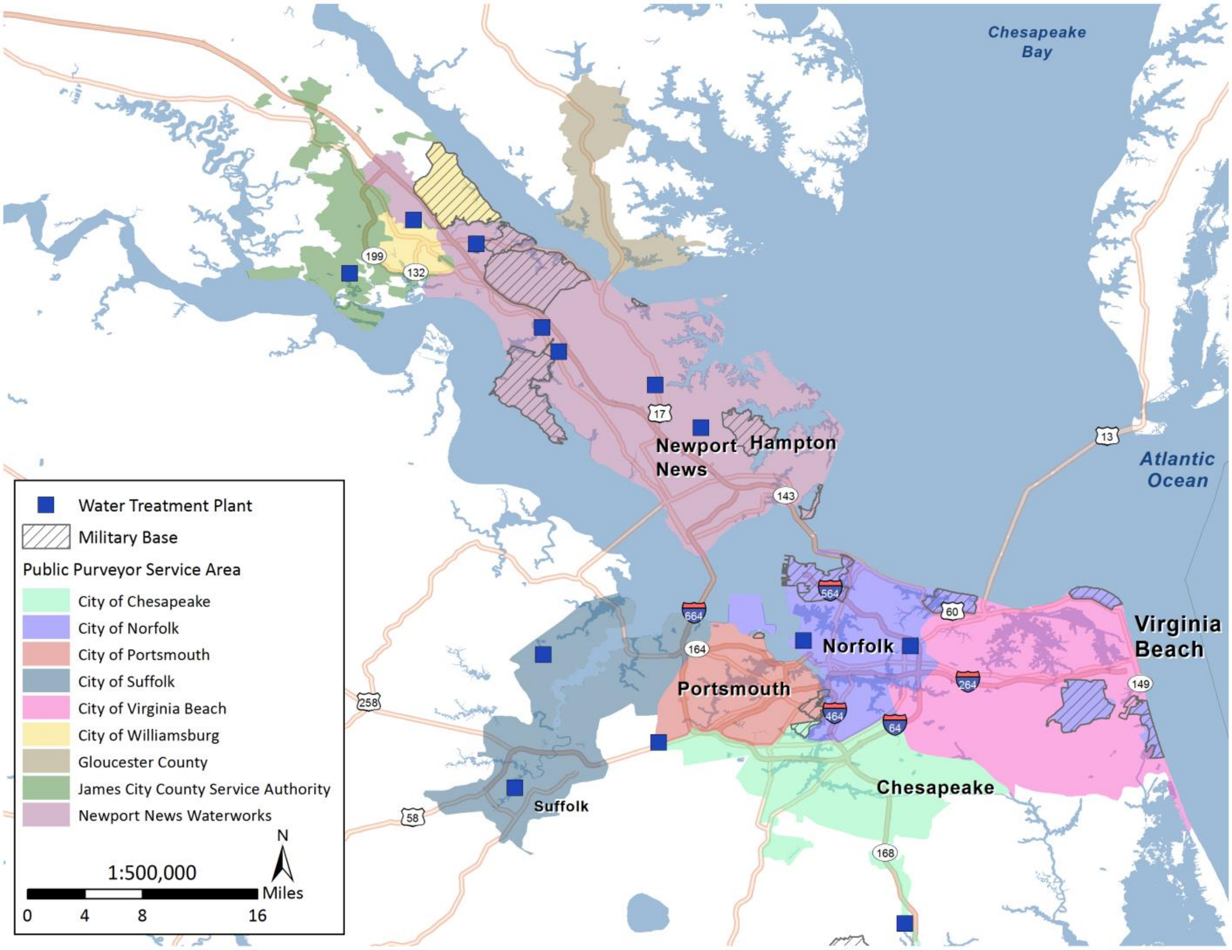

FIGURE 3—COMMUNITY WATER SYSTEMS AND SERVICE TERRITORIES[16]

The Peninsula subregion includes the cities of Hampton, Newport News, Poquoson, and Williamsburg, and the counties of Gloucester, James City, and York. The total population in the area is 512,000. The primary water provider for the Peninsula subregion is the Newport News Waterworks, which provides water to more than 400,000 people. The primary water supply for Newport News Waterworks is surface water diverted from the Chickahominy River and stored in a series of five reservoir impoundments. The surface water is treated at either the Lee Hall Water Treatment Plant or Harwood's Mill Water Treatment Plant. Newport News Waterworks also has a secondary source of brackish groundwater that is treated at the Lee Hall reverse osmosis plant. Newport News Waterworks has several wholesale customers, including Naval Weapons Stations Yorktown, Joint Base Langley-Eustis, and the Port of Norfolk Newport News Marine Terminal. Smaller water utilities in the Peninsula region include the James City Service Authority, which serves 46,000 people. It treats brackish water at the Five Forks reverse osmosis plant. The city of Williamsburg serves 12,800 people. It treats a combination of surface and groundwater at the Waller Mill Water Treatment Plant.

The Southside subregion consists of the cities of Chesapeake, Norfolk, Portsmouth, Suffolk, and Virginia Beach. The city of Norfolk provides drinking water to 850,000 people. Its water supply comes from eight reservoirs (Western Branch, Lake Prince, Lake Burnt Mills, Lake Smith, Lake Lawson, Little Creek, Lake Whitehurst, and Lake Wright); two rivers (Blackwater River, Nottoway River); and four deep wells. Water is treated at either the 37th Street Water Treatment Plant or Moore's Bridge Water Treatment Plant. The city of Norfolk is also a wholesale supplier to other communities, including the cities of Chesapeake, Virginia Beach, and Portsmouth.

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[16] Hampton Road Planning District Commission, "Hampton Roads Regional Water Supply Plan (2011)," www.hrpdcva.gov/Documents/HRRegWaterSupplyPlan/FINAL_HR%20RWSP_Jul2011_Report_only.pdf, accessed 5 May 2015.

In addition, the city of Norfolk provides drinking water to the Naval Station Norfolk, Naval Support Activity Hampton Roads, Joint Expeditionary Base Little Creek-Fort Story, and the Port of Norfolk-Norfolk International Terminal. Fifteen publicly owned water systems serve approximately 974,000 people.

Surface and groundwater resources supply the city of Chesapeake water system with drinking water. The city also receives water from the city of Norfolk, the city of Portsmouth, city of Chesapeake and private wells, and the Northwest River. The water from the city wells and the Northwest River is treated at the city's Northwest River Water Treatment Plant and the Lake Gaston Water Treatment Plant.[17] The Northwest River Water Treatment Plant treats 10 million gallons per day (MGD) from the Northwest River. This plant also treats brackish groundwater from city wells. The Lake Gaston Water Treatment Plant includes a storage tank with a capacity of 2 million gallons and supplies 8 MGD to the city.

OCIA–NISAC identified water treatment facilities at risk of flooding from sea level rise, storm surge, and a combination of sea level rise and storm surge based on geolocation data provided in the Los Alamos National Laboratory water and wastewater facilities database. Table 9 lists the facilities expected to be affected.

TABLE 9—AFFECTED WATER TREATMENT FACILITIES BY SCENARIO

Scenario	Facility Name	Owner
Sea Level Rise Only		
Scenario 1	No vulnerable facilities	
Scenario 2		
Scenario 3		
Scenario 4		
Hurricane Scenarios		
Scenario 0S	Moore's Bridges Water Treatment Plant 37th Street Water Treatment Plant	city of Norfolk
Scenario 1A	Moore's Bridges Water Treatment Plant 37th Street Water Treatment Plant	city of Norfolk
Scenario 2S	Moore's Bridges Water Treatment Plant 37th Street Water Treatment Plant	city of Norfolk
Scenario 3S	Moore's Bridge's Water Treatment Plant 37th Street Water Treatment Plant	city of Norfolk
Scenario 4S	Moore's Bridges Water Treatment Plant 37th Street Water Treatment Plant Northwest River Water Treatment Plant	city of Norfolk city of Chesapeake

The following summarizes the impacts to water treatment infrastructure:

- Sea level rise only:
    - No water treatment plants in the Hampton Roads area are at risk of flooding in the next 50 years (Scenarios 1–4, Table 9).
    - In addition, none of the water treatment facilities has electric power dependencies affected by sea level rise only.
- For the hurricane scenarios:

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[17] City of Chesapeake, "Forward Chesapeake 2026 Comprehensive Plan 2006," www.cityofchesapeake.net/Assets/documents/departments/planning/complan/12-Section_3_Water-$!26-Sewer.pdf, accessed 10 May 2015.

- In Scenarios 0S-3S, the hurricane storm surge inundates the Moore's Bridges and 37th Street Water Treatment Plants in the city of Norfolk. The city of Norfolk has interconnections with Chesapeake and Virginia Beach, but NISAC does not have data for the interconnection capacities.
- The additional sea level rise in Scenario 4S, results in the storm surge inundating the Northwest River Water Treatment Plant, which affects the drinking water of about 23,000 customers, mainly in the city of Chesapeake.
- Under the hurricane scenario, all of the water treatment plants in Table 9 have dependencies on electric power facilities that will be affected during a hurricane. However, the city of Norfolk maintains electric power backup generation at its water treatment plants, including an onsite fuel tanker truck to refuel generators with the expectation that backup generation could be used for weeks.[18]

Another dependency is the extraction of groundwater used as a significant source of drinking water for some locations in the Hampton Roads area. There may be environmental impacts (groundwater supply contamination, saltwater intrusion, impacts to the ecosystem) of groundwater intrusion due to flooding and sea level rise, which would affect drinking water. Groundwater extraction depends on electric power, however, and power supply to well pumps was not considered in this analysis.

In addition to the dependencies discussed above, a potential impact of sea level rise is that the salinity of the surface water supplies in this region might be affected as sea level rise pushes the saltwater transition zone in tidal rivers inland. This could present long-term drinking water sustainability problems for locations in which treatment plants are not designed to treat brackish water. Even in those water treatment plants designed to treat brackish water, for example the Northwest River Water Treatment Plant, higher salinity would increase treatment costs. Newport News Waterworks has already had instances in which water withdrawals were curtailed on the Chickahominy River because of tidal influences.

WASTEWATER

Wastewater systems are located in the lowest elevations within urban environments to collect wastewater through gravity-driven flow and forced flow through lift stations, treat, and discharge to local bodies of water. These systems are inherently vulnerable to disruption and damage in coastal environments during storm events. Moreover, wastewater systems are increasingly vulnerable to rising seas and increased intensity and frequency of precipitation events. This analysis identifies the vulnerability of critical wastewater assets relative to expected exposure to flood waters.

The Hampton Roads Sanitation District is the primary provider of wastewater treatment services in the Hampton Roads area and the only wastewater utility considered in this analysis. The Hampton Roads Sanitation District covers 17 counties, serving more than 1.6 million people. The infrastructure system consists of nearly 600 miles of pipe ranging from 6 to 66 inches in diameter. Because the system is located in low-lying areas around the Chesapeake Bay and James River, much of the main sewer lines are force-mains, indicating that these main sewer lines operate under pressure rather than gravity flow. As such, more than 70 pump stations are located throughout the system. There are 13 wastewater treatment plants located throughout the area with a combined capacity of nearly 250 MGD.

Table 10 lists the treatment plants, their capacities, normal flows, and waterbodies accepting treated effluent. The table also lists the treatment plant elevations provided by Hampton Roads Sanitation District as well as National Elevation Data-derived treatment plant elevations. The comparisons between the two elevation datasets highlight the potential differences in vulnerability assessments based on best-available elevation data. The discrepancy in the data is related to the methods in which the data are collected, such as remote sensing versus ground survey.

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[18] Conversation with City of Norfolk Department of Utilities Deputy Director, Eric Tucker, April 29, 2015.

TABLE 10—HAMPTON ROADS SANITATION DISTRICT WASTEWATER TREATMENT PLANTS

Facility	Date Installed	Capacity (MGD)	Normal Flow (MGD)	Discharge Waterbody	Hampton Roads Sanitation District Elevation (feet)	National Elevation Data Elevation (feet)
Army Base	1945	18	12.74	Elizabeth River	10.03	8.71
Atlantic	1983	36	30.29	Atlantic Ocean	8.4	4.16
Boat Harbor	1946	25	15.84	James River	6.77	8.7
Chesapeake Elizabeth	1965	24	21.04	Chesapeake Bay	10.95	9.17
James River	1968	20	15.17	James River	29.06	24.56
King William	1997	0.025	0.004	York River	not available	40.2
Nansemond	1979	30	20.58	James River	14.12	13.89
Urbanna	1970	0.1	0.06	Rappahannock River	NA	62.8
Virginia Initiative	1987	40	28.41	Elizabeth River	10.96	8.47
West Point	1950	0.6	0.56	York River	NA	9.04
Williamsburg	1970	22.5	14.47	James River	59.38	63.81
York River	1984	15	12.76	York River	8.63	2.83

The Hampton Roads Sanitation District provided OCIA–NISAC with a geospatial representation of the sewer network, which OCIA–NISAC used to identify vulnerable wastewater systems infrastructure for all scenarios. In addition, OCIA–NISAC identified electric power dependencies for the wastewater system and the impact that flooding from the event will have on electric power service for the critical wastewater components. OCIA–NISAC does not know if Hampton Roads Sanitation District facilities have backup power generation. Floodwater within wastewater treatment facilities and lift stations will likely damage electrical components and result in disruption, resulting in potential spillage of untreated wastewater. There are potential disruptions from lift stations that are directly flooded and those that are connected to flooded substations. Table 11 lists the vulnerable lift stations and Table 12 lists the vulnerable wastewater treatment plants.

TABLE 11—HAMPTON ROADS SANITATION DISTRICT LIFT STATIONS AT RISK OF FLOODING

Scenario	Lift Station	Treatment Plant Service Area	Population Served
Sea Level Rise Only			
Scenario 1	Ashland Circle experiences minimal flooding		
Scenario 2	Ashland Circle	Virginia Initiative Wastewater Treatment Plant	< 1,000
	Hanover Avenue	Virginia Initiative Wastewater Treatment Plant	< 1,000
Scenario 3	Jamestown Crescent	Virginia Initiative Wastewater Treatment Plant	< 1,000
Scenario 4	No Additional Lift Stations Inundated		
Hurricane Scenarios			
Scenario 1S	No Additional Lift Stations Inundated		
Scenario 2S	33rd Street	Boat Harbor Wastewater Treatment Plant	< 1,000
Scenario 3S	Quail Avenue	Virginia Initiative Wastewater Treatment Plant	5,300

Scenario	Lift Station	Treatment Plant Service Area	Population Served
Scenario 4S	No Additional Lift Stations Inundated		

TABLE 12—WASTEWATER TREATMENT PLANTS AT RISK OF FLOODING

Storm Surge Scenario	Wastewater Treatment Plant	Population Served
Sea Level Rise Only		
Scenario 1	No Wastewater Treatment Plants Inundated	
Scenario 2		
Scenario 3		
Scenario 4		
Hurricane Scenarios		
Scenario 0S	Boat Harbor Wastewater Treatment Plant	708,000
	Army Base Wastewater Treatment Plant*	
	Chesapeake Elizabeth Wastewater Treatment Plant	
	Virginia Initiative Wastewater Treatment Plant*	
	York River Wastewater Treatment Plant*	
Scenario 1S	Nansemond Wastewater Treatment Plant	891,300
Scenario 2S	Atlantic Wastewater Treatment Plant*	1,242,000
Scenario 3S	No additional inundated wastewater treatment plants	
Scenario 4S		
*These wastewater treatment plants depend on substations that are flooded for all scenarios, with the exception of the Atlantic Wastewater Treatment Plant, which has a substation dependency affected only by the 50-year mean sea level rise.		

Figures 4 and 5 show the locations of wastewater infrastructure at risk from sea level rise and storm surge, respectively.

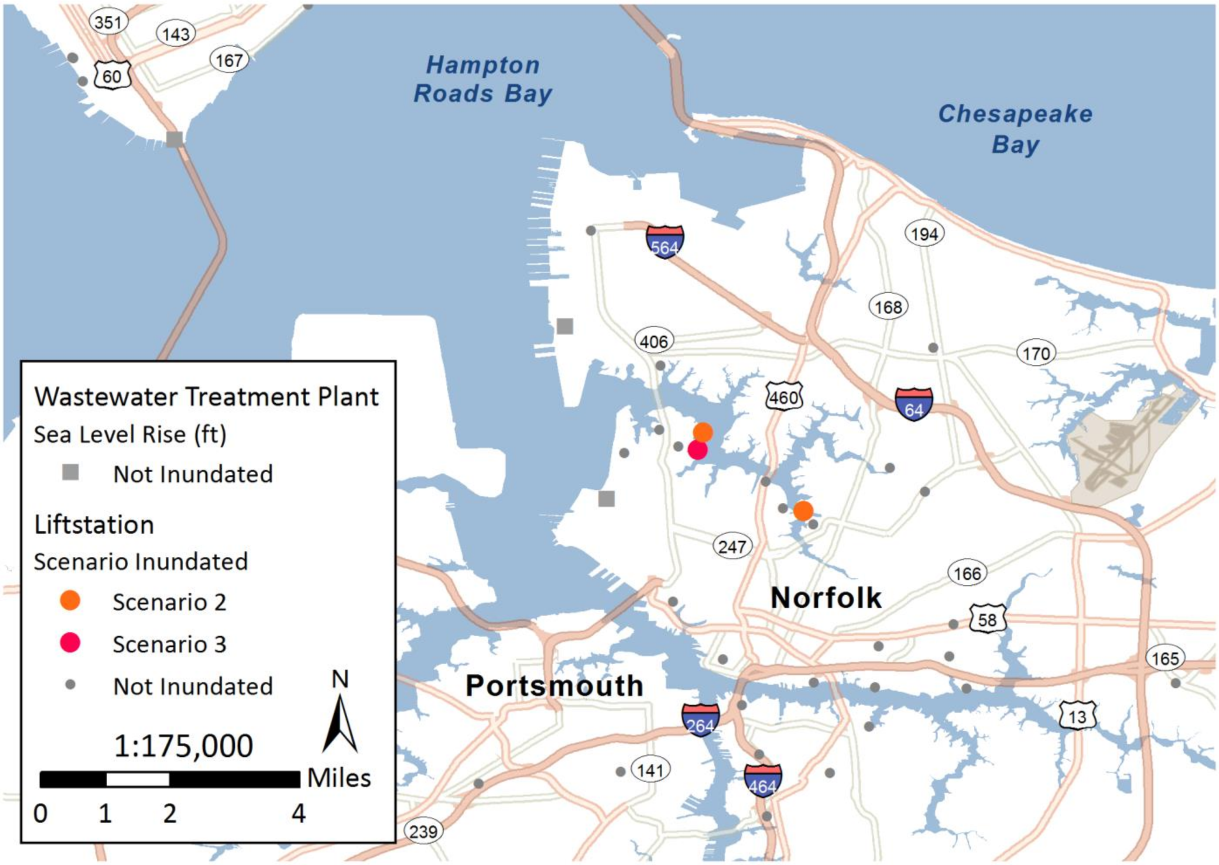

FIGURE 4—WASTEWATER INFRASTRUCTURE AT RISK OF FLOODING FROM SEA LEVEL RISE ONLY

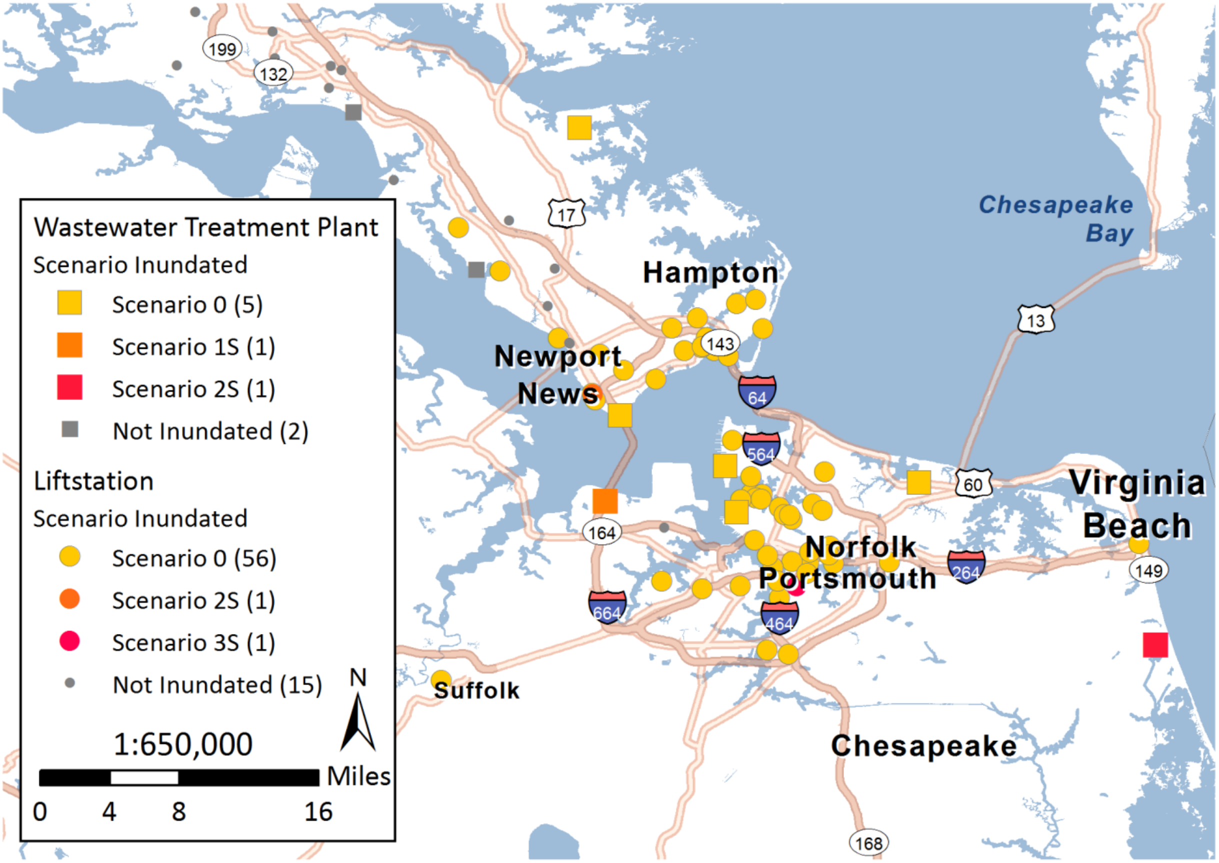

FIGURE 5—WASTEWATER INFRASTRUCTURE AT RISK OF FLOODING FROM STORM SURGE

The following summarizes the impacts to wastewater infrastructure:

- Sea level rise alone:
  - Sea level rise alone is not expected to affect wastewater treatment facilities in the region.
  - In Scenario 1, no lift stations are expected to be inundated by sea level rise. The lowest lying lift station, Ashland Circle, is elevated slightly higher than sea level, but could be subject to nuisance flooding.
  - In Scenario 2, the Ashland Circle and Hanover Avenue lift stations are expected to be inundated.
  - In Scenario 3, the Jamestown Station lift station is expected to be flooded in addition to the facilities identified in Scenario 2, which serve approximately 2,000 people in the city of Norfolk and are all located within the Virginia Initiative Plant service territory.
  - NISAC expects that no electric power substations providing power to critical wastewater facilities will be exposed to sea level rise within 50 years.
- Hurricane scenarios:
  - In the Scenario 0S, five wastewater treatment plants that collect sewage from approximately 708,000 people are inundated. Scenario 0S also inundates 56 lift stations. The Quail Avenue and Cedar Lane lift stations are not flooded but depend on a flooded electric power substation. The 56 lift stations that are potentially inoperable, flooded, or without electric power, collect sewage from nearly 280,000 people.
  - Under Scenario 2S, the Nansemond Wastewater Treatment Plant is inundated. It is not expected that any additional lift stations will be affected.

- Under Scenario 3S, the Atlantic Wastewater Treatment Plant is inundated. The 33rd Street and Quail Avenue lift stations are at increased risk of flooding under this scenario. These two lift stations serve fewer than 6,000 people.
- No additional wastewater infrastructure are expected to be inundated under Scenario 4S.

This analysis does not explicitly represent the impact of sea level rise on inflow and infiltration. Inflow and infiltration in a sewer system describes the water that enters the system through manholes, leaky joints, or surface entrances of facilities. Inflow and infiltration can have a significant effect on the amount of water conveyed in the system and can easily exceed design capacity. For example, Hampton Roads Sanitation District frequently has sewer overflow events from precipitation events. An overflow event occurs when the capacity of the infrastructure is exceeded and untreated sewage exits the system through lift stations or manholes. Infiltration and inundation can also result in capacity exceedance at the treatment plant requiring operators to bypass treatment and release untreated sewage into receiving waters. The risk of infiltration and inundation can increase with the onset of climate change. Appendix F presents the results of an investigation of nonstationary precipitation in the Hampton Roads area.

CONCLUSIONS

For this analysis, OCIA–NISAC examined the potential impacts of flooding in the Hampton Roads area relative to sea level rise only, impacts from a Category 3 hurricane, and a combined threat of hurricane-driven storm surge and sea level rise, with specific focus on the impacts to the electric power, water and wastewater, and transportation infrastructure systems. Because this analysis does not include assumptions for mitigation strategies, for example, hardening infrastructure or relocating population, the results present the worst-case scenario.

OCIA assesses that infrastructure stakeholders and planners need to be aware of, plan for, and invest in infrastructure that considers the potential impacts of the interaction of climate change, sea level rise, and hurricanes.

OCIA assesses that there will be impacts on the Electric Power Subsector from inundation from sea level rise. The analysis shows a relatively small population impact from flooding, in the Hampton Roads area, in the sea level rise only scenarios because of the small-developed area within the total area at risk of flooding. Sea level rise only impacts to electric power infrastructure represent a longer-term infrastructure mitigation challenge. OCIA assesses that no water or wastewater treatment plants in the Hampton Roads area are at risk of flooding from the sea level rise only scenarios.

OCIA assesses that sea level rise will amplify the effect of flooding on the population during hurricanes in the Hampton Roads area, particularly on electric power substations during hurricanes. Sea level rise conditions at the time of the storm surge from the Category 3 hurricane will disrupt roadways to a greater degree. For the Category 3 hurricane scenario in this report, three additional substations are at risk of flooding by 2035, and 8–12 additional substations are at risk of flooding by 2065. Sea level rise will increase the vulnerability of some water and wastewater infrastructure during hurricanes. For the Category 3 hurricane scenario in this report, one additional wastewater treatment plant will be flooded by 2035, and one additional water treatment plant and wastewater treatment plant will be flooded by 2065.

APPENDIX A: UNCERTAINTY

The results presented in this report are intended to accurately describe the modeling and analysis that supported the given scenario of sea level rise, combined with a Category 3 hurricane in the Hampton Roads, Virginia area. Although OCIA–NISAC takes great care in developing and verifying models and gathering and vetting data, many sources of uncertainty can influence the analyses and the results. The main sources of uncertainty in this report stem from the data, the models, and other information that is unknown or unavailable to NISAC.

Data can introduce uncertainty because of the variability in standards that occurs when using individual data sources, lack of data availability, and general data errors. OCIA–NISAC assumes that data are accurate and geocoded. In some cases, data used in this analytic effort are a compilation, including reference sources used in conjunction with commercial and other sources to most accurately represent the sector parameters. In many cases, OCIA–NISAC compiled data from several sources to compensate for missing information. When using multiple datasets, OCIA–NISAC made every effort to ensure accuracy and completeness, but data on some aspects of a system may not be included in a dataset. Other data errors, including typos, exist and may be unnoticed during or after the analysis. Errors in the geographic location of sector assets can change analysis results completely. For example, geolocated assets in a sector are superimposed over the geographic electric power outage areas; if the geolocation of an asset is incorrect, the analysis may not accurately reflect the impact of the scenario event.

OCIA–NISAC assumes that when factual data critical to forming any analysis are unavailable, increased uncertainty will result. For example, although OCIA–NISAC can report whether people remain in or relocate from an affected area if that data is available, OCIA–NISAC cannot know with certainty what people will do 20 or 50 years from now. Likewise, OCIA–NISAC can assume that infrastructure assets do not change over time but, again, it is impossible to know with certainty what will happen in the future. This analysis assumes that both the population and infrastructure are static during the 20–50 year period. OCIA–NISAC also based estimates for sea level rise on climate projections that assume a socioeconomic scenario for future emissions of greenhouse gases and other atmospheric constituents. Finally, OCIA–NISAC assumed that stakeholders do not implement mitigation strategies. These business-as-usual assumptions result in a worst-case scenario. Mitigation strategies that altered population or infrastructure would alter the combined effects of sea level rise and storm surge.

Models are a point of uncertainty since OCIA–NISAC cannot shut down infrastructure to analyze the impacts of an event on a system. OCIA–NISAC uses system models to simulate how a scenario affects performance. A model is a representation of a physical system used to examine the effects of external influences on that system. Because models are representations, they are unlikely to capture all the interactions and parameters of the real-world systems they represent. Modeling and analysis associated with this product use established and documented models of infrastructure in conjunction with subject matter expert judgment.

General unknowns exist in modeling the real world. These unknowns can include the general status of an area or asset before an earthquake or other exogenous factors. The status of an asset can be important. For example, a roadway that is under construction cannot be used for evacuation or restoration activities. Other exogenous factors, such as human behavior, will always affect the outcome of a catastrophic event. Although many models try to predict what people will do, human behavior is unpredictable.

OCIA–NISAC typically uses a robust approach to modeling impacts to infrastructure systems. Although these methods involve uncertainty from many sources, retrospective analyses of past events have validated the accuracy of the model results described in this analysis.

No water treatment plants in the Hampton Roads area are at risk of flooding from sea level rise only in the next 50 years (Scenarios 1–4, Table 9). In addition, none of the water treatment facilities has electric power dependencies affected by sea level rise only. For the sea level rise considered in Scenarios 0S-3S, the scenario hurricane storm surge inundates the Moore's Bridges and 37th Street Water Treatment Plants in the city of Norfolk. The city of Norfolk has interconnections with Chesapeake and Virginia Beach, but NISAC does not have data for the interconnection capacities. The additional sea level rise in Scenario 4S, results in the storm surge inundating the Northwest River Water Treatment Plant, which affects the drinking water of about 23,000 people, mainly in the city of Chesapeake.

All of the water treatment plants in Table 9 have dependencies on electric power facilities that will be affected during a hurricane. However, the city of Norfolk maintains electric power backup generation at its water treatment plants, including an onsite fuel tanker truck to refuel generators with the expectation that backup generation could be used for weeks.

APPENDIX B: SEA LEVEL RISE AND STORM SURGE DEVELOPMENT

METHOD

The National Infrastructure Simulation and Analysis Center (NISAC) based estimates for sea level rise on climate projections that assume a socioeconomic scenario for future emissions of greenhouse gases and other atmospheric constituents. Sea level rise depends on the increase or decrease of global warming, which in turn depends on the future fossil fuel use trajectory. Four standard emission scenarios, or Representative Concentration Pathways (RCPs), are identified by Kopp, et al.: low (RCP 2.6), medium (RCP 4.5), medium-high (RCP 6.0), and high (RCP 8.5).[19] In practice, the medium and medium-high emission scenarios are similar, so this analysis will analyze the two scenarios as if they were only one scenario. OCIA–NISAC did not attempt to assign relative likelihoods or levels of plausibility to each scenario. To examine the risk of more severe climate change without focusing on the worst-case scenario, OCIA–NISAC analyzed the medium and medium-high RCPs 4.5 and 6.0 scenarios.

OCIA–NISAC used the open source LocalizeSL tool for the Hampton Roads area sea level rise projections.[20] The LocalizeSL tool is a state-of-the-art probabilistic data fusion method that combines modern climate model projections, subject matter expert judgment when models are lacking, and historical tide gauge data. It provides projections of local sea level rise during the 21st century at tide gauge locations, expressed as probability distributions that evolve over time. In addition, it accounts for all major sources of sea level rise, including oceanographic changes in heat content, salt content, and circulation patterns; glacier and ice sheet melting; the gravitational attraction of ice sheets on the nearby ocean; and transfer of water between the ocean and land reservoirs. Moreover, the LocalizeSL tool accounts for local changes in coastal land elevation from slow geological adjustment to the removal of glaciers from the last ice age, sediment compaction, plate tectonics, and groundwater withdrawal. Sea level rise and land elevation changes combine to affect the local sea level, that is, the height of the sea relative to the coastline. For this report, sea level rise is equated to local sea level rise.

The probability distribution for sea level rise is estimated using the data from the tide gauge at Sewells Point, Virginia, from 2015 to 2100. This data was used for all analysis in this report. The mean projected sea level rise represents a 50 percent chance that the sea level rise will be above or below this projected median sea level rise depth. The 95 and 99 percent statistical confidence levels, which indicate that sea level rise is likely to be exceeded with 5 percent and 1 percent probability, respectively, are also estimated. This study projects what sea level rise will be in 2035 and 2065.

SEA LEVEL RISE ASSUMPTIONS

For this analysis, OCIA–NISAC assumes that the RCPs 4.5 and 6.0 scenarios approximately represent the world's future fossil fuel emissions. Economists who help formulate future climate scenarios consider the RCPs 4.5 and 6.0 emission scenarios plausible, and they are widely used in climate change studies. OCIA–NISAC also assumes that the current generation of climate models provides a reasonable range of projections for oceanographic changes in sea level. The LocalizeSL tool assumes that the oceanographic and other sources of sea level rise are independent of each other. For this study, the LocalizeSL tool identifies the oceanographic change projections as the dominant source of sea level rise at Norfolk during the next 50 years. Although not dominant during the next 50 years, the sea level rise contribution of Antarctic ice sheet disintegration becomes a significant source of uncertainty.

Because computer modeling of Antarctic ice physics is still in its infancy, OCIA–NISAC based the Antarctic projections climate scientist expert judgment at Los Alamos National Laboratory, albeit informed by observational measurements and computer simulation. Although climate models have well-known problems in projecting future ice sheet melting, particularly in Antarctica, they are considered the current best source of projections for oceanographic changes. Alternative, newer scenarios for Antarctic ice melt exist in the scientific literature, some of

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[19] Kopp, R., Horton, R., Little, C., et al., "Probabilistic 21st and 22nd century sea level projections at a global network of tide-gauge sites," *Earth's Future*, 2(8)(2014), pp. 383–406.
[20] Ibid.

which differ from the expert assessment used in this analysis. None of the individual research group studies is built upon a wide survey of scientific opinion. OCIA–NISAC relied on climate scientist expert judgment at Los Alamos National Laboratory as the best available consensus science.

The assumption that sources of sea level rise are independent of each other is probably not correct. However, no probabilistic method is found in the scientific literature for projecting sea level rise that accounts for statistical correlations between different sources of sea level rise—this is an ongoing research problem. The assumption, therefore, likely underestimates the probability of extreme sea level rise scenarios; for example, scenarios with high global warming should have both a large ocean thermal expansion and a high rate of ice melt. The typical estimates used for this analysis are less affected by this assumption.

SEA LEVEL RISE DATA

OCIA–NISAC used the following data to develop estimates of sea level rise and storm surge flooding:

- The Intergovernmental Panel on Climate Change—the RCP 6.0 emissions scenario
- Coupled Model Intercomparison Project database of all major current-generation climate model simulations—oceanographic changes in sea level rise
- Intergovernmental Panel on Climate Change's most recent assessment report
- Sea level rise estimates[21]
- Tide gauge sea level data from the UK Permanent Service for Mean Sea Level archive
- LocalizeSL and other minor data sources detailed in Kopp, et al.[22]
- U.S. Geological Survey 10-meter National Elevation Dataset, supplemented with NOAA's Digital Coast Data (~1-meter) in the Norfolk area
- NOAA Tides and Currents gauge data

SEA LEVEL RISE IMPACT ANALYSIS METHOD

Using the characteristics of sea level rise and the scenario hurricane, OCIA–NISAC developed 10 flood hazard scenarios to assess infrastructure, population, and economic vulnerabilities. OCIA–NISAC used the NOAA Sea, Lake, and Overland Surge from Hurricanes model to generate the storm surge inundation maps.[23] OCIA–NISAC propagated the sea level rise projection through the Sea, Lake, and Overland Surge from Hurricanes model by including tide and sea level rise as base data for the hydrodynamic simulations. The speed of the simulation is one of the advantages of using Sea, Lake, and Overland Surge from Hurricanes for hurricane simulations; however, the resolution of the topography and bathymetry—measurements of the water depths—is relatively coarse, which can result in inaccuracies in determining which assets are flooded. To rectify the resolution limitation, NISAC used a post-processing algorithm to refine the resolution using best available topography data. The strong Category 3 hurricane results in a peak tide level of nearly 14 feet above the North Atlantic Vertical Datum 88. Sea level rise was considered with and without storm surge; NISAC did not consider wave action and erosion in assessments of infrastructure damage. This study did not include hurricane intensification over time.

To identify the critical infrastructure at risk, OCIA–NISAC compared the storm-surge inundation areas with the infrastructure locations identified in Homeland Security Infrastructure Program Gold data set (for electric power sector assets) and the Los Alamos National Laboratory water and wastewater database.[24] When necessary, these databases were supplemented with utility-specific information obtained through stakeholder engagements. To estimate the extent of damage of the infrastructure at risk, OCIA–NISAC uses the Los Alamos National Laboratory fragility model, which includes the Federal Emergency Management Agency Hazards United States

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[21] Bamber, J. L., and Aspinall, W. P. "An expert judgement assessment of future sea level rise from the ice sheets," *Nature Climate Change* 3.4(2013): pp. 424-427.

[22] Kopp, R., Horton, R., Little, C., et al., "Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites," *Earth's Future* 2(2014): pp. 383–406.

[23] National Weather Service, "Sea, Lake, and Overland Surges from Hurricanes Model," www.nhc.noaa.gov/surge/slosh.php, accessed 12 April 2015.

[24] See Homeland Security Infrastructure Program (HSIP) Gold, www.hifldwg.org.

fragility curves. OCIA–NISAC did not conduct a hydraulic analysis of the water and wastewater network. Assessments of vulnerability and potential disruption of water and wastewater infrastructure are based on exposure to flood water only.

OCIA–NISAC uses assumptions when factual data are unavailable. For example, OCIA–NISAC makes an assumption about whether people will remain or stay in an affected area, because it cannot know with certainty what people will do 20 or 50 years from now. Likewise, OCIA–NISAC can assume that infrastructure assets do not change over time; still, it is impossible to know with certainty what the future holds.

OCIA–NISAC used the following assumptions to support this analysis:

- Population and economic activity remain constant at the 2010 levels.
- Number and location of future electric power, water, and wastewater infrastructure assets are the same as in 2015.
- Geospatial location of infrastructure is an accurate representation of the asset, and the underlying digital elevation model represents actual asset base elevation. Where available, OCIA–NISAC supplemented asset elevations with data from utility owners.
- Sea level rise combined with storm surge scenarios represent the specific storm simulated. Hurricane characteristics can vary resulting in changes in infrastructure vulnerability.
- Power failure because of hurricane winds will remain unchanged during the next 50 years.
- Electric power service territories are inferred through geospatial analysis of loads. Water and wastewater and electric power dependencies are assumed based on the electric power service territory where the facility is geographically located.

DATA

In addition to the data used to develop the sea level rise scenarios, OCIA–NISAC used the following to support various aspects of this analysis:

- U.S. Geological Survey National Elevation Data[25]
- Wastewater infrastructure data provided by Hampton Roads Sanitation District[26]
- Homeland Security Infrastructure Program Gold substation data and Federal Energy Regulatory Commission bus data
- Los Alamos National Laboratory water and wastewater asset database[27]
- HERE.com (navigation, mapping, location platform) transportation data—the HERE model is an open source model providing real-time traffic flow patterns[28]
- Population and business activity at tract level from 2010 census
- National Land Cover Database 2011 impervious surface dataset

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[25] The National Map Viewer and Download Platform, http://nationalmap.gov/viewer.html.

[26] Hampton Roads Regional Waste Supply Plan, www.hrpdcva.gov/Documents/HRRegWaterSupplyPlan/FINAL_HR%20RWSP_Jul2011_Report_only.pdf, accessed 5 May 2015.

[27] Los Alamos National Laboratory database.

[28] HERE, company.here.com/here/.

APPENDIX C: SEA LEVEL RISE ANALYSES

The Norfolk sea level rise projections are obtained from the open source LocalizeSL code based on the scientific publication.[29] This is a state-of-the-art probabilistic data fusion method that combines modern climate model projections, subject matter expert judgment where models are lacking, and historical tide gauge data. It provides projections of local sea level rise during the 21st century at tide gauge locations, expressed as probability distributions that evolve.

The method accounts for all major sources of sea level rise, including the following:

- Oceanographic
  - Heat content changes
  - Salt content changes
  - Circulation pattern changes
- Ice melting
  - Large ice sheets (Greenland and Antarctica)
  - Gravitational attraction of ice sheets on the nearby ocean
  - Small glaciers and ice caps
- Land elevation changes
  - Groundwater withdrawal
  - Slow geological adjustment from the last ice age
  - Sediment compaction
  - Plate tectonics

Both sea level rise and land elevation changes combine to affect the local sea level, that is, the height of the sea relative to the coastline.

The method OCIA–NISAC used for this study differs in some ways from previous analyses, such as the Department of Energy (DOE) 2014 report entitled, "Effect of Sea Level Rise on Energy Infrastructure in Four Major Metropolitan Areas."[30] The DOE study obtained sea level projections from the 2012 National Climate Assessment scenarios.[31] The National Climate Assessment scenarios are based on the Intergovernmental Panel on Climate Change fourth assessment report, whereas the LocalizeSL projections are based on the fifth assessment report.[32,33] The 2007 Intergovernmental Panel on Climate Change report revised the projections of both oceanographic and ice sheet contributions to sea level rise. LocalizeSL also provides uncertainty bounds, unlike the National Climate Assessment, and decomposes the projections into individual sources of sea level rise, which provides flexibility in updating the projections as new science becomes available. The RCP 6.0 mean sea level scenario NISAC considers for Norfolk corresponds roughly, in rate of global sea level rise, to the National Climate Assessment "Intermediate Low" scenario. The National Climate Assessment "Intermediate High" scenario would correspond roughly to LocalizeSL projections for RCP 8.5 emissions at the 95th percentile; OCIA instead considers these upper bound scenarios for RCP 6.0 emissions.

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[29] Kopp, R., Horton, R., Little, C., et al., "Probabilistic 21st and 22nd century sea level projections at a global network of tide-gauge sites," *Earth's Future*, 2(8)(2014), p. 383–406., http://zenodo.org/record/15507.

[30] Office of Electricity Delivery and Energy Reliability, "Effect of Sea Level Rise on Energy Infrastructure in Four Major Metropolitan Areas," September 2014, http://energy.gov/sites/prod/files/2014/10/f18/DOE-OE_SLR%20Public%20Report_Final%20_2014-10-10.pdf, accessed 14 April 2015.

[31] Parris, A., P. Bromirski, V. Burkett, et al., (2012). "Global Sea Level Rise Scenarios for the US National Climate Assessment," NOAA Tech Memo OAR CPO-1. 37 http://scenarios.globalchange.gov/sites/default/files/NOAA_SLR_r3_0.pdf, accessed 14 April 2015.

[32] Pachauri, R.K., and Reisinger, A.. "IPCC fourth assessment report," IPCC, Geneva. (2007), www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_full_report.pdf, accessed 14 April 2015.

[33] Stocker, T.F., et al. (2013). "IPCC, 2013: climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change."

APPENDIX D: ROAD TRANSPORTATION DISRUPTION ANALYSIS METHODOLOGY

In each case, OCIA–NISAC superimposed the surge levels from a fragility analysis on the road network to estimate the road sections that would be out of service because of the storm and sea level conditions. These roadway disruptions will cause traffic to be rerouted to alternative roadways. The alternative roads will experience excessive vehicle loads leading to excessive volume to capacity ratios and extended travel times.

OCIA–NISAC used TransCAD, a tool in the FastTrans suite, to examine traffic disruptions resulting from the scenario hurricane, analyzing the flow of traffic under normal circumstances and under storm-surge and sea level rise conditions. OCIA–NISAC used the surge projections to assess interruptions in the roadway system, particularly with the major highways and thoroughfares. This analysis assumes that no mandatory evacuation order is in effect.

Simulations developed in TransCAD provide numerical and geographical representations of traffic flows. The analysis used a transportation network and 2010 demographic data from the HERE.com website for the road transportation analysis.[34] The transportation network data provides a detailed map of the region of interest used to analyze the network and display the results. OCIA–NISAC used 2007 business data from Dun & Bradstreet, the most recent available to OCIA–NISAC, to estimate travel from home and work for business and nonbusiness purposes, and to localize the destinations of trips on the transportation network for employees and patrons of those businesses and facilities.

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[34] HERE, company.here.com/here/.

APPENDIX E: HURRICANE INTENSIFICATION

Hurricanes or tropical cyclones constitute the most important recurring natural hazards affecting people in the global tropics and subtropics, including the United States. The Galveston hurricane of 1900 remains the deadliest natural disaster to ever strike the United States, whereas Hurricane Katrina in August 2005 remains the costliest. With peer-reviewed literature suggesting an increase in tropical cyclone activity under global warming, developing an understanding of the future of hurricanes and the vulnerability of coastal regions to the devastating effects of the storm surge associated with them becomes pertinent.[35,36] The Potential Intensity (is a framework to understand the conduciveness of the large-scale ocean-atmosphere thermodynamic state to promote hurricane development. The Potential Intensity, calculated using sea surface temperature, sea level pressure, and atmospheric vertical profiles of temperature and humidity, is the theoretical limit to the maximum possible intensity that a hurricane can achieve under the given environmental conditions.[37] The Potential Intensity is also an important parameter used in operational forecasting of hurricanes by the National Hurricane Center.

To understand future changes in Atlantic hurricane activity, OCIA–NISAC evaluated the changes in Potential Intensity using climate model output from the Intergovernmental Panel on Climate Change's Coupled Model Inter-comparison Project—Phase 5 (CMIP5). OCIA–NISAC randomly selected the following 10 different climate models from the CMIP5 archive for this analysis:

- Version 1.1 of Beijing Climate Center's Climate System Model (BCC–CSM1)
- Version 2 of Canadian Center for Climate Modeling and Analysis's Earth System Model (CanESM2)
- Version 5 of National Centre for Meteorological Research's Climate Model (CNRM–CM5)
- Version 3 of the Centre for Australian Weather and Climate Research's Atmosphere Ocean Global Climate Model (CSIRO–Mk3)
- Version 3 of Geophysical Fluid Dynamics Laboratory's Coupled Model (GFDL–CM3)
- Geophysical Fluid Dynamics Laboratory's Earth System Model (GFDL–ESM2G)
- Version 2 of Goddard Institute for Space Studies' Model E (GISS–E2)
- Version 2 of UK Met Office's Global Environment Model (HadGEM2–CC)
- Version 4 of Institute of Numerical Mathematics' Climate Model (INMCM4)
- Version 4 of the National Center for Atmospheric Research's Community Climate System Model (CCSM4)

OCIA–NISAC used 20 years of data between 1981 and 2000 from the historical runs of the models to correspond to present-day conditions. For future projections, OCIA–NISAC used 20 years of data between 2081 and 2100 from the RCP 4.5, an intermediate range emissions scenario in which the increase in radiative forcing asymptotes to a value of 4.5 watt per square meter. For this study, "change" indicates the difference between an average from 2081 to 2100 and an average between 1981 and 2000.

OCIA–NISAC finds that for the early and peak hurricane months June–September, the Potential Intensity changes are not significant over most of the Atlantic except for a small area near 75W and 35N. The Potential Intensity critically depends on the difference in enthalpy at the air-sea interface. In other words, the stronger the thermal disequilibrium is at the air-sea boundary, the more likely the ocean-atmosphere coupled state is to promote deep convection. Thus, although the sea surface temperature increases June–September, the Potential Intensity may not increase significantly if the changes in atmosphere are not in tandem. The Potential Intensity increases significantly along a swath oriented in a northwest-southeast direction, extending approximately between 70W 30N and 30W 10N. The strongest increase occurs in the northwestern tropical Atlantic between 80W and 50W and 10W and 30N. A few small and isolated regions of significant Potential Intensity increase exist in the Gulf of Mexico. Thus hurricanes, whose paths carry them over these regions of Potential Intensity increase in the future,

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[35] Emanuel, K, "Increasing destructiveness of tropical cyclones over the past 30 years," Nature 436.7051 (2005): 686–688.
[36] Elsner, J. B., Kossin,J. P., and Jagger, T. H.. "The increasing intensity of the strongest tropical cyclones," Nature 455.7209 (2008): 92–95.
[37] Emanuel, Kerry A. "Thermodynamic control of hurricane intensity," Nature 401.6754 (1999): 665–669.

may increase in intensity because of favorable thermodynamic conditions experienced by them in such regions (Figure 6).

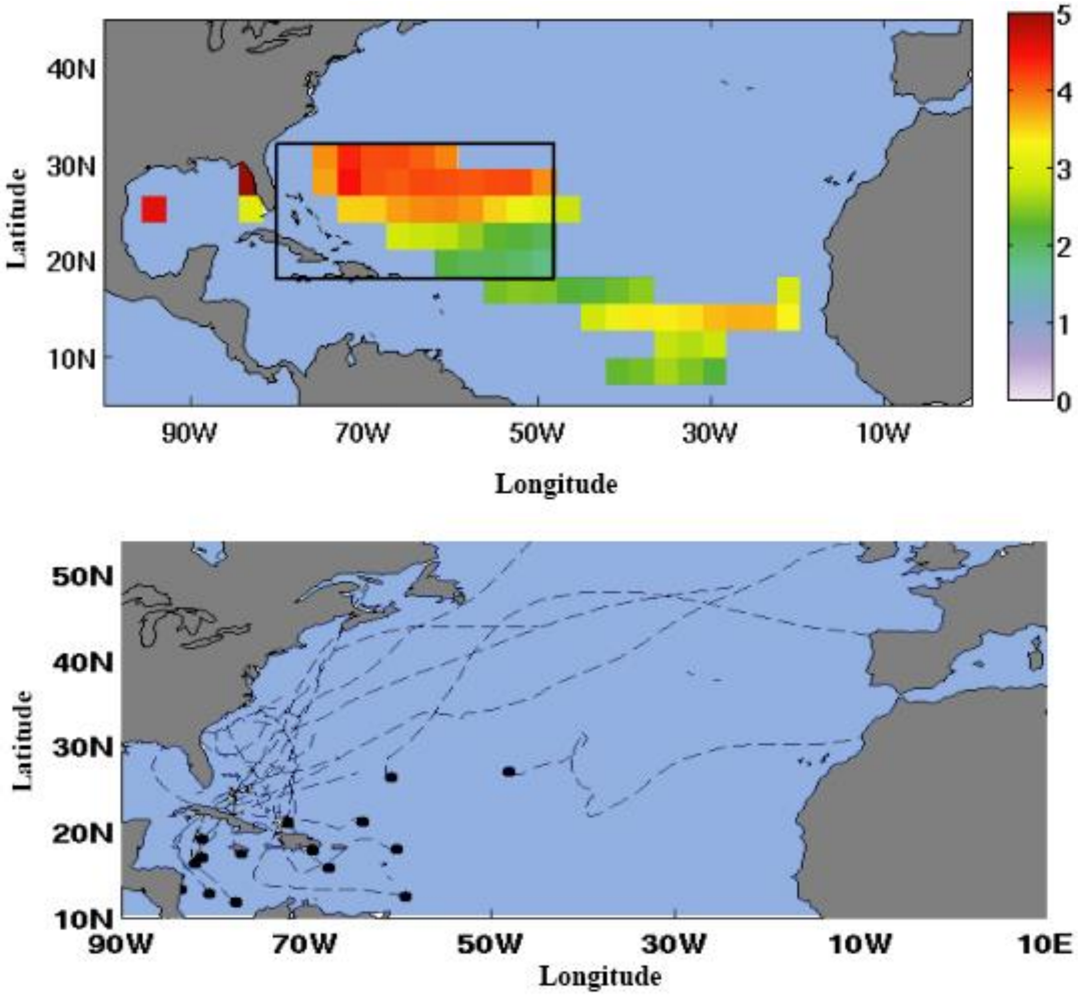

FIGURE 6—CHANGE IN POTENTIAL INTENSITY (M/S) (UPPER) AND TRACKS OF ATLANTIC LAND FALLING HURRICANES (LOWER) FOR OCTOBER AND NOVEMBER (LOWER)

OCIA–NISAC also considered the historical landfall hurricane tracks that will likely experience favorable Potential Intensity conditions under climate change. The hurricane track data are obtained from the hurricane database of the National Hurricane Center. The tracks of Atlantic landfall hurricanes for October and November are shown along with their genesis locations in the bottom panel of Figure 7. Almost all hurricanes form in the western tropical Atlantic between 90W and 50W and 10N and 30N, and many of these tracks pass over the region of significant Potential Intensity increase identified previously (rectangular box in the top panel). Based on their spatial structure, the hurricane tracks can broadly be classified into two categories. Although all hurricanes form near the Caribbean and Antilles Islands and track northward, some are steered to the west and make landfall on the eastern flank of the Gulf of Mexico or along the east coast between Florida and Virginia. Notably, this set of tracks includes Hurricane Sandy, the notorious late season hurricane from 2012. The other set of hurricane tracks steer eastward and make landfall over Canada or Europe as extra-tropical storms. Many of these regions of landfall along the east coast of continental North America display some of the largest positive trends in sea level making them vulnerable to the devastating effects of storm surge.[38] Although sea level trends of 0 to 3 millimeters per year have been detected between Florida and North Carolina, trends in sea level have been as high as 6 millimeters per year near New York. Thus, a combined effect of increasing hurricane intensity and rising sea levels may mean increasing

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[38] Woodruff, J. D., Irish, J. L., and Camargo, S. J. (2013). "Coastal flooding by tropical cyclones and sea level rise," Nature 504.7478 , p. 44–52.

destruction from hurricanes for the coastal regions of the United States, particularly during the late season of October and November.

APPENDIX F: PRECIPITATION INTENSIFICATION

BACKGROUND

Hampton Roads is a low-elevation coastal region with industrial, military, urban, and suburban areas. Norfolk is considered to be at increased risk of damage from ongoing sea level rise resulting from climate change. In addition to sea level rise, change in precipitation intensity and frequency has potential consequences pertaining to infrastructure planning and resiliency. For example, urban storm water systems are typically designed to convey runoff from design storm precipitation events based on historical data. Much has been published that discusses the state of knowledge related to climate change and what can and cannot be known from the multitude of climate models. The literature discusses annual and seasonal changes predicted by the models on global and large basin scale, whereas others focus on the prediction of extreme events under climate change and the dynamic nature of extreme events.[39,40,41]

Kao and Ganguly predict increased precipitation intensity, frequency, and depth in a warming climate.[42] However, they note that many uncertainties exist at smaller scales in time and space (decadal and regional, respectively). Although not all climate models agree, Kao and Ganguly show that historical patterns of precipitation are changing (i.e., nonstationary) in some locations and that this dynamic should be considered in future planning to better anticipate potential risks and design challenges. They also noted that these extreme rain events would affect intensity-duration-frequency curves often used in infrastructure design. Cheng, et al. state that the assumption of stationary patterns of precipitation may underestimate extreme precipitation events by as much as 60 percent.[43]

The research described here uses historical observed precipitation data, gridded regional precipitation data, and regionally downscaled precipitation data from a climate model to understand potential future changes in precipitation patterns. By showing the linkages between historical and projected precipitation datasets, inferences can be drawn of potential future precipitation changes.

NISAC assumed that no mitigation strategies are implemented. This business-as-usual assumption results in a worst-case scenario. Mitigation strategies would alter the combined effects of sea level rise and storm surge on the population, infrastructure, and economy.

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[39] Gao, Y., L.R. Leung, J. Lu, et al. (2014). Robust spring drying in the southwestern U.S. and seasonal migration of wet/dry patterns in a warmer climate, *Geophys.* Res. Lett., 41, 1745–1751, doi:10.1002/2014GL059562.

[40] Kunkel, K. E., et al., "Monitoring and understanding trends in extreme storms: State of knowledge." *Bulletin of the American Meteorological Society* 94.4 (2013): 499–514.

[41] Cheng, L., and AghaKouchak, A. "Nonstationary precipitation intensity-duration-frequency curves for infrastructure design in a changing climate," *Scientific Reports* 4 (2014).

[42] Kao, S.C., and Ganguly, A. R. (2011), Intensity, duration, and frequency of precipitation extremes under 21st-century warming scenarios, *J. Geophys.* Res., 116, D16119, doi:10.1029/2010JD015529.

[43] Cheng, L., and AghaKouchak, A.. "Nonstationary precipitation intensity-duration-frequency curves for infrastructure design in a changing climate." *Scientific Reports* 4 (2014).

DATA

The following datasets were used to support the investigation:

- Historical observations at Joint Base Langley-Eustis (hourly), Naval Station Norfolk (daily), and Norfolk International Airport (daily).[44]
- Gridded data products (North American Land Data Assimilation System) that represent one-eighth degree "tiles" of weather data. These data have been created for the United States based on a variety of data sources from 1979 to the present. These data were extracted for eight grid points in the Norfolk region.[45]
- NOAA Atlas 14 Intensity Duration Frequency values across the United States.[46]
- Precipitation projections at the North American Land Data Assimilation System location for historical and two climate-change scenarios described in Gao, et al.[47] These are from a single member of the Global Climate Models from the Coupled Model Intercomparison Project Phase 5 archive (i.e., the Community Climate System). Model v.4 was downscaled with a regional climate model using the coupled Weather Research and Forecasting and Community Land Model. These climate model data included the modeling of a historical period ("Historical" 1975 to 2005) and two future scenarios, the RCP 4.5 and RCP 8.5. The former is a medium emission scenario, the latter a fossil fuel intensive scenario.

Table 13 provides a summary of the precipitation data used in this analysis and Figure 7 shows the locations.

TABLE 13—PRECIPITATION DATA USED IN THIS STUDY

Location	Type	Years Collected
Joint Base Langley-Eustis	Daily	1893–2006
Naval Station Norfolk	Daily	1945–2014
Norfolk Airport	Hourly	1949–2013
NOAA Atlas 14 (three sites)	IDF Data	
North American Land Data Assimilation System (eight sites)	Hourly	1979–2013
Climate Historical (three sites)	Hourly	1975–2004
RCP 4.5 (three sites)	Hourly	2005–2100
RCP 8.5 (three sites)	Hourly	2005–2100

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[44] National Centers for Environmental Information, "Climate Data Online," National Oceanic and Atmospheric Administration, www.ncdc.noaa.gov/cdo-web/, accessed 5 May 2015.

[45] National Aeronautics and Space Administration, "North American Land Data Assimilation System, http://ldas.gsfc.nasa.gov/nldas/NLDAS2forcing.php, accessed 15 May 2015.

[46] National Weather Service, "Current NWS Precipitation Frequency Documents," National Oceanic and Atmospheric Administration, www.nws.noaa.gov/oh/hdsc/currentpf.htm., accessed 15 May 2015.

[47] Gao, Y., L.R. Leung, J. L., et al. (2014), Robust spring drying in the southwestern U.S. and seasonal migration of wet/dry patterns in a warmer climate, *Geophys. Res. Lett.*, 41, 1745–1751, doi:10.1002/2014GL059562.

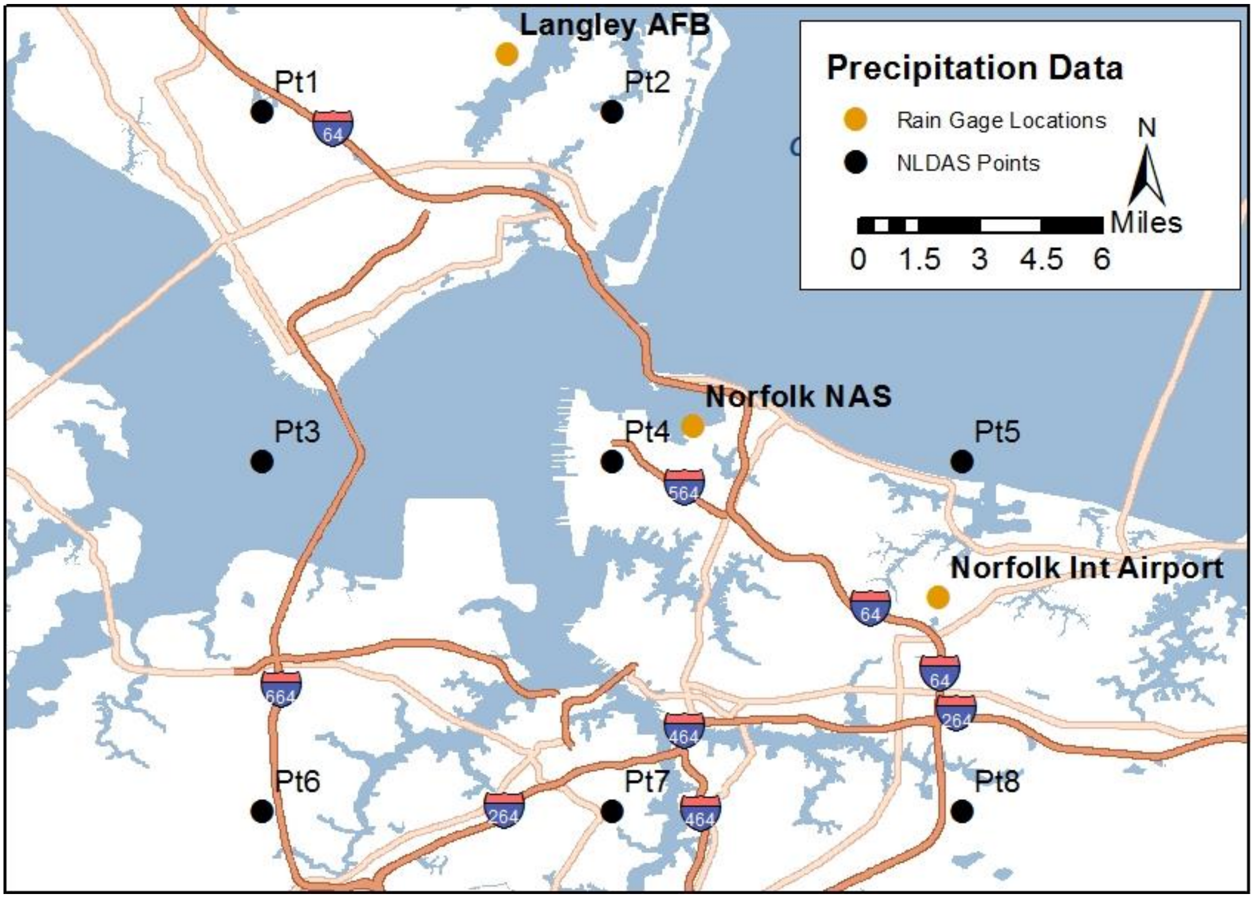


FIGURE 7—PRECIPITATION SITES WITH LONG-TERM PRECIPITATION AND NORTH AMERICAN LAND DATA ASSIMILATION SYSTEM LOCATIONS METHOD

The objective of this analysis was to determine whether any trends were detectable in precipitation intensity in the Hampton Roads area. The approach consisted of the following steps:

1. Screen the data values for quality.
2. Extract the maximum precipitation depth for each duration in each year.
3. Evaluate the data for trends or shifts in the mean values of the annual maxima series over time.
4. Apply the methods of L-moments to fit a statistical distribution to the annual maxima.
5. Use statistical distributions to estimate quantiles, the precipitation depths corresponding to desired probabilities.
6. Estimate confidence intervals for the quantiles to provide a measure of uncertainty and to aid in comparison among different datasets.

All datasets underwent steps 1–3; results from steps 3 and 4 were used to make critical selections or decisions before steps 5 and 6. It is important to understand the relationship between the precipitation data sources. Differences exist in the datasets, and understanding the underlying reasons for those differences is important. These data range from hourly at point locations to regional-scale data products that have been bias corrected to monthly, thus spanning a large range of temporal and spatial scales. It is not expected that analysis of these disparate data will yield the same result; rather, it will guide the interpretation of the modeled climate change data.

To compare the datasets, precipitation depth-duration-frequency plots were created for each data source. NOAA Atlas 14 data are based on the observed data and, therefore, good agreement between NOAA Atlas 14 data and

Norfolk data is expected. The North American Land Data Assimilation System data represent a larger area (one-eighth degree vs. a point) and are expected to underestimate the precipitation depth in the depth-duration-frequency plots for shorter durations. The climate model historical data were bias corrected to match the monthly statistics of the North American Land Data Assimilation System data. Consequently, OCIA–NISAC expects underestimation of precipitation for the shorter duration relative to the North American Land Data Assimilation System data. In these climate data, however, one looks for trends rather than absolute values. All data sources give similar results for the longer durations (greater than 1 day) although the North American Land Data Assimilation System and historical modeled data are consistently lower than the observed and NOAA Atlas 14 data.

ANALYSIS OF EXTREME PRECIPITATION, HAMPTON ROADS AREA

The precipitation datasets were evaluated for possible change in extreme precipitation over time. Precipitation extremes are typically characterized as depths of rainfall that happen during certain intervals (e.g., 1 hour, 1 day) at low probability or frequency. The probability of a given precipitation event is defined in this study as its annual exceedance probability, or the probability that a storm will equal or exceed the value in any year. For discussion, annual exceedance probability is usually converted to time, the average period between years when a particular value is exceeded. This period is called the average recurrence interval in this appendix. Longer recurrence intervals result in more extreme events. Precipitation depths with short recurrence intervals (e.g., 2 years) are always less than those with long recurrence intervals (e.g., 100 years). For example, the 2-year, 1-hour rainfall at Norfolk Airport is estimated as 40 millimeters, and the 100-year, 1-hour value is 91 millimeters.

The annual maxima time series from the three measured sites—Naval Station Norfolk, Norfolk Airport, and Joint Base Langley-Eustis—did not have statistically significant trends or shifts for most durations (Figure 8 and 9). The one exception was a detected trend at the 1-day duration for Langley, which also resulted in its being included as a site with positive change over time in NOAA Atlas 14, the only site in the Norfolk area thus noted. The North American Land Data Assimilation System datasets consistently indicate positive trends or shifts, from about 1990 (Figure 10). The Historical and RCP 4.5 climate simulations lack any trends. Figure 10 shows the depths corresponding to four historical datasets: Norfolk Airport, North American Land Data Assimilation System, historical, and NOAA Atlas 14. Agreement between Norfolk Airport and Atlas 14 is reasonably good and superior to the North American Land Data Assimilation System and Historical values. These latter two datasets underestimate depths, especially at shorter durations. The North American Land Data Assimilation System is closest to Norfolk Airport and NOAA Atlas 14, which is expected, since it is derived in part from local station data.

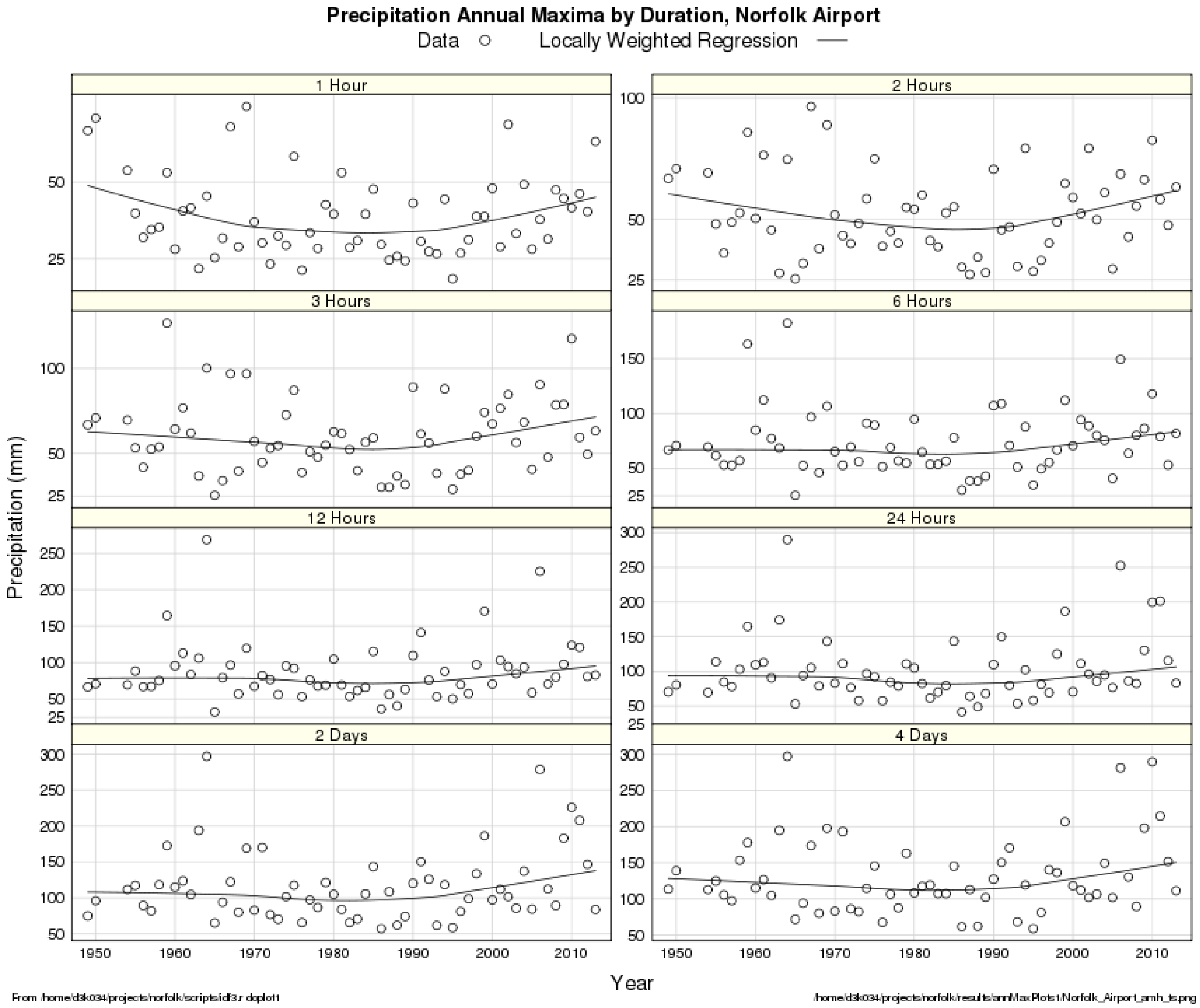


FIGURE 8—ANNUAL MAXIMUM PRECIPITATION FOR VARIOUS DURATIONS AT NORFOLK AIRPORT

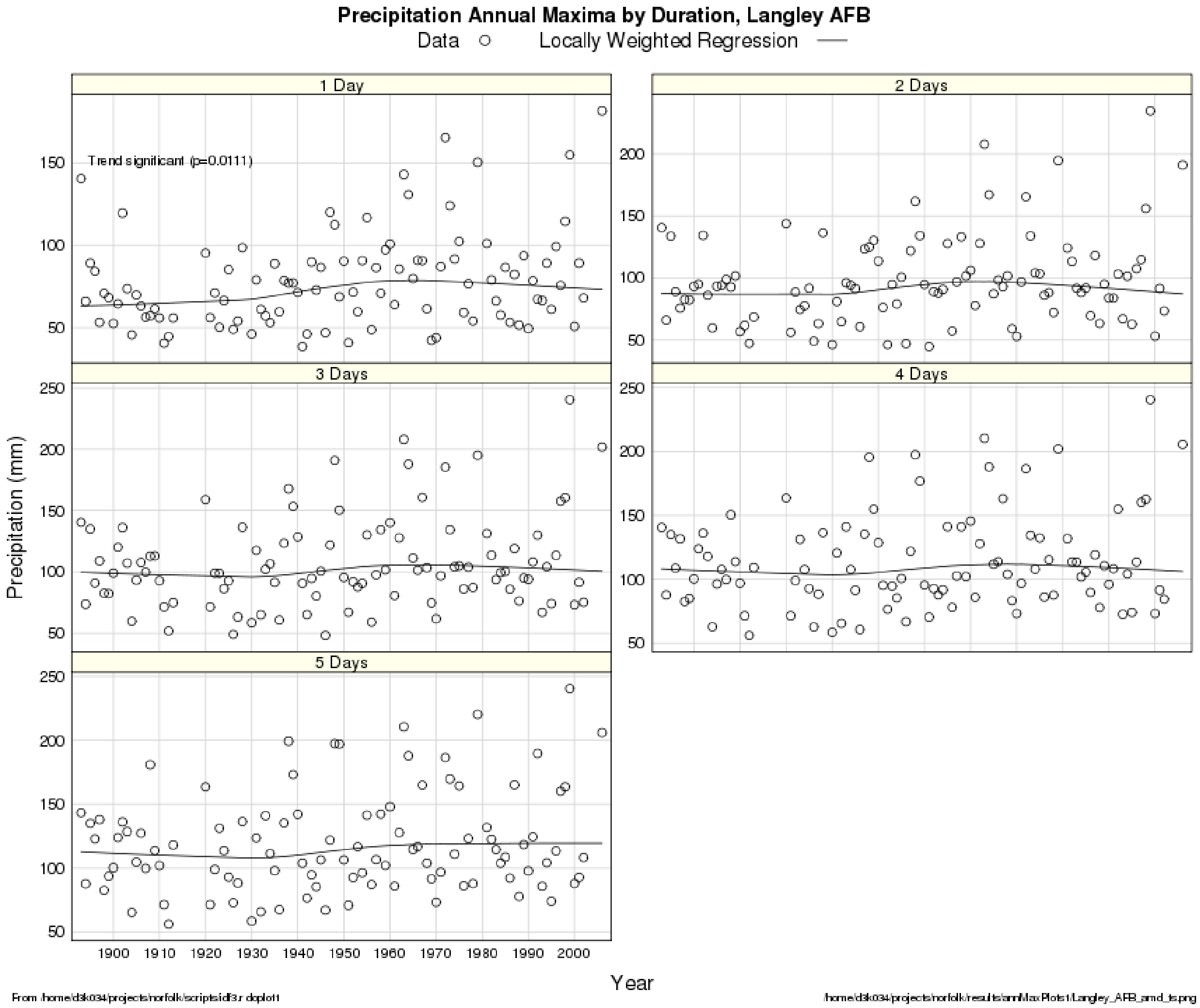


FIGURE 9—ANNUAL MAXIMUM PRECIPITATION FOR VARIOUS DURATIONS AT JOINT BASE LANGLEY-EUSTIS

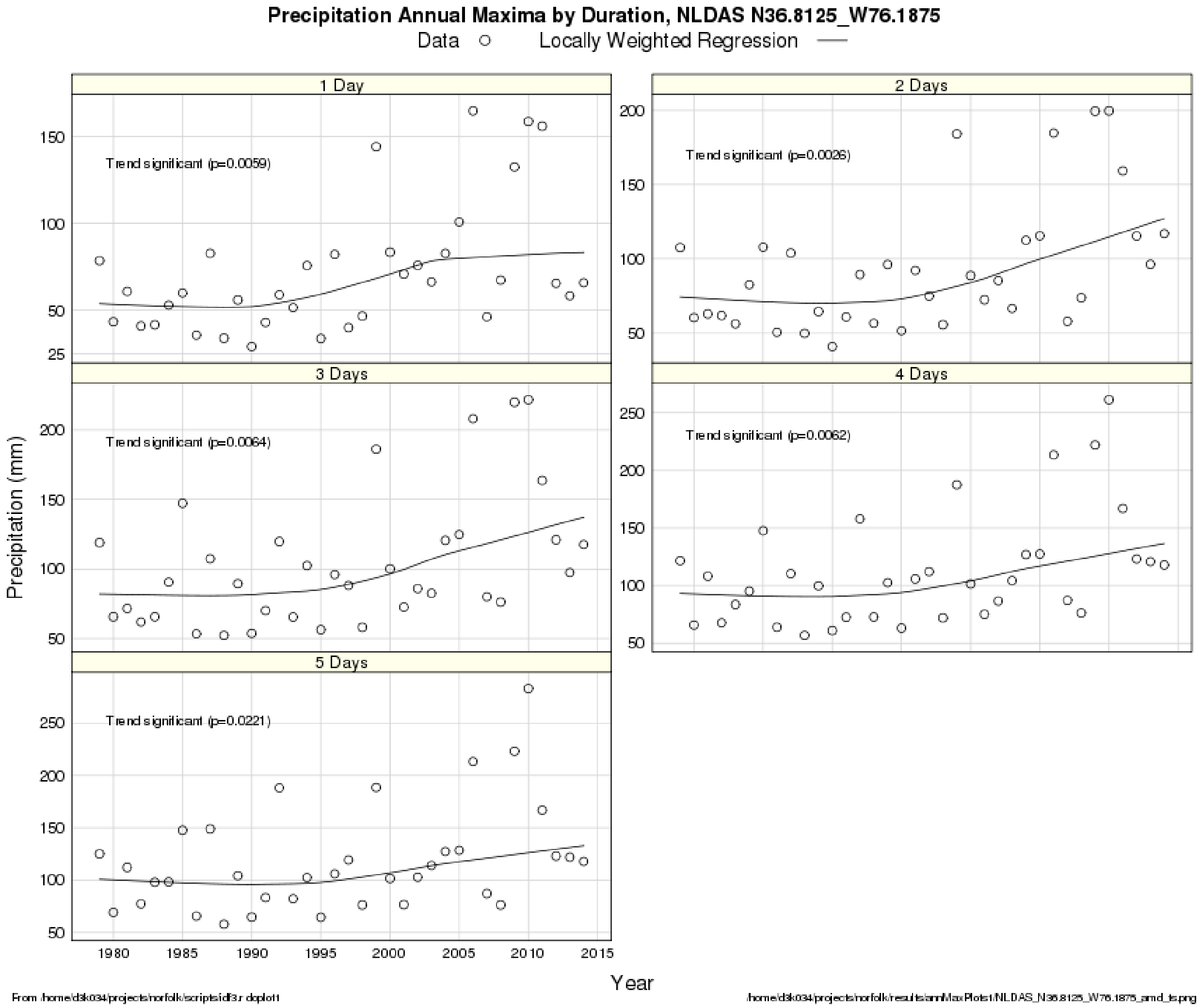


FIGURE 10—ANNUAL MAXIMUM PRECIPITATION FOR VARIOUS DURATIONS FROM NORTH AMERICAN LAND DATA ASSIMILATION SYSTEM AT PT8

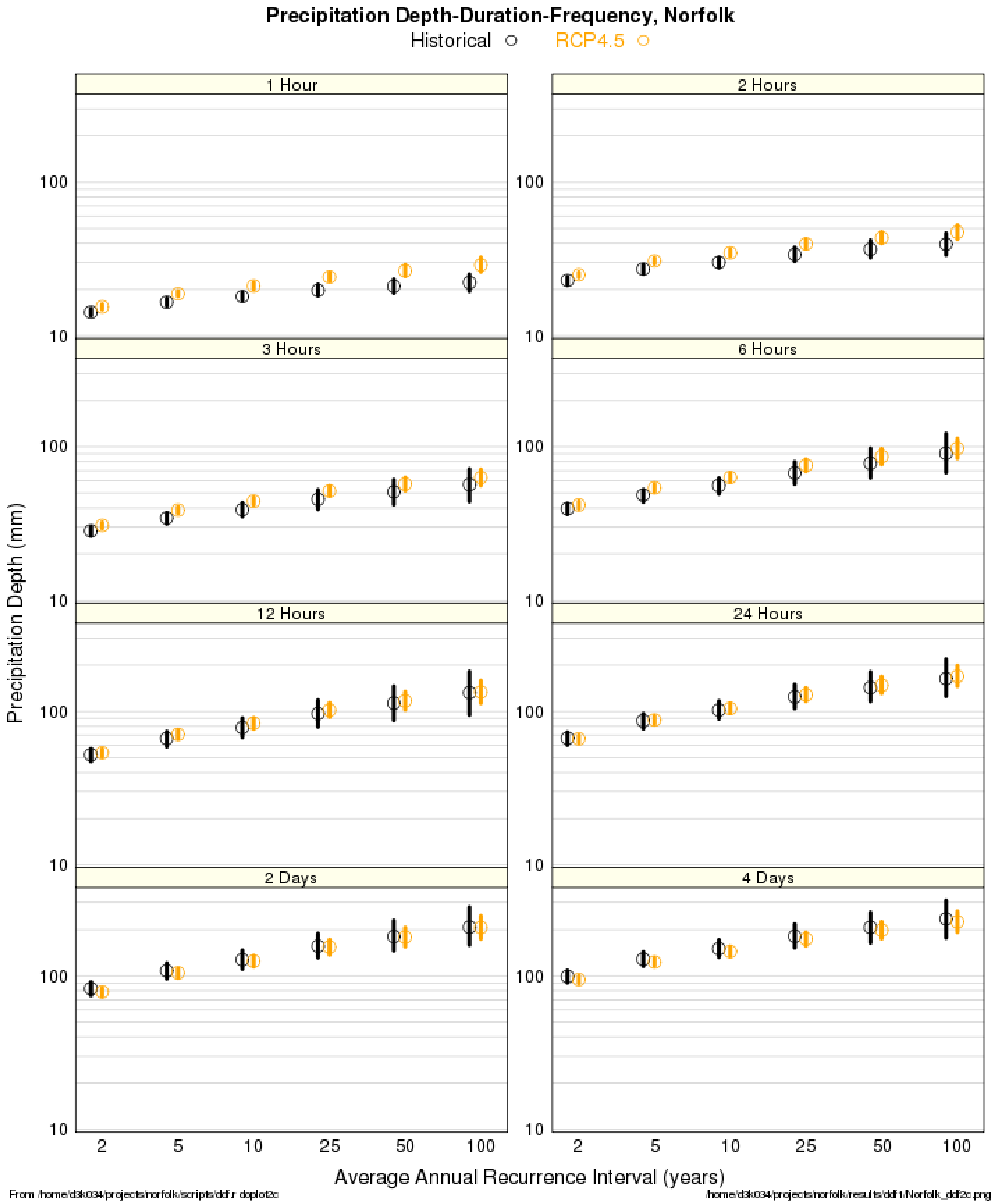
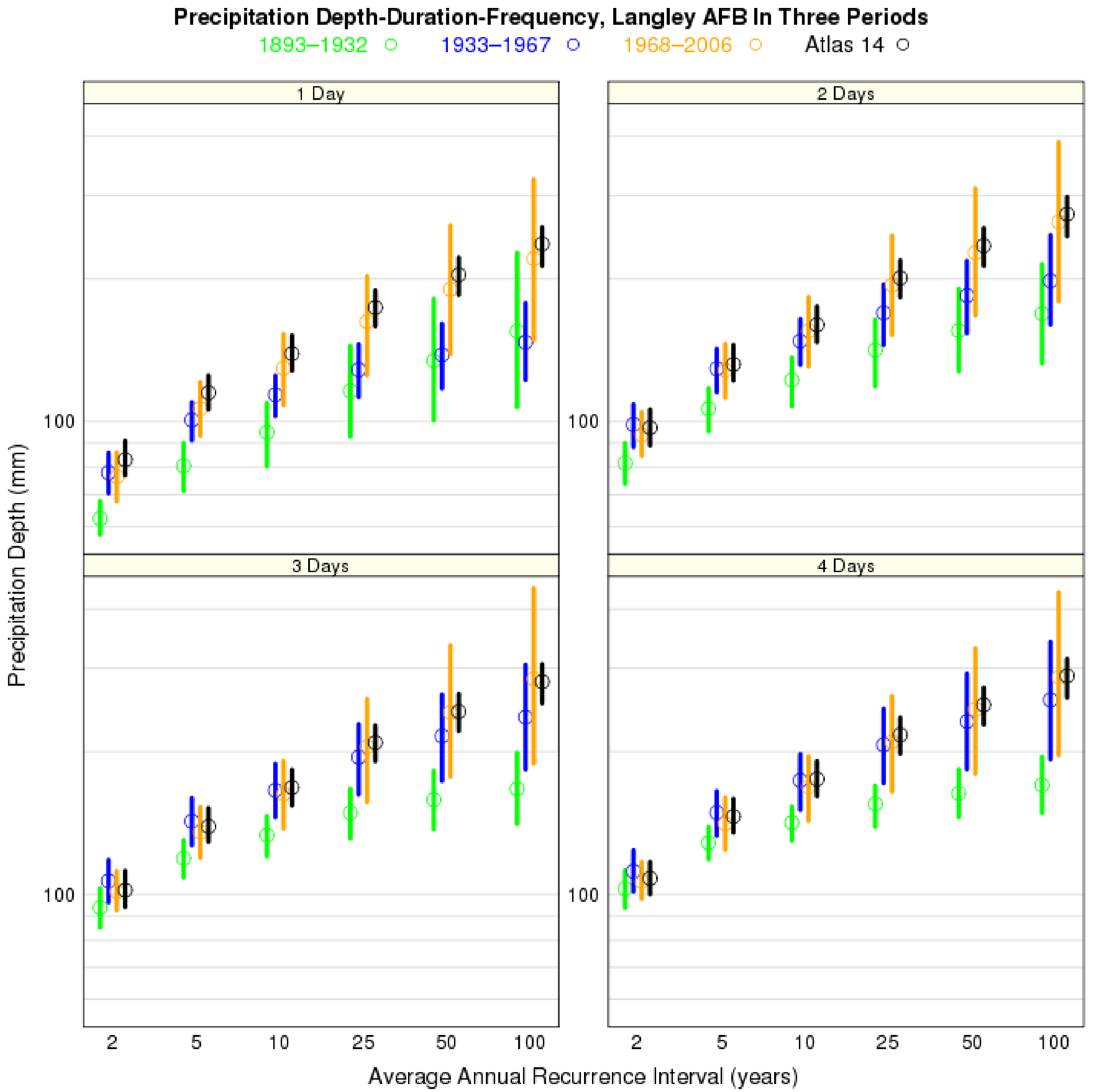


FIGURE 11—PRECIPITATION DEPTHS AS ESTIMATED WITH REGIONAL FREQUENCY ANALYSIS BY THE L-MOMENTS METHOD (WITH 95-PERCENT CONFIDENCE INTERVALS)

Figure 11 provides a record of precipitation depths for Norfolk. The long record of Joint Base Langley-Eustis has some statistically significant positive trends and shifts in precipitation extremes. The NOAA Atlas 14 noted this site as one of a number in eastern Virginia with a positive trend. The Langley dataset was studied further by dividing the record into three successive and approximately equal periods and separately performing the frequency analysis on each period. The results show that extremes during the first period, 1893–1932, were distinctly lower than the later periods. Based on the heavy overlap of the confidence intervals for the second and third periods, no significant change took place in the latter part of the 20th century. A comparison of historical data and climate model data is provided (Figure 12). RCP 4.5 predicts small increases in precipitation depths. These increases are more prevalent for short duration events.



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/home/d3k034/projects/norfolk/results/ddf1/Langley_ddf3a.png

FIGURE 12—PRECIPITATION DEPTHS AT LANGLEY OVER TIME, AS ESTIMATED WITH THE L-MOMENTS METHOD FROM ONLY LANGLEY DATA, AND SEPARATELY FOR EACH OF THREE SUCCESSIVE PERIODS

Overall, the results based directly on the station data do not indicate change in extreme precipitation during the past half century. The North American Land Data Assimilation System results do indicate significant increases in extremes, although that dataset matches neither station data nor NOAA Atlas 14 for reasons discussed in the previous section, and its record length is too short for dividing into subperiods for further analysis.

The climate model historic data under-predicts precipitation extremes as expected, especially at short durations. However, if trends and relative differences between historical and future climates are realistic, then the climate models suggest an increase in precipitation extremes at durations less than 12 hours and little change at longer durations.

POTENTIAL IMPACTS OF CHANGING PRECIPITATION DEPTH-DURATION-FREQUENCY

OCIA–NISAC reviewed Hampton Roads Sanitation District daily flow summaries and overflow reports to see if potential impacts resulted from using a shifting intensity-duration-frequency curve. Using documented pump station capacities and records of daily flows for 2009–2014 provided by Hampton Roads Sanitation District, it was possible to consider the impacts of an increase in precipitation depths in a future changing climate. Much of the peer-reviewed literature suggests that, although annual average precipitation may not have a significant trend, the intensity of the precipitation will increase.[48] This upward trend is supported by the analysis in this study.

Hampton Roads Sanitation District daily flows exceeding the stated wastewater treatment plant capacity were counted for 2009–2014 (Table 14) and then plotted for plant capacity (Figure 13) and average plant utilization as a percent (Figure 14). Although the higher capacity facilities have more days exceeding capacity (e.g., Virginia Initiative Plant [VIP] and Atlantic), the York River site has low capacity (15 MGD) and the most days exceeding that capacity during this period. However, the York River site has high average utilization of capacity (12.76/15 = 85 percent). York River is one of the lower lying facilities in the system (8.63-foot elevation) and thus more susceptible to sea level rise (and storm surge) influences that might further reduce its capacity.

TABLE 14—STATION, CAPACITY, AND DAYS ABOVE CAPACITY 2009–2014

Wastewater Treatment Plant	Capacity (million gallons per day)	Average Inflow (million gallons per day)	Average Utilization (percent)	Days Above Capacity
Army Base	18	12.74	71	38
Atlantic	36	30.29	84	123
Boat Harbor	25	15.84	63	69
Chesapeake Elizabeth	24	21.04	88	106
James River	20	15.17	76	74
Nansemond	30	20.58	69	1
Virginia Initiative	40	28.41	71	182
Williamsburg	22.5	14.47	64	4
York River	15	12.76	85	282

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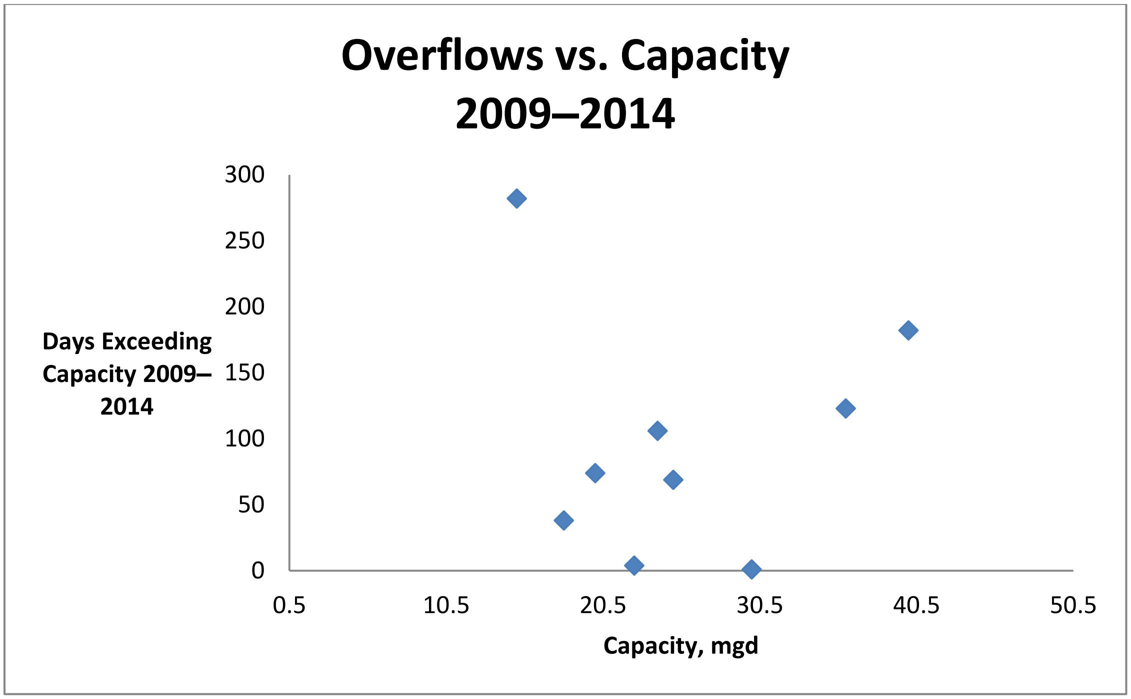
[48] Kao, S.C., and Ganguly, A. R. (2011), Intensity, Duration, and Frequency of Precipitation Extremes Under 21st-Century Warming Scenarios, J. Geophys. Res., 116, D16119, doi: 10.1029/2010JD015529.



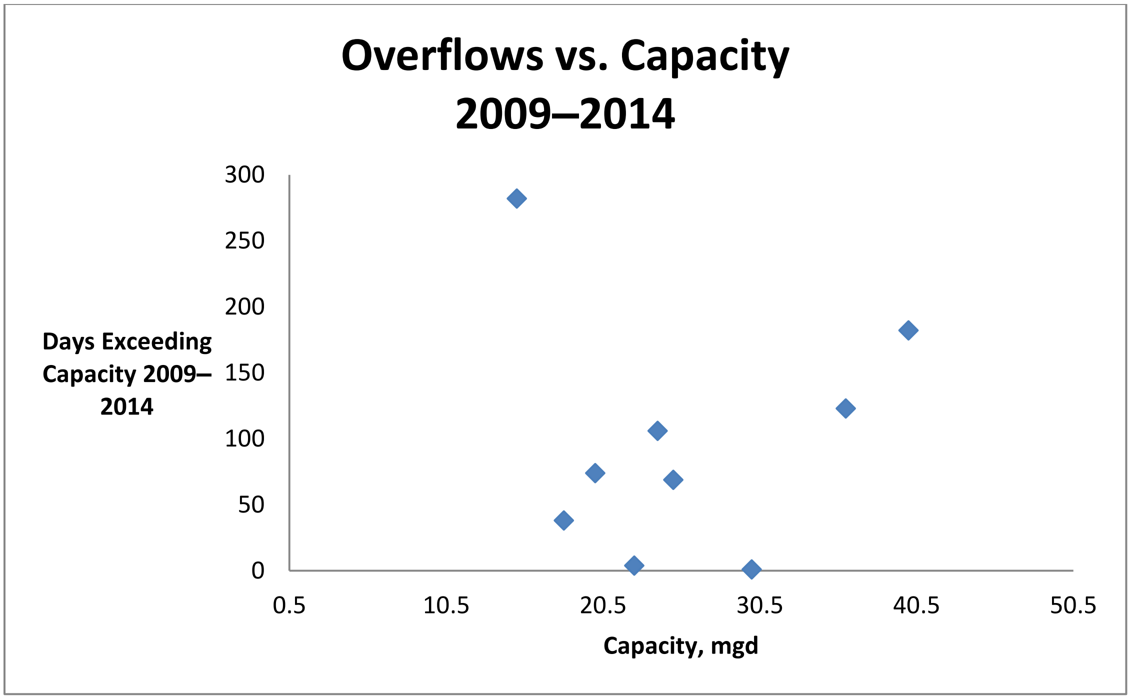
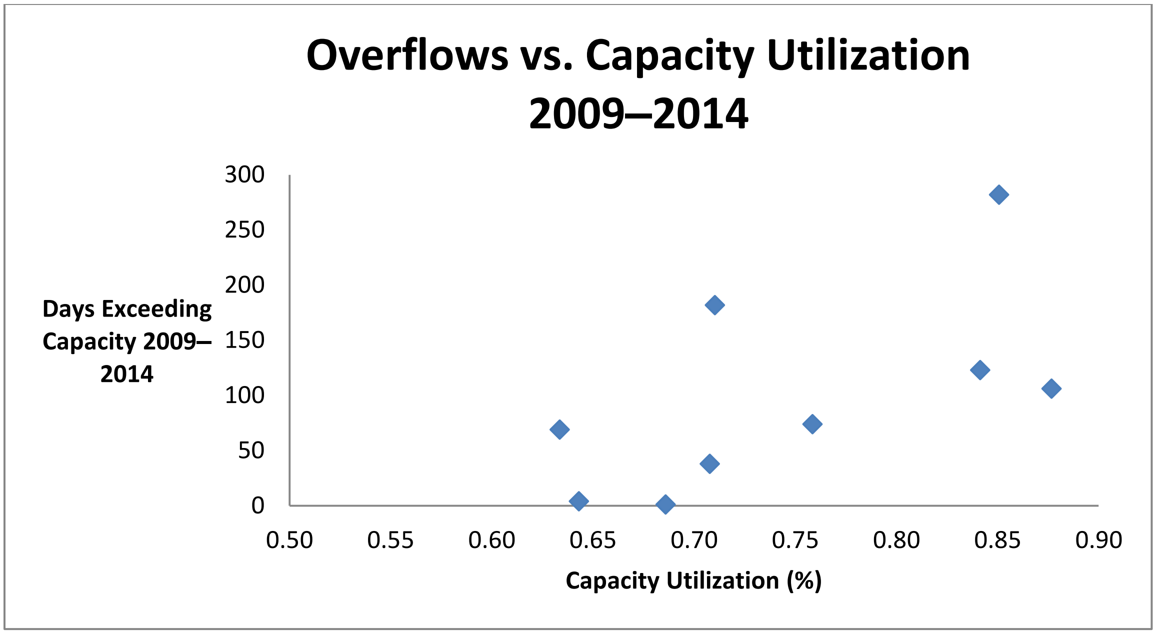


FIGURE 13—HAMPTON ROADS SANITATION DISTRICT FACILITY DAYS EXCEEDING CAPACITY



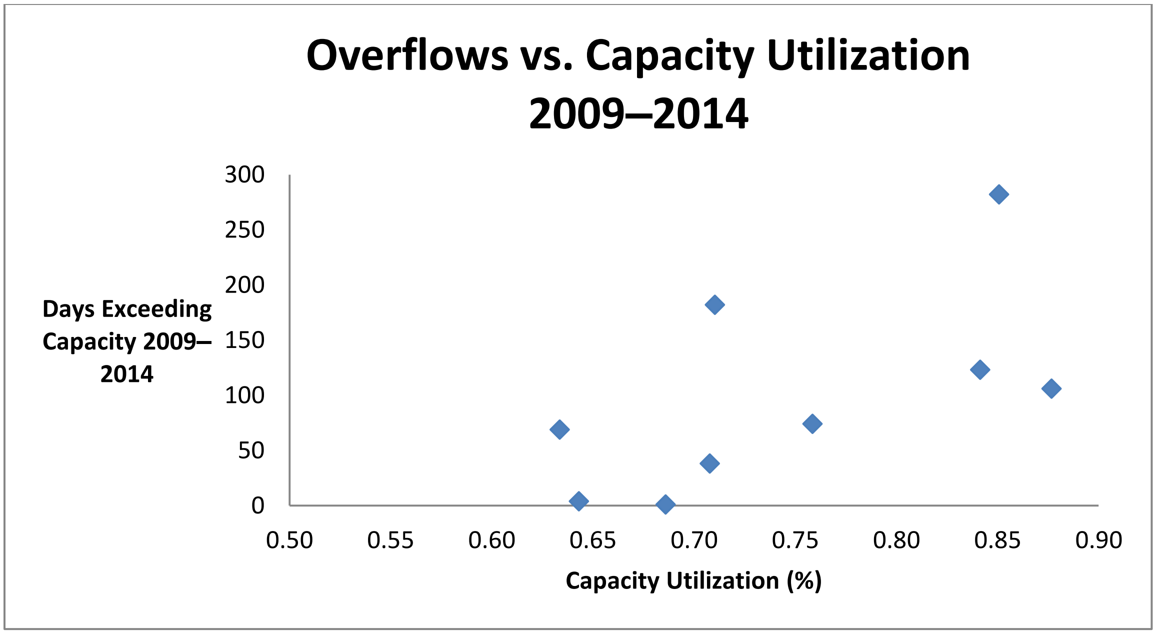


FIGURE 14—HAMPTON ROADS SANITATION DISTRICT FACILITY DAYS EXCEEDING CAPACITY AND THE TYPICAL CAPACITY UTILIZATION AS A PERCENT

To further understand the nature of the days exceeding capacity, the data were plotted for 2014 with the Joint Base Langley-Eustis daily precipitation depths on a secondary axis for York River Wastewater Treatment Plant, Atlantic Wastewater Treatment Plant, and VIP Wastewater Treatment Plant. Precipitation events appear to increase the inflow for these and other stations; however, the impact of a given precipitation depth might not lead to exceeding capacity at a particular station.

Figure 15 examines the first 4 months of 2014 at York River when many of the events exceeding capacity occurred. The daily flow volumes are close to station capacity, and any additional inflow from the rainfall results in inflows exceeding capacity. Increased rain depths and similar changes in inflow volume from later in the year (Figure 16) result in fewer days above capacity since the average inflow is lower.

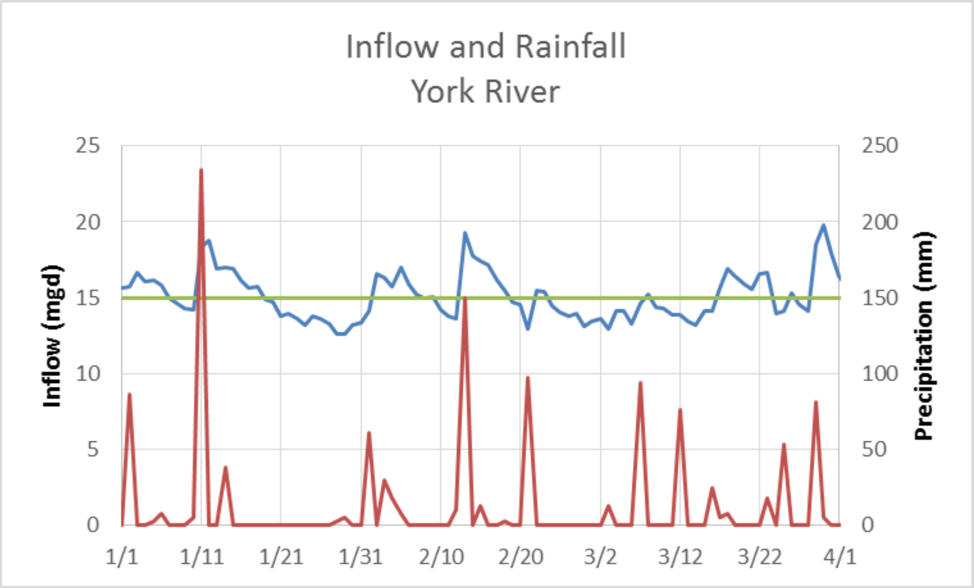


FIGURE 15—YORK RIVER STATION INFLOW (BLUE) AND DAILY PRECIPITATION (RED) JANUARY TO MARCH 2014

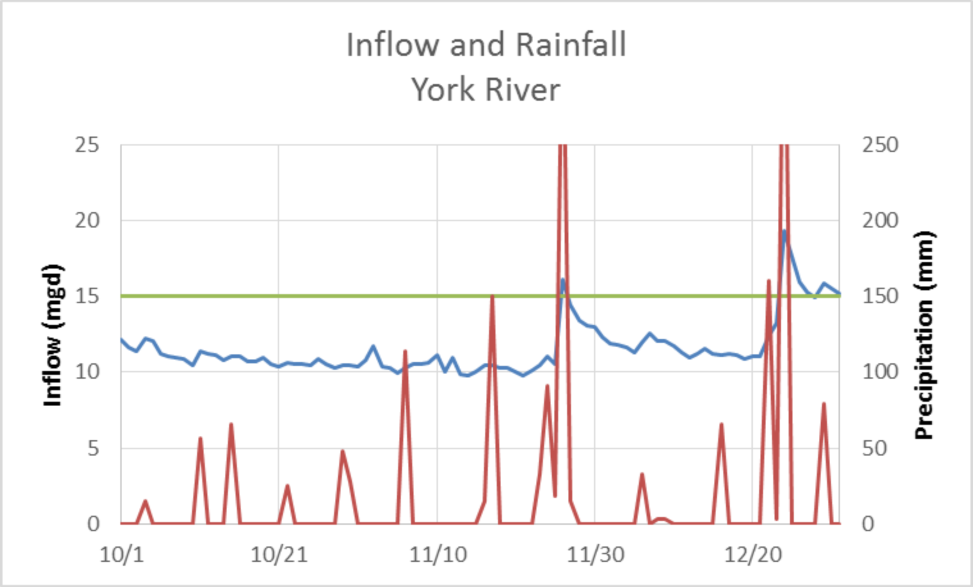


FIGURE 16—YORK RIVER STATION INFLOW (BLUE) AND DAILY PRECIPITATION (RED) OCTOBER TO DECEMBER 2014

These results point out the influence of precipitation on station inflows and the role of relative capacity in use. For low-lying stations, interaction with rising sea levels is also possible. Figures 17 and 18 show similar data for the Atlantic station. This is a low elevation, higher capacity site that could be vulnerable to future sea level rise. This station also shows that running below capacity accommodates additional inflow from precipitation without going above capacity. In addition, the hourly flow data show morning and evening peaks with a low inflow period during the night.[49] The daily inflow data do not capture these patterns. For example, the week of September 8, 2014, is shown in Figure 19. The maximum hourly flow rate reported at Atlantic was 78.9 MGD, whereas the daily value is less than 60 MGD for a station with a capacity of 36 MGD.

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[49] Hampton Roads Sanitation District (2014), Post Storm Report, September 8 and 9, 2014.

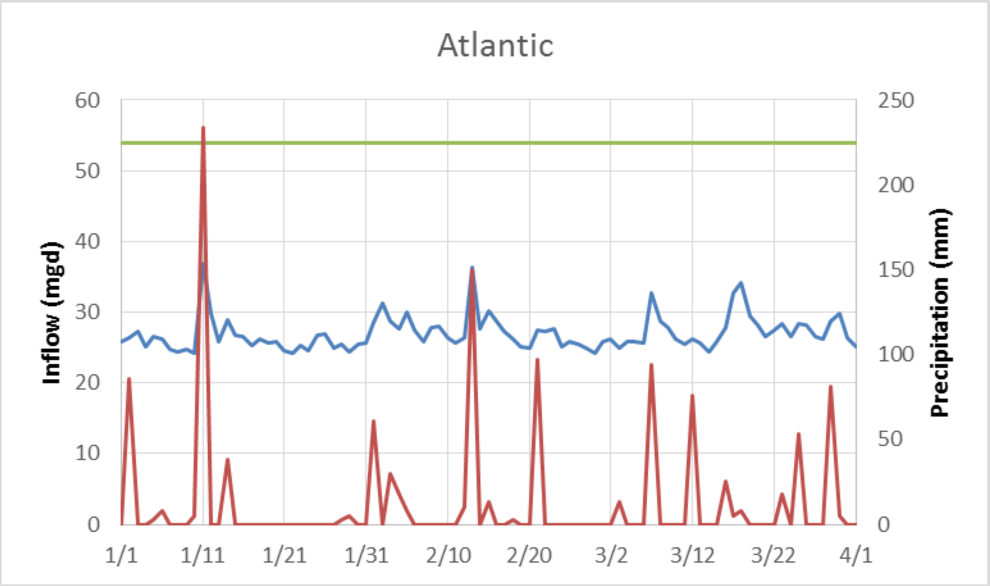

FIGURE 17—ATLANTIC STATION INFLOW (BLUE) AND DAILY PRECIPITATION (RED) JANUARY TO MARCH 2014

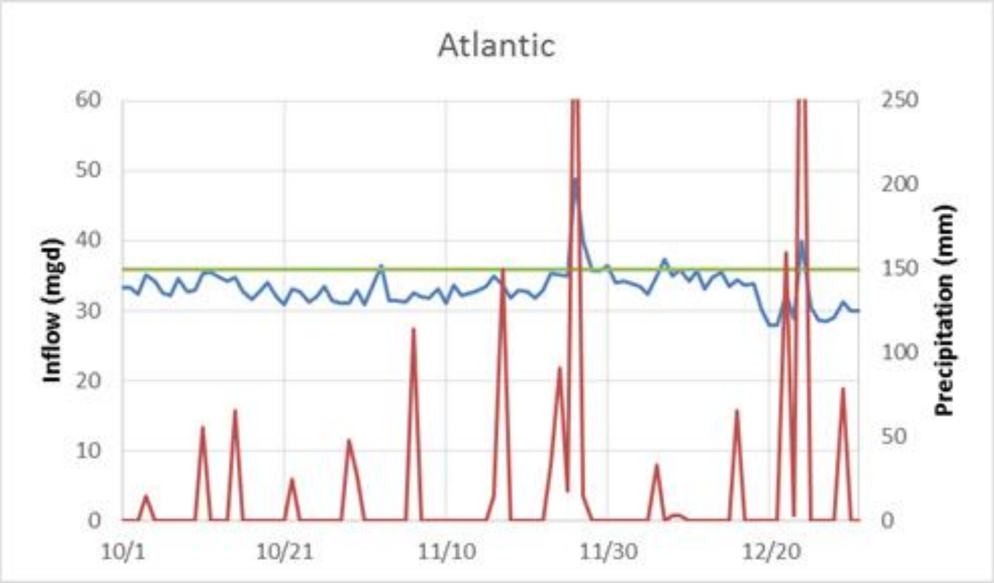

FIGURE 18—ATLANTIC STATION INFLOW (BLUE), CAPACITY (GREEN), AND RAINFALL (RED) OCTOBER TO DECEMBER 2014

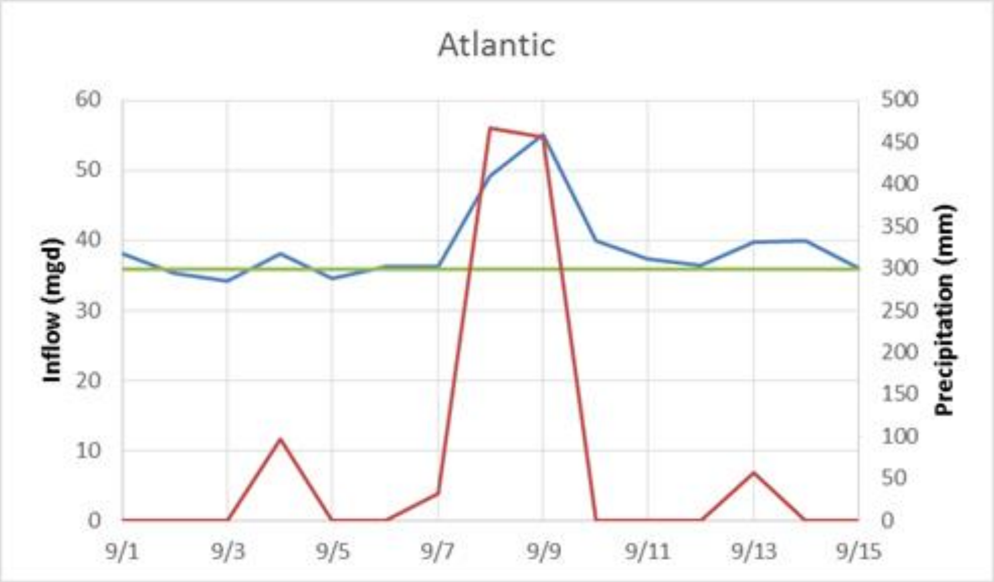

FIGURE 19—ATLANTIC STATION, SEPTEMBER 2014; PEAK HOURLY FLOW WAS 78.9 MGD

APPENDIX G: ACRONYMS LIST

DHS	U.S. Department of Homeland Security
DOD	U.S. Department of Defense
GDP	gross domestic product
MGD	millions of gallons per day
mph	miles per hour
NISAC	National Infrastructure Simulation and Analysis Center
NOAA	National Oceanic and Atmospheric Administration
OCIA	Office of Cyber and Infrastructure Analysis
RCP	Representative Concentration Pathway

DHS POINT OF CONTACT

Office of Cyber and Infrastructure Analysis
National Protection and Programs Directorate
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OCIA@dhs.gov

OMB Control No.: 1670-0027
Expiration Date: 10/31/2017

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Homeland Security

National Protection and Programs Directorate

NPPD Customer Feedback Survey

Product Title: OCIA - Norfolk Virginia Sea Level Rise Analysis

1. Please select the partner type that best describes your organization. Select One

2. Overall, how satisfied are you with the usefulness of this product?

○ **Very Satisfied** ○ **Somewhat Satisfied** ○ **Neither Satisfied Nor Dissatisfied** ○ **Somewhat Dissatisfied** ○ **Very Dissatisfied**

3. How did you use this product in support of your mission?

☐ Integrated into one of my own organization's information or analytic products

☐ Used contents to improve my own organization's security or resiliency efforts or plans

If so, which efforts?

☐ Shared contents with government partners

If so, which partners?

☐ Shared contents with private sector partners

If so, which partners?

☐ Other (please specify)

4. Please rank this product's relevance to your mission. ***(Please portion mark comments.)***

○ Critical
○ Very Important
○ Somewhat Important
○ Not Important
○ N/A

5. Please rate your satisfaction with each of the following:

	Very Satisfied	**Somewhat Satisfied**	**Somewhat Dissatisfied**	**Very Dissatisfied**	**N/A**
Timeliness of product or support	○	○	○	○	○
Relevance to your information needs	○	○	○	○	○

6. How could this product or service be improved to increase its value to your mission? ***(Please portion mark comments.)***

To help us understand more about your organization so we can better tailor future products, please provide (OPTIONAL):

Name:
Organization:
Contact Number:
Position:
State: Select One
Email:

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REV: 3 March 2015