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Development of an Urban Resilience Analysis Framework with Application to Norfolk, VA

Robert Jeffers, William Fogleman, Emma Grazier, Sarah Walsh, Sophie Rothman, Calvin Shaneyfelt, Munaf Aamir, Jessica Gibson, Vanessa Vargas, Eric Vugrin, Stephen Conrad, Howard Passell

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Development of an Urban Resilience Analysis Framework with Application to Norfolk, VA

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Abstract

The same water that makes Norfolk, VA an ideal home for international ports and naval installations is also increasingly flooding large parts of the city and the surrounding Hampton Roads region. This report describes the development of a process to analyze the resilience of urban regions to the shocks and stresses that those cities care about, and applies this process to address flooding in Norfolk and Hampton Roads. The goal is to provide Norfolk city officials and regional asset owners with actionable information to plan the infrastructure improvements that will most greatly enhance the region's resilience to flooding. Results suggest that there are wide-ranging impacts of a major acute flooding event beyond the Hampton Roads region. A single four-day, 100-year flood event in Hampton Roads would cause on the order of $355-606 million in detrimental impacts to global production, with greater impacts occurring in the future as net sea levels rise. This report highlights the infrastructure behaviors, interdependencies, and the economic analyses that determine these impacts.

ACKNOWLEDGMENTS

The authors wish to acknowledge the many officials and experts that provided their knowledge and guidance through the urban resilience analysis process. Thanks first and foremost are offered to the City of Norfolk, Virginia; namely Christine Morris, Katerina Oskarsson, Kyle Spencer, Fraser Picard, Leonard Newcomb, Eric Tucker, and James Redick. We show our appreciation for the framework and connections provided by the 100 Resilient Cities organization, especially to José Baptista and Amy Armstrong. Utmost appreciation to external reviewers: Katerina and Christine from the City of Norfolk, Kit Chope and Scott Whitehurst from the Port of Virginia, and Brian Ballard, Regional Community Plans & Liaison Officer for the Navy Mid-Atlantic Region. Thanks are given to Mark McVey at Dominion Virginia Power for conversations about resilience and electricity markets. Acknowledgements go to the individuals that unlocked funding for this work within Sandia National Laboratories, namely Bill Rhodes, Russ Skocypec, Stephen Conrad, and Howard Passell. And appreciation is offered to Eric Vugrin for his guidance on all things resilience.

We appreciate all of your efforts and look forward to our collaborations in the future.

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NOMENCLATURE

100RC	100 Resilient Cities Pioneered by the Rockefeller Foundation
BEA	United States Bureau of Economic Analysis
CRO	Chief Resilience Officer
DEM	Digital Elevation Model
DOD	United States Department of Defense
DOE	United States Department of Energy
DTA	Dominion Terminal Associates
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Map
MSA	Metropolitan Statistical Area
NAVSTA Norfolk	United States Naval Station Norfolk
NISAC	National Infrastructure Simulation and Analysis Center
NIT	Norfolk International Terminals
NNMT	Newport News Marine Terminal
PMT	Portsmouth Marine Terminal
Port of VA	Port of Virginia
PPD-21	Presidential Policy Directive 21
REAcct	Regional Economic Accounting Tool
Sandia	Sandia National Laboratories
VIG	Virginia International Gateway

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1. DEVELOPING AN URBAN RESILIENCE ANALYSIS PROCESS

1.1. Cities as resilience incubators

The United States is beginning to consider infrastructure resilience as a high priority for national security. Presidential Policy Directive 21 (PPD-21) on critical infrastructure epitomizes this prioritization. PPD-21 establishes a national policy on infrastructure security and resilience and defines resilience as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions." Additionally, PPD-21 recognizes a strong need for public-private partnerships and partnerships across levels of government in order to develop, evaluate, and implement resilience strategies.[1]

> **Resilience:**
> *The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions.* *-PPD-21*

Cities are a great place to start. The world is rapidly urbanizing and cities are becoming more critical in the response to and prevention against natural and malicious disruptions, as they have the most direct and operational means to affect change. Cities often "own" public works. Infrastructure distribution networks and service areas naturally parallel with urban boundaries. Moreover, cities have the ability to convene all public and private stakeholders needed to enact change. Cities represent a scale of analysis that is conducive to determining a manageable set of potentially disruptive events and can serve as efficient and effective mechanisms for implementation of resilience improvements.

Cities do not normally possess the analytical capability to fully assess how their investments can improve resilience, or how their own resilience may affect that of other cities and regions. Cities do however possess the knowledge, data, and connections with asset owners that could enable enhanced analysis and investment decisions. In order to prioritize the vast amount of investment necessary to improve our nation's resilience, in-depth analysis of the performance of our cities under their most critical shocks and stresses is needed. Furthermore, a mechanism for identifying and prioritizing the most effective resilience enhancing investments at this holistic level does not currently exist. City planners require this type of framework if they are to work with federal policy makers to implement national-level resilience. Just as states are "laboratories of democracy," so too can cities be the natural laboratories for advancing promising resilience concepts.

Sandia National Laboratories (Sandia) has aspired to develop a clear and usable process for resilience analysis that connects multi-scale assessment with local investment. This report outlines the urban resilience analysis process developed at Sandia, highlighting how it is being used for the City of Norfolk, VA. The goal is to show how this process is applied to Norfolk and how it can be improved and used for many cities throughout the United States.

[1] PPD-21 access: https://www.whitehouse.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil

1.2. Adjusting the lens of resilience analysis

The Department of Homeland Security has funded multiple analyses of consequence to high-priority shocks and stresses to date, many of which have been performed by the National Infrastructure Simulation and Analysis Center (NISAC). NISAC comprises analysts from Washington D.C., Sandia National Laboratories, and Los Alamos National Laboratory, skilled in critical infrastructure modeling and simulation. To date, most NISAC analyses are performed on certain types of threats to certain infrastructures in particular regions of the country.[2] In this way, analyses are prioritized by vulnerability – the regions of the country that are perceived to be the most vulnerable given an all-hazards viewpoint are analyzed first. These analyses often go so far as to estimate national consequence given a selected threat, but are often not plugged in to local options for improving resilience to these threats.

Researchers at Sandia are incorporating the tools and processes developed within NISAC as well as the vast amount of subject matter expertise to shift the lens of resilience analysis toward mitigation prioritization for cities. Essentially, Sandia is engaging cities to prioritize the resilience enhancing policies and investments that will work for them, but will also best improve regional- and national-scale resilience. The 100 Resilient Cities organization (100RC) pioneered by the Rockefeller Foundation has been instrumental in connecting Sandia with cities that are eager to think along these lines.[3] 100RC has developed a network of cities that are incorporating resilience into their planning paradigms, and has provided these cities with resources necessary to achieve their resilience goals, including supporting a Chief Resilience Officer for each city and providing access to platform partners that are able to analyze and/or implement resilience solutions. Sandia serves as a platform partner for 100RC, offering cities access to several NISAC capabilities such as infrastructure subject matter expertise, infrastructure simulation, interdependency assessment, economic assessment, and consequence estimation.

Figure 1 outlines the process that Sandia has developed for cities based on a history of analyzing national and regional resilience. The process is cyclical, starting at the top and progressing clockwise. The central item of stakeholder engagement is called out to highlight that this process always iterates with the parties – including the city governments – that have the motivation and wherewithal to enact resilience improvements. At each stage in the process, stakeholder engagement keeps the analysis focused on providing information that will eventually inform selection of resilience-enhancing investments.

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[2] See: Conrad, S., Kaplan, P. (2011) *Modeling the Impact of Loss in US Soybean Production Resulting from Soy Rust Disease*. Sandia National Laboratories, SAND 2005-4827C.
Corbet, T., Conrad, S., Beyeler, W., Thomas, R. (2010) *Evaluating the Economic Impact of Port Security Initiatives on Container Operations*. Sandia National Laboratories, SAND 2005-0888A.
And other reports available at: <http://www.sandia.gov/nisac/publications/>

[3] <http://www.100resilientcities.org/>

Figure 1. The urban resilience analysis process.

1.2.1 Stakeholder Engagement

The first step of the urban resilience analysis process – stakeholder engagement – is the most indispensable. In order to develop analysis products that are useful for real decisions, at minimum the decision-makers and other affected parties must be engaged at the beginning of the analysis and periodically through every subsequent step. Stakeholders will often include owners and operators of assets that play a major role in improving resilience, such as city managers, utility representatives, emergency planners, and local industry. Some stakeholders will be brought in after subsequent stages. For example, if the response of the community is identified as an important contributor to resilience for a particular shock or stress, community leaders would be included.

1.2.2 Identification of Shocks, Stresses, and Infrastructures

To appropriately bound the analysis, the most critical shocks and stresses are identified with coordination and feedback from stakeholders. These are essentially the threats that the city wants to be resilient against. Shocks tend to be acute threats that occur abruptly and create massive consequence all at once. Stresses can be just as damaging, but occur more subtly over longer periods of time. For example, flooding can be both a shock and a stress. Nuisance flooding over long periods of time can cause a drain on productivity and attractiveness to labor,

while a single large flooding event can be detrimental to immediate human and business livelihood. The identification of shocks and stresses often has an implicit calculation of risk involved. Cities understand inherently the combination of the likelihood of certain threats occurring with the potential consequences of these threats. High-risk shocks and stresses tend to be good candidates for urban resilience analysis.

A good place to start outlining the shocks and stresses that pose the most risk for an urban region is their Regional Hazard Mitigation Plan. The Federal Emergency Management Agency (FEMA) requires that state, tribal, and local governments develop and adopt these plans as a condition to receive certain types of non-emergency disaster aid. These documents are updated at least once every five years. Often these documents focus more closely on shocks than stresses, so if the city is interested in more long-term holistic resilience the Hazard Mitigation Plan should not be solely relied upon.

Upon selection of shocks and stresses, infrastructures are identified that are critical under these scenarios. The selection of infrastructures is also inherently a risk calculation. Infrastructures can be prioritized by their hypothesized vulnerability to the shock or stress combined with the potential consequences should the infrastructures fail. Sandia begins with the list of 16 critical infrastructure sectors defined by the Department of Homeland Security.[4]

1.2.3 Selection of Assessment Methods and Data Collection

Once the resilience analysis problem has been defined, assessment methods and available data are identified. A critical step in identifying assessment methods and data is the designation of metrics for measuring the resilience of the city to identified shocks and stresses. Resilience metrics give cities a measurable basis for comparison between alternative scenarios. These metrics tend to be most useful when they relate to the performance of systems that the stakeholders are most concerned about. For example, a city planner may be interested in the effectiveness of electric power delivery during a hurricane. A simple non-performance-based metric for analysis could be a measurement of redundant delivery pathways to buildings or regions that the planner is concerned about. This leads to very simple assessment methods: an analyst could simply count the various paths from generation sources to consumers. However, a better metric for comparison would be the projected likelihood that the electric grid maintains service to these assets. This metric, while being more difficult to forecast, is also more useful because it provides clear insight into the performance of these buildings or regions during the hurricane.

The selection of resilience metrics confines the determination of assessment methods. For example, if stakeholders are interested in economic performance of the region, economic analysis methods should be pursued. At this stage, data collection and assessment method determination should be performed in parallel because they tend to be strongly co-dependent. Data about capacity and elevation of roads are critical to an assessment of transportation

[4] <http://www.dhs.gov/critical-infrastructure-sectors>

performance during a flood. Without capacity information, for example, an analysis of evacuation times becomes merely a conjecture. Stakeholders often have data sources that would be unattainable without their involvement. They may also have preferred assessment methods with which they are more confident or familiar.

1.2.4 Assessment of Infrastructure Performance

Using the defined assessment methods and the collected data, analysis of the performance of identified infrastructures is performed in coordination with subject matter experts such as the owners and operators of each infrastructure. If these experts were consulted during the assessment methods stage, then the infrastructure performance metrics should be familiar to them. Sandia specializes in integrated infrastructure performance assessment. This means that the interdependencies between infrastructures are included during this stage of analysis.

1.2.5 Assessment of Regional Performance

This assessment step zooms out to the overall impact of the shocks and/or stresses on regional performance. Essentially, the performance assessment of the individual infrastructures is packaged into an analysis of the overall region's performance along a smaller set of metrics. Often this metric will be economic in nature. For example, regional performance could be measured by gross municipal product over the time window of the analysis. Multiple regions may also be considered. For instance, depending on the hypothetical size and scale of disruption, it may aid city planners to contrast the performance of the local municipality, the surrounding region, the state, the nation, and even the world using comparable metrics.

1.2.6 Assessment of Resilience Enhancing Investments

The final step in the urban resilience analysis process is heavily iterative. After the regional performance assessment is shared with stakeholders, options for improving this performance through investments are discussed and incorporated. Steps 3 and 4 are then reprocessed with each investment option, or portfolios of options in place. At the conclusion of this process, both the infrastructure and the regional performance metrics can be compared against the base case scenario with no investments in place. Depending on the selection of performance metrics, this could feed directly into a cost-benefit analysis, a risk management analysis, or could stand alone as a planning tool.

The remainder of this report outlines Sandia's completion of steps 1 through 4 of the urban resilience analysis process for Norfolk. Future studies should attempt to close this loop by assessing the resilience enhancing investments under consideration by Norfolk.

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2. NORFOLK AS A RESILIENCE TESTBED

Norfolk, VA was chosen to exercise Sandia's urban resilience analysis process for several reasons. Norfolk is one of the 100 Resilient Cities organization's (100RC) member cities, and has been moving quickly to define the shocks, stresses, and mitigation pathways that work for their city to improve resilience. As a platform partner 100RC, Sandia strives to provide its analysis capability to cities that want to quantify the impacts of shocks and stresses in terms of consequence to their areas as well as to the nation. Relationship managers within 100RC identified Norfolk as the United States city that would be most ready to participate in this process.

As a central implementation mechanism of the 100RC process, cities appoint a Chief Resilience Officer who works as a city government employee to foster long-term integrated resilience planning. The Norfolk CRO, Christine Morris, along with additional staff members within the City of Norfolk have been the central stakeholders for this analysis. Feedback at every stage of the urban resilience analysis process has been received in order to tailor the analysis to inform actionable decisions related to resilience enhancement. Norfolk views themselves as being a testbed for new ideas about resilience, particularly related to flooding and other risks associated with sea level rise.

2.1. Norfolk Plays a Role in National Security

Norfolk is a city of approximately 250,000 residents located at the mouth of the Chesapeake Bay in southeastern Virginia. It is a part of the Hampton Roads Metropolitan Statistical Area (MSA), which also contains the cities of Newport News, Chesapeake, Hampton, Portsmouth and Virginia Beach. The population of the Hampton Roads MSA is approximately 1.7 million, ranked 37th in the nation.[5] This population is distributed among the cities and counties, not concentrated in one metropolitan center. The region had a Gross Domestic Product of $88.6 billion in 2013, up from $86.9 billion in 2012 and ranked 39th in the nation.[6] Norfolk can be viewed as a gateway to the Hampton Roads region because Norfolk hosts three of its most globally significant assets: Naval Station Norfolk, Norfolk International Terminals, and the Pier 6 (Lambert's Point) coal terminal. An overview of the facilities mentioned in this study is presented as Figure 2. The hypothesis that Norfolk's importance to the nation is greater than would be initially suggested by its population or GDP is partially tested in this study.

Norfolk hosts the largest naval installation in the United States – the Naval Station Norfolk (NAVSTA Norfolk).[7] NAVSTA Norfolk's role in the Navy's overall mission space is extremely important because they support the operational readiness of the US Atlantic Fleet, which

[5] United States Census Bureau, Population Division (2015) *Annual Estimates of the Population of Metropolitan and Micropolitan Statistical Areas: April 1, 2010 to July 1, 2014 (CSV).* 2014 Population Estimates, March 2015. Retrieved March 26, 2015.

[6] Bureau of Economic Analysis (2015) *Regional Economic Accounts*. Accessed online, October 09, 2015. <http://www.bea.gov/regional/>

[7] <http://www.cnic.navy.mil/regions/cnrma/installations/ns_norfolk.html>

currently totals four carrier strike groups and houses a fifth carrier currently undergoing Refueling Complex Over-Haul. A carrier strike group is a naval operational formation consisting of one aircraft carrier and several supporting vessels, housing roughly 7,500 personnel. They are one of the principal elements of power projection across the globe by the United States. The US Navy maintains 11 carriers in total, ten of which are based in the United States and one which is forward deployed in Japan.[8] Norfolk supports more carrier strike groups than any other facility in the country.

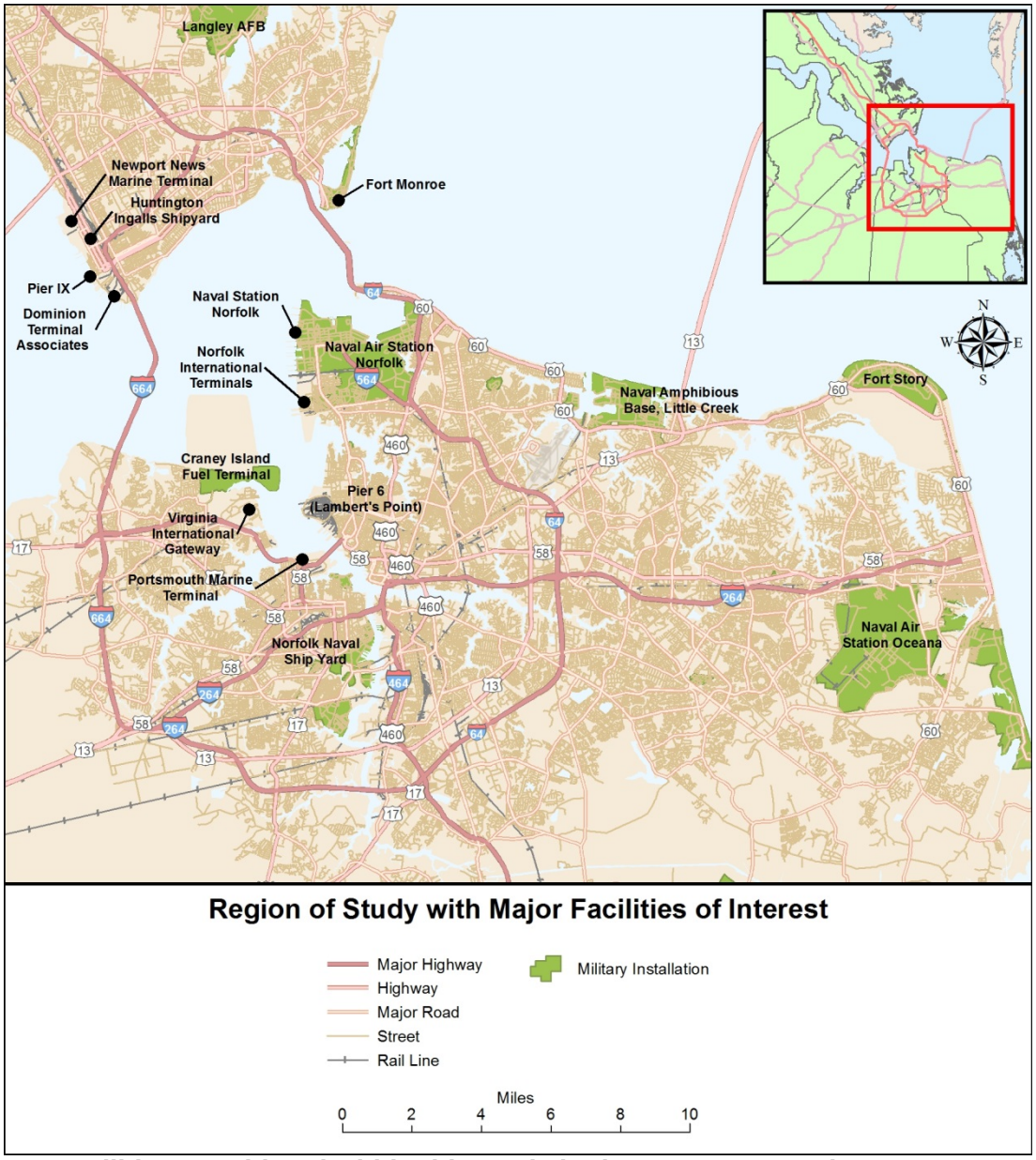

Figure 2. Facilities considered within this study in the Hampton Roads area.

[8] GlobalSecurity.org (2015) *Where are the carriers?* Accessed online, October 09, 2015. <http://www.globalsecurity.org/military/ops/where.htm>

There are many other Department of Defense (DOD) establishments in the Hampton Roads region in addition to or in support of Naval Station Norfolk. These include Langley Air Force Base, Newport News Shipbuilding, the Norfolk Naval Shipyard, Joint Expeditionary Base Little Creek, Naval Air Station Oceana, Craney Island Fuel Terminal, Fort Eustis, and Camp Pendleton to name a subset.[9] No other region on earth has such a high concentration of military facilities.[10] Nearly ¼ of United States military personnel are stationed in Hampton Roads. In 2011, DOD spending on salaries, retirement, and procurement accounted for approximately 40% of the 995,000 employees in the region.[11] Therefore, in a conversation about Norfolk's resilience impact on global security, one must include their interdependence with the military.

Norfolk is home to Norfolk International Terminals (NIT) – one of the primary components of the Port of Virginia (Port of VA). The Port of VA is the fifth-busiest port by twenty-foot equivalent units (TEU's) in the United States.[12] NIT primarily serves containerized vessels, capable of handling around 1.4 million TEUs per year and served by 14 Super Post-Panamax Class quay cranes.[13] Its neighbor across the James River – Newport News Marine Terminal (NNMT) – is another primary component of the Port of VA. NNMT specializes in bulk goods and roll-on/roll-off capabilities. Other Port of VA facilities in the region include the Portsmouth Marine Terminal (PMT) and Virginia International Gateway (VIG) located on the Elizabeth River in Portsmouth, VA. Taken together, NIT and VIG process the majority of container traffic for the Port of VA.

The third globally relevant economic asset that calls Norfolk home is Pier 6 (Lambert's Point), the largest and fastest coal transloading facility in the Northern Hemisphere. Lambert's Point is operated and served by Norfolk Southern, which also owns rail service to coal mines throughout the Appalachian region. Pier 6 maintains the capacity to move nearly 35 million tons of coal per year.[14] There are also two significant coal terminals in Newport News: Dominion Terminal Associates (DTA) and Pier IX. DTA is operated by the Virginia General Partnership, which is owned by subsidiaries of Alpha natural Resources, Arch Coal, and Peabody Energy.[15] DTA has an approximate annual coal shipment capacity of 19 million tons. Pier IX, operated by Kinder Morgan, has an approximate shipment capacity of 16 million tons per year. DTA and Pier IX are served by the CSX rail network.

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[9] Hampton Roads Transportation Planning Organization (2012) *Hampton Roads Military Transportation Needs Study: Military Commuter Survey*. HRTPO, September 2012.

[10] Hampton Roads Partnership (2015) *Hampton Roads: "Americas First Region" Is a Region of Firsts*. <http://www.hrp.org/>

[11] Hampton Roads Planning District Commission (2013) *Economic Impact of the Department of Defense in Hampton Roads*. Hampton Roads PDC, October 2013.

[12] YesVirginia.org (2014) *The Port of Virginia – The Only Port on the U.S. East Coast Ready Now for Post-Panamax Vessels*. Accessed online, September 18, 2015. <http://www.yesvirginia.org/BlogSpot/?tag=/Norfolk+International+Terminals>

[13] <http://www.portofvirginia.com/facilities/>

[14] USCoalExports.org (2015) *Existing and Potential Coal Port Infrastructure*. Accessed online, September 26, 2015. <http://www.uscoalexports.org/data/Coal-Port-Capacity-and-Projections.pdf>

[15] <http://www.dominionterminal.com/Facility%20Description.htm>

Figure 3 depicts approximate shipment capacities for United States coal terminals that serve the Atlantic Ocean. Together, the Hampton Roads region accounts for about 40% of all coal exported from the United States, and about 70% of coal capacity along the eastern seaboard.[16,17] Approximately 75% of the coal exported through Hampton Roads is metallurgical coal, which is primarily used in the production of steel. The remaining 25% is thermal coal, primarily used to generate steam for electricity production or other thermal processes. Metallurgical coal has a higher economic value than thermal coal, and the United States is the world's number two exporter of metallurgical coal behind Australia.[18]

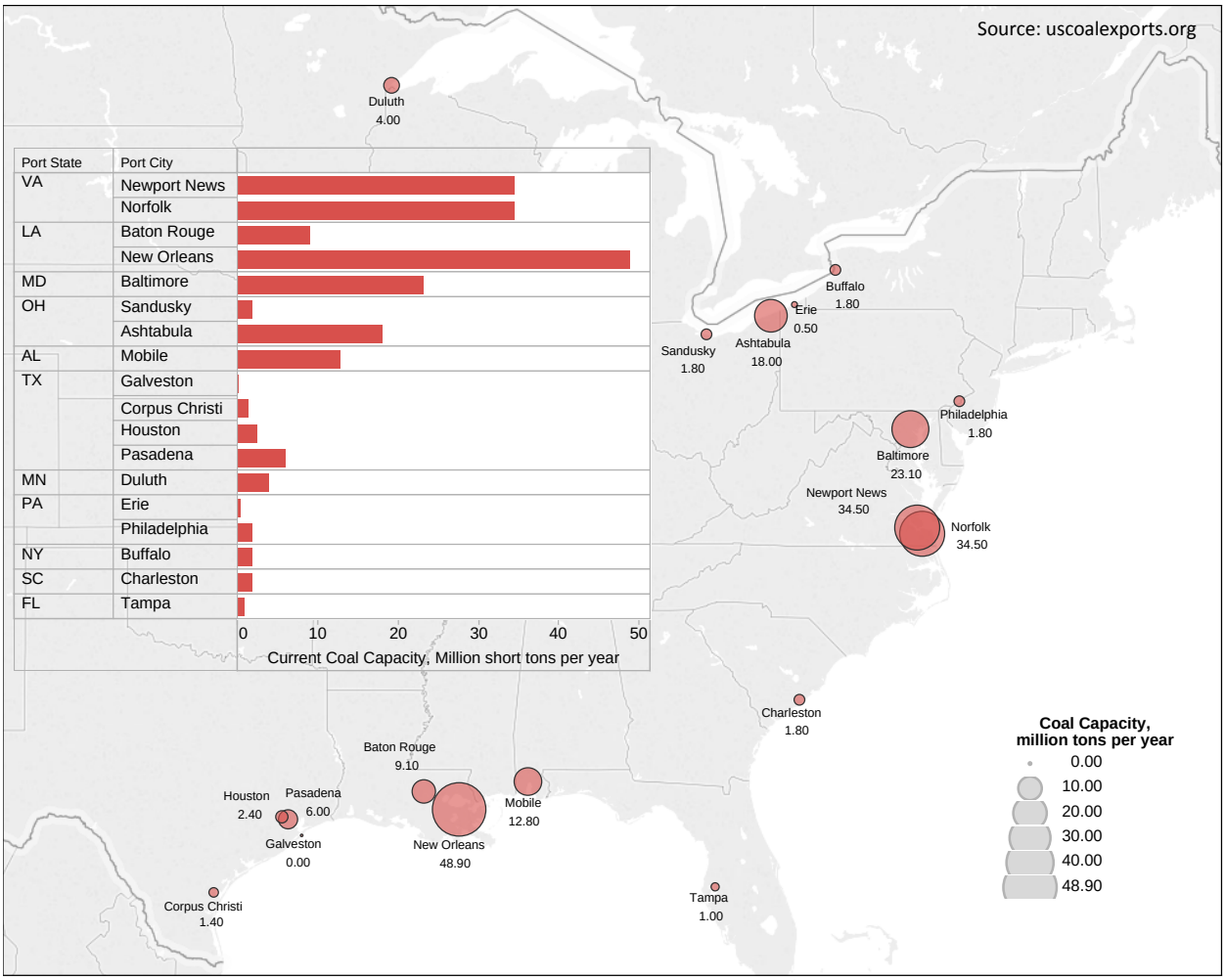

Figure 3. Coal export capacities along the eastern seaboard.[19]

[16] Old Dominion University (2013) Coal: A Very Important Economic Engine in Hampton Roads. *14th Annual State of the Region Report*. Old Dominion University Regional Studies Institute.

[17] UsCoalExports.org (2015)

[18] World Coal Association (2014) *Coal Statistics*. Accessed online, October 09, 2015. <http://www.worldcoal.org/resources/coal-statistics/>

[19] UsCoalExports.org (2015)

Taken together, NAVSTA Norfolk, NIT, and Lambert's Point connect Norfolk tightly to the rest of the world. Because of this disproportionate role in the economy and security – both nationally and globally – Norfolk identified these assets as being of primary concern for an analysis of Norfolk's impact to regional, national, and global resilience. Much of the reason that these assets have chosen to stay in Norfolk is access to water. Hampton Roads houses a large, protected, and naturally deep harbor with fast access to the ocean and strong inland transportation connections. Perhaps ironically, it is this very water that is increasingly threatening Norfolk's economy. As will be described in this analysis, flooding is Norfolk's primary resilience concern. To focus the analysis on developing actionable information, two major questions related to these assets were addressed:

1. What is a likely consequence scenario for these assets given a significant yet plausible flooding event?
2. Under this scenario, what are the impacts outside of Norfolk? What role does Norfolk's resilience play in national security?

To answer these questions, Sandia first investigated the economic and global security drivers and trends that will lead to changing relationships between Norfolk, the assets of concern, and outside entities through time. Sandia then took a regional view of the flood risk and the infrastructure interdependencies for all of Hampton Roads. Sandia focused in on the impacts of a set of representative flooding scenarios on the assets within Norfolk, VA itself. Finally, the analysis team calculated the indirect economic impacts to entities outside the region by gaining a better viewpoint on the areas outside of Norfolk that strongly depend on Norfolk's assets. In this way, this study allows city planners to think globally about overall impacts but have the necessary information to act locally in order to mitigate these impacts.

Notably, this analysis does not complete the urban resilience analysis process described in Figure 1. Norfolk's prioritization of resilience-enhancing investments is a work in progress. This analysis was performed to help Norfolk consider how they might protect their infrastructure within their overall consideration of mitigation options, and how their economic performance during a flood event might impact economies outside of Hampton Roads. The next step is for Norfolk to use all of their information at hand to develop potential resilience-enhancing investments. At that point, the same process employed here can assess the potential infrastructure and economic performance-based impacts of those investments.

2.2. Norfolk's Evolving Economy

To understand how national security is improved if Norfolk is more resilient, it is important to understand regional and national dependencies on Norfolk and how these are changing through time. Norfolk is likely to remain strongly dependent on the military's presence in the region. Referencing Figure 4, the largest industries in Norfolk are *Education, Health Care and Social Assistance* (19 percent), *Military* (18 percent), *Retail Trade* (10 percent), *Arts, Entertainment and Recreation* (9 percent), and *Professional, Scientific and Management* (9 percent). As a comparison, the U.S. military's national share of employment is under 1

percent.[20] *Manufacturing* composes 5 percent of Norfolk's economy, as opposed to 11 percent of the U.S. economy.

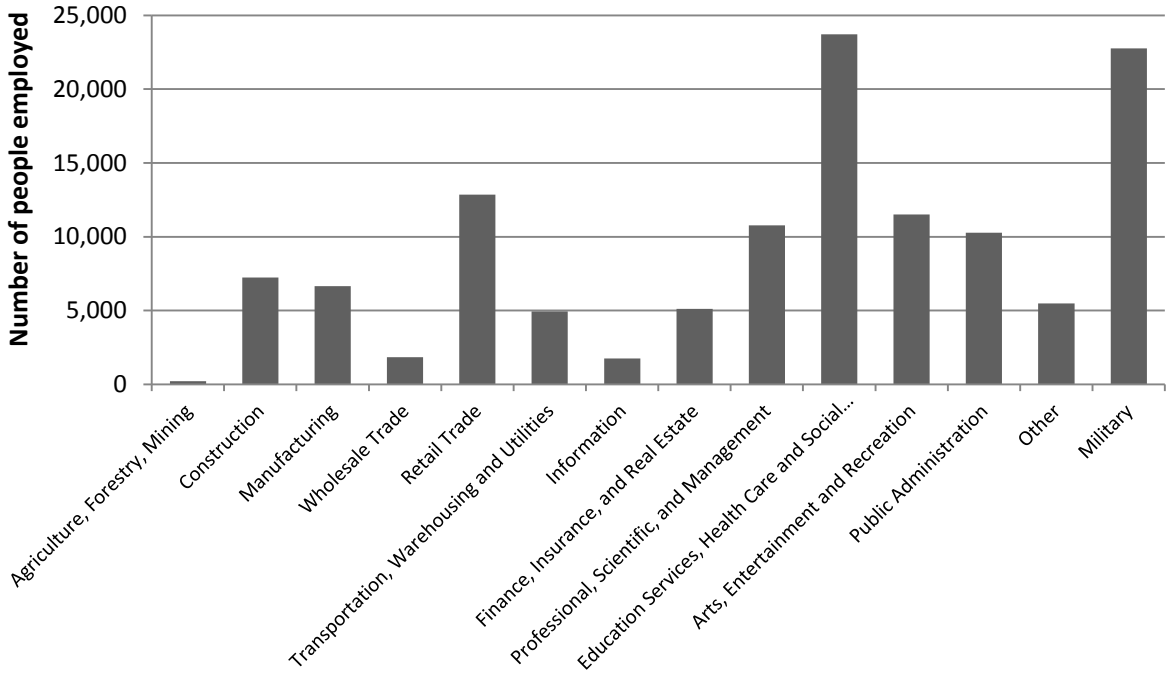

Figure 4. Industry size in Norfolk, VA by number of people employed.[21]

Figure 5 illustrates Norfolk's employment by industry compared to the Hampton Roads Metropolitan Area. Norfolk has a large share of regional military jobs (18 percent of Norfolk's employment and 8 percent of Hampton Roads MSA's employment). It also has a regionally significant *Arts, Entertainment, and Recreation* industry, and *Transportation, Warehousing and Utilities* industry. The *Agriculture, Forestry and Mining* and the *Manufacturing* industries within Hampton Roads are concentrated more heavily outside of Norfolk. Many of the manufacturing sector's jobs are heavily intertwined with Naval Station Norfolk. For example, the Huntington Ingalls Shipyard in Newport News, the Norfolk Naval Shipyard in Portsmouth, and the Norfolk Shipbuilding and Drydock Corporation (NORSHIPCO) in Norfolk are significant sources of manufacturing jobs for the region.

[20] United States Census (2015a) *QuickFacts Beta*. Accessed online, October 09, 2015. <http://www.census.gov/quickfacts>

[21] United States Department of Labor, Bureau of Labor Statistics (2015) *Economy at a Glance: Virginia Beach-Norfolk-Newport News, VA-NC*. Accessed online, September 09, 2015. <http://www.bls.gov/eag/eag.va_virginiabeach_msa.htm>

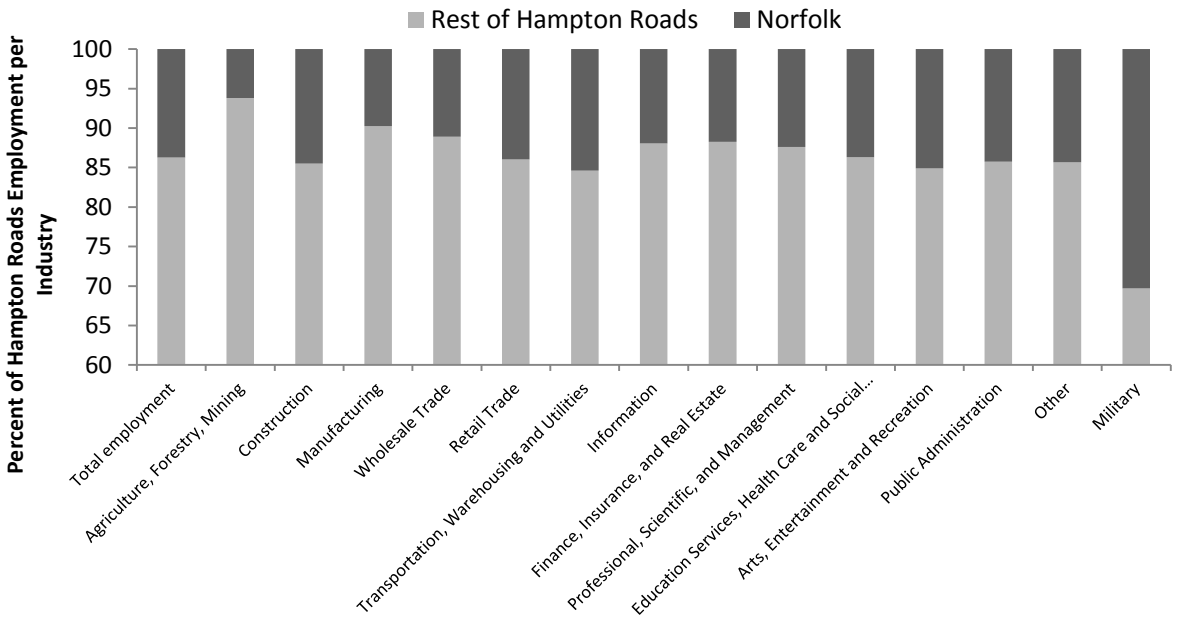

Figure 5. Norfolk as a percentage of Hampton Roads total employment by industry.[22]

Unemployment figures in Hampton Roads have generally followed statewide trends, as indicated by Figure 6. Hampton Roads has displayed a higher unemployment rate than the State of Virginia since 2010, when the recent recession caused unemployment to spike from 3.1 to 8.2 percent between 2008 and 2010. The United States rate of unemployment topped out at 9.9 percent in March of 2010, so Virginia and Hampton Roads were somewhat insulated in comparison, perhaps due to a higher proportion of federal spending.[23] Unemployment has shown steady annual decline since 2010.[24]

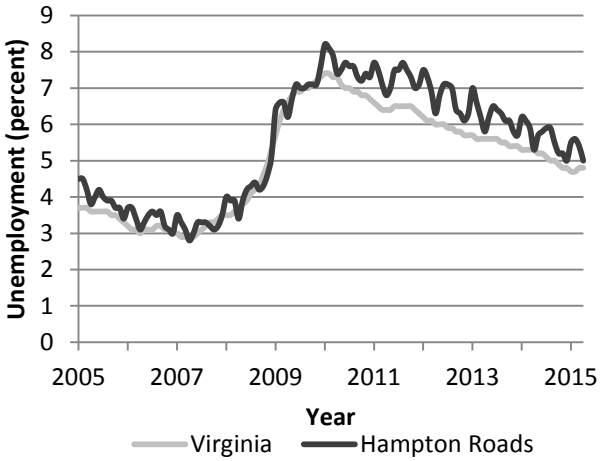

Figure 6. Unemployment in Hampton Roads and Virginia from 2005-2015.

Trade through Norfolk and the Hampton Roads region is evolving. Overall, the value of commodities being shipped through Hampton Roads ports is increasing, as illustrated at left in Figure 7.[25] This data combines shipments through NIT, NNMT, PMT, VIG, as well as the

[22] United States Census (2015a)
[23] Old Dominion University (2014) *The State of the Region: Hampton Roads 2014*. Old Dominion University Regional Studies Institute.
[24] United States Department of Labor, Bureau of Labor Statistics (2015)
[25] United States Census (2015b) *USA Trade Online*. Accessed online, October 19, 2015. <https://usatrade.census.gov/>

Lambert's point, Pier IX, and DTA coal terminals. Hampton Roads imports a higher overall value of goods than they export. Contrastingly, the exports far outweigh the imports by sheer mass as illustrated at right in Figure 7. The large change in mass exported in 2013 and 2014 is primarily due to a spike in coal exports. The combination of these data suggest that the Hampton Roads ports generally import relatively high-value, low mass commodities and export relatively low-value, high mass commodities.

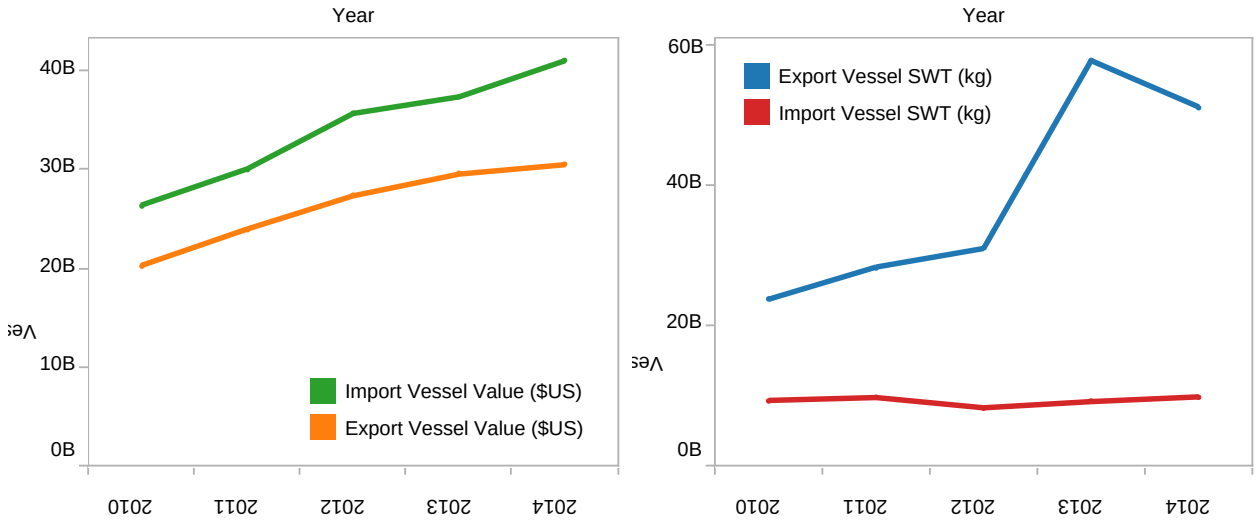

Figure 7. Comparison of import and export vessel value (left) as well as import and export vessel weight (right) through Hampton Roads ports.[26]

The type of commodities shipped through the region is changing less rapidly than the coal volume. Figure 8 and Figure 9 show the top 15 goods based on dollar value imported and exported respectively through the Hampton Roads ports. By value, the top imports are *boilers and machinery*, *vehicles*, *electric machinery and electronics*, *furniture,* and *pharmaceuticals*. The top exports by value are *boilers and machinery*, *plastics*, *pharmaceuticals*, *vehicles*, and *organic chemicals*. The categorical overlap between imports and exports is not significantly notable, as these items tend to be highly traded globally and of high value to weight ratio.

[26] United States Census (2015b)

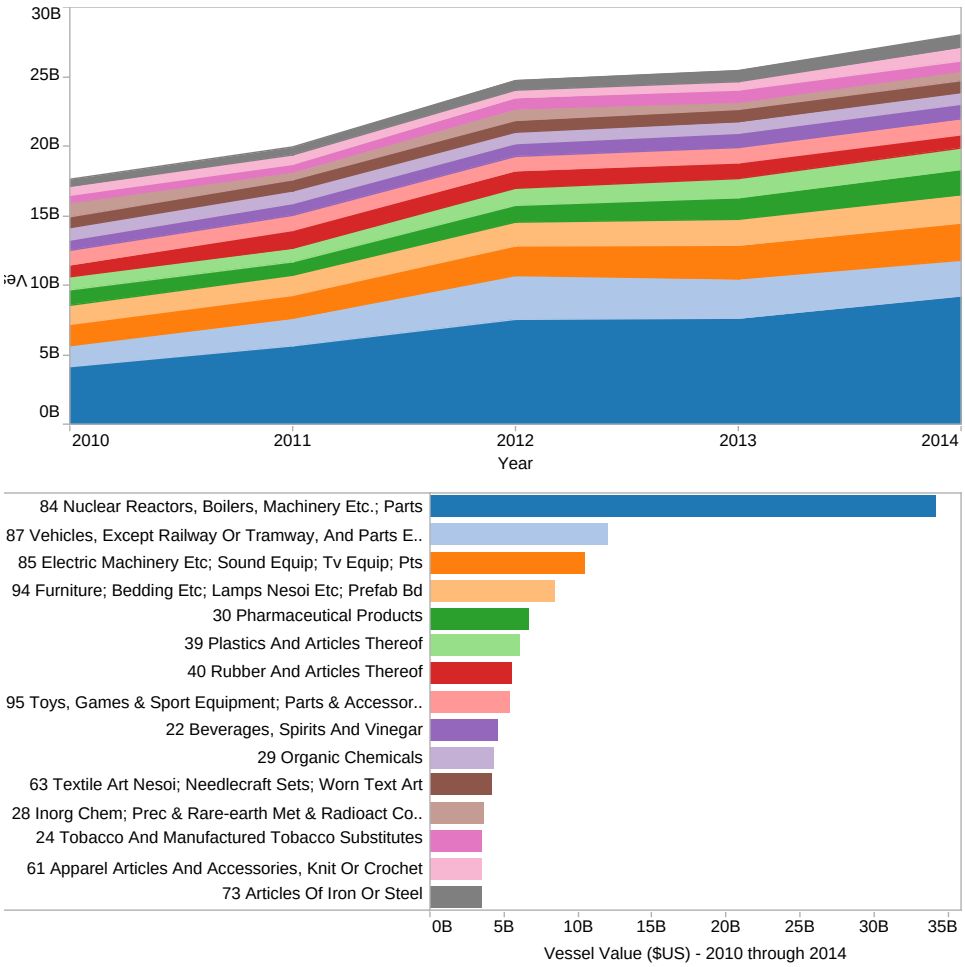

Figure 8. Trends and ranking by value of commodities imported through Hampton Roads.[27]

[27] United States Census (2015b)

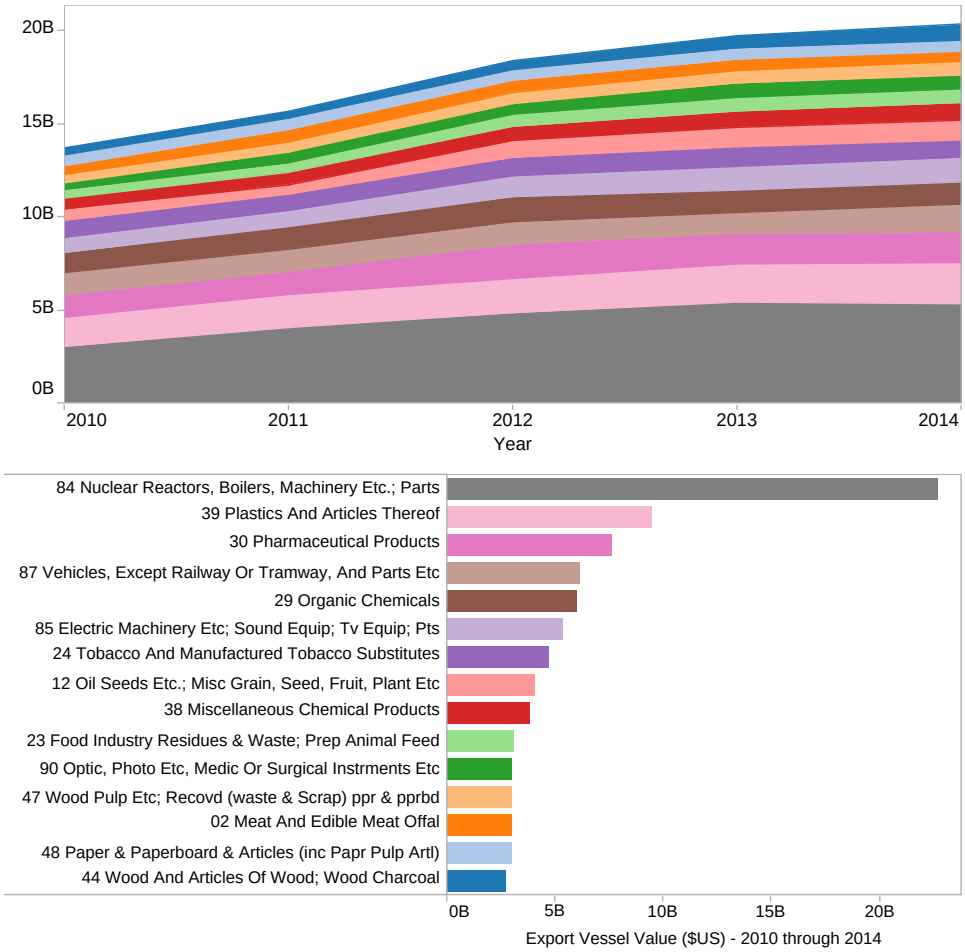

Figure 9. Trends and ranking by value of commodities exported through Hampton Roads.[28]

Examining the type of commodities shipped through Hampton Roads by weight helps to understand the goods that cause the highest throughput loading on the ports. Figure 10 and Figure 11 show the top 15 goods based on weight imported and exported respectively through Hampton Roads ports. The top imports by weight are *mineral fuel and oil*, *boilers and machinery*, *salt and stone*, *furniture*, and *fertilizers*. Coal makes up about half of the *mineral fuel and oil* import category, while crude oil makes up most of the remaining portion. Notably, imports of coal through Hampton Roads were nearly eliminated in 2012, causing the sharp drop in this category. The top exports by weight are *mineral fuel and oil*, *oil seeds and grain*, *wood pulp and scrap*, *wood and articles thereof*, and *food wastes and animal feed*. By weight, coal dominates exports, making up 70 percent of all mass exported through Hampton Roads from 2010 through 2014.

[28] United States Census (2015b)

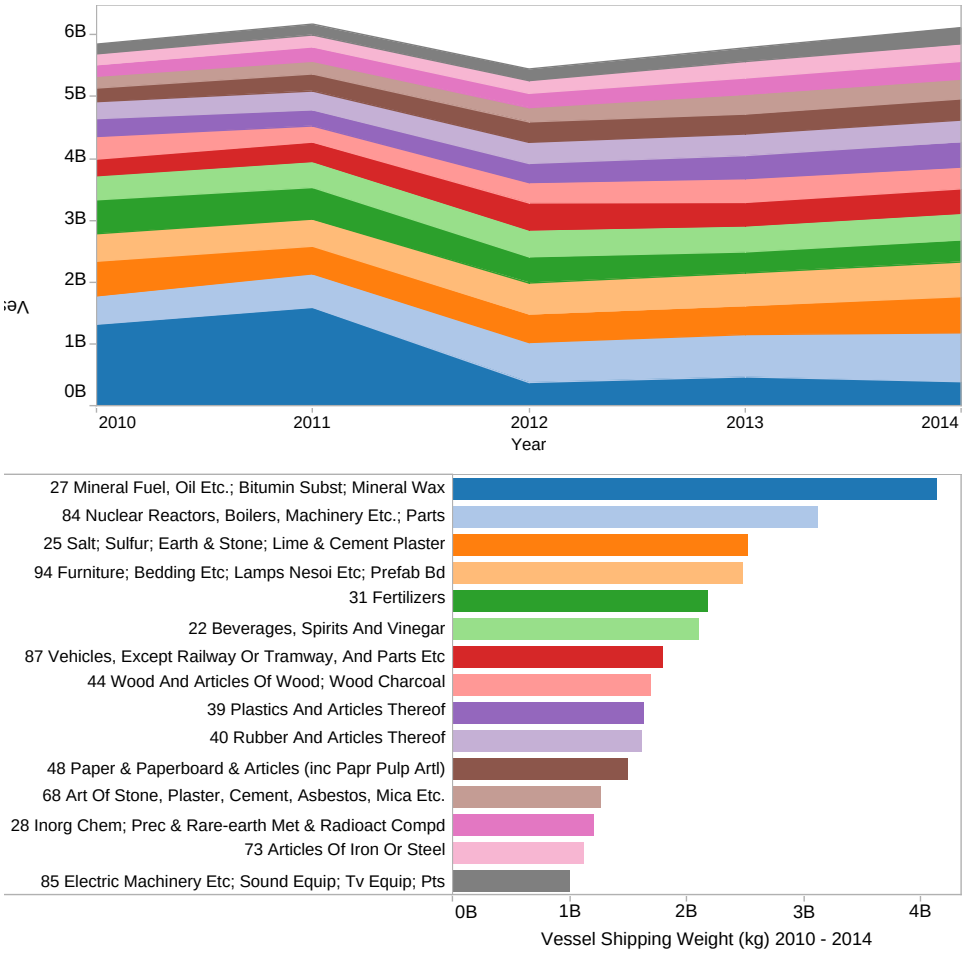

Figure 10. Trends and ranking by weight of commodities imported through Hampton Roads.[29]

Four major takeaways from this economic analysis are important to consider when forecasting the impact of a major flood on Norfolk, and how this flood may have national and global impacts:

- Norfolk operates as a major cog in the Hampton Roads port machine. Because of this, protecting Norfolk from flooding will protect approximately half of Hampton Roads' coal shipping capacity, half of its container shipping capacity, but none of the bulk commodity or roll-on-roll-off capacity of the facilities outside of Norfolk, such as NNMT.
- Norfolk is innately intertwined with successful operation of NAVSTA Norfolk and supporting facilities. Norfolk's flooding resilience will have an impact to the individuals that work and serve at these facilities, as well as the facilities themselves.
- Changes in global trade will also change Norfolk's impact to outside entities. The decrease in coal imports and spike in coal exports that occurred between 2011 and 2013 are examples of shifts in Norfolk's role in global supply chains.
- Changes in high-value items, such as machinery, define much of the economic value of trade through Norfolk and Hampton Roads, and these changes have happened relatively

[29] United States Census (2015b)

slowly. Coal actually has very little impact on the dollar value of exports through Hampton Roads. Other commodities such as *oil seeds and grain* and *plastics* register as high-volume, relatively high-value traded commodities. The relative value of these commodities has changed little in the past five years, while Norfolk has increased in overall value of imports and exports during this time.

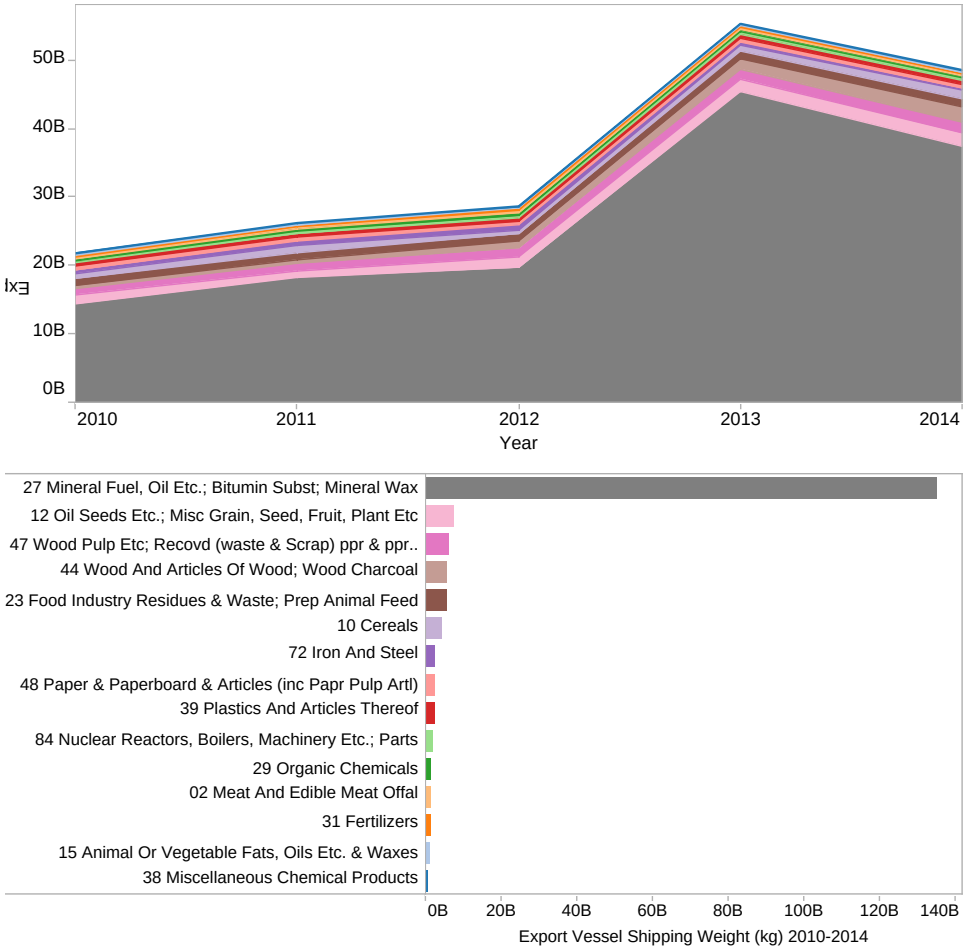

Figure 11. Trends and ranking by weight of commodities exported through Hampton Roads.[30]

2.3. Norfolk's Evolving Flood Risk

Flooding in Norfolk and the Hampton Roads region is already experienced on a yearly if not monthly basis. Nuisance flooding from major rainstorms or high tides is a common occurrence, happening as recently as July and October 2015.[31,32] Old Dominion University researchers found this region to be a "hotspot for accelerated flooding," which could cause the region to

[30] United States Census (2015b)

[31] Brown, E. (2015) *Flood waters, lightning cause problems in cities in Hampton Roads*. ABC 13 News Now online. <http://www.13newsnow.com/story/weather/2015/07/12/flood-water-lightning/30040301/>

[32] Ballesteros, S. (2015) *Update: Coastal Flood Advisory issued in Norfolk until Tuesday Morning*. 10 On Your Side WAVY.com. Accessed online, October 08, 2015. <http://wavy.com/2015/10/04/major-tidal-flooding-underway/>

experience both increased frequency of nuisance flooding as well as longer duration of high-water periods.[33] While this type of flooding is a constant drain to productivity in Norfolk, a rarer but larger event – such as Superstorm Sandy or Hurricane Katrina – is also concerning because of the acute impacts it can have to people and the economy. Additionally, when designing a portfolio of resilience enhancing investments, many options designed to protect from the large flooding event will also protect from the chronic nuisance flooding. For these reasons, Sandia focused on the acute flood event in this analysis, with acknowledgement that chronic flooding also has long-term economic impacts.

A major flooding event in the Hampton Roads region could take two primary forms. Because of the geography, a hurricane with a specific storm track such as Irene in August 2011, or a major nor'easter storm such as that which the region experienced in November of 2009 each present strong potential for major flooding.[34] Flooding happens via two interacting drivers in this region – rainfall and coastal flooding. These drivers interact via the storm drainage system, which has a relatively shallow gradient due to regional topography. As coastal flooding increases the short-term sea level, this gradient decreases and storm drains become impacted. For this reason, there are localized lowland inland regions that can be majorly impacted with such a flooding event.

Drivers of coastal flooding and precipitation-driven flooding are changing in the region. First, climate change is most likely causing major storms to become more intense and frequent in the area, but current data and analyses are limited in defining the precise trend.[35] Second, sea level rise due to climate change is changing the shoreline and the high tide in Hampton Roads. Third, the area around the Southern Chesapeake Bay is undergoing subsidence due to glacial isostatic adjustment and compaction caused by aquifer withdrawals. Glacial isostatic adjustment is the sinking of land over periods of thousands of years in reaction to the removal of glacier burdens on the land.[36] Another commonly cited reason for the subsidence – the settling of sediments due to the Chesapeake Bay meteor that struck over 35 million years ago – is not believed to be a major cause.[37] Due to the combination of subsidence and sea level rise, sea levels along this section of the East Coast are rising three to four times faster than the global average.

Considering these dynamics, Sandia used the 100 year flood with varying levels of net sea level rise as the significant yet plausible event to drive consequence analysis. With feedback from Norfolk, Sandia chose three levels of net sea level rise – 0 feet, 1.5 feet, and 3 feet – to

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[33] Ezer, T., Atkinson, L. (2014) Accelerated flooding along the U.S. East Coast: On the impact of sea-level rise, tides, storms, the Gulf Stream, and the North Atlantic Oscillations. *Earth's Future*, 2:8, pp.362-382, John Wiley & Sons.

[34] Fugro Atlantic (2012) *Preliminary City-Wide Coastal Flooding Mitigation Concept Evaluation and Master Plan Development: City of Norfolk*. Fugro Project no. 04.81110022.

[35] Virginia Institute of Marine Science (2013) *Recurrent Flooding Study for Tidewater Virginia*. William & Mary Center for Coastal Resources Management.

[36] National Oceanic and Atmospheric Administration (2015) *What is glacial isostatic adjustment?* National Ocean Service. Accessed online, October 04, 2015. <http://oceanservice.noaa.gov/facts/glacial-adjustment.html>

[37] US Geological Survey (2013) *Land Subsidence and Relative Sea-Level Rise in the Southern Chesapeake Bay Region*. US Department of the Interior, USGS Circular 1392.

represent the changing flood risk through time. For the purpose of this study, these are referred to as the +0ft, +1.5ft, and +3ft scenarios respectively. Other studies that have addressed flooding in the Hampton roads region have used similar levels of net sea level rise.[38] For a coastal region such as Norfolk, the 100 year flood signifies a still water level (SWL) that may be expected to be equaled or exceeded once in the next 100 years, which means there is a 1% chance of this event occurring in any year. In Hampton Roads, this event could be a hurricane or it could be a nor'easter. For the purposes of this analysis, Sandia assumed the nor'easter event, which nominally has a longer lasting storm surge along with much lower wind speeds than a hurricane. Sandia assumed the nor'easter event after feedback from Norfolk stating that it could involve higher amounts of flooding for longer periods of time than the hurricane scenario, and therefore may have higher economic consequence. Also, addressing the nor'easter event simplifies the analysis to not closely consider wind damages, and simplification is useful when proving a concept such as the urban resilience analysis process.

Sandia used a compilation of multiple flood insurance rate maps (FIRMs) in combination with a digital elevation model (DEM) for the entire Hampton Roads Region to extrapolate the base flood maps into a SWL surface using GIS techniques such as topographic contour extrapolation.[39,40] The results show a significant impact of sea level rise on the region, as indicated by Figure 12, which shows flooding extent for Norfolk. The difference between the SWL surface and the DEM gives an indication of flooding depths, as illustrated for the three scenarios in Figure 13, Figure 14, and Figure 15. One major benefit of using topographic contour extrapolation is that missing areas in the FIRM layers – such as areas on federal land – can be filled in. This gives a more complete picture of the full range of flooding that may be expected in the Hampton Roads area as well as Norfolk more specifically.

For this analysis, the flood levels are assumed to last a total of four days. This is consistent with previous major nor'easters as well as expert opinion.[41] The four days is significant when considering time-sensitive components of critical infrastructure, such as fuel for backup generators, and the needs of the globally important assets over this extended period.

The flood projections in Figure 12 through Figure 15 tell a striking story of the increase in the potential extent and depth of flooding as net sea levels rise in Norfolk. Specifically, the +3ft scenario appears to constitute a major change over the +1.5ft scenario on the southern Norfolk peninsula between the Elizabeth and Lafayette rivers. The northwest portion of NAVSTA Norfolk shows a major difference between the +0ft and +1.5ft scenario extents. Much of the deepest floodwaters are along old creek channels, such as those surrounding The Hague neighborhood and the Brambleton area, as well as creek beds that are no longer connected to the rivers, such as Lambert's Creek to the south of the Lambert's Point coal terminal.

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[38] See: Virginia Institute of Marine Science (2013), Fugro Atlantic (2012)

[39] Federal Emergency Management Agency (2015) *Flood Map Service Center*. Accessed online, August 16, 2015. <https://msc.fema.gov/portal>

[40] US Geological Survey (2015) *The National Map: US 10-meter digital elevation model*. Accessed online, August 16, 2015. <http://viewer.nationalmap.gov/basic/>

[41] Mark McVey, personal communication, June 2015.

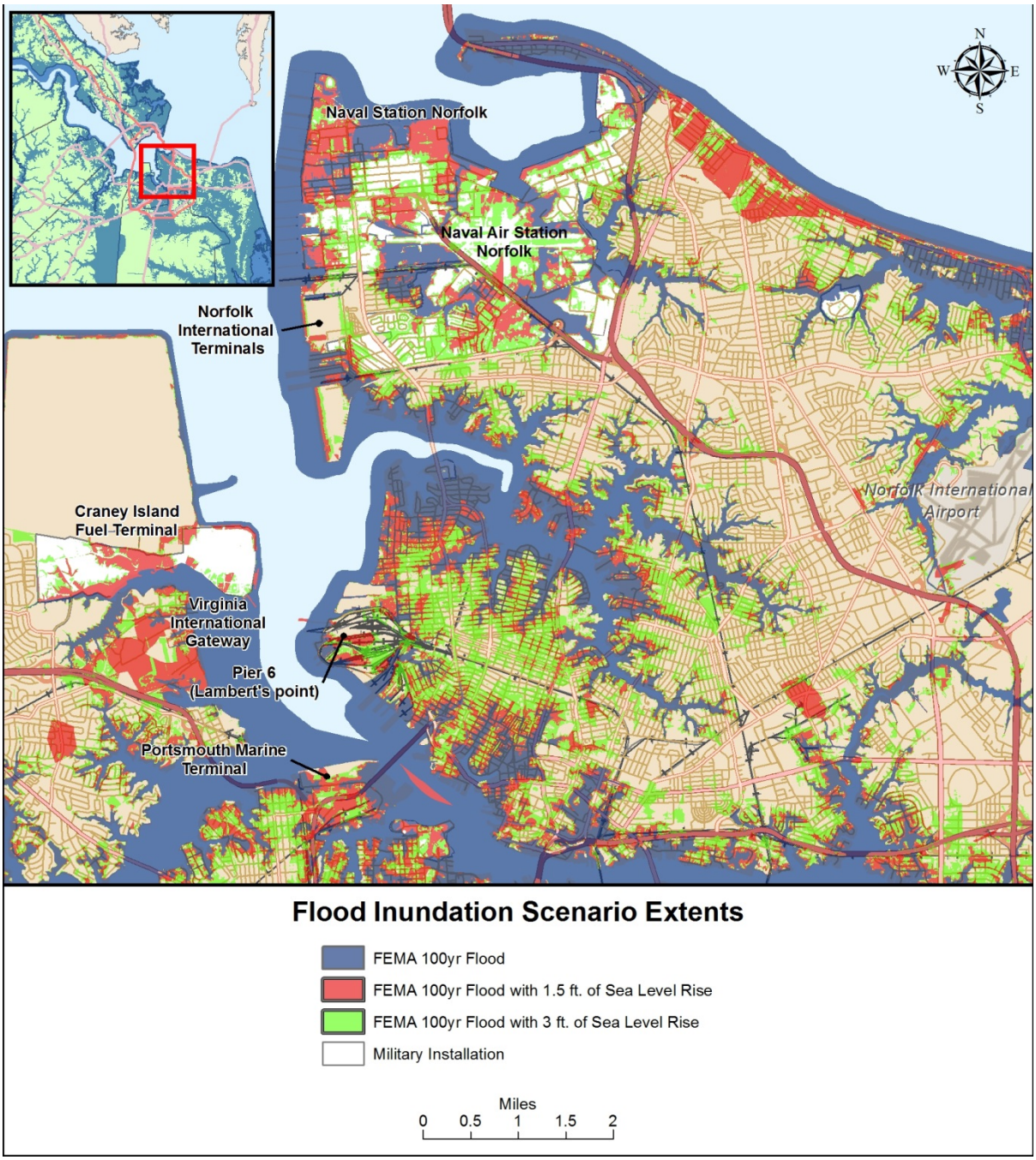

Figure 12. Flood inundation extent for the three scenarios relative to net sea level rise.

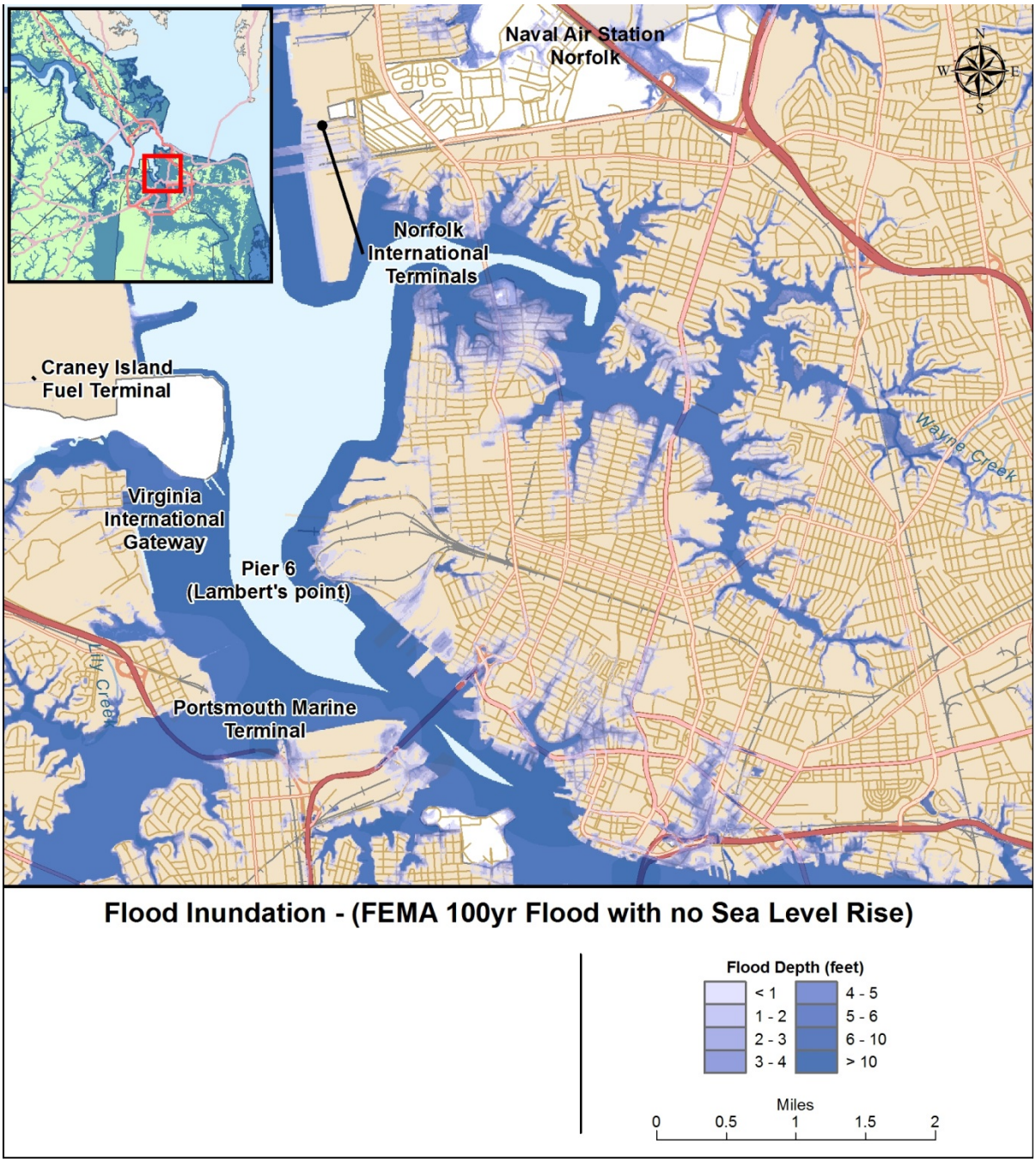

Figure 13. Flood depths for southern Norfolk under the +0ft scenario.

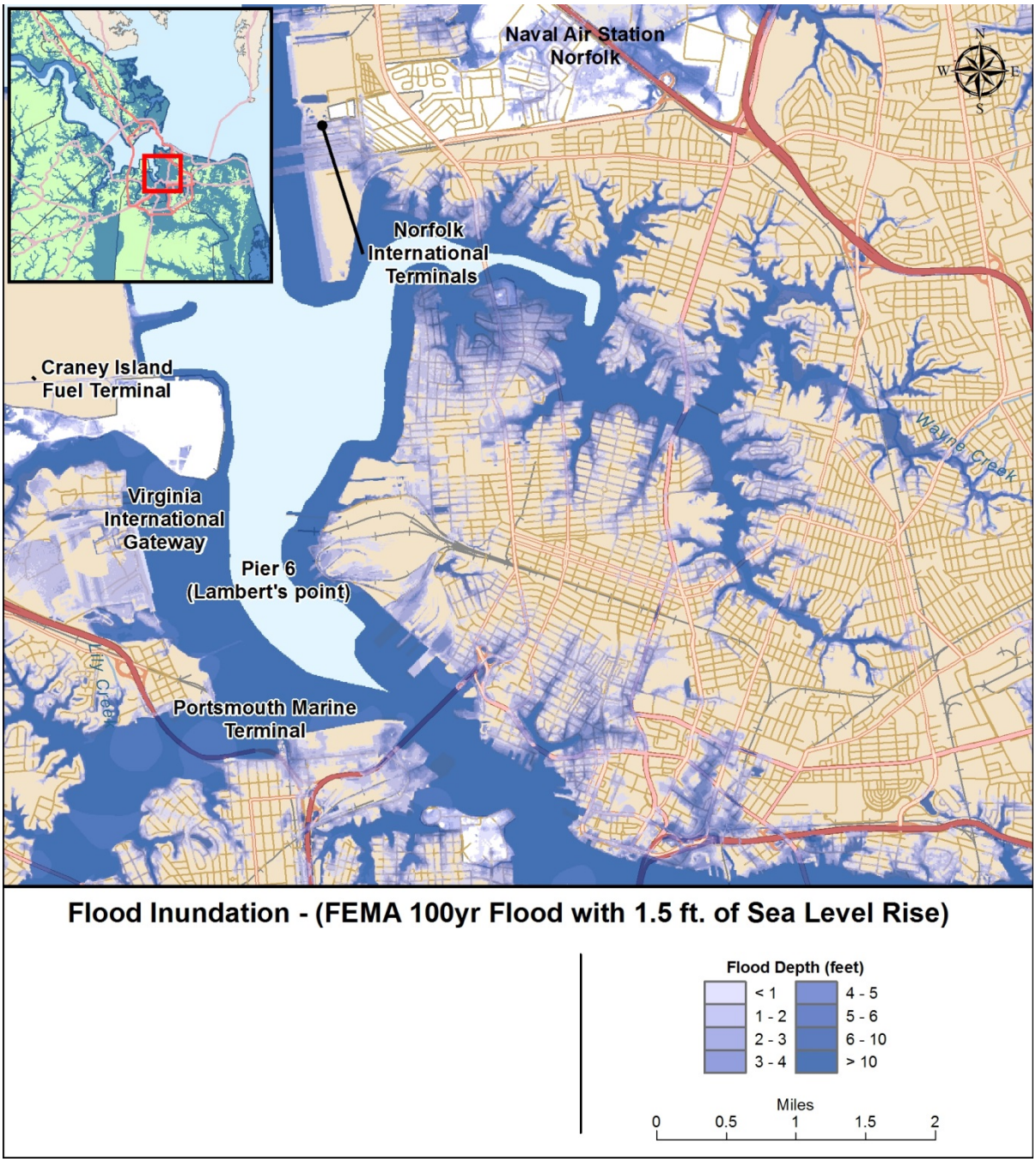

Figure 14. Flood depths for southern Norfolk under the +1.5ft scenario.

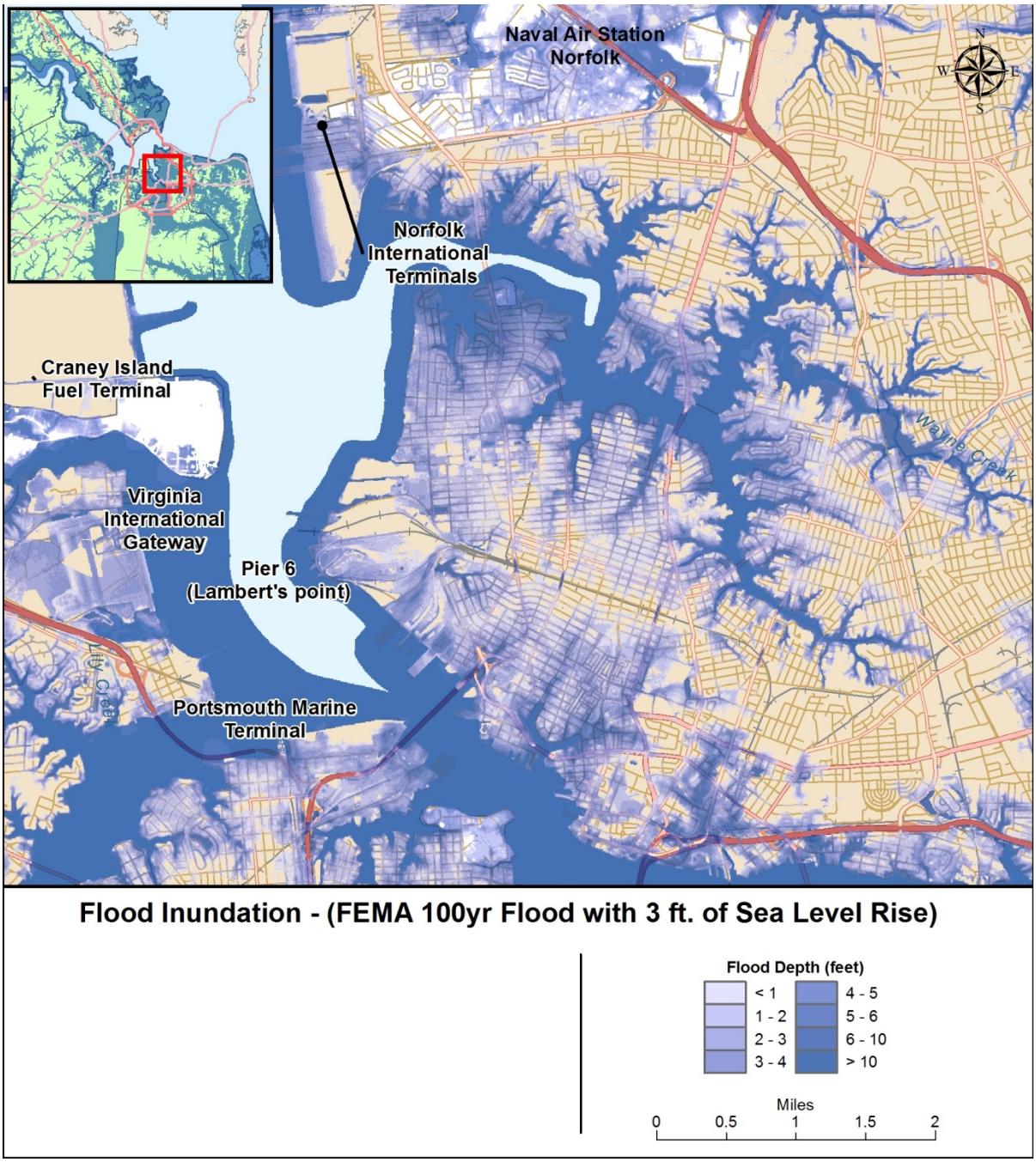

Figure 15. Flood depths for southern Norfolk under the +3ft scenario.

2.4. Impacts to Critical Infrastructure

Based on the flooding analysis, Sandia performed an analysis of critical infrastructure performance in the Hampton Roads region, with a more specific eye toward Norfolk and the globally significant assets under study. NISAC maintains a host of infrastructure data, modeling capability, and subject matter expertise for infrastructure consequence analysis. For this study, Sandia largely utilized the combination of data integration and subject matter expert elicitation

to analyze infrastructure impacts as opposed to high-fidelity models, because a broad analysis in a short amount of time was preferred over a detailed analysis of just one or two infrastructures. Additional models can be engaged in the future if infrastructures are of particular interest or if a more in-depth simulation of outage is warranted.

Four primary infrastructures were assessed for this effort: Electric power, telecommunications, transportation fuels, and transportation. Assessment of additional infrastructures and services, such as emergency services and drinking water delivery, may also lead to consequences not considered herein. To assess the potential for damage due to flooding, Sandia overlaid infrastructure GIS layers on the flood depth layers representing the three net sea level change scenarios. For polygon-represented infrastructure layers such as electric substations the maximum flood depth is reported, which represents the highest value of flood depth that intersects with each polygon. For point-represented layers such as wire centers, the value of flood depth directly under that point is reported. For line-represented layers such as roads and rail lines, sections of the line are reported that intersect at or below a certain flood depth.

2.4.1 Electric Power Infrastructure

The primary electric utility in the Hampton Roads region is Dominion Power, with operating revenue of $15.2 billion and assets valued at $42.8 billion.[42] Their portfolio includes approximately 26,400 megawatts of generation and 6,455 miles of electric transmission lines, serving over 2 million homes and businesses in Virginia and northeastern North Carolina.[43] Dominion is a vertically integrated utility, meaning they own and operate electrical generation, transmission, and distribution assets. Dominion also owns and operates a natural gas transportation and storage service. As a company, they are structured such that management of each of these pieces is highly segregated.

Dominion serves power to all three of the major assets under consideration in this study: NIT, Lambert's Point, and NAVSTA Norfolk. To analyze dependency on power infrastructure at a high level, Sandia generated open-source mappings of transmission-level substations and transmission lines operated by Dominion.[44,45,46] Because of confidentiality concerns, information at a more detailed level is not available for open-source publication. Sandia did not acquire open source distribution-level power system data for the Hampton Roads region. Therefore insight into the full extent of a power outage due to the flooding scenarios is limited to discussion of likely scenarios at the transmission level.

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[42] Dominion (2015a) *Our Company*. Accessed online, September 25, 2015. <https://www.dom.com/corporate/reports/environmental-report/our-company>

[43] Edison Electric Institute (2015) *National Key Accounts, Directory of Utility Contacts: Dominion Virginia Power / Dominion North Carolina Power*.

[44] Dominion (2015b) *Transmission Lines and Projects*. Accessed online, August 16, 2015. <https://www.dom.com/corporate/what-we-do/electricity/transmission-lines-and-projects>

[45] Open Street Map (2015) *Feature Export*. Accessed online, September 14, 2015. <https://www.openstreetmap.org/#map=19/36.87308/-76.29823&layers=H>

[46] US Energy Information Administration (2015) *Electric Power Annual*. Accessed online, September 14, 2015. <http://www.eia.gov/electricity/annual/?>

For Hampton Roads, a major nor'easter storm is not expected to generate significant enough wind to damage the transmission system because it is hardened to a category III hurricane.[47] It may generate wind that causes damage to the power distribution system, however. The most vulnerable power assets to flooding are the major equipment in the substations, such as circuit breakers, transformers, and associated control and protection equipment. For transmission-level substations where flooding is a concern, Dominion has made an effort to raise breakers and transformers twenty-eight inches from their previous levels. They have also re-routed many of the control system conduits such that they enter at the top of the local substation control building instead of the bottom.[48] Distribution-level substations and other ground-level distribution assets such as point-of-service pad mounted transformers are often highly vulnerable to major flooding and significant wind events. Much of the distribution system can be expected to trip offline during the 100-year flood in order to de-energize and protect these assets, leaving much of the area that is served via vulnerable distribution substations or pad mounted transformers without power. Homes and small-to-medium businesses are nearly always served by distribution feeders from distribution substations. Larger loads or generation facilities, such as industrial customers, may be served via a transmission-level substation depending on a host of factors including their reliability requirements.

To avoid risking complete loss of a substation, Dominion will likely de-energize many transmission-level transformers, placing all load on a single transformer in those substations with multiple transformers. Because a de-energized transformer has a much lower risk of being damaged when it takes on water than an energized one, this procedure greatly reduces the risk of long-lasting electrical outages due to flooding. Transmission-level transformers are very expensive and replacements have very long lead times, so the importance of redundancy and flood emergency procedures cannot be overstated.

Figure 16 depicts the transmission-level power system in and around Norfolk, with maximum flood depths shown for the +3ft scenario. In general the transmission system is designed to be robust, with multiple points of service to most substations. Some substations do experience significant flood depths in the 100-year flood scenarios. Table 1 lists the substations that are under more than 1 foot of water in the +3ft flood scenario for the entire region studied. Bold numbers in this table designate flood depths of greater than 2 feet. Of the 68 total transmission substations in the Hampton Roads study area, 24 meet these criteria. Notably, four substations serving the Norfolk area experience significant inundation: Industrial Park, Reeves Avenue, Tanners Point, and Thole Street. Reeves Avenue is of greatest concern because it is a major point of connectivity to generation and transmission infrastructure south of Norfolk. Tanners Point is also of concern, since it serves as a major point of connectivity across the Elizabeth River to the west. None of the substations within Norfolk experience more than 2 feet of inundation in the +0ft scenario. Notably, Dominion power has recently raised many transformers in the area by 28 inches, which likely protects sufficiently from the +0ft scenario, but offers less protection as net sea level rises.

[47] Mark McVey, personal communication, June 2015.
[48] *Ibid.*

Table 1. Substations under more than 1ft of maximum flood inundation in the +3ft scenario, with depths of greater than 2 ft. highlighted in **bold**.

Substation Name	City/County	Max depth +0ft – (ft)	Max depth +1.5ft – (ft)	Max depth +3ft – (ft)
Berkley	Chesapeake, VA	0.53	**2.03**	**3.53**
Chesapeake	Chesapeake, VA	1.32	**2.82**	**4.32**
Cradock	Chesapeake, VA	0.78	**2.28**	**3.78**
Dozier	Chesapeake, VA	**2.88**	**4.38**	**5.88**
Elizabeth River NUG	Chesapeake, VA	0.00	0.00	1.40
Gosport	Chesapeake, VA	0.45	1.95	**3.45**
Greenwich	Chesapeake, VA	0.00	1.18	**2.68**
Huntsman Chemical	Chesapeake, VA	0.85	**2.35**	**3.85**
Tap 5369va115	Chesapeake, VA	0.00	0.79	**2.29**
Bloxoms Corner	Hampton, VA	**3.17**	**4.67**	**6.17**
Navy North	Hampton, VA	0.24	1.74	**3.24**
Shellbank	Hampton, VA	**2.67**	**4.17**	**5.67**
Industrial Park	Norfolk, VA	0.00	**2.52**	**4.02**
McLaughlin	Norfolk, VA	0.00	0.00	1.05
Reeves Avenue	Norfolk, VA	1.69	**3.19**	**4.69**
Tanners Point	Norfolk, VA	0.00	**3.18**	**4.68**
Thole Street	Norfolk, VA	1.65	**3.15**	**4.65**
Union Carbide	Poquoson, VA	0.00	0.98	**2.48**
Churchland	Portsmouth, VA	0.00	0.00	**2.56**
Cogentrix Portsmouth	Portsmouth, VA	0.02	**2.95**	**4.45**
Shea	Portsmouth, VA	0.00	0.00	**2.84**
Green Run	Virginia Beach, VA	0.00	0.00	1.32
Long Creek	Virginia Beach, VA	**2.12**	**3.62**	**5.12**
Lynnhaven	Virginia Beach, VA	0.00	0.58	**2.46**

Addressing the primary assets of concern, it is highly likely that Lambert's Point is served via distribution lines originating from the McLaughlin substation along W 25th street. This area is relatively highly positioned compared to the rest of downtown Norfolk, and the substation itself is expected to be unaffected by flooding. Localized flooding is likely for the +3ft scenario along Morton Ave and W 24th street, as well as all streets south of W 23rd, so access to the surrounding distribution system and to the substation for restoration is likely to be an issue. In the +1.5ft and +0ft scenarios, much less of the area is inundated and access appears more feasible. Because of these factors, Sandia expects a high likelihood of temporary loss of utility service to Lambert's Point in the +3ft scenario, and a medium likelihood of loss of service in the +0ft and + 1.5ft scenarios. This is heavily dependent on the local distribution infrastructure at Lambert's point, which will require a conversation with Norfolk Southern and Dominion to assess more closely.

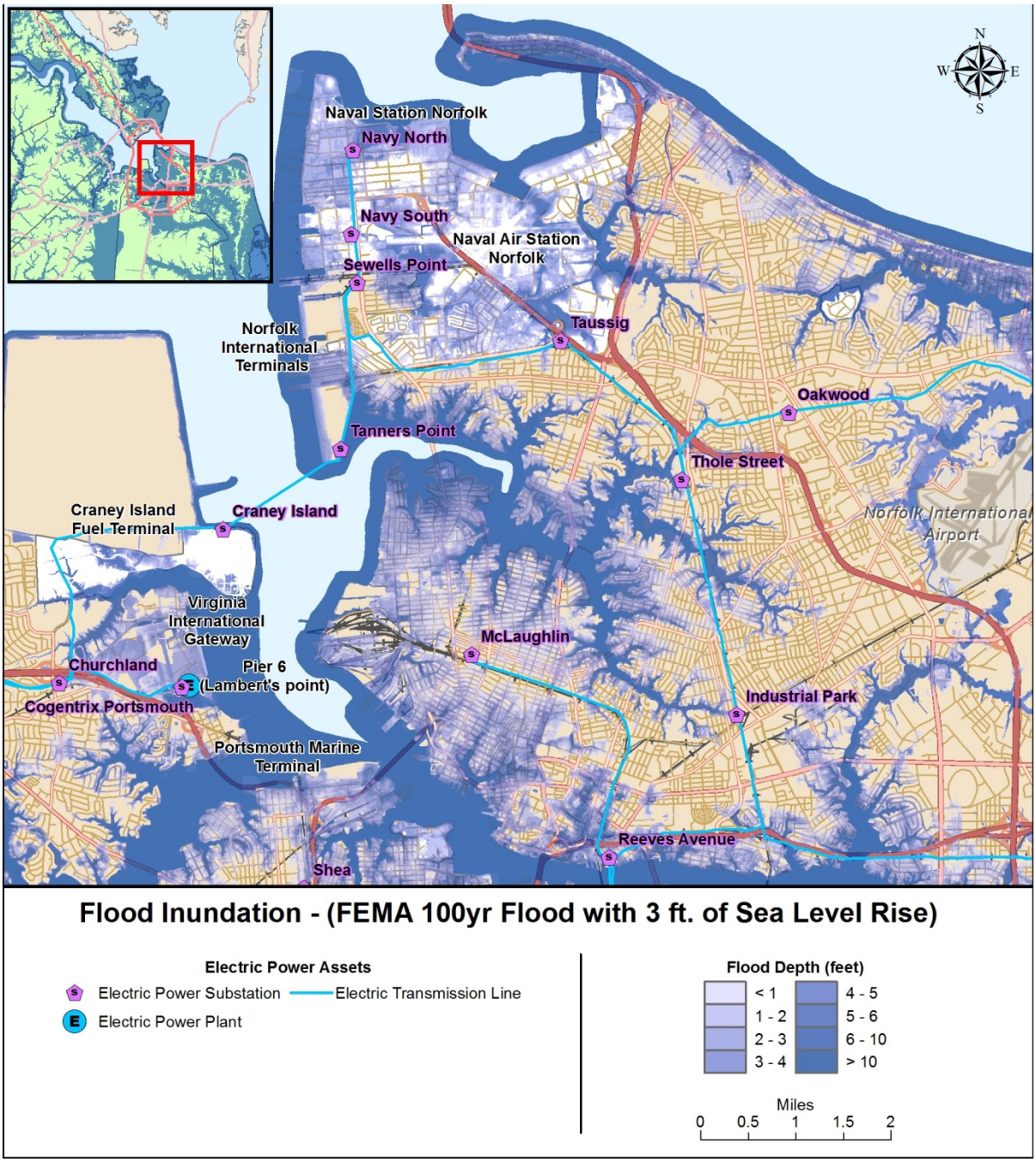

Figure 16. Transmission level electric power assets in the Norfolk Region with flood depths under the +3ft scenario.

NIT is more tightly connected to transmission infrastructure than Lambert's Point. Two transmission-level substations are located adjacent to NIT. The primary feed to NIT is the northernmost substation of this pair: Sewell's Point. Per the flooding analysis, the southernmost substation, Tanner's Point, has the potential to experience about 3 feet of flood depth in the +1.5ft scenario and over 4 feet in the +3ft scenario. The northernmost substation, Sewell's Point, is not inundated in any scenario. Because of this, it is expected that Sewell's Point and by extension NIT would be more likely to lose the southern transmission feed from

Tanner's Point, especially in the +3ft scenario, and would be much less likely to lose the connection to the Taussig substation to the East. Sandia expects a low likelihood of loss of utility service to NIT in the +0ft and +1.5ft scenarios, and a medium likelihood in the +3ft scenario.

NAVSTA Norfolk is also tightly connected to Dominion's transmission infrastructure. Two transmission-level substations exist on the base itself, and two additional substations are directly adjacent to the installation. The northernmost substation on base, Navy North, becomes inundated by approximately 3 feet of water in the +3ft scenario, while the remaining substations are not inundated in any scenario. Sandia expects NAVSTA Norfolk's risk of loss of complete utility service to be very similar to NIT's: a low likelihood in the +0ft and +1.5ft scenarios, and a medium likelihood in the +3ft scenario. NAVSTA Norfolk is expected to have backup generation or battery storage at critical facilities.

2.4.2 Telecommunications Infrastructure

Voice telecommunications services in Hampton Roads are provided by multiple carriers, including Verizon, Cox, CenturyLink, NTelos, Sprint, AT&T, U.S. Cellular, and Vonage, which provide landline, wireless, or voice over IP (VoIP) services. Regardless of the type of service, calls are directed through wire centers, which are physical locations that contain telecommunications switches. Different types of switches and their relationships are described in Figure 17. The switches that a wire center houses will largely define that location's roles in the communications network.

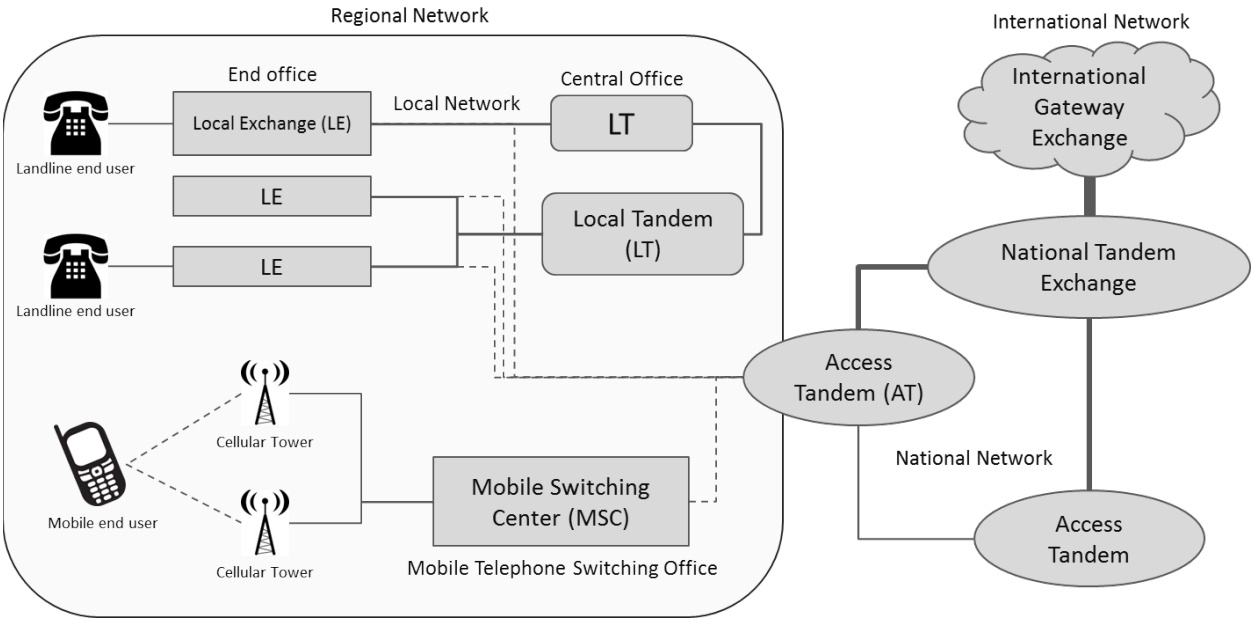

Figure 17. Generic voice switching diagram for routing of landline and cellular communications.

Multiple switches for multiple carriers or multiple functional roles can be housed in one wire center building. Local exchange switches (LEs) provide landline dial tone service to customers

within their service territories. Local tandems (LTs) provide interconnection between local exchanges, though in some cases Access Tandems (ATs) perform this function as well. Access tandems (ATs) are responsible for routing between networks that belong to different providers, for example cellular and landline networks, or between regional networks as well as long distance calls. There will most likely be multiple ATs in a region the size of Norfolk. Notably, the network at the AT level is heavily meshed – it often takes loss of more than one AT to lose routing capability between networks. Customers losing their direct local exchange will not have a dial tone. Customers losing their LT will have a dial tone but may not be able to place calls to customers that are not served by the same exchange. However, wire centers containing LTs tend to have rigorous hardening to flooding, as well as battery backup systems and backup generation.

Some wire centers – especially those in remote areas - do not actually have the ability to switch their own calls, but instead use the services of a host switch housed at a more central facility. These are called remote wire centers, which are served by host wire centers. If a host wire center is disabled, the remotes that it hosts will also potentially lose call routing capability. A customer of this remote wire center will likely have a dial tone, but will be unable to place a call. The data presented in this report has limited detail on hosts and remotes because of the reporting at the open source level.

A depiction of the Norfolk telecommunications infrastructure as subject to the +3ft scenario is shown in Figure 18. As with the power system, Sandia compiled this information from multiple open sources.[49,50,51] Incumbent carriers are the primary landline carrier in the region. Competitive providers, also known as competitive local exchange carriers (CLECs), provide landline service in competition with the incumbent carrier in the region. From the open source information used, there are two remote wire centers in Norfolk. These are located at 9555 15th Bay St. in the Little Creek area and 5215 Hampton Blvd. on the Old Dominion University campus. Although it cannot be inferred which wire center hosts these remotes, both of these wire centers happen to be among the few that experience significant inundation in the flood scenarios. Referring to Table 2, which lists the wire centers that experience more than 1 ft. of flooding in the +3ft scenario, the wire center codes of these two facilities are NRFLVAOV and NRFLVAOD respectively. The third Norfolk wire center that experiences significant inundation in Norfolk is the NRFLVABS facility. This facility is along West Bute St. to the west of the Scope Arena, and only experiences significant flooding in the +3ft scenario. It is, however, one of the more densely populated wire centers in the area.

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[49] Sandman.com (2015) *Central Office Search*. Accessed online, September 07, 2015. <http://www.sandman.com/cosearch.asp>

[50] TelcoData.us (2015) *Telecommunications Database*. Accessed online, September 07, 2015. <https://telcodata.us/>

[51] Central Office Buildings (2015) *Area 757 Telephone Central Office Building Pictures*. Accessed online, September 07, 2105. <http://www.co-buildings.com/va/757/>

Table 2. Wire centers under more than 1ft of maximum flood inundation in the +3ft scenario, with depths of greater than 2 ft. highlighted in **bold**.

Wire Center Code	No. Switches	City/County	Max depth +0ft – (ft)	Max depth +1.5ft – (ft)	Max depth +3ft – (ft)
GRBRVAXA	2	Chesapeake, VA	0.00	1.25	**2.75**
NRFLVABS	11	Norfolk, VA	0.00	0.00	1.20
NRFLVAHA	1	Norfolk, VA	0.00	0.04	1.54
NRFLVAOD	1	Norfolk, VA	0.00	0.34	1.84
NRFLVAOV	1	Norfolk, VA	1.50	**3.00**	**4.50**
NRFMVADV	1	Norfolk, VA	0.00	0.04	1.54
HMPNVAQN	1	Hampton, VA	0.28	1.78	**3.28**
PTMOVAHS	1	Portsmouth, VA	0.00	0.00	1.18

Because of the small number of wire centers that experience significant inundation in these flood scenarios, outage estimates for wireline and wireless communications are primarily dependent on the system maintaining electrical power through the disruption. Wire centers (including incumbent, competitive, and mobile switching centers) are required to maintain 24 hours of backup power, typically provided by generator. Remote switches are required to have 8 hours of backup power, which may be provided by battery. Cellular towers and base stations are moving towards generators with about 24 hours of backup, but many may still only have battery backup with 4-8 hours of backup power under large calling volumes. Generators located in basements are a concern for flooding scenarios, so this should be addressed for the wire centers which experience significant flood risk.

The area north and west of downtown, which likely serves the Lambert's Point facility, experiences the worst localized power outages and also has two inundated wire centers. Because of this combination, Lambert's Point has a high likelihood of losing both landline and wireless communications during the disruption in the +3ft scenario, and a medium likelihood in the +1.5ft and +0ft scenarios.

Because of the potential for a dual power transmission feed to the NIT area, power outages here will also be localized and depend mostly on the locations of power distribution substations. The two incumbent wire centers in northern Norfolk are both unflooded in all scenarios. Therefore it is expected that both NIT and NAVSTA Norfolk maintain at least local landline communication through the flood. Long distance communication and landline-to-wireless communication are largely dependent on the status of the access tandem through the disruption.

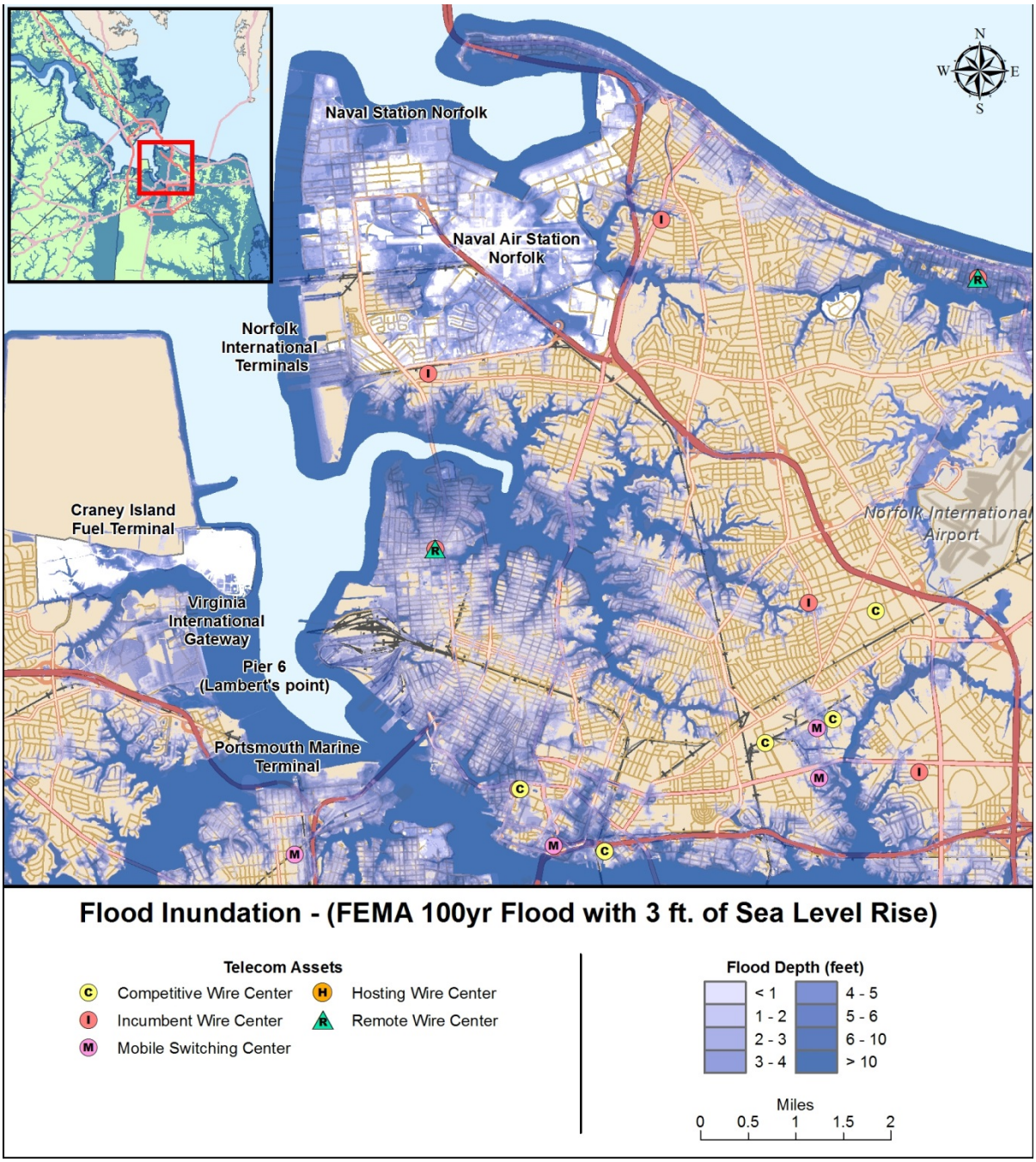

Figure 18. Telecommunications infrastructure subject to the +3ft scenario.

2.4.3 Transportation Fuels Infrastructure

The transportation fuels infrastructure consists of the supply chain of crude oil down to fuel used for transportation: primarily gasoline, diesel, and bunker fuel in various forms. For simplicity, it helps to think of this system as moving and storing two commodities: unrefined product (i.e. crude oil) and refined product (i.e. gasoline, diesel, fuel oil, bunker fuel, etc.). There is currently no crude refining capacity in the Hampton Roads area. The entire

transportation fuel infrastructure in the region is centered on importing/exporting, storing, and distributing refined product.

The Hampton Roads region has two mechanisms for suppling refined product. The first, and likely the primary mechanism is a pipeline spur of the Colonial pipeline to the Richmond, VA area, where it connects with the main Colonial and Plantation pipelines bringing product from refineries in the Gulf Coast. The second mechanism for supply is importing the fuel through terminals located along the Elizabeth River. Figure 19 shows the locations of these fuel terminals, while Table 3 lists their names and capacities. These facilities also serve as storage for both civilian and military uses.

In a previous analysis, Sandia assessed the impact of a hypothetical Category 4 hurricane on the transportation fuels network along the mid-Atlantic region.[52] Power outages were found to be the primary cause of disruption to the pipeline infrastructure. Once power is restored to the pipeline, it is able to resume service to the region. The port terminals themselves, however, may suffer lasting damage due to flooding. One major source of damage and long-term impact to these facilities is the tendency of fuel storage tanks to float when flooded, causing fuel spillage leading to long-term repair and cleanup operations. The risk of this occurring increases if the tanks are empty, and also increases with depth of flooding. Table 3 indicates that nearly all of the fuel terminals in all 100-year flood scenarios are projected to experience significant maximum flood depths. Therefore, it is highly likely that the refined product ports experience a decrease in capacity after all of the 100-year flood scenarios.

Although the fuel terminals are projected to suffer significant impact from the 100-year flood, it is not expected that there will be a long-term shortfall in supply due to this event. This is because of the amount of storage present in Norfolk combined with the presence of the refined product pipeline, as well as the decreased demand during the event. There may be localized shortfalls at individual refueling stations as the floodwaters rise due to stockpiling behavior coupled with an inability to mobilize refueling trucks. This would be exacerbated by a major evacuation, so it would be important to understand the level of storage at the fuel terminals directly before evacuations as well as procedures in place for securing the tanks at these terminals. Once the floodwaters have receded and power is restored to the Colonial Spur from Richmond, and once supply trucks are able to distribute via the road network, supply shortfalls are expected to end. This limits shortfalls to less than one week from the start of the event.

[52] Wilson, M., Corbet, T., Baker, A., O'Rourke, J. (2015) *Simulating Impacts of Disruptions to Liquid Fuels Infrastructure*. Sandia National Laboratories, SAND2015-2696.

Table 3. Fuel terminals under more than 1ft of maximum flood inundation in the +3ft scenario, with depths of greater than 2 ft. highlighted in **bold**.[53]

Terminal Name	City/County	Capacity (bbl)	Max depth +0ft – (ft)	Max depth +1.5ft – (ft)	Max depth +3ft – (ft)
ARC Petroleum	Chesapeake, VA	199,756	**10.68**	**12.18**	**13.68**
Buckeye	Chesapeake, VA	980,000	**3.45**	**4.95**	**6.45**
Center Point	Chesapeake, VA	567,930	**4.38**	**5.88**	**7.38**
CITGO Petroleum	Chesapeake, VA	347,286	**4.34**	**5.84**	**7.34**
DCP Midstream Partners	Chesapeake, VA	480,000	**10.50**	**12.00**	**13.50**
International Matex Tank	Chesapeake, VA	963,000	**4.52**	**6.02**	**7.52**
Kinder Morgan Liquids	Chesapeake, VA	1,400,000	**5.48**	**6.98**	**8.48**
Kinder Morgan Southeast	Chesapeake, VA	375,000	**2.93**	**4.43**	**5.93**
Trans Montaigne Product Services	Chesapeake, VA	1,337,703	**10.10**	**11.60**	**13.10**
Kinder Morgan Liquids	Norfolk, VA	420,000	**10.65**	**12.15**	**13.65**
Norfolk Oil Transit	Norfolk, VA	73,331	**4.52**	**6.02**	**7.52**
Naval Station Norfolk - Craney Island	Portsmouth, VA	---[54]	**11.06**	**13.46**	**14.96**

For the three specific assets under consideration in this study, transportation fuel is of most importance for operations at NAVSTA Norfolk and NIT. Lambert's Point relies on transportation fuel less heavily for operations, whereas NAVSTA Norfolk and NIT have more significant ground transportation dependencies. During this four-day flood event, it is expected that other drivers such as ships leaving the harbor to avoid the storm conditions, direct inundation and loss of power at facilities will cause Lambert's Point and NIT to shut down the majority of their operations. For NAVSTA Norfolk, management of fuel supplies to meet mission needs without resupply for up to 7 days, and a close examination of flood operations at the Craney Island fuel terminal are recommended. A potential mitigation under these scenarios is to fully refuel ships several days in advance of anticipated flooding. Modern aircraft carriers are fueled by nuclear reactors and have limited need for transportation fuels.

[53] TankTerminals.com (2015) *Find tank terminals worldwide*. Accessed online, September 12, 2015. <https://www.tankterminals.com/index.php>

[54] Fuel terminal capacity for military terminals not available at time of study.

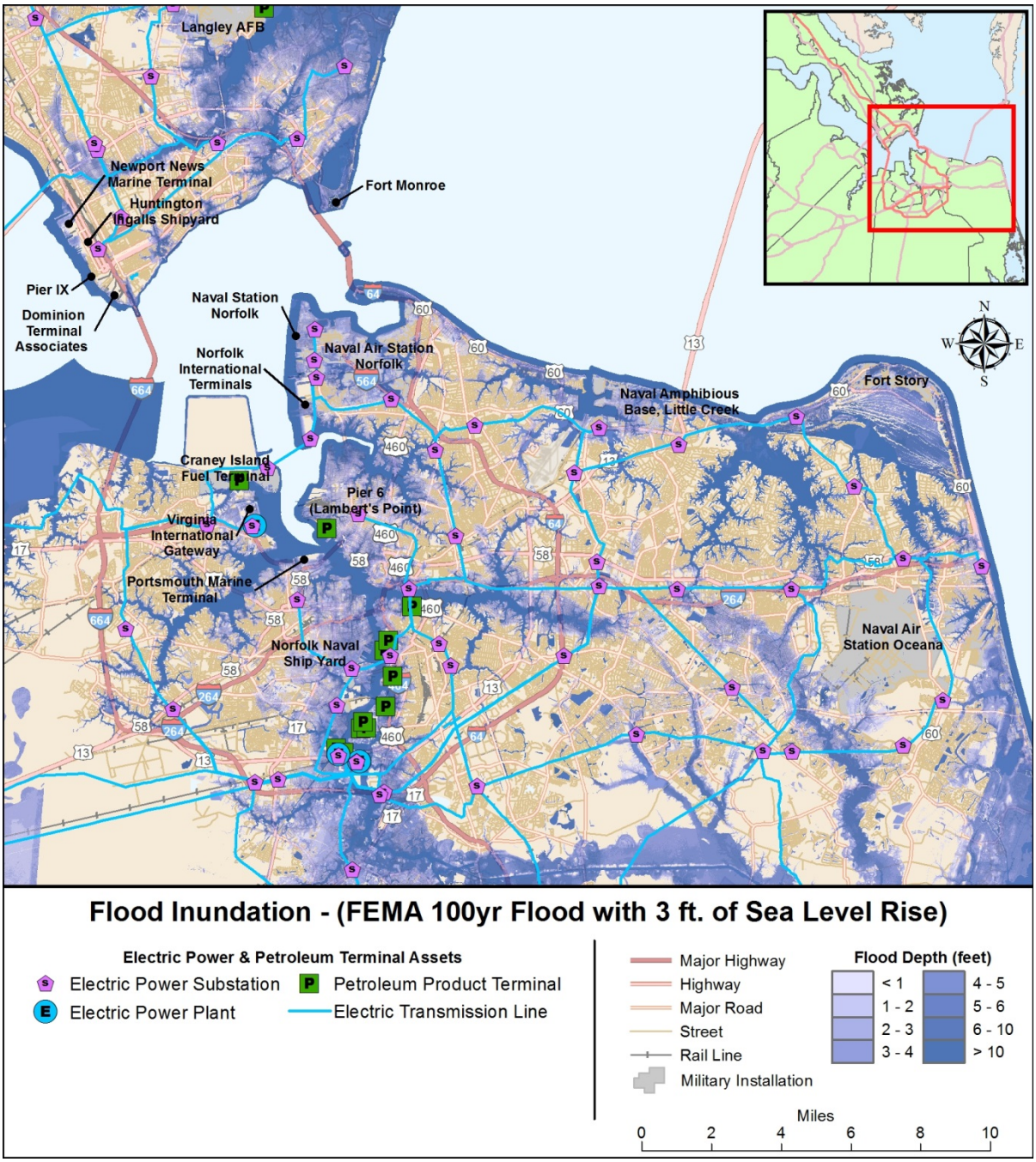

Figure 19. Fuel terminals and electric power transmission infrastructure subject to the +3ft scenario.

2.4.4 Transportation Infrastructure

The transportation infrastructure in Hampton Roads is critical to economic activity in the region. While the harbor and rivers provide an important natural resource to the Hampton Roads economy, they also create natural boundaries and chokepoints for ground transportation. Because of this, bridges and tunnels are a large part of transportation concern during a major flood event. Table 4 lists the bridges and tunnels that Sandia considered for the

flood analysis, along with the expected risk of being closed or severely impacted during the 100-year flood based on analysis of inundation depth and review of previous analyses.[55]

The Hampton Roads Transportation Planning Organization (HRTPO) performed three consecutive studies on the criticality of transportation routes to the military in Hampton Roads given expected flooding. In phase 1 of this effort, a highway network analysis identified the major transportation needs for the military.[56] Their analysis focused on roadways that impact military mission performance effectiveness and efficiency, yet many of these roadways also support other economic functions in the region. All of the major interstates and most major state highways in Hampton Roads were included as important supporting infrastructure. A large reason for this is that most of the military workforce – active duty, civilian, and contractors – live somewhere other than the military installations.

Phase 2 of the HRTPO study focused on understanding the transportation needs of military commuters, largely through survey activities.[57] The survey also created an understanding of the home residences of force members working at the various military installations. For instance, of the 4,746 responses from individuals working at NAVSTA Norfolk, 1,104 (23%) claimed to live in Norfolk compared to 1,794 (38%) in Virginia Beach, 892 (19%) in Chesapeake, and 238 (5%) in Suffolk. A total of 436 respondents (9%) list their residence within the cities and counties across the James River on the Virginia Peninsula. Of all responses to the survey, 22% claimed that flooded roadways were a recurrent problem on their commute to work.

With this understanding in place, the third phase of the HRTPO study worked with the Virginia Institute for Marine Science to examine historic flooding frequency and projected roadway flooding given an expected flooding event.[58] The HRTPO chose a projection of 1.5 ft. of relative sea level rise and a 3 ft. total storm surge, using GIS techniques including LiDAR (Light Detection and Ranging) elevation and road surface data to estimate roadways that will be flooded in this scenario. Their scenario is very similar to the +1.5ft scenario included herein. Figure 20 shows the HRTPO data for potentially inundated roadways in this scenario overlaid with our +3ft flood scenario depths. Because of the HRTPO scenario's similarity to our 1.5ft scenario, the combination of this data helps to extrapolate the additional roadways that may be flooded in the +3ft scenario.

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[55] Hampton Roads Transportation Planning Organization (2013) *Hampton Roads Military Transportation Needs Study: Roadways Serving the Military and Sea Level Rise/Storm Surge*. HRTPO, July 2013.

[56] Hampton Roads Transportation Planning Organization (2011) *Hampton Roads Military Transportation Needs Study: Highway Network Analysis*. HRTPO, September 2011.

[57] Hampton Roads Transportation Planning Organization (2012)

[58] Hampton Roads Transportation Planning Organization (2013)

Table 4. Major bridges and tunnels in Hampton Roads with anticipated risk of closure due to the 100-year flood.[59]

Bridge Name	Route	City/County From	City/County To	Expected Flood Risk
Hampton Roads Bridge Tunnel	I-64	Norfolk, VA	Hampton, VA	High
Monitor Merrimac Bridge Tunnel	I-664	Suffolk, VA	Newport News, VA	High
Berkeley Bridge and Downtown Tunnel	I-264	Norfolk, VA	Norfolk, VA	High
South Norfolk Jordan Bridge	Rte. 337	Chesapeake, VA	Portsmouth, VA	Med
Midtown Tunnel	Rte. 58	Norfolk, VA	Portsmouth, VA	High
High Rise Bridge	I-64	Chesapeake, VA	Chesapeake, VA	Med
Gilmerton Bridge	Rts. 460, 13	Chesapeake, VA	Chesapeake, VA	Low
Chesapeake Bay Bridge Tunnel	Rte. 13	Virginia Beach, VA	Kiptopeke, VA	High
Norfolk Southern Railroad Bridge	NS Rail	Norfolk, VA	Norfolk, VA	Med

From this analysis, the transportation system is a major limiting infrastructure during the 100-year flood in Hampton Roads. Both bridge-tunnels providing access across the harbor to the Virginia Peninsula have historically experienced flooding and closures, and are projected to be at high risk for closure in all scenarios. This effectively cuts off access between northern and southern Hampton Roads, although the James River Bridge on Rte. 17 / Rte. 32 appears to be at lower risk and could be a viable alternative route. To protect the integrity of the infrastructure, some tunnels physically close during extreme flooding using either gates or inflatable stoppers. Although many bridges are sufficiently elevated above flood waters, the elevation and structural integrity of their approaches cause the majority of closure risk. Many roads are also inundated further inland, causing choke points and hot spots, particularly in western Norfolk and along the Elizabeth River. Downtown Norfolk and the area around Old Dominion University appear to be particularly difficult to access during the scenario due to topography and the flooding of many major pathways. In general, crossing the Elizabeth or Lafayette rivers from these locations will be nearly impossible in this scenario. Eastward toward I-64 is the preferred access/evacuation route, although the low-lying area north of Harbor Park cuts off major east-west corridors as well, including I-264 and Rte. 58. East Princess Anne Rd. may be a less risky alternative to Rte. 58 in this case.

[59] Open Street Map (2015)

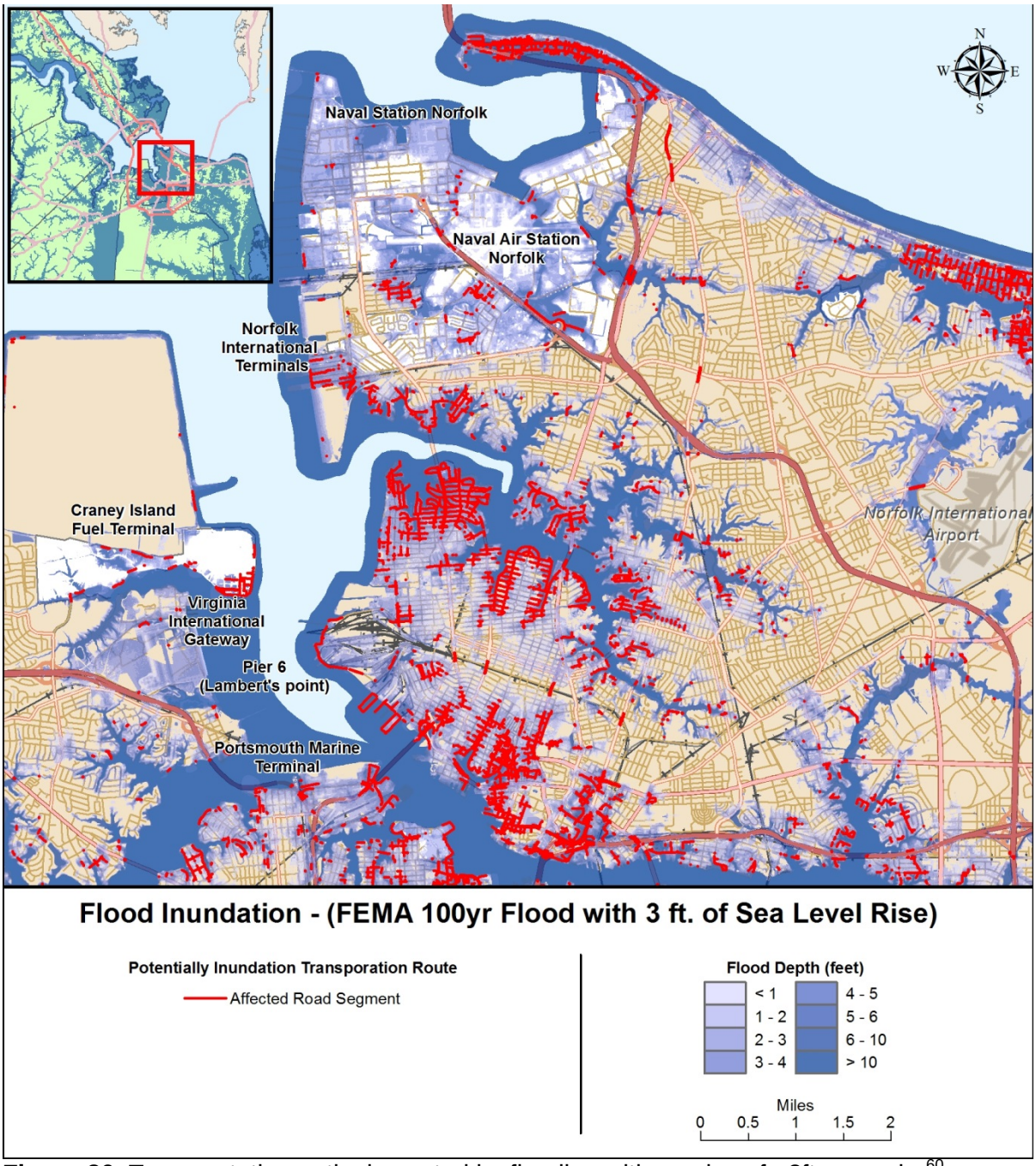

Figure 20. Transportation paths impacted by flooding with overlay of +3ft scenario.[60]

Because of the intensive flooding on the western Norfolk Peninsula, transportation closures greatly impact the viability of the Lambert's Point coal terminal during the flood. The Norfolk Southern rail line is at higher elevation than the surrounding roads, but its crossing of the Elizabeth River near Harbor Park is potentially temporarily compromised during the event. Access to the facility by employees via Redgate Ave. to Norfolk Southern Terminal Dr. is nearly impossible during the event, and may be unavailable for several days afterward due to the

[60] Affected Road Segment layer provided by: Hampton Roads Transportation Planning Organization (2013)

heavy amount of cleanup effort expected for this area, especially near this road's crossing of Lambert's creek. The rail line itself may be the preferred mode of access to Lambert's Point after the event.

NIT's facilities are projected to experience flooding along the access roads south and west of the rail line. The rail line may serve as a dyke to protect many facilities to its north and east. Egress along Terminal Blvd. appears feasible, with access to I-564 and I-64. The rail line serving NIT has potential inundation points at its crossing of Wayne Creek and further south where it crosses Gilligan Creek and the Southern Branch of the Elizabeth River. Rail access may be limited after the event due to re-inspection of rail crossings, but road access appears feasible immediately after the event.

NAVSTA Norfolk also relies heavily on I-64 for access and egress before and during the 100-year flood. Because of the likely closure to the Hampton Roads Bridge Tunnel, transportation paths to the east and south are the likely option. Interstate 64 itself is projected to experience some inundation on the approach to the High Rise Bridge crossing the Southern Branch of the Elizabeth River. The Rte. 13 bridge to the north of this crossing is a potential alternative. On the naval station itself, there are two particularly low-lying areas likely to be inundated. The first is near the intersection of Maryland Ave. and Dillingham Blvd. at the northwestern point. The second is the Fleet Recreation Park area near 90th St.

2.4.5 Infrastructure Interdependencies and Conclusions

The 100-year flood event poses significant direct impacts to electric power and transportation infrastructures in Hampton Roads, and particularly in Norfolk. These risks increase with net sea level rise. In comparison, the telecommunications infrastructure in the region is less directly impacted by the flood, but relies heavily on the electric power infrastructure to maintain service. The transportation fuels infrastructure is heavily impacted through port terminals along the Elizabeth River, but poses a lower risk of supply shortfall because of the sheer amount of distributed storage involved and the multiple sources of supply. Interdependencies between infrastructures are likely to extend the recovery time for each of these infrastructures. Namely telecommunications and transportation outages impact recovery of electric substations by making it harder to dispatch crews, and harder for crews to reach impacted areas. Ensuring that telecommunications wire centers have sufficient generator backup, and that those facilities which are expected to be inundated keep their generators dry during the event, would greatly reduce the risk of losing both electric power and telecommunications to an area at the same time. The peninsula between the Elizabeth and Lafayette Rivers is especially vulnerable to this interdependency.

Lambert's Point has a greater potential to suffer an outage lasting beyond the four-day inundation period than NIT or NAVSTA Norfolk. This is partially because of its location near the end of a heavily impacted peninsula, partially because of potential damage to the local road system, and also because of its dependence on the electrical power distribution system instead of a direct feed from a transmission-level substation. NAVSTA Norfolk, in comparison, has the

lowest potential for lasting loss of service because of their direct tie to transmission substations, direct ties to Interstate 64, an airfield on the facility, and a high likelihood of backup systems for critical infrastructure functions.

After infrastructures have restored service, getting people to work and cleaning up will be the primary source of lasting impact from the 100-year flood. Much of the labor force will be busy salvaging and repairing the incredible damage that the flood has done to their homes. For this reason, it is important for the city to balance protecting critical infrastructure with protecting neighborhoods and homes. Protecting a single critical substation can avoid widespread power outage as well as a costly and impactful power transformer replacement, but protecting a neighborhood can ensure that the labor force is back to work quickly and effectively.

2.5. Flooding Consequence Locally and Nationally

With the flooding scenario defined and the impact to infrastructures investigated, Sandia turned attention to the economic consequences of the 100-year flood scenarios. During the four-day period of inundation the city will most likely be in impact mitigation mode, transitioning to recovery mode as the flood waters recede. This analysis concentrated on the economic consequence to the region as well as the rest of the country in this four-day mitigation period. Near-term economic recovery often follows an exponential decay pattern as shown in Figure 21. Impacts during this recovery period were not calculated herein, but would naturally increase the economic numbers reported. Notably, we assume that after the flood, economic activity returns to previous levels over time. If the flooding were a chronic disruption as opposed to the acute disruption considered here, the output would likely not return to previous levels. An assumption of flooding as a chronic disruption would produce different model outcomes.

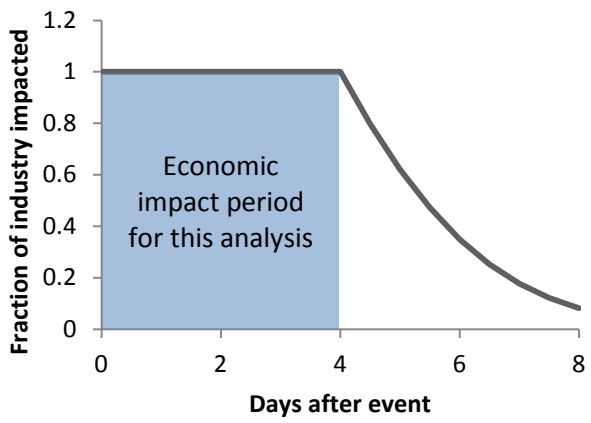

Figure 21. Pattern of economic impacts during mitigation and recovery periods.

Sandia employed the Regional Economic Accounting Tool (REAcct) to estimate regional and national impacts to economic activity during the flooding period. REAcct was developed by NISAC economists to assess the economic impacts due to a host of all-hazard disruptions. It is used to generate rapid order-of-magnitude estimates of events lasting from days up to a full year. A detailed description and model formulation is provided by Vargas and Ehlen.[61]

[61] Ehlen, M., Vargas, V. (2013) Multi-hazard, multi-infrastructure, economic scenario analysis. *Environment Systems & Decisions*, 22, 1, 60-75.

2.5.1 Direct Economic Impacts to the Region

A major component of the economic impacts from the flood will be felt within the Hampton Roads area. These direct economic impacts are defined as the economic activity lost because of firm closures or loss of production directly due to the flood. According to the REAcct analysis, the combined direct effects for the Hampton Roads region across the three scenarios ranges between $135-231 million.

Direct impacts in the region to individual industries are illustrated in Figure 22 and quantified in Table 5. These impacts, measured in millions of US dollars, do not line up with the largest employers in the region because the REAcct model accounts for multiple additional factors to economic impact such as wages and production dependencies. Additionally, the REAcct analysis was driven by the spatial representation of inundation as well as the infrastructure availability estimates from section 2.4. Therefore, businesses in areas that are more heavily impacted by the flood have higher direct losses in this analysis.

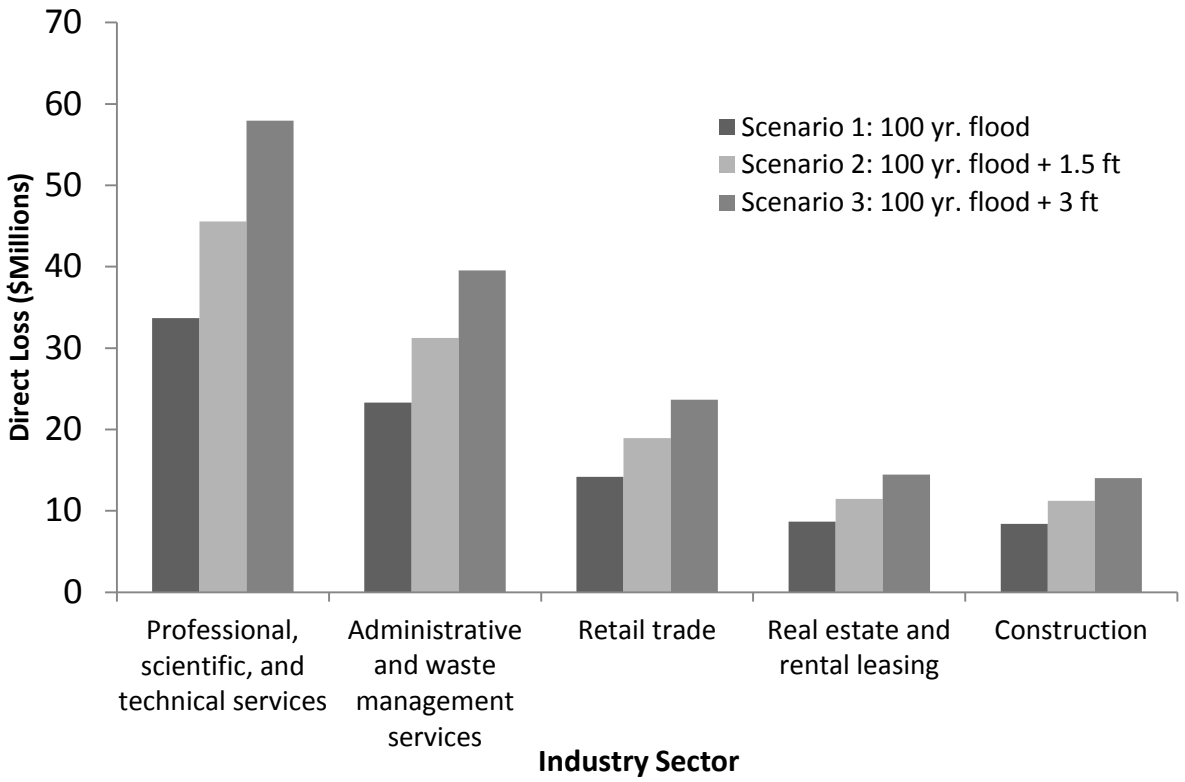

Figure 22. Top 5 Industries ranked by four day direct losses.

Certain industry sectors are disproportionately affected over others. The four-day disruption heavily impacts the *Professional, scientific, and technical services* industry for example, as well as industries related to real estate and housing. The *Professional, scientific, and technical services* industry likely ranks highly because of their relatively high wages. Real estate, housing,

and construction related industries rank highly because of the complete elimination of all real estate market activity during the flood.

Table 5. Top 5 Industries by four day direct losses.

Industry	Annual Direct Losses ($Millions)		
	Scenario 1	Scenario 2	Scenario 3
Professional, scientific, and technical services	33.68	45.56	57.96
Administrative and waste management services	23.31	31.24	39.55
Retail trade	14.19	18.94	23.65
Real estate and rental leasing	8.68	11.48	14.44
Construction	8.41	11.23	14.03

Sandia also investigated the direct economic impacts to the cities and counties in the Hampton Roads region. Virginia Beach and Norfolk are the hardest hit economically given the full range of expected flooding and infrastructure impacts addressed. Virginia Beach and Norfolk comprise over half of the total economic losses for the area in all scenarios. The top five counties by direct economic losses are illustrated in Figure 23 and Table 6.

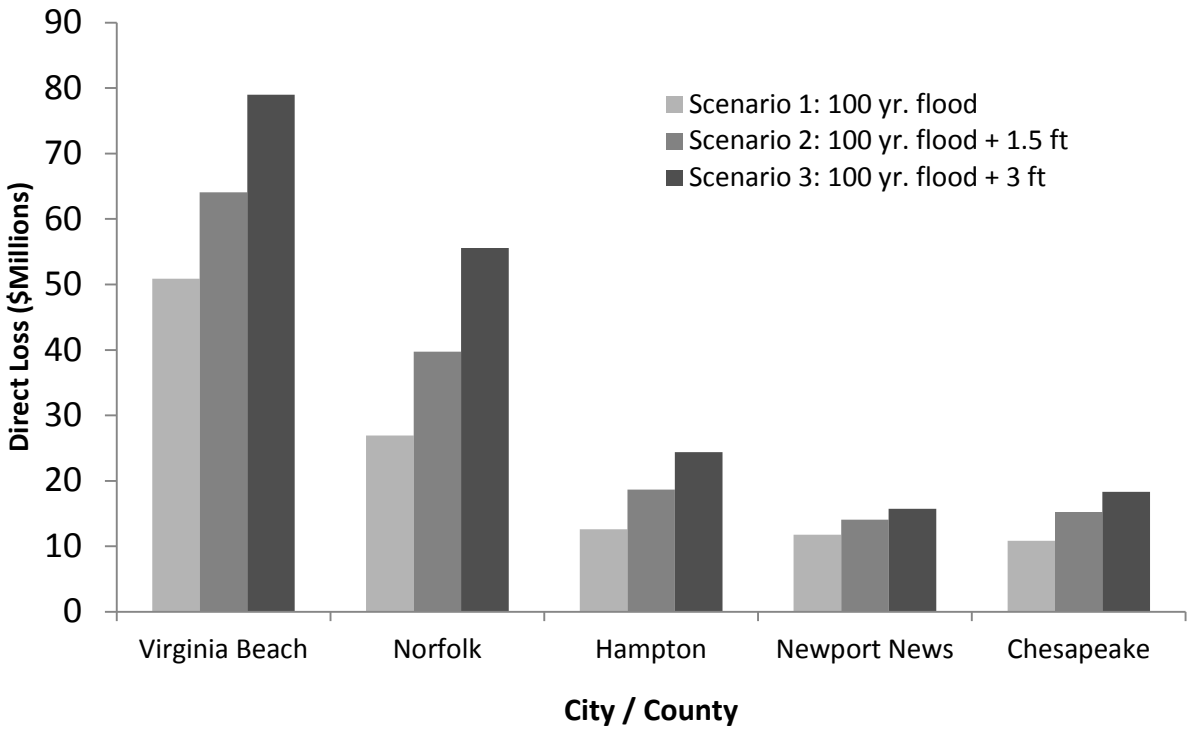

Figure 23. Top 5 cities or counties by four day direct losses.

Based on the analysis of direct losses, a four day period of the 100-year flood in Hampton Roads has $26.92 million worth of direct impacts to industries within Norfolk with no further sea level rise, and $55.6 million with 3 feet of net sea level rise – an increase of 107 percent. In contrast, Virginia Beach's economic losses increase 55 percent and Hampton's losses increase 94 percent

over the same difference in scenario. Norfolk and Hampton appear to be much more sensitive to net sea level rise than their neighbors. Contrastingly, industry sectors appear to have a sensitivity that is directly proportional to the size of their losses in the +0ft scenario.

Table 6. Top 5 cities or counties by four day direct losses.

City/County	Annual Direct Losses ($Millions)		
	Scenario 1	Scenario 2	Scenario 3
Virginia Beach	50.90	64.08	79.02
Norfolk	26.92	39.71	55.60
Hampton	12.59	18.66	24.39
Newport News	11.75	14.07	15.73
Chesapeake	10.83	15.22	18.33

2.5.2 Indirect Economic Impacts and Impacts outside the Region

While these direct impacts in terms of lost economic activity are significant, they do not give insight into how the resilience of Norfolk impacts the resilience of other regions. For this insight, indirect economic impacts were calculated. Indirect impacts are defined as economic losses that are compounded through supply chain disruptions and other production dependencies. Many of these indirect losses are experienced within the region, since it is natural that firms within Hampton Roads are dependent on each other more than on firms outside the region. However, the primary assets under consideration – Lambert's Point, NIT, and NAVSTA Norfolk – are exceptions to this rule. These entities have interdependencies that stretch nationally and globally.

Indirect impacts of a 4 day flood, calculated using the Regional Industrial Multiplier System (RIMS II) provided by the US Bureau of Economic Analysis, substantially increase the economic effects.[62] The most affected industries are shown in Figure 24. Service industries are the most impacted, both in direct and indirect calculations, however the *real estate and rental leasing* industry is not present in the top five of the indirect ranking. This is because there are fewer economic relationships between it and other industries comparatively. Total direct + indirect impacts from this flooding scenario are expected to range between $354.5-606.4 million over the four day period, as summarized in Table 7.

[62] US Department of Commerce (2015) BEA

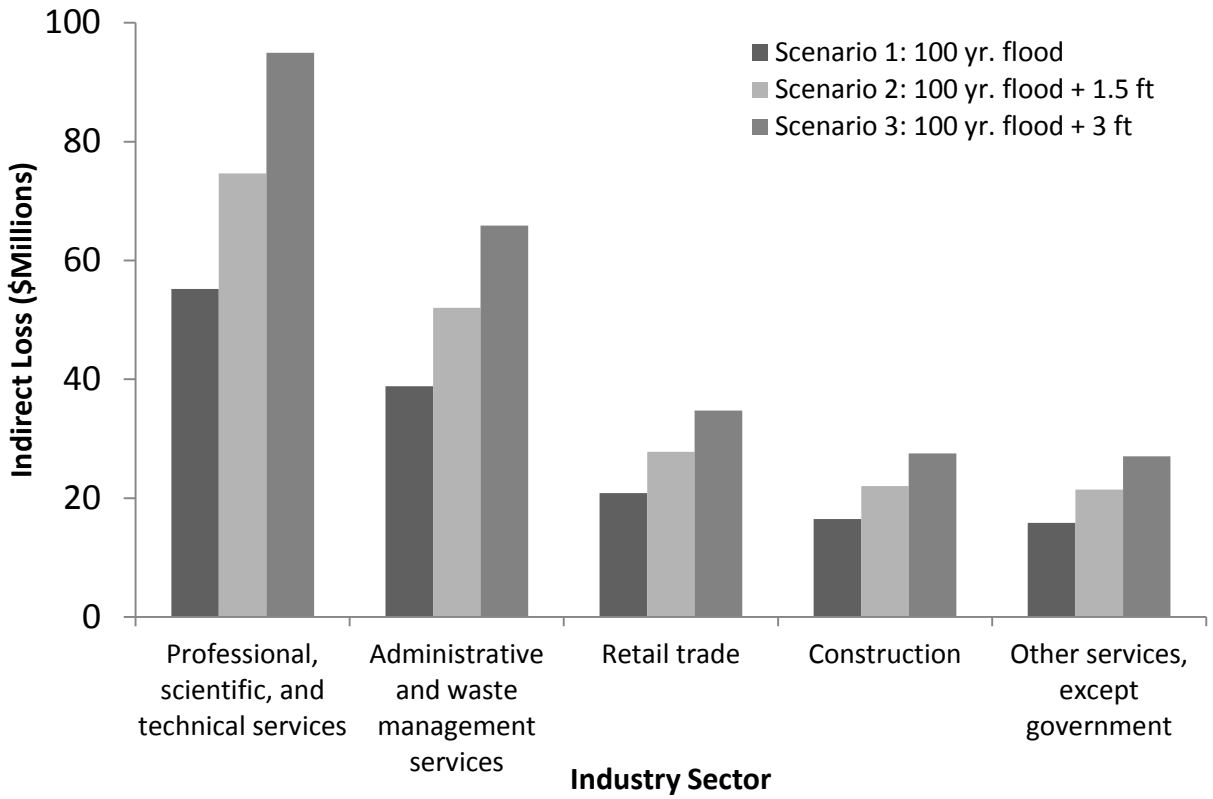

Figure 24. Top 5 industries by four day indirect losses.

Table 7. Summary of four day direct and indirect losses for three flooding scenarios.

	Scenario 1	Scenario 2	Scenario 3
Four Day Direct Losses	$135.1 M	$182.3 M	$230.9 M
Four Day Indirect Losses	$219.4 M	$296.3 M	$375.5 M
Total	$354.5 M	$478.7 M	$606.4 M

Some fraction of the indirect effects is likely to be spread out among firms in several geographic regions. An analysis of the commodities that flow through the Hampton Roads ports, as well as their origins and destinations helps to estimate the regions that depend most on Norfolk and Hampton Roads shipping availability. To lend insight into the areas that make up the indirect impacts, Sandia utilized a data integration capability that estimates the origins and destinations for imports and exports of containerized freight by different modes and commodities.[63]

Figure 25 describes the destinations of containerized import traffic that flows through Norfolk. NIT in Norfolk is the primary containerized port in Hampton Roads, with PMT and VIG also providing significant container capacity. Much of the containerized import traffic that leaves via truck from NIT heads to regions surrounding Philadelphia, New York, and Hampton Roads itself. Via rail, traffic largely progresses through the Washington, D.C. area and along an arc through

[63] Levine, B., Nozick, L., Jones, D.(2008) *Estimating an Origin-Destination Table for US Imports of Waterborne Containerized Freight*. Master's Thesis, Cornell University, Ithaca, NY.

Midwestern states toward St. Louis, MO and Tulsa, OK. As indicated in section 2.4, NIT has a relatively strong and unflooded connection to Interstate 64, with one bridge showing potential flooding along the trucking route. The rail line to NIT has three bridges that would potentially need to be inspected before traffic could resume.

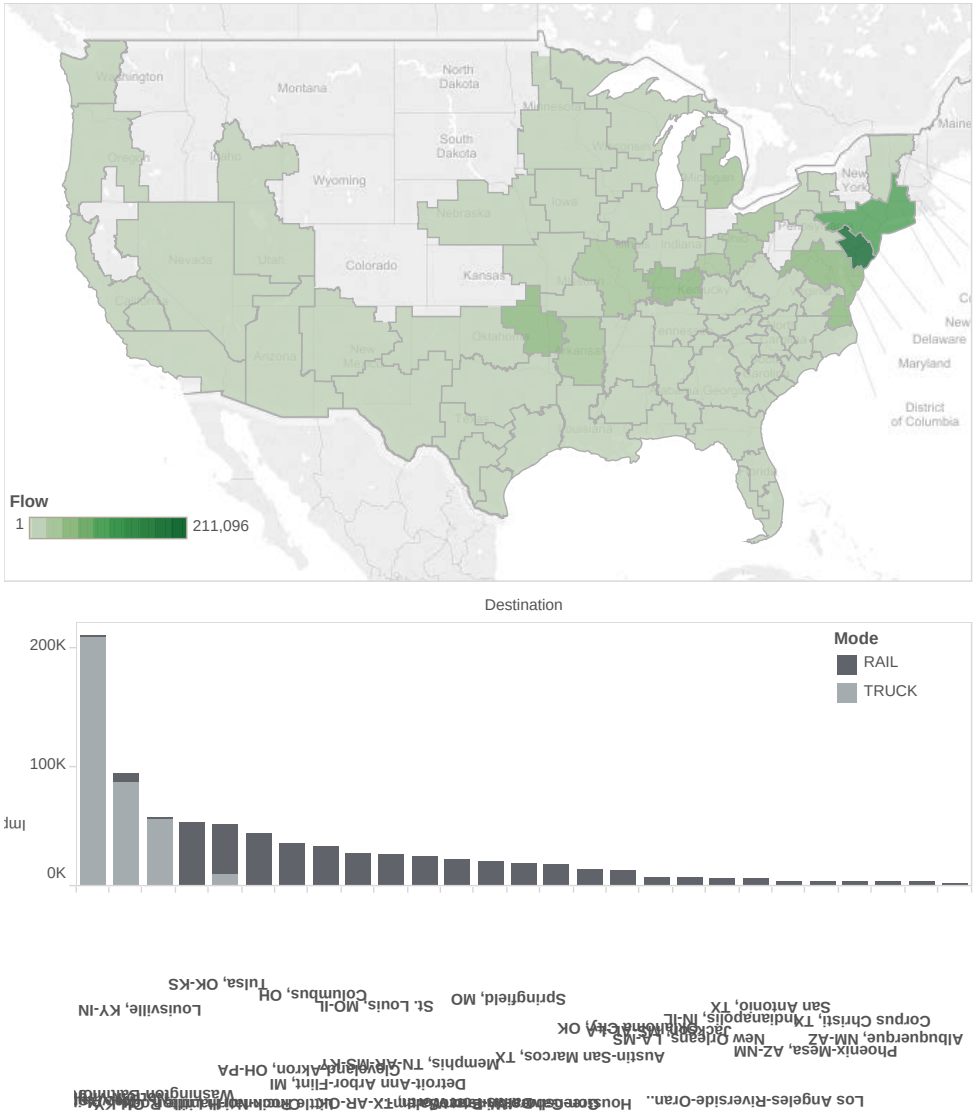

Figure 25. Map of containerized import destinations (top) and bar chart describing the mode and destination of transport (bottom) for goods passing through NIT in 2013.[64]

Sandia also utilized US Census data that describes the country of origin or destination respectively for imports and exports through Hampton Roads.[65] This gives a broad picture of the types of commodities – whether containerized, bulk, or roll-on-roll-off – that flow through the ports as well as where these commodities originate. Figure 8 through Figure 11 describe the

[64] American Association of Port Authorities (2010) *North American Port Container Traffic, 2013*. Accessed online June 10, 2015 at <www.aapa-ports.org>

[65] United States Census (2015b)

types of commodities flowing through the ports by value and weight. Figure 26 shows the countries of origin for imports through Hampton Roads, while Figure 27 shows the country of destination for exports through Hampton Roads. These results are ranked by dollar value of the commodities as opposed to weight. China and Germany are the top trading partners for both imports and exports. Imports from Italy are of significantly higher value than exports to Italy.

Sizable imports from China fall under the categories *boilers and machinery*, *furniture*, *electric machinery and electronics*, and *toys and games*. Germany also ranks highly for *boilers and machinery* as well as *electric machinery and electronics*, but much higher in terms of *pharmaceuticals* and *vehicles*. India ships largely *pharmaceuticals* and *textiles and art* by value.

Exports to China are highly diverse by value. The top five exports through this region by value are *boilers and machinery*, *oil seeds and grain*, *plastics*, *wood pulp and scrap*, and *wood and articles thereof*. For Germany, exports of *pharmaceuticals* and *boilers and machinery* dominate other categories. Brazil is also more diverse, with *boilers and machinery*, *plastics*, *vehicles*, and *electric machinery and electronics* being the predominant exports through Hampton Roads.

Figure 26. Countries of origin for imports through Hampton Roads ports.[66]

[66] United States Census (2015b)

Figure 27. Countries of destination for exports through Hampton Roads ports.[67]

This analysis highlights many of the countries and commodity types that would be impacted if the port facilities in Hampton Roads were to shut down temporarily due to flood. This effect on shipping may not manifest in a long-term economic impact because of a number of factors. First, some of these commodities do not necessitate a just-in-time supply chain, and have significant storage at the site of demand. *Oil seeds and grain* is a good example of such a commodity. Goods such as *boilers and machinery* and *vehicles* may necessitate a more just-in-time supply chain. The second factor that limits some of the indirect economic impacts is substitutability of the commodities. Food products are a classic example of a highly substitutable good at the point of end use. The third limit to economic impacts is rerouting and alternative supply. Highly valuable or supply-chain-critical goods such as *boilers and machinery* may be rerouted through a different port or purchased from an alternative supplier if consumers have forecasted knowledge of the flood.

Coal is a commodity for which the Hampton Roads ports are a unique terminal. If Lambert's Point, DTA, and the Pier IX coal terminals are inactive, it is unlikely that coal suppliers would have export capacity for their desired shipments, as indicated by Figure 3 and Sandia's judgement of rail shipping decisions. Around 75% of this coal is blended and specified for metallurgical use, with the remaining 25% being specified as thermal coal for heat generation.[68]

[67] United States Census (2015b)
[68] Old Dominion University (2013)

Metallurgical coal is used in steel production, has a higher value and is less substitutable than thermal coal. The major use of metallurgical coal in the steel industry is fuel in a blast furnace to produce coke and heat. The coke offers high carbon content and a pure fuel for smelting iron ore. Because these processes do not have simple substitutes for the coal, countries that import metallurgical coal through Hampton Roads depend heavily on operation of these terminals. They may have storage at the point of use, which will partially isolate them from the acute event.

Figure 28 shows the countries that receive coal through Norfolk and Newport News terminals. Brazil, Italy, the Netherlands, Turkey, France, and the United Kingdom all receive a substantial amount of coal through these ports. In continental Europe, notably, the point of receiving (e.g. the Netherlands) is not always coincident with the point of use.

The coal that passes through Hampton Roads is mined almost exclusively in the Appalachian region of the United States. As shown in Figure 29 most of this coal comes from a small area, largely in southern West Virginia and southwestern Virginia. If the Hampton Roads terminals were unavailable for a period of four days, it is likely that there would be no considerable impact to mining activity because of the amount of storage at the point of extraction, the shipping terminal, and the point of use. However, a more chronic unavailability from periodic nuisance flooding or an extended outage due to complications after a major flood may drive coal shipments through other ports, most likely through Baltimore and barged along the Ohio and Mississippi Rivers to New Orleans.

Figure 28. Country destinations of coal shipped through Norfolk and Newport News.[69]

[69] United States Census (2015b)

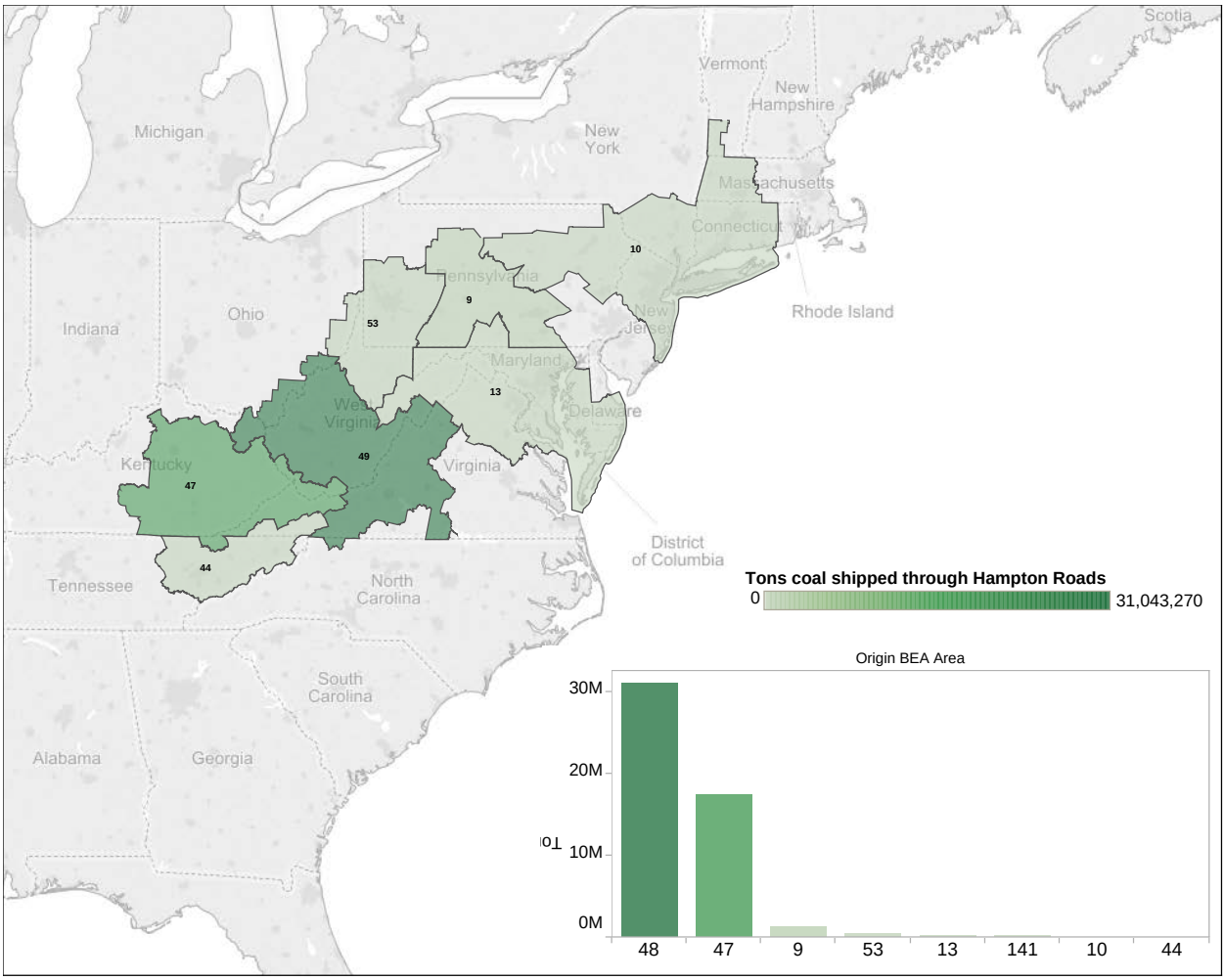

Figure 29. Sources of coal exported through Norfolk and Newport News aggregated by Bureau of Economic Analysis (BEA) economic areas.[70]

2.5.3 Impacts to the Department of Defense

The 100-year flood is felt by the Department of Defense in Hampton Roads as an impact to the primary missions, and more precisely as an impact to the near-term cost of serving these missions. The flooding does not necessarily prevent NAVSTA Norfolk and others from completing their missions, but it makes these missions more costly and more time intensive. For NAVSTA Norfolk, the primary mission is the operational readiness of the US Atlantic Naval Fleet. Partially because of NAVSTA Norfolk's importance, the Navy maintains an all-hazard Emergency Management Plan.[71] This plan has been updated with lessons learned from

[70] Data aggregated by BEA, sampled from the Carload Waybill Sample (2013). Surface Transportation Board.

[71] Naval Station Norfolk Emergency Management Plan. NAVSTANORVAINST 3440.17A. Available by phone request: (757) 322-2320.

Hurricanes Katrina, Rita, and Wilma, as well as through naval exercises. Namely, the plan now contains specific actions for evacuation planning and execution.[72]

Because of the breadth and complexity of Norfolk's operations the Navy has developed resources for Norfolk staff and their families.[73] In particular, these resources spotlight hurricane preparedness and provide background on the kinds of scenarios for which Norfolk plans. Figure 12 through Figure 15 show the expected Norfolk inundation from this analysis given the three scenarios of net sea level rise. Figure 30 is a similar view from NAVSTA Norfolk's hurricane preparedness documentation, which describes the expected inundation areas given different hurricane categories. It is apparent from this diagram that a category 4 hurricane creates high inundation risk for the entire installation, and especially for the northwestern portion of the facility.

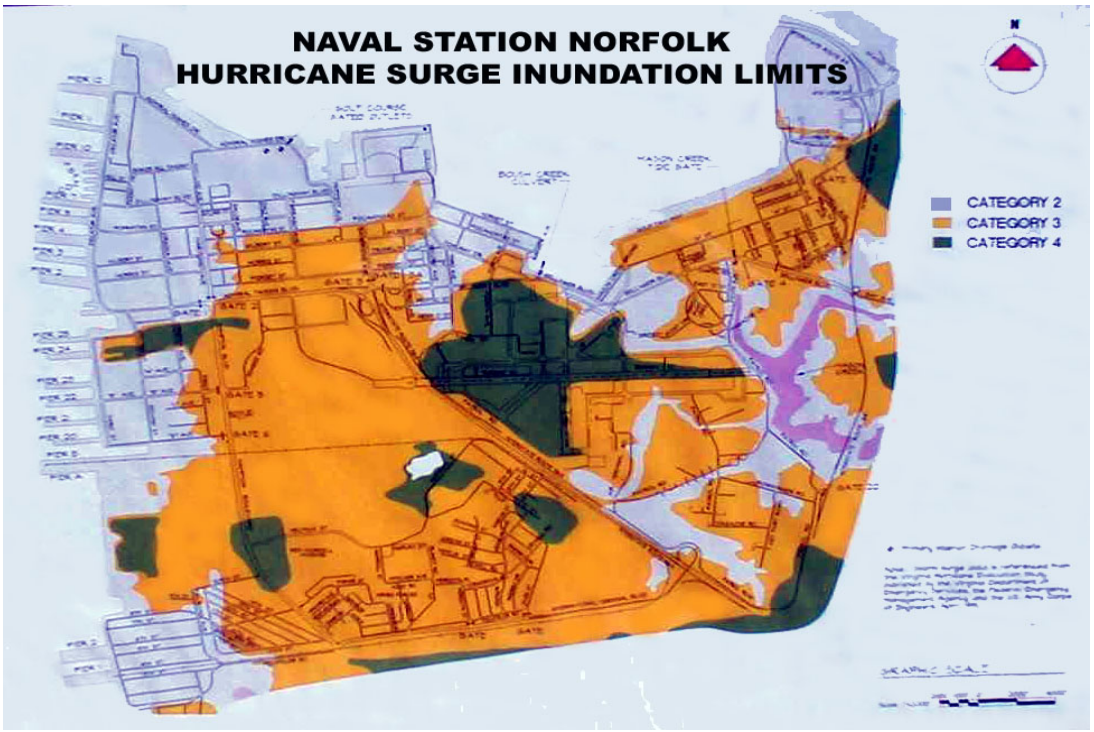

Figure 30. Naval Station Norfolk hurricane surge inundation limits as presented in preparedness documentation.[74]

During a major flood, the Navy may decide to sortie their larger ships to protect them and structures around the harbor. The decision to sortie is based on projections of wind and storm surge, but is ultimately up to the Commander of US Fleet Forces. During Hurricane Irene in

[72] Commander, Navy Installations Command (2006). *Addition of Evacuation Planning Procedures to the CNIC Emergency Management Program Manual*. CNIC Instruction 3440.17 Change Transmittal 1.

[73] US Fleet Forces Command (2015) *Family Hurricane/Destructive Weather Planning*. Accessed online, October 01, 2015. <http://www.public.navy.mil/usff/Pages/disaster_preparedness.aspx>

[74] Naval Support Activity, Norfolk (no date) *Preparations for an Ordered Evacuation*. Available at: <http://www.public.navy.mil/usff/Documents/nsa_preps_for_ordered_evac.ppt>

2011, twenty-seven ships were ordered to depart the harbor and to rendezvous at sea. Others were taken to various safe havens such as dock facilities that are more secure than the piers in Norfolk Harbor.[75] During Hurricane Sandy in 2012, ships were initially ordered to depart, but that decision was reversed after monitoring the storm.[76]

Also during an event as extreme as the 100-year flood, an evacuation may be ordered by the Regional Commander in consultation with the Installation Commanding Officer, and would likely be in coordination with local and state authorities. Evacuations could be ordered either as mandatory or voluntary. Evacuations greatly impact NAVSTA Norfolk's personnel, and by association the mission readiness of the installation. They are viewed as a relatively extreme measure to ensure human safety and long-term continuation of mission. This evacuation decision is dependent on multiple factors, including the nature of the extreme event, the availability or viability of transportation, and any prior planning operations in place.[77]

NAVSTA Norfolk may assemble a Continuity of Operations (COOP) Site in Raleigh North Carolina to coordinate recovery operations. The COOP center in Raleigh will be responsible for coordinating evacuated personnel in the 500-mile Raleigh centered evacuation radius that constitutes NAVSTA Norfolk's Safe Haven Area for evacuation.[78] There are other preparedness efforts that NAVSTA Norfolk will take, including stockpiling of resources and informing other agencies.[79]

Much of the cost of ensuring mission readiness will be related to ensuring missions are served from these remote locations. For instance, the NAVSTA Norfolk population includes over 80,000 active duty personnel, 112,000 family members and 30,000 civilians.[80] It is difficult to predict the issuance and the scale of an evacuation due to the 100-year flood, but assuming 80 percent of this population were to evacuate, the cost of reimbursing travel expenses, per diem, and lodging to these families would be on the order of $13-37 million per day.[81] The remaining 20 percent of this population might be housed on the sortied carrier groups themselves or retained on base as essential personnel, which will not incur a significantly higher operational

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[75] Commander, US 2nd Fleet Public Affairs (2011) *All Sortie Ships Underway in Preparation for Hurricane Irene*. US Department of the Navy. Accessed online October 09, 2015. <http://www.navy.mil/submit/display.asp?story_id=62403>

[76] Cahn, D., Hutchins, S. (2012) *Navy: Ships to remain in port during Hurricane Sandy*. PilotOnline.com. Accessed online, October 09, 2015. <http://hamptonroads.com/2012/10/navy-orders-most-local-ships-sea-avoid-storm>

[77] Commander, Navy Installations Command (2006)

[78] Naval Support Activity, Norfolk (no date)

[79] U.S. Coast Guard (no date) *USCG CAMSLANT INSTRUCTION 3141.1R*. Available online at: <http://www.uscg.mil/lantarea/camslant/hurricane/CAMSLANT%20INST%203141.1R-DESTRUCTIVE%20WEATHER%20PLAN.pdf>

[80] Naval-Technology.com (2015) *Naval Station Norfolk, Virginia, United States of America: Key Data*. Accessed online October 09, 2015. <http://www.naval-technology.com/projects/navalstationnorfolkv/>

[81] Based on an assumption of the range of lodging allowances, meals and incidental expenses for average military family size of 2.4 persons from <http://www.gsa.gov/portal> and <http://www.prb.org/pdf11/segal-military-families-presentation.pdf> and <www.defensetravel.dod.mil/Docs/perdiem/JTR.pdf>

cost than normal. There are times when an impact to NAVSTA Norfolk may be more costly, such as immediately before a major deployment or during an exercise.

Post-disaster, the station prescribes a phased recovery plan. Depending on the circumstance, the most critical individuals to recovery and operations will return to base and begin recovery and restoration procedures. Primary personnel that will be recalled to the base first include Damage Assessment Team member, pilots, Air Traffic Control personnel, Security personnel, Public Works Personnel, etc.[82] Resources from FEMA and other Federal organizations can assist NAVSTA Norfolk in recovery following a major disaster when directed.

Sandia addressed the likelihood of impact to the base given the infrastructure impacts addressed in Section 2.4. Based on these impacts, NAVSTA Norfolk is expected to maintain utility service from the Navy South substation, but potentially lose service from the Navy North substation in all scenarios. Depending on the configuration of the distribution grid on NAVSTA Norfolk, this may or may not cause loss of utility service at the northern section of the base. Much of this distribution infrastructure is also likely to be damaged unless it is hardened to flooding. The distribution grid is expected to fail in areas that are heavily inundated because of ground-located components such as switchgear and pad-mounted transformers. For buildings served by this infrastructure, the cost of maintaining and operating backup generation is a major component of the cost of serving the mission during such an event. This cost could be partially mitigated by ensuring the protection of Navy North and the NAVSTA Norfolk distribution system to flood depths shown in Figure 15. Potential actions the City of Norfolk could consider include hardening the area around the Tanner's Point substation to the projected flooding of up to 2.78 feet, which would improve reliability and resilience of service to the NAVSTA Norfolk substations.

Telecommunication systems are less impacted than the electric power system on this side of Norfolk. Neither of the two landline wire centers that likely serve NAVSTA Norfolk is inundated in any scenario considered here. Either may experience temporary outage due to loss of electric power. It is expected that NAVSTA Norfolk maintains backup communication options for critical missions, and that these communications options do not constitute a major portion of the cost of operation during the 100-year flood event.

The impact of damage to the Craney Island Fuel Terminal may result in a major recovery cost to the Navy after the 100-year flood. This terminal undergoes significant flooding in all scenarios. Short-term operational costs are not expected to be highly dependent on a temporary loss of fuel storage at Craney Island, however.

[82] Commanding Officer Norfolk Naval Station (2010). SOPAADMINNORFOLKSUBAREA / NAVSTANORVANOTE 3141. Available at: <http://www.public.navy.mil/airfor/hm15/Documents/HURRICANE%20EVACUATION%20INFORMATION%20PACKAGE.pdf>

The loss of transportation from NAVSTA Norfolk to the Virginia Peninsula across the harbor is also not likely to add significant cost. Unscientific surveys suggest that the majority of NAVSTA Norfolk servicemen and staff do not reside on the Virginia Peninsula.[83] During the event, NAVSTA Norfolk may be largely disconnected by road from supporting/coordinating facilities such as Newport News Shipbuilding, and the Naval Weapons Station Yorktown. However, it is unlikely that all of the bridges and bridge-tunnels across the harbor suffer long-term damage that lead to significant coordination problems with these facilities.

Although the Navy does incur significant cost to ensure their mission readiness during a major flooding event, they are also integral to the recovery effort of the region. For instance, following hurricanes Katrina and Rita in the Gulf of Mexico, the Navy along with the Coast Guard and the Army Corps of Engineers played a supportive role in the cleanup, salvage, and restoration effort.[84]

[83] Hampton Roads Transportation Planning Organization (2012).

[84] Commander, Naval Sea Systems Command (2007) *U.S. Navy Salvage Report, Hurricanes Katrina and Rita.* Accessed online at: <https://www.uscg.mil/history/katrina/docs/USNKatrinaSalvageRpt.pdf>

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3. LESSONS LEARNED

For several reasons, flooding and sea level rise in Norfolk presents both a challenge and an opportunity to the urban resilience community. Norfolk and the greater Hampton Roads region are heavily dependent on access to water for business and national security purposes, so the simple option of retreating to higher ground may not be the most effective in all cases. Moreover, as net sea levels rise, Norfolk will experience greater frequency and magnitude of nuisance flooding. As indicated in section 2.5, the economic impact of a major flooding event increases at a faster rate for Norfolk than the surrounding Hampton Roads cities and counties as net sea levels rise. For these reasons, flooding is an evolving consideration for urban planners and policy makers in Hampton Roads. The decision to harden, retreat, or simply live with the water will need to take into account how the flooding threat is changing. More optimistically, Norfolk's participation in the 100RC community creates an opportunity to develop best practices for all cities facing increasing flood risk. As an early mover toward integrated resilience planning, Norfolk is helping to lead the charge for the global community to find ways of retrofitting an existing city to be more resilient to flooding and sea level rise.

This report presents a framework for analyzing urban resilience, and applies this framework to Norfolk, VA and the surrounding Hampton Roads region. The urban resilience analysis projects impacts of a major flooding event in Hampton Roads, and uses an integrated approach to estimate performance of key infrastructures during this event. Existing flooding analyses are improved by creating 100-year flood layers that give insight into flooding extent and depth for all land ownership types over three separate net sea level rise scenarios for the entire Hampton Roads region. This flooding information, including the assumption of a four-day flooding window, is overlain with open source infrastructure information, which allowed subject matter experts to provide relevant information about infrastructure assets that would be most at risk and would lead to the greatest consequence during such an event. To estimate consequence in terms that city governments and infrastructure owners can use directly, the collection of flooding information and infrastructure behavior feeds an economic impact assessment that provides loss-of-production dollar estimates in terms of direct and indirect impact over the four-day event window. The impact estimates, ranging in sum from $355 to $606 million for the region, represent approximately 0.4 to 0.6% of the region's annual GDP. The analysis furthermore gives context to these numbers by shedding light on the industries and regions outside of Hampton Roads that could be impacted indirectly by a major flooding event. Finally, insight is provided into the connection between Norfolk's resilience and operational cost at NAVSTA Norfolk.

A primary lesson learned from performing the analysis is that the acute 100-year flood represents a single data point among the many potential events that are likely to impact the region. From the economic perspective, while many industries will have contingencies and buffers to the single event, the increasing pace of chronic flooding within Hampton Roads will create a greater and greater drain on economic and defense activity that will be difficult to account for directly. The good news is that protecting from the 100-year flood event also protects from the more common smaller flooding events. Therefore, insights from this analysis

can be used to plan infrastructure improvements that protect against both acute and chronic flooding.

This report represents only the beginning for an integrated urban resilience analysis that provides actionable benefit to Norfolk and other cities. Step five in Sandia's urban resilience analysis framework – a reevaluation of performance given the city's potential resilience-enhancing investments – is left as future work to be accomplished. To provide the most benefit to cities, future work should also develop generalizations and lessons learned that will aid other cities in becoming more resilient to the shocks and stresses faced by Norfolk. This report will be successful if it enhances the resilience planning conversation between the city, asset owners, resilience experts, and potential federal representatives.

APPENDIX – ADDITIONAL FIGURES

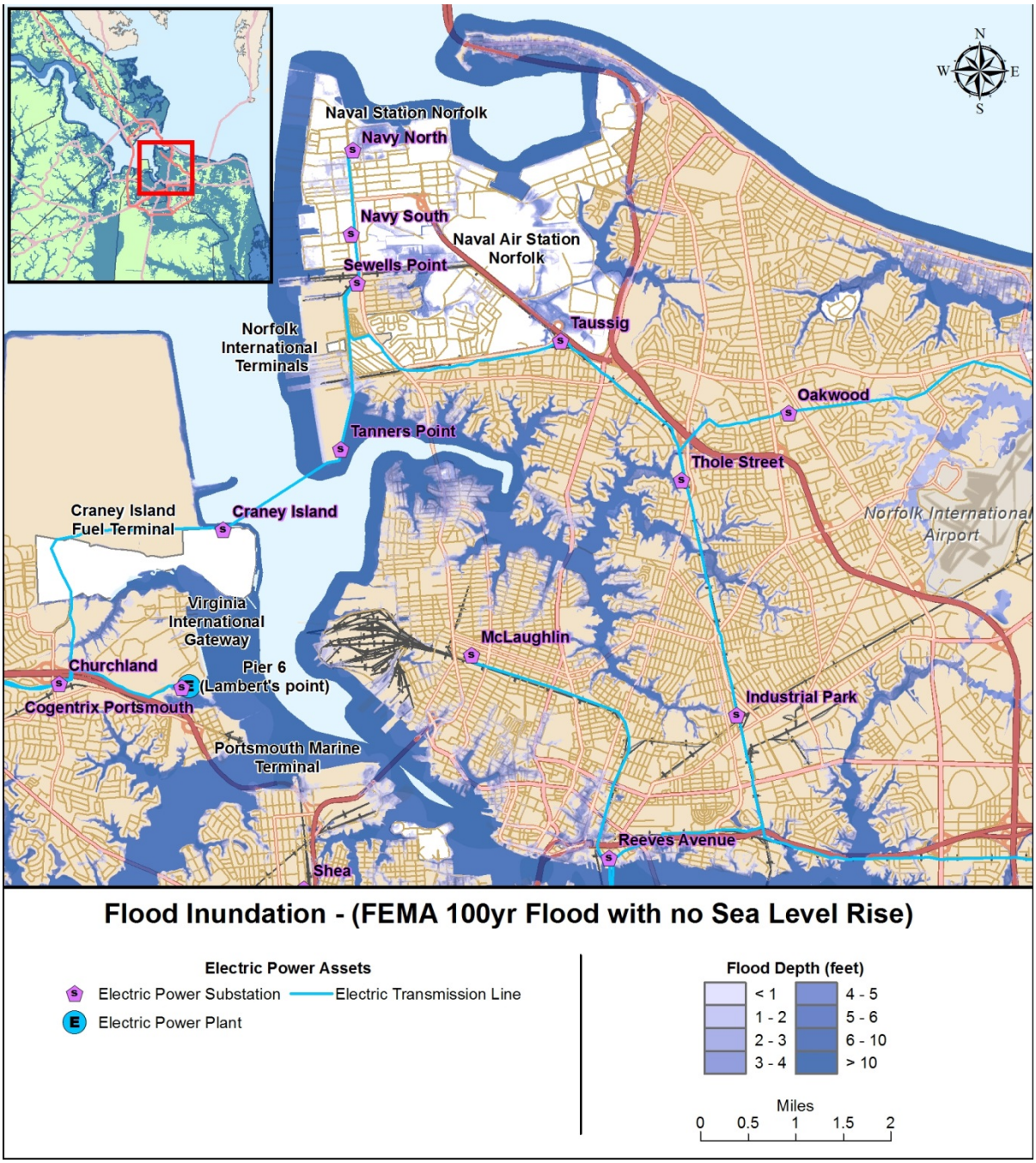

Figure A 1. Transmission level electric power assets in the Norfolk Region with flood depths under the +0ft scenario.

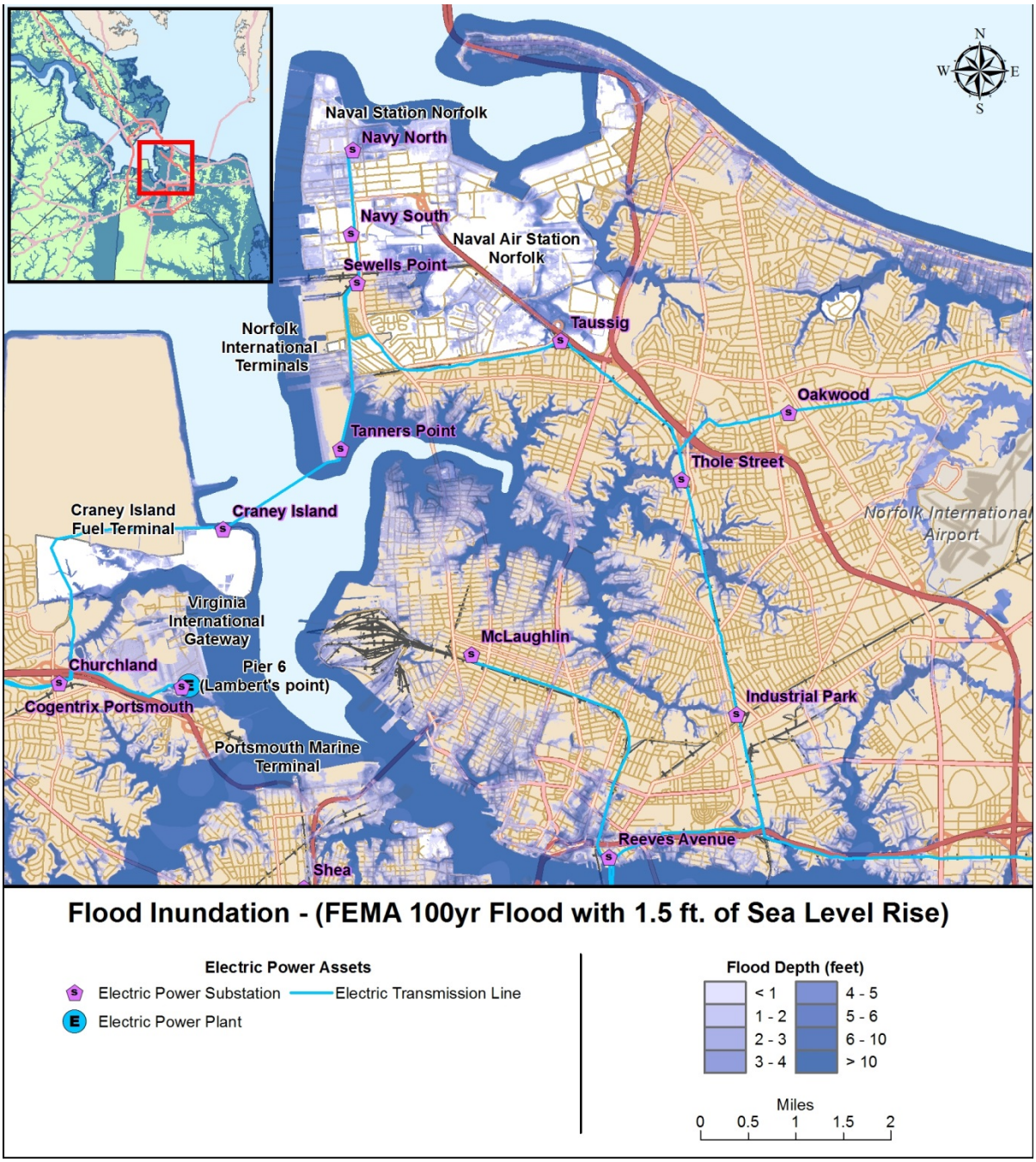

Figure A 2. Transmission level electric power assets in the Norfolk Region with flood depths under the +1.5ft scenario.

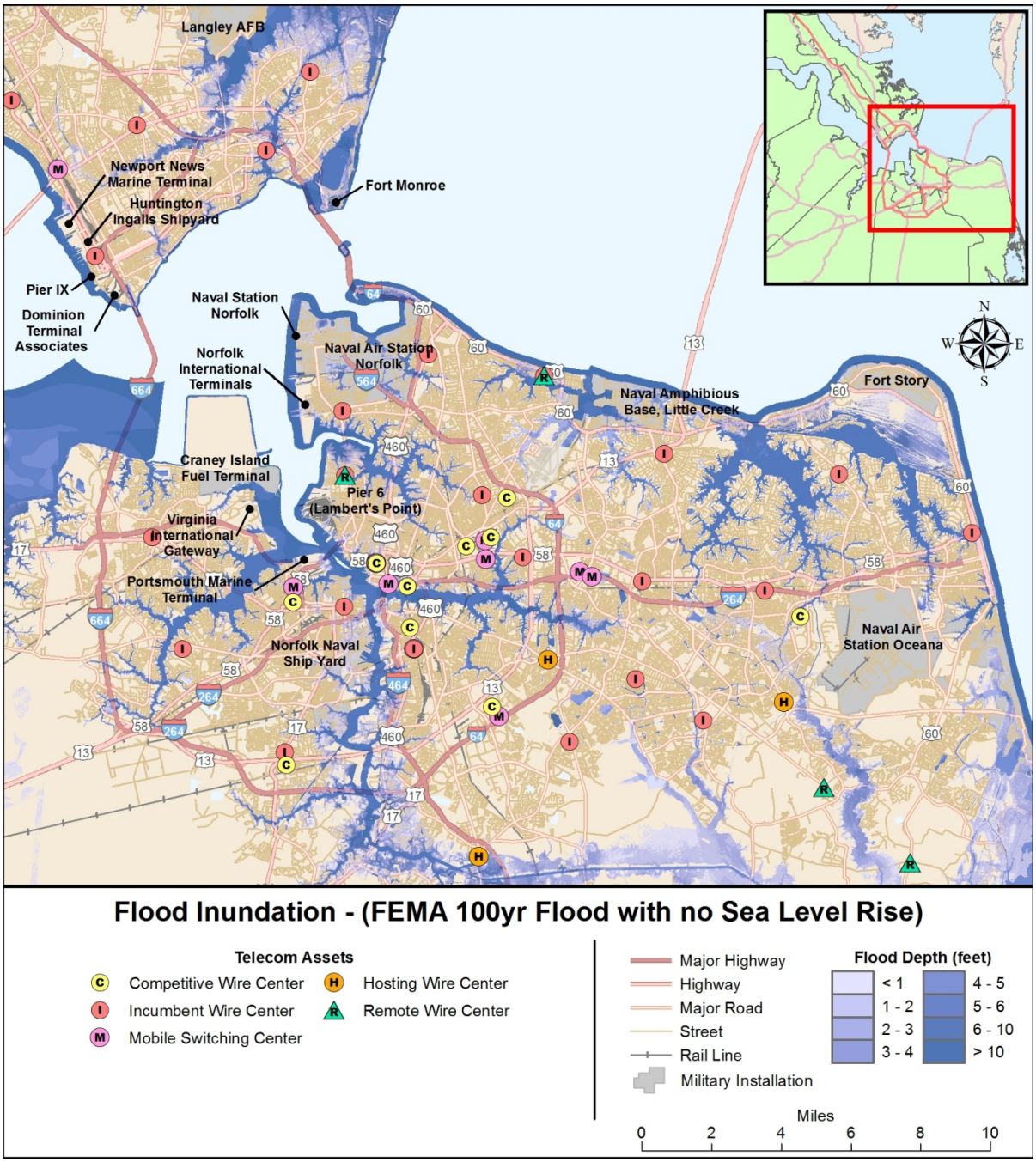

Figure A 3. Regional telecommunications assets with flood depths under the +0ft scenario.

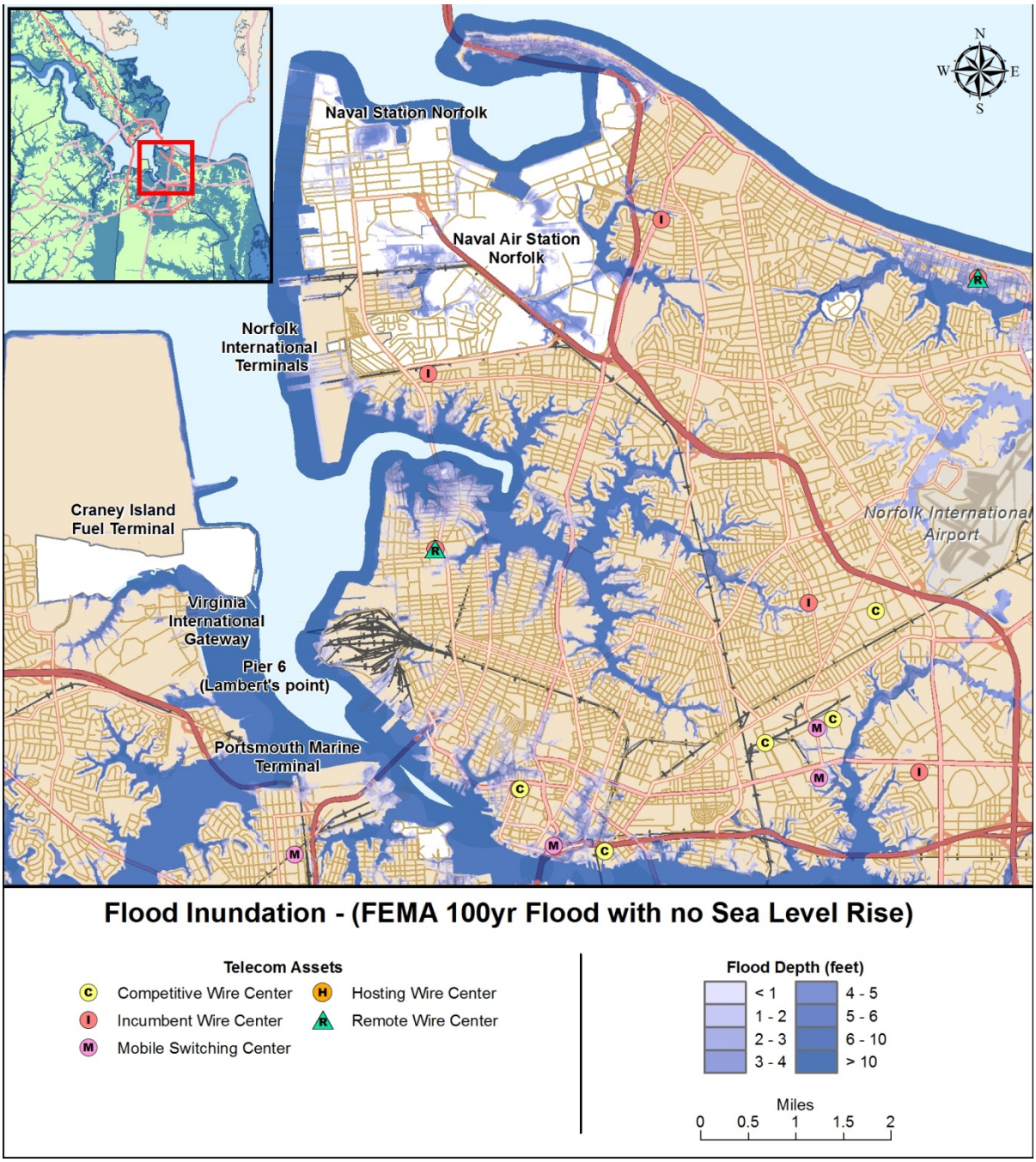

Figure A 4. Norfolk telecommunication assets with flood depths under the +0ft scenario.

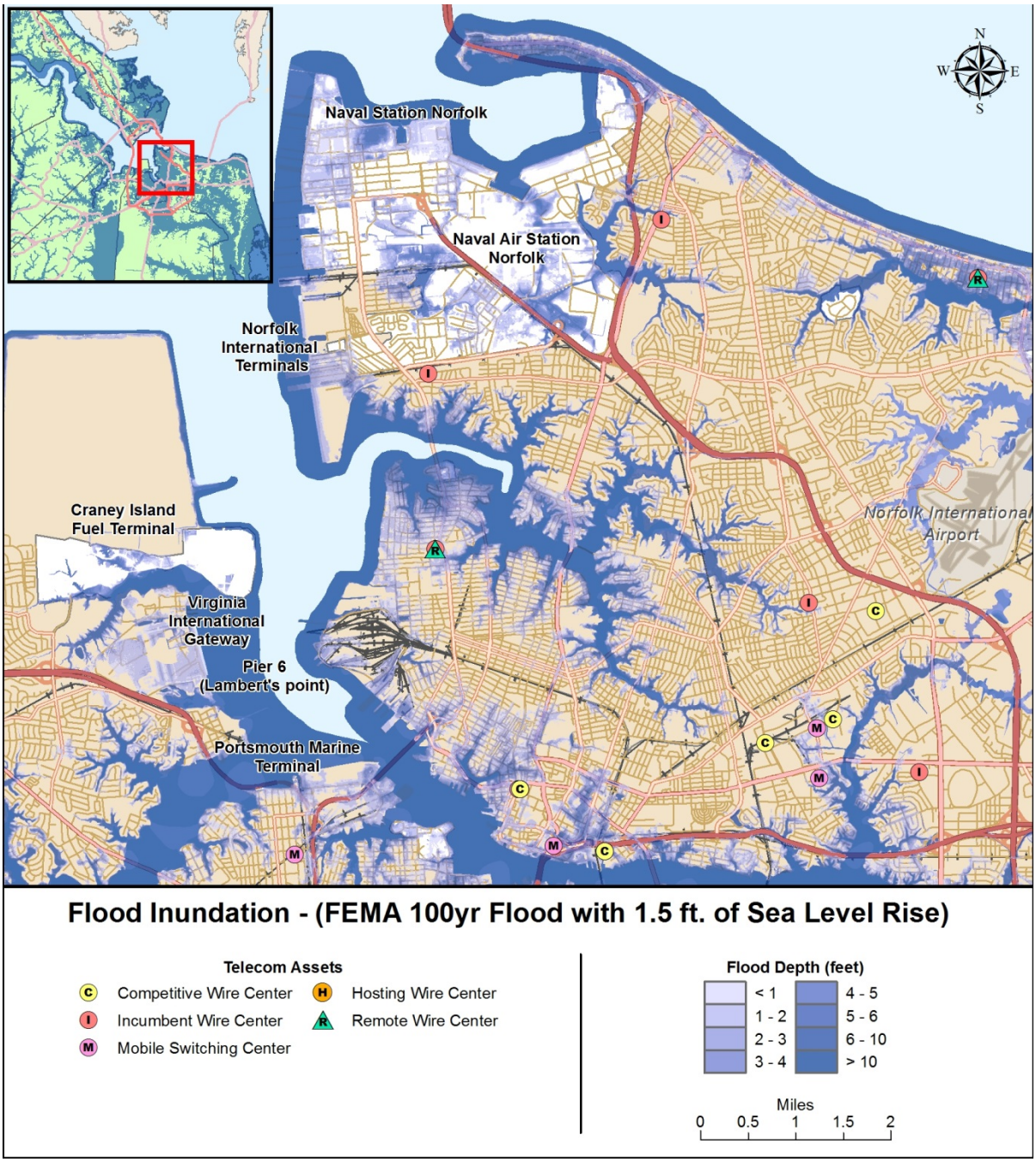

Figure A 5. Norfolk telecommunication assets with flood depths under the +1.5ft scenario.

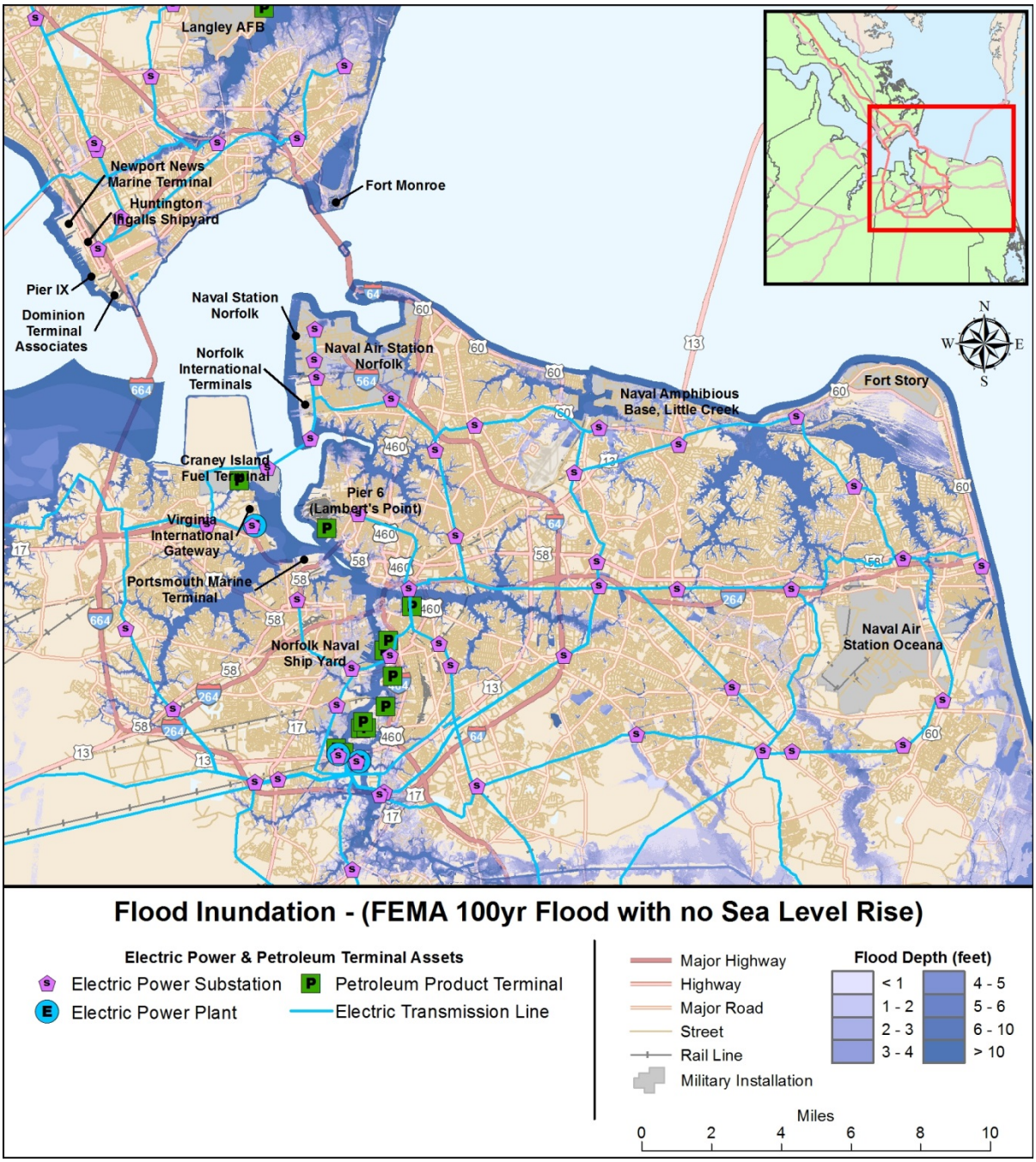

Figure A 6. Regional transportation fuels and electric power assets with flood depths under the +0ft scenario.

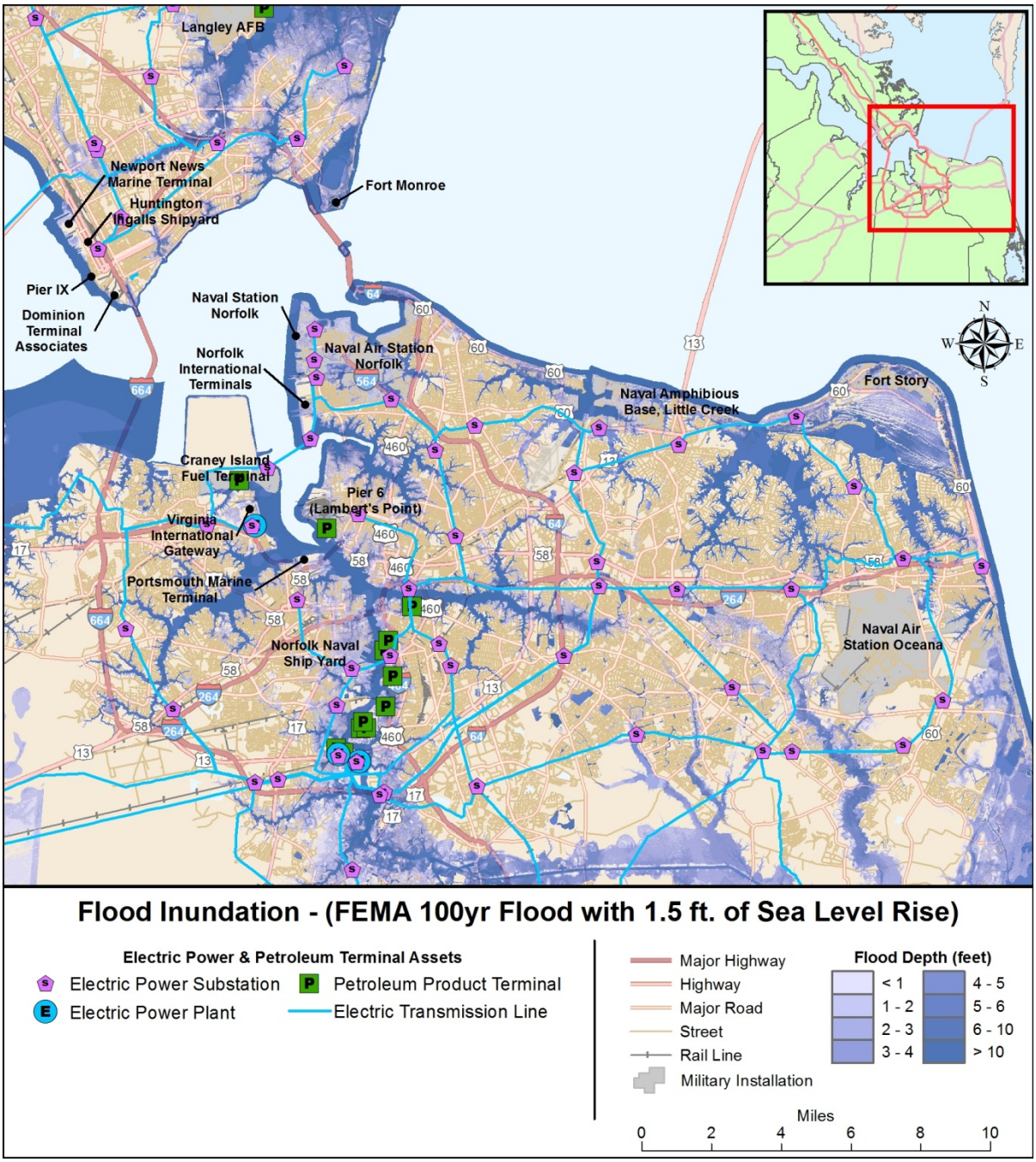

Figure A 7. Regional transportation fuels and electric power assets with flood depths under the +1.5ft scenario.

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