Effect of Sea Level Rise on Energy Infrastructure in the Norfolk Metropolitan Statistical Area

Office of Electricity Delivery and Energy Reliability
U.S. Department of Energy

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Introduction and Key Findings

This report summarizes recent work undertaken by the Energy Infrastructure and Modeling and Analysis Division (EIMA) of the U.S. Department of Energy Office of Electricity Delivery and Energy Reliability (OE) to assess the potential exposure of energy facilities in the Norfolk Metropolitan Statistical Area (MSA)[1] to a general rise in sea level and from storm surge at these higher sea levels. The analysis focuses on the risk in 2050 and 2100, and includes more than 180 energy assets in the Norfolk MSA including electricity assets (including power plants and substations), natural gas assets (including a liquefied natural gas (LNG) storage facility and pipelines), and petroleum assets (including terminals, a refinery, and a pipeline).

The analysis indicates that under the U.S. National Climate Assessment (NCA) Low Sea Level Rise (SLR) Scenario, 1 foot of inundation will occur between 2080 and 2090 in the Norfolk MSA. Under the NCA Intermediate-High Scenario, 1 foot of inundation will occur prior to 2050, 4 feet of inundation just prior to 2100, and 5 feet of inundation in 2100 or soon after, depending on location within the MSA.[2]

The analysis results show that under the NCA Intermediate-High SLR Scenario no electricity asset or power facilities would be inundated by 2050. However, the Norfolk MSA has many large assets clustered near the coast and a 1 foot SLR in conjunction with a storm surge associated with a Category 4 storm would inundate large and critical electricity, petroleum, and natural gas assets including:

- 39 substations (>230 kV)
- 2 power plants (>100 MW)
- 11 petroleum terminals (>100,000 bbl)
- 1 LNG storage facility (the sole LNG storage facility in the MSA)
- 1 petroleum pipeline
- 2 natural gas pipelines

In 2100, with 5 feet of SLR under the NCA Intermediate-High Scenario, the SLR alone would inundate three large substations, three large petroleum terminals, one petroleum pipeline, and two natural gas pipelines. A storm surge associated with a Category 1 storm in addition to 5 feet of SLR would cause extensive inundation, including the following large assets:

- 11 substations
- 1 power plant
- 10 petroleum terminals
- 1 LNG storage facility
- 1 petroleum pipeline
- 2 natural gas pipelines

A storm surge associated with a Category 4 storm in conjunction with 5 feet of SLR would inundate most of the coastal energy infrastructure in the MSA.

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1 The U.S. Census Bureau defines the Virginia Beach-Norfolk-Newport News, VA-NC MSA as 16 county-level jurisdictions—five counties and nine independent cities in Virginia, and two counties in North Carolina. For purposes of this report, we refer to this area as the Norfolk MSA.

2 Five feet is used in the figures presented in this report, representing the approximate level of inundation in the Norfolk MSA at the end of the century (i.e., 2100) under the NCA Intermediate-High SLR Scenario.

The remainder of this report provides background on the analysis and describes important caveats. An Appendix presents the detailed information in a table and set of maps. A second Appendix provides additional detail on the approach to estimating SLR and storm surge.

Background and Approach

The EIMA Division within OE conducts studies of potential risks to the nation's energy infrastructure. EIMA's mission is to ensure the reliability and resiliency of U.S. energy infrastructure and systems through robust analytical, modeling, and assessment capabilities. The Division is focused on conducting risk analyses and predictive modeling, and providing analytical products intended to inform decision makers at the public and private levels.

In 2014, EIMA launched an effort to evaluate the effects of SLR on energy assets. A pilot study was conducted that examined the implications of SLR for energy assets in four MSAs—New York, Miami, Houston, and Los Angeles. The goal of the study was to demonstrate an effective approach to examining SLR that could be generalized and extended to other regions of the country. The final report, published in September 2014, describes the analytical approach and the results of the study. The study relied on scenarios of sea level rise developed by the NCA. These include a range of plausible trajectories of global mean SLR, ranging from 8 inches to 6.6 feet by 2100.[3] For the purpose of assessing the exposure of energy assets to SLR, the study used the NCA's SLR scenarios, adjusted for local factors, such as subsidence. For a detailed explanation of how the SLR analysis was conducted please see Chapter 3 of the report.[4]

The pilot study examined energy facilities at risk from SLR but did not take into account impacts from storm surge. In late 2014, the Oak Ridge National Laboratory (ORNL) published a report demonstrating a method for incorporating storm surge with SLR.[5] EIMA has adapted that approach and has begun to evaluate the combined effects of SLR and storm surge on energy assets. Norfolk is one of the first areas to which this method has been applied.

Norfolk is an area of active study with regard to SLR and storm surge. For example, the Hampton Roads Planning District Commission (HRPDC) three-part study, "Climate Change in Hampton Roads," includes analyses of storm surge and local sea level rise. The 2013 report "Coastal Resiliency: Adapting to Climate Change in Hampton Roads" by NOAA, the HRPDC, and the Virginia Coastal Zone Management Program, provides an excellent overview of local SLR exposure. In addition, the United States Department of Homeland Security has analyzed resilience to storm surge in Norfolk.[6]

The method employed for this analysis uses the approach from the pilot study for estimating sea level rise impacts and adapts the approach developed by ORNL that adds storm surge modeled inundations as

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[3] Parris, A., et al. 2012. Global Sea Level Rise Scenarios for the US National Climate Assessment. NOAA Tech Memo OAR CPO-1.

[4] A copy of the report, *Effects of Sea Level Rise on Energy Infrastructure in Four Major Metropolitan Areas* (2014), can be downloaded at http://energy.gov/oe/downloads/effect-sea-level-rise-energy-infrastructure-four-major-metropolitan-areas-september.

[5] Maloney, M.C. and B.L. Preston, 2014. A geospatial dataset for U.S. hurricane storm surge and sea-level rise vulnerability: Development and case study applications. *Climate Risk Management*, 2, 26-41.

[6] A compilation of reports and additional resources are available through the Center for Sea Level Rise (http://www.centerforsealevelrise.org/).

developed by NOAA's National Weather Service using the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model. [7] Surge is estimated based on a composite of model runs assuming hypothetical hurricanes of varying characteristics. The result is a Maximum Envelope of Water (MEOW) which shows the highest surge values at each grid location for a given storm characteristic. This study uses the Maximum of MEOWs, or MOM, for estimates of storm surge heights. Storm surge associated with intense storms is mapped on top of the SLR. This calculated elevation was then extended toward the coast to find the extent of the possible inundation. These inundation layers were then intersected with the infrastructure locations to determine facilities that may be affected by such a combined impact (for example, what power plants might be inundated by a Category 4 storm occurring after 5 feet of sea level rise). No new numerical modeling was conducted for this study. (See Appendix B for additional details on the methodology.)[8]

During the course of this analysis, it became apparent that several assets, while not completely inundated, were obviously projected to be affected by SLR and storm surge. Assets were deemed to be *affected* if they are projected to be completely surrounded by water or if water encroaches the sites but does not completely envelop the facilities. A visual assessment was made to determine whether non-inundated large assets might be affected. Both types of impacts were identified in the analysis.

For the purpose of this analysis, two storm categories were examined. Category 1 storms were analyzed to illustrate the effects of exacerbation from SLR on smaller storms. To account for potentially stronger storms in the future, the study analyzed Category 4 storms. Since storms have been assigned categories by the Saffir-Simpson Wind Scale, the strongest hurricane to reach landfall in Virginia was a Category 2, but the strongest hurricane to reach landfall in North Carolina was a Category 4. Given that the Norfolk MSA includes two counties in North Carolina, a Category 4 hurricane hitting the Norfolk MSA is plausible in the future.

The objective of this and the other studies has been to develop a first order estimate of the exposure of energy assets to SLR by itself and future storm surge at the higher sea levels forecast by the NCA. It is expected that where these studies identify potential exposure, more detailed studies could be undertaken to refine and better understand the risks. These studies aim to align the analysis and results with the level of detail and certainty needed to inform decisions regarding which energy assets may be vulnerable to SLR and storm surge.

Caveats and Limitations

Because of the relatively high-level nature of the SLR and storm surge analysis, there are limitations that should be acknowledged. The study employs a method of moderate complexity that takes advantage of publicly available data and can be run with standard desktop processing power, while providing results at a level of certainty sufficient to identify the potential effects of combined SLR and storm surge. These features make the method useful for comparing results across multiple areas. The method also localized

[7] Available at: http://www.nhc.noaa.gov/surge/slosh.php.

[8] The SLOSH model estimates storm surge heights associated with hurricanes by simulating the effects of storm size, forward speed, track, wind speed, and atmospheric pressure on water heights in the coastal zone. Model output data are available for 39 basins along the Atlantic and Gulf coasts. The SLR data are from the NOAA Coastal Services Center (NOAA CSC) inundation maps showing shoreline effects of SLR between 1 and 6 feet in 1-foot increments. The land surface data are from USGS National Elevation Data output.

estimates of SLR from global projections using information about local SLR trends, improving the accuracy of results.

Useful Life of Energy Assets – The SLR study extends beyond the economic life of most of the energy assets shown to be affected. Many of these assets could be retired within the next 25 to 30 years. The analysis does identify, however, the potential risk areas for the location of new assets.

Asset Hardening and Protection – The data do not indicate whether utility or facility operators have undertaken projects to reduce exposure to higher sea levels. In some areas, asset owners have been making efforts to minimize exposure to high water—by the construction of berms, for example. However, information on the types of hardening or resilience measures taken by asset owners and operators is not accounted for in the study. Also not accounted for are sea walls, dunes, or other factors that would impede permanent inundation or temporary flooding.

Asset Interdependencies – The study does not identify interdependencies among energy assets, such as for example, the effect of a substation outage on another energy asset.

Data Limitations – The study relies on data regarding energy assets drawn from numerous sources. The scope of this study included hundreds of assets, including many small assets. (The accompanying maps show only the large energy assets.) Sometimes these data are incomplete or assets are not accurately located.

Modeling Limitations – There are trade-offs regarding resolution and certainty of modeling results. The underlying models of future changes to global sea levels have various sources of uncertainty that also contribute to uncertainty of models of relative sea levels and the interactive effects of sea level rise and storm surge. The SLR analysis does not take into account erosion. The method used in this study takes an additive approach to SLR and storm surge, which does not fully capture the nonlinear interaction of SLR and storm surge[9]; therefore, in instances where there is less tolerance for uncertainty, surge modeling may need to be performed on the projected future local sea level.

The SLOSH model does not include wind-driven waves or waves on top of surge, rainfall amounts, or river flows when determining surge height.[10] The model also lacks processes such as coastal accretion and recession, changes in near-shore bathymetry, and coastal barrier features[11], which can affect local estimates of total water height during a storm. The SLOSH model resolution is also coarse compared to state-of-the-art surge models, such as the ADCIRC model,[12] which contributes to uncertainty in the findings. In some cases this results in inundation mapping that appears not to follow a natural shoreline and are unnaturally straight or have geometric shapes.

Future Policy – The results, as presented, assess exposure of present-day energy infrastructure over the next 85 years to SLR and storm surge. Future changes to energy infrastructure—through modifications such as asset hardening and new construction, among others—are not accounted for in this study. Activities planned in the Norfolk area by local government are not reflected in the modeling.

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[9] Zhang et al., 2013.

[10] Available at: http://www.nhc.noaa.gov/surge/faq.php#10.

[11] Maloney and Preston, 2014.

[12] Available at: http://adcirc.org/.

Next Steps

EIMA is pleased to share this analysis with the hope that it fulfills the purpose for which it has been undertaken: to identify areas of potential exposure that can lead to more detailed analysis. EIMA hopes that this study will be useful in work ongoing in the Hampton Road region with regard to energy asset impacts from sea level rise.

Contact

The Energy Infrastructure Modeling and Analysis (EIMA) division is focused on ensuring the reliability and resiliency of the U.S. electric grid through robust analytical, modeling, and assessment capabilities to address issues of national importance.

For more information about the analysis included herein, please contact:

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Appendix A: Table and Maps of Results

The following pages contain a table and maps from the results of the analysis. An explanatory note for Table 1 is provided here and additional details can be found noted in the subsequent figures. Maps are only provided for those scenarios and time periods (i.e., 2050 or 2100) where assets are projected to be inundated; under the Intermediate-High Scenario in 2050 of 1-foot SLR, only portions of pipeline assets are projected to be inundated and no map is provided.

More than 180 assets were examined including:

- >130 substations
- >25 power plants
- 13 petroleum terminals
- 1 refinery
- 1 petroleum pipeline
- 2 natural gas pipelines
- 1 LNG storage facility

There are 59 miles of petroleum pipeline and 154 miles of natural gas pipeline in the MSA. This study analyzed potential inundation of these pipelines.

Asset data sources included the following: for electric assets: Homeland Security Infrastructure Protection Gold (HSIP Gold), 2011 and Ventyx, accessed July 2015; for natural gas assets: HSIP Gold, 2013; for petroleum assets: HSIP Gold, 2013 and Argonne National Labs, accessed 2013.

The maps present specific information on only the large energy assets in the MSA, specifically:

- power plants greater than 100 MW and substations greater than 230 kV
- petroleum terminals greater than 100,000 barrels storage capacity and petroleum pipelines
- LNG storage facility or refineries of any size and gas pipelines

Table 1. Years Corresponding to SLR Increments in the Norfolk MSA under Four NCA Scenarios

The analysis begins with SLR. Table 1 shows the years in which sea levels are projected to increase from their current level to 1 foot higher, 2 feet higher, and up through 6 feet of sea level rise under each of the NCA SLR scenarios. The SLR data are from the NOAA Coastal Services Center (NOAA CSC) inundation maps showing shoreline effects of SLR between one and six feet in one foot increments.[13] The calculation of the year takes into account local subsidence trends using tidal information from NOAA, National Ocean Service.[14] The columns highlighted in red are for SLR by 2050 (midcentury); the columns highlighted in yellow are for SLR by 2100 (end of century). The timing of inundation is important for informing risk management actions, and results from 2050 and 2100 are presented to give perspective on potential near-term and long-term levels of inundation, which may require different actions or affect different types of decisions.

[13] Available at: http://coast.noaa.gov/slrdata/.

[14] Tidal Datums. Available at: http://tidesandcurrents.noaa.gov/datum_options.html.

Additional Figures

Refer to Figures 1a–5b for relevant maps displaying the impact of SLR in various scenarios.

Figure 1a. Large Electricity Assets Inundated by 5-Feet SLR under the NCA Intermediate-High Scenario in Norfolk MSA by ~2100

Figure 1b. Large Petroleum and Natural Gas Assets Inundated by 5-Feet SLR under the NCA Intermediate-High Scenario in Norfolk MSA by ~2100

Figure 2a. Large Electricity Assets Inundated by 1-Foot SLR under the NCA Intermediate-High Scenario and Category 1 Storm Surge in Norfolk MSA

Figure 2b. Large Petroleum and Natural Gas Assets Inundated by 1-Foot SLR under the NCA Intermediate-High Scenario and Category 1 Storm Surge in Norfolk MSA

Figure 3a. Large Electricity Assets Inundated by 1-Foot SLR under the NCA Intermediate-High Scenario and Category 4 Storm Surge in Norfolk MSA

Figure 3b. Large Petroleum and Natural Gas Assets Inundated by 1-Foot SLR under the NCA Intermediate-High Scenario and Category 4 Storm Surge in Norfolk MSA

Figure 4a. Large Electricity Assets Inundated by 5-Feet SLR under the NCA Intermediate-High Scenario and Category 1 Storm Surge in Norfolk MSA

Figure 4b. Large Petroleum and Natural Gas Assets Inundated by 5-Feet SLR under the NCA Intermediate-High Scenario and Category 1 Storm Surge in Norfolk MSA

Figure 5a. Large Electricity Assets Inundated by 5-Feet SLR under the NCA Intermediate-High Scenario and Category 4 Storm Surge in Norfolk MSA

Figure 5b. Large Petroleum and Natural Gas Assets Inundated by 5-Feet SLR under the NCA Intermediate-High Scenario and Category 4 Storm Surge in Norfolk MSA

Table 1. Years Corresponding to SLR Increments in the Norfolk MSA under Four NCA Scenarios

	NCA Low Scenario						NCA Intermediate-Low Scenario					
County	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft
Currituck, NC	2094	>2100	>2100	>2100	>2100	>2100	2062	2099	>2100	>2100	>2100	>2100
Gates, NC	2094	>2100	>2100	>2100	>2100	>2100	2062	2099	>2100	>2100	>2100	>2100
Chesapeake, VA	2094	>2100	>2100	>2100	>2100	>2100	2062	2099	>2100	>2100	>2100	>2100
Gloucester, VA	2093	>2100	>2100	>2100	>2100	>2100	2061	2098	>2100	>2100	>2100	>2100
Hampton, VA	2081	>2100	>2100	>2100	>2100	>2100	2057	2092	>2100	>2100	>2100	>2100
Isle of Wight, VA	2081	>2100	>2100	>2100	>2100	>2100	2057	2092	>2100	>2100	>2100	>2100
James City, VA	2093	>2100	>2100	>2100	>2100	>2100	2061	2098	>2100	>2100	>2100	>2100
Mathews, VA	2093	>2100	>2100	>2100	>2100	>2100	2061	2098	>2100	>2100	>2100	>2100
Newport News, VA	2093	>2100	>2100	>2100	>2100	>2100	2061	2098	>2100	>2100	>2100	>2100
Norfolk, VA	2081	>2100	>2100	>2100	>2100	>2100	2057	2092	>2100	>2100	>2100	>2100
Virginia Beach, VA	2062	>2100	>2100	>2100	>2100	>2100	2049	2080	>2100	>2100	>2100	>2100
Poquoson, VA	2093	>2100	>2100	>2100	>2100	>2100	2061	2098	>2100	>2100	>2100	>2100
Portsmouth, VA	2094	>2100	>2100	>2100	>2100	>2100	2062	2099	>2100	>2100	>2100	>2100
Suffolk, VA	2081	>2100	>2100	>2100	>2100	>2100	2057	2092	>2100	>2100	>2100	>2100
Williamsburg, VA	2093	>2100	>2100	>2100	>2100	>2100	2061	2098	>2100	>2100	>2100	>2100
York, VA	2093	>2100	>2100	>2100	>2100	>2100	2061	2098	>2100	>2100	>2100	>2100

	NCA Intermediate-High Scenario						NCA High Scenario					
County	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft	1 Ft	2 Ft	3 Ft	4 Ft	5 Ft	6 Ft
Currituck, NC	2042	2063	2081	2096	>2100	>2100	2033	2049	2062	2073	2083	2093
Gates, NC	2042	2063	2081	2096	>2100	>2100	2033	2049	2062	2073	2083	2093
Chesapeake, VA	2042	2063	2081	2096	>2100	>2100	2033	2049	2062	2073	2083	2093
Gloucester, VA	2042	2063	2081	2096	>2100	>2100	2033	2049	2062	2073	2083	2092
Hampton, VA	2040	2061	2078	2093	>2100	>2100	2032	2048	2061	2072	2082	2091
Isle of Wight, VA	2040	2061	2078	2093	>2100	>2100	2032	2048	2061	2072	2082	2091
James City, VA	2042	2063	2081	2096	>2100	>2100	2033	2049	2062	2073	2083	2092
Mathews, VA	2042	2063	2081	2096	>2100	>2100	2033	2049	2062	2073	2083	2092
Newport News, VA	2042	2063	2081	2096	>2100	>2100	2033	2049	2062	2073	2083	2092
Norfolk, VA	2040	2061	2078	2093	>2100	>2100	2032	2048	2061	2072	2082	2091
Poquoson, VA	2042	2063	2081	2096	>2100	>2100	2033	2049	2062	2073	2083	2092
Portsmouth, VA	2042	2063	2081	2096	>2100	>2100	2033	2049	2062	2073	2083	2093
Suffolk, VA	2040	2061	2078	2093	>2100	>2100	2032	2048	2061	2072	2082	2091
Williamsburg, VA	2042	2063	2081	2096	>2100	>2100	2033	2049	2062	2073	2083	2092
Virginia Beach, VA	2037	2056	2073	2087	>2100	>2100	2030	2045	2058	2069	2078	2087
York, VA	2042	2063	2081	2096	>2100	>2100	2033	2049	2062	2073	2083	2092

Notes:

* Red cells indicate when the inundation level (in feet) shown in the top row occurs around 2050 and well before 2100;
* Yellow cells indicate when inundation levels (in feet) shown in the top row occurs between 2050 and approximately 2100. In the NCA Intermediate-High scenario, five feet of inundation is projected at or near to 2100 and therefore shaded yellow.
* The analysis above incorporates the National Climate Assessment scenarios for SLR as described in *Global Sea Level Rise Scenarios for the U.S. National Climate Assessment. NOAA Tech Memo OAR CPO-1*. NOAA Climate Program Office (2012), http://cpo.noaa.gov/sites/cpo/Reports/2012/NOAA_SLR_r3.pdf.
* The inundation levels are taken from NOAA, Coastal Services Center. *Method Description - Detailed Methodology for Mapping Sea Level Rise Inundation* (2012), http://www.csc.noaa.gov/slr/viewer/assets/pdfs/Inundation_Methods.pdf.
* The years in which the levels of inundation would occur under each NCA scenario are adjusted for local subsidence trends using tidal information from NOAA, National Ocean Service. *Tidal Datums.* http://tidesandcurrents.noaa.gov/datum_options.html.
* As noted in the text, a more detailed methodological discussion appears in *Effects of Sea Level Rise on Energy Infrastructure in Four Major Metropolitan Areas* (2014), http://energy.gov/oe/downloads/effect-sea-level-rise-energy-infrastructure-four-major-metropolitan-areas-september.

Figure 1a. Large Electricity Assets Inundated by 5-Feet SLR under the NCA Intermediate-High Scenario in Norfolk MSA by ~2100

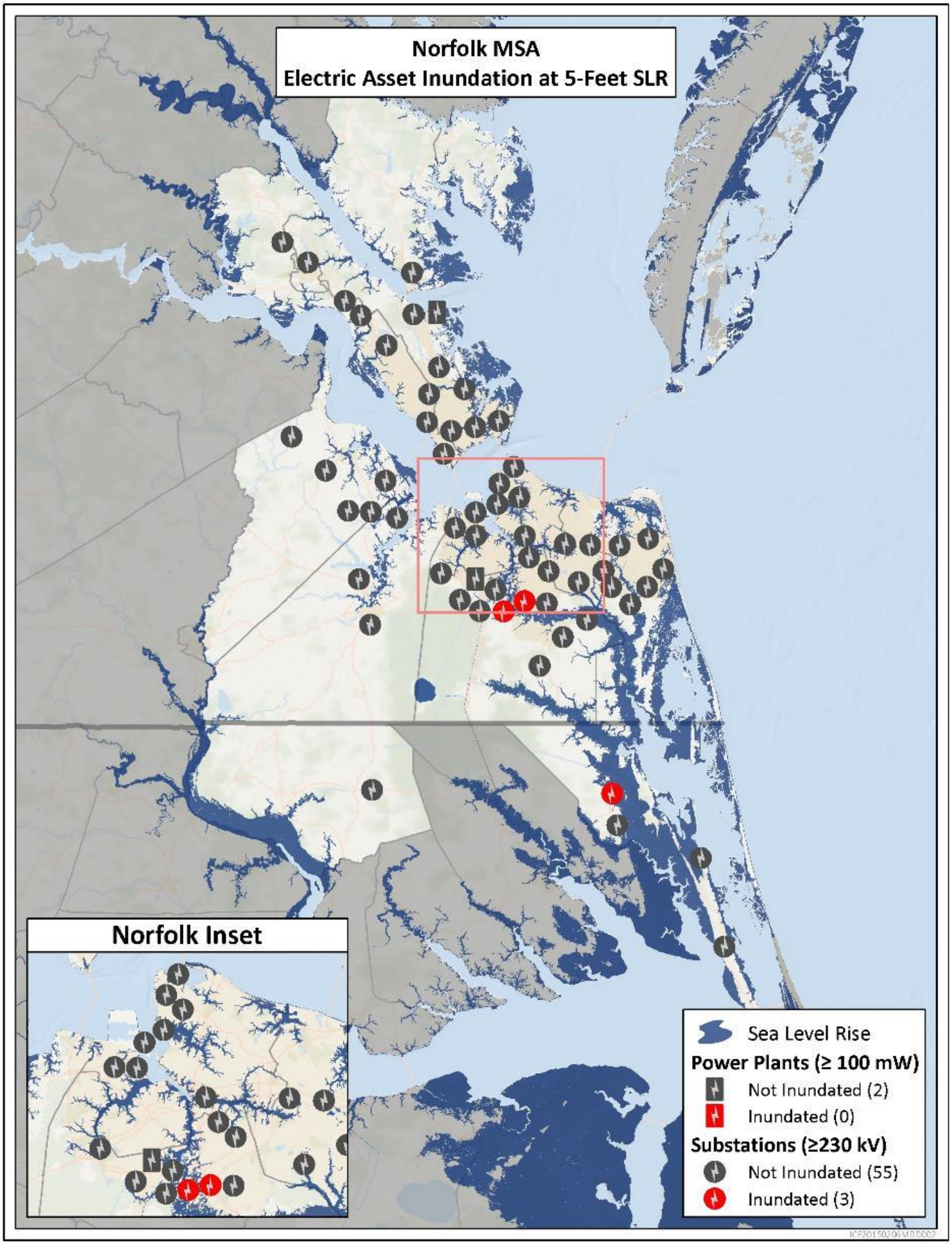


Figure 1b. Large Petroleum and Natural Gas Assets Inundated by 5-Feet SLR under the NCA Intermediate-High Scenario in Norfolk MSA by ~2100

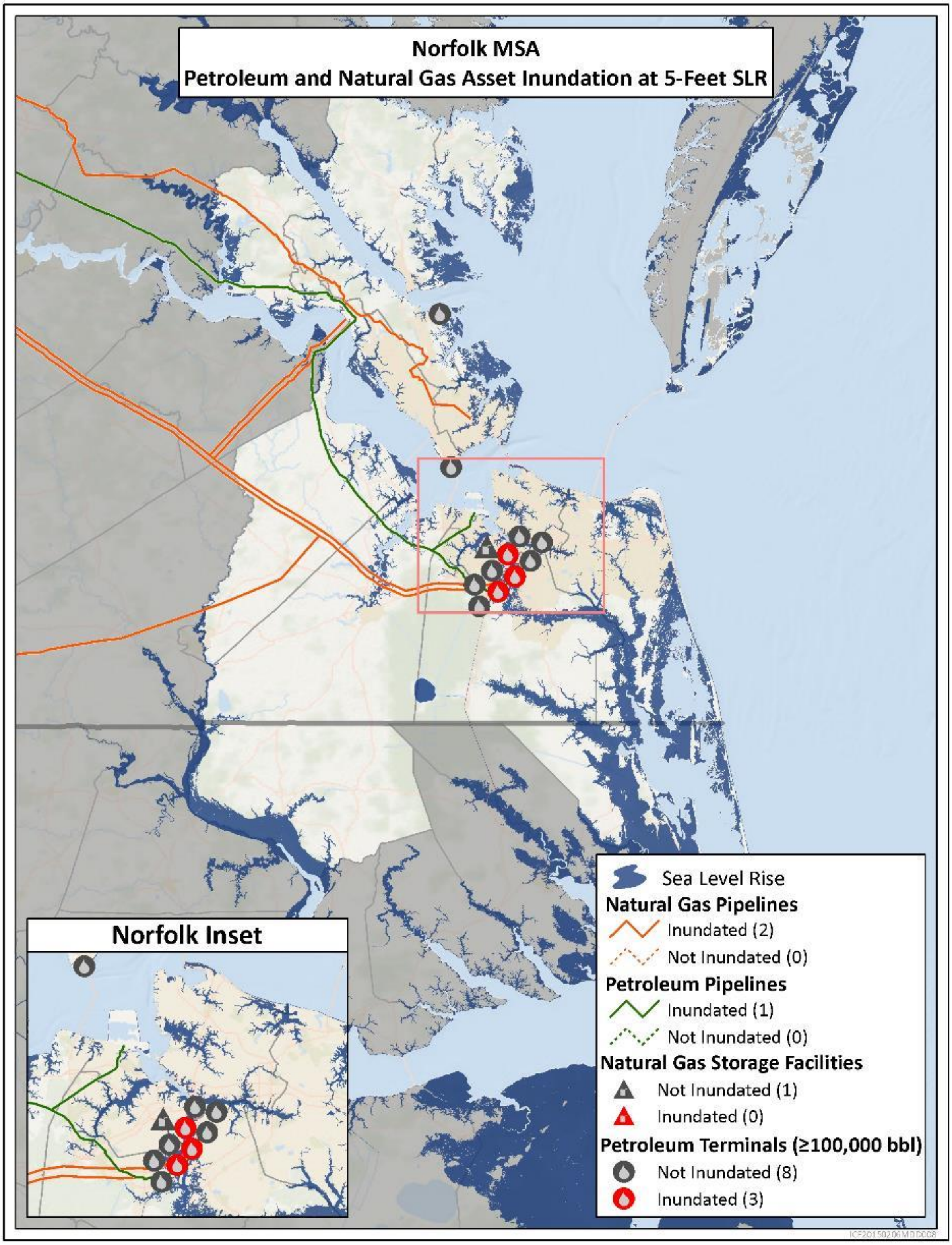


Figure 2a. Large Electricity Assets Inundated by 1-Foot SLR under the NCA Intermediate-High Scenario and Category 1 Storm Surge in Norfolk MSA

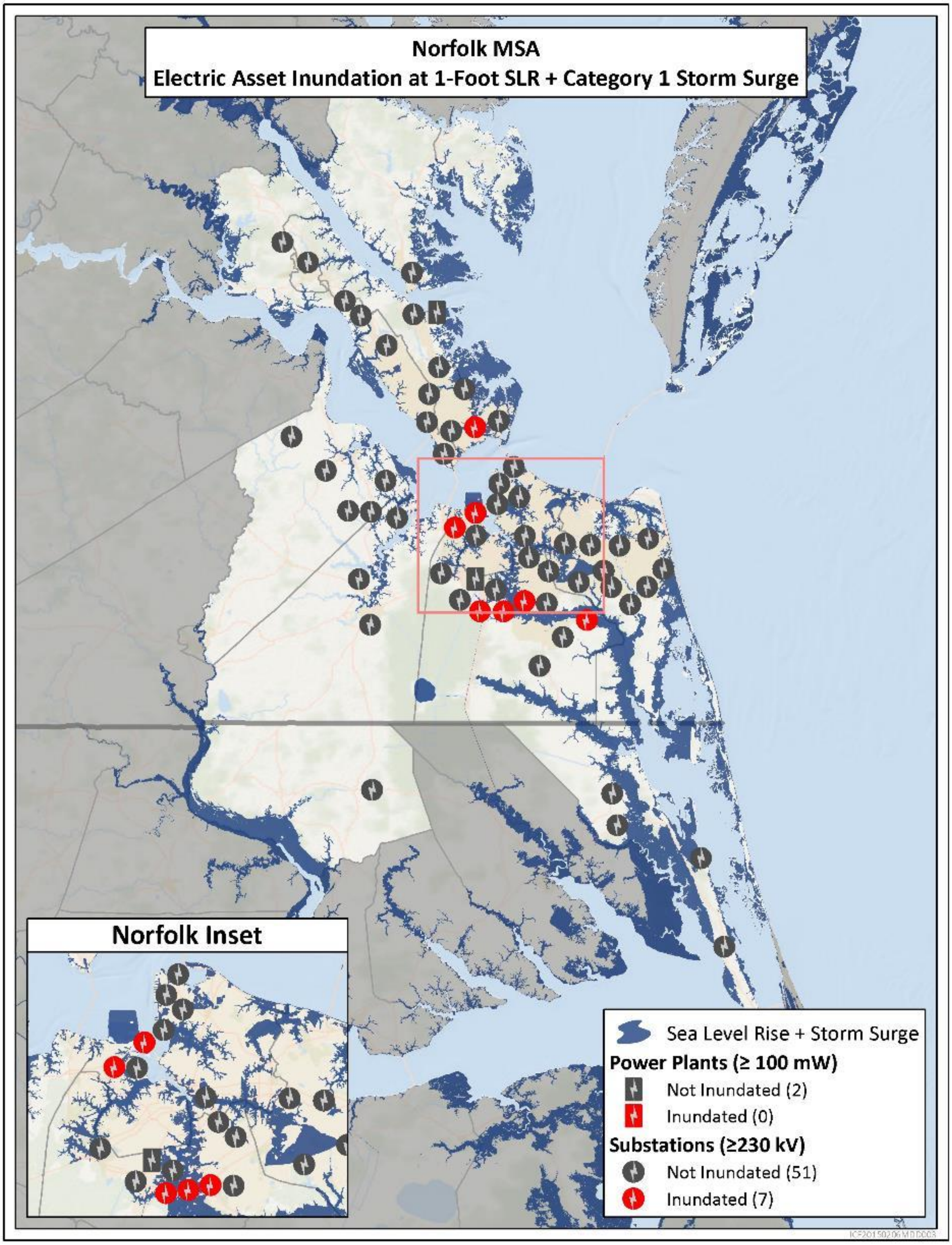


Figure 2b. Large Petroleum and Natural Gas Assets Inundated by 1-Foot SLR under the NCA Intermediate-High Scenario and Category 1 Storm Surge in Norfolk MSA

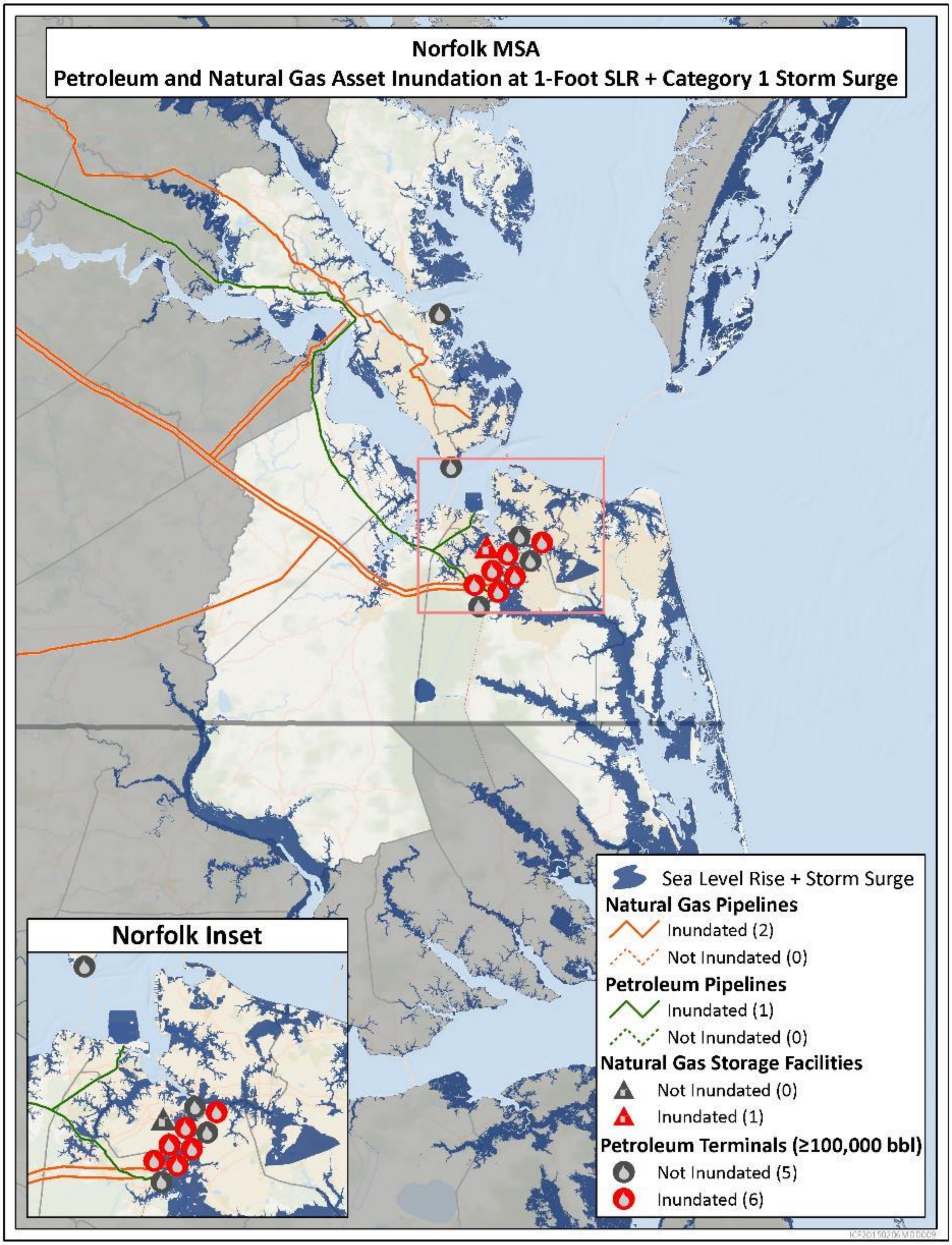


Figure 3a. Large Electricity Assets Inundated by 1-Foot SLR under the NCA intermediate-High Scenario and Category 4 Storm Surge in Norfolk MSA

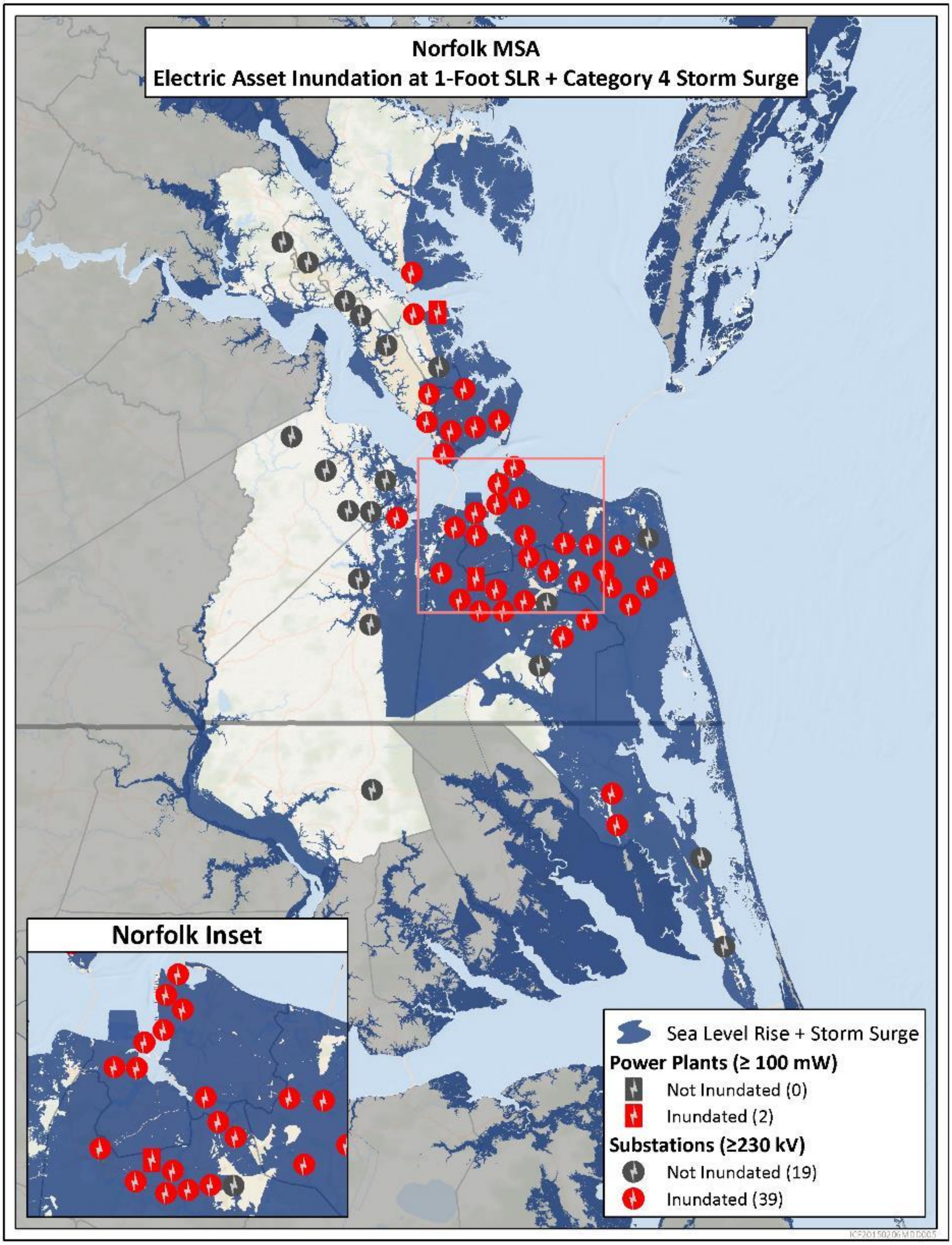


Figure 3b. Large Petroleum and Natural Gas Assets Inundated by 1-Foot SLR under the NCA Intermediate-High Scenario and Category 4 Storm Surge in Norfolk MSA

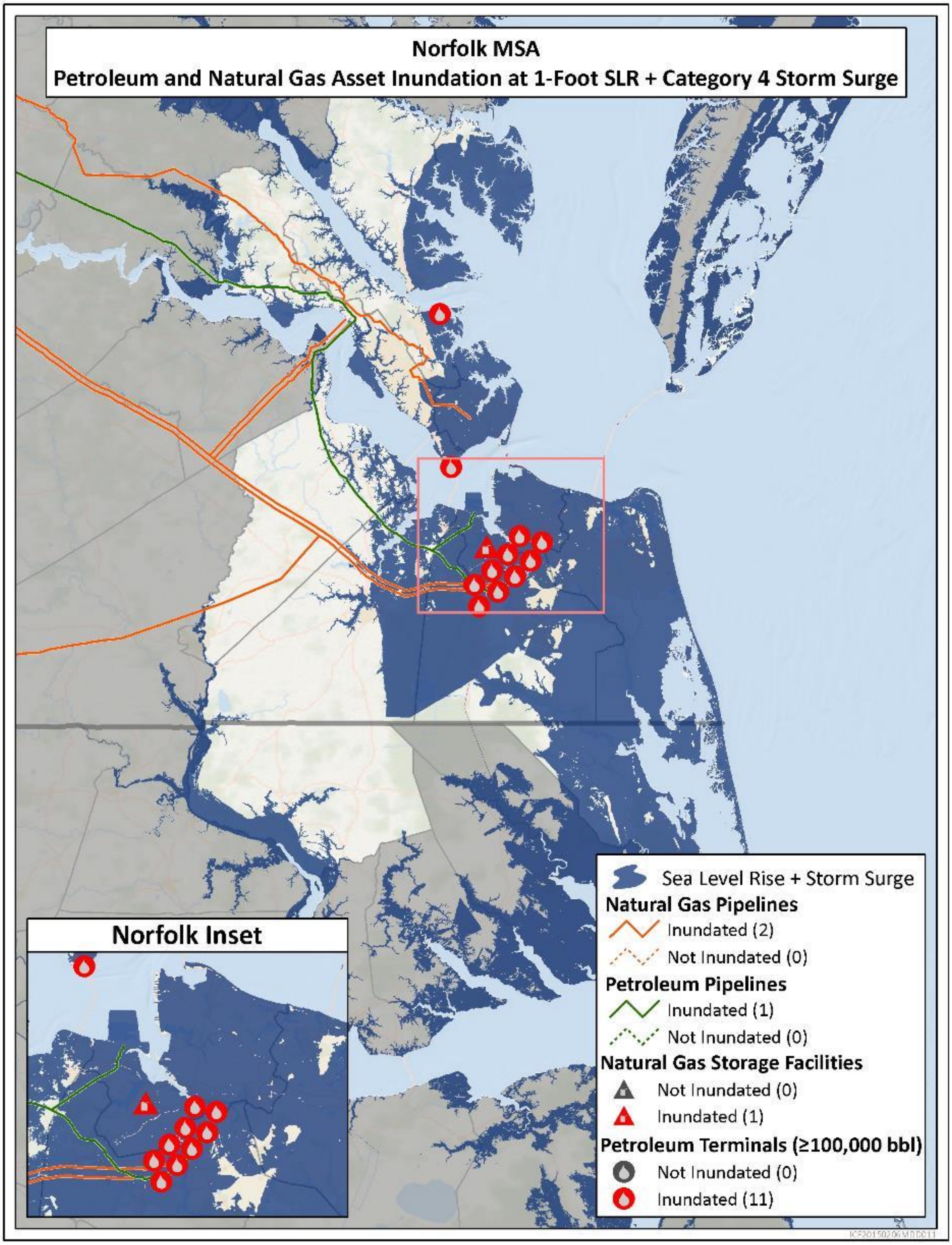


Figure 4a. Large Electricity Assets Inundated by 5-Feet SLR under the NCA Intermediate-High Scenario and Category 1 Storm Surge in Norfolk MSA

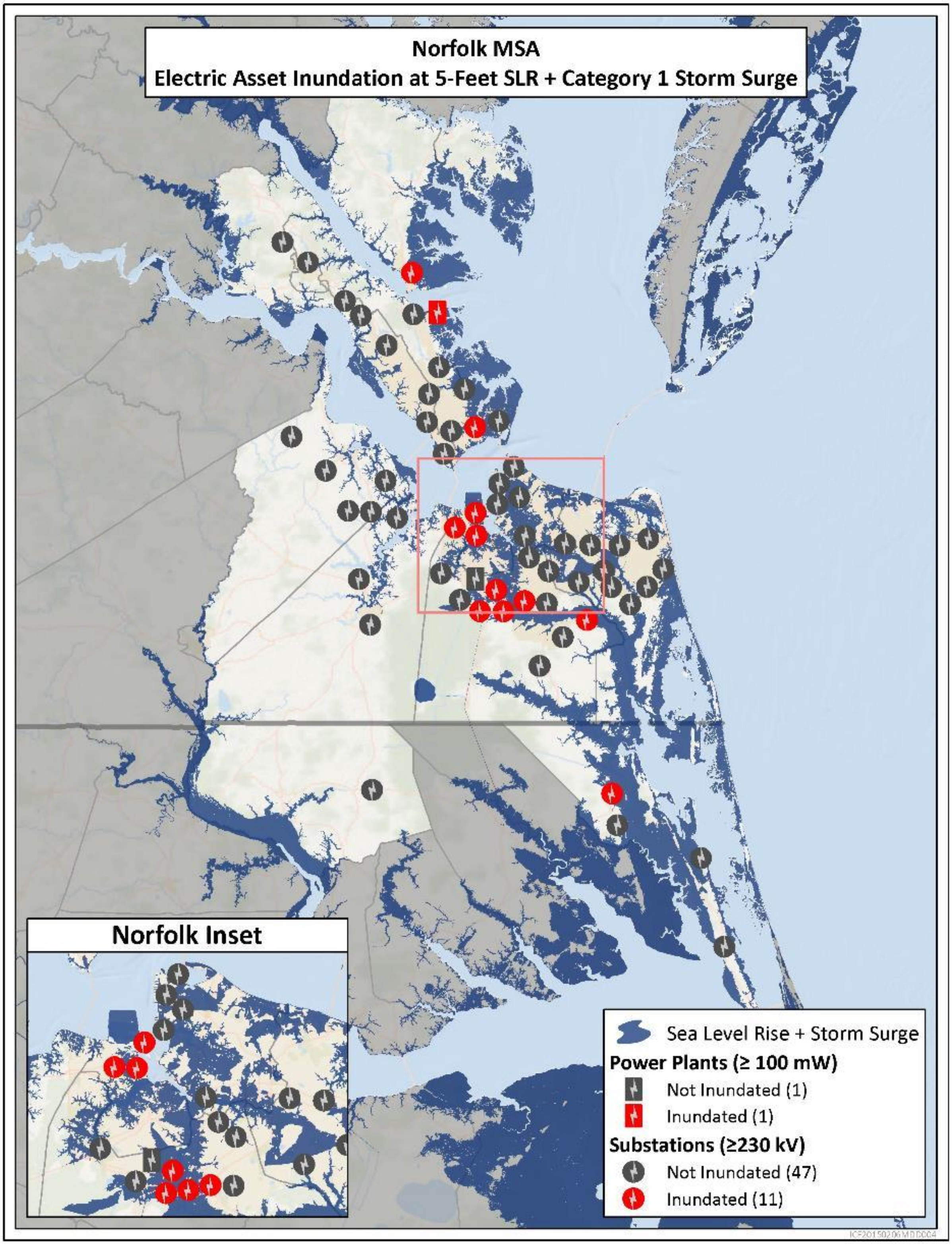


Figure 4b. Large Petroleum and Natural Gas Assets Inundated by 5-Feet SLR under the NCA Intermediate-High Scenario and Category 1 Storm Surge in Norfolk MSA

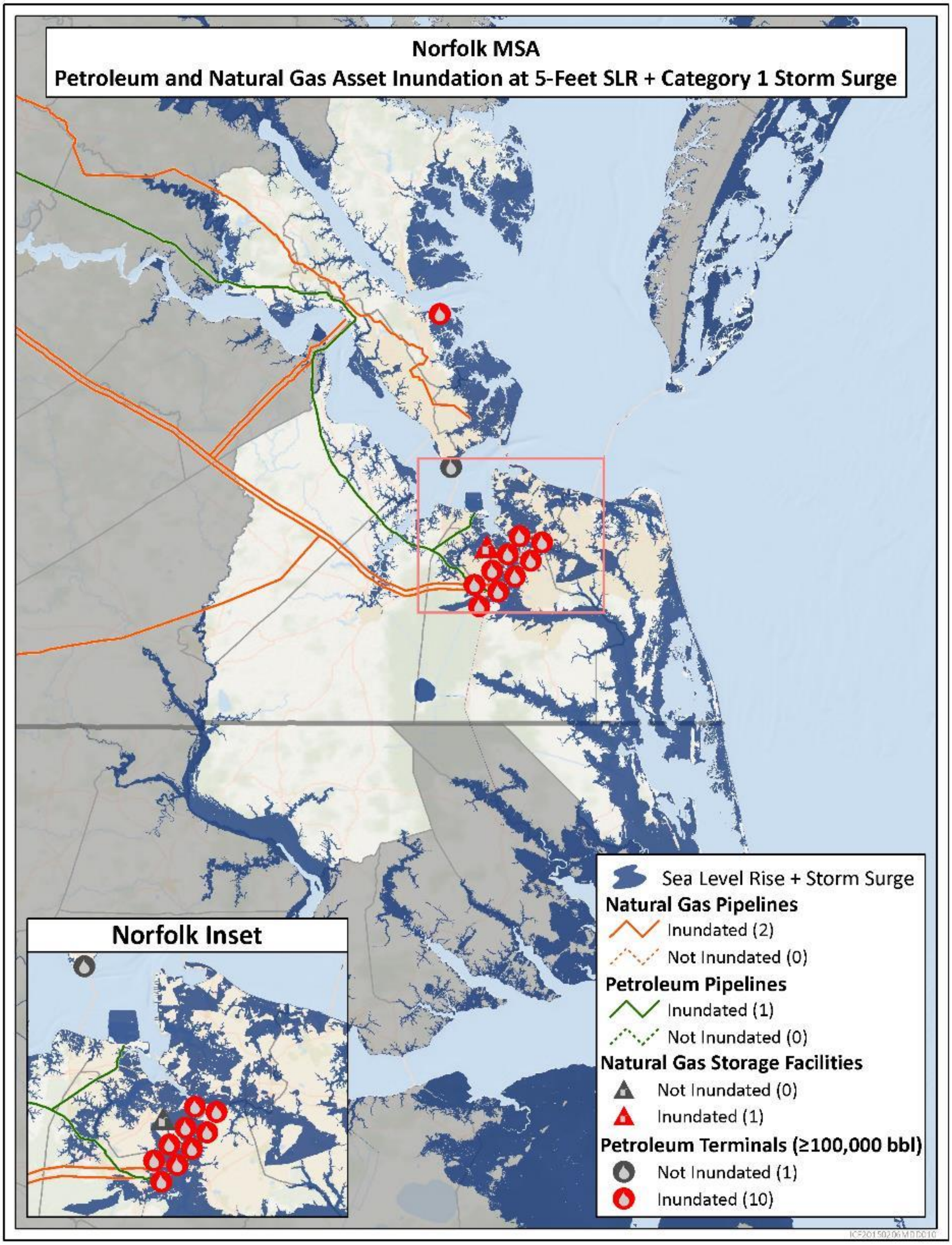


Figure 5a. Large Electricity Assets Inundated by 5-Feet SLR under the NCA Intermediate-High Scenario and Category 4 Storm Surge in Norfolk MSA

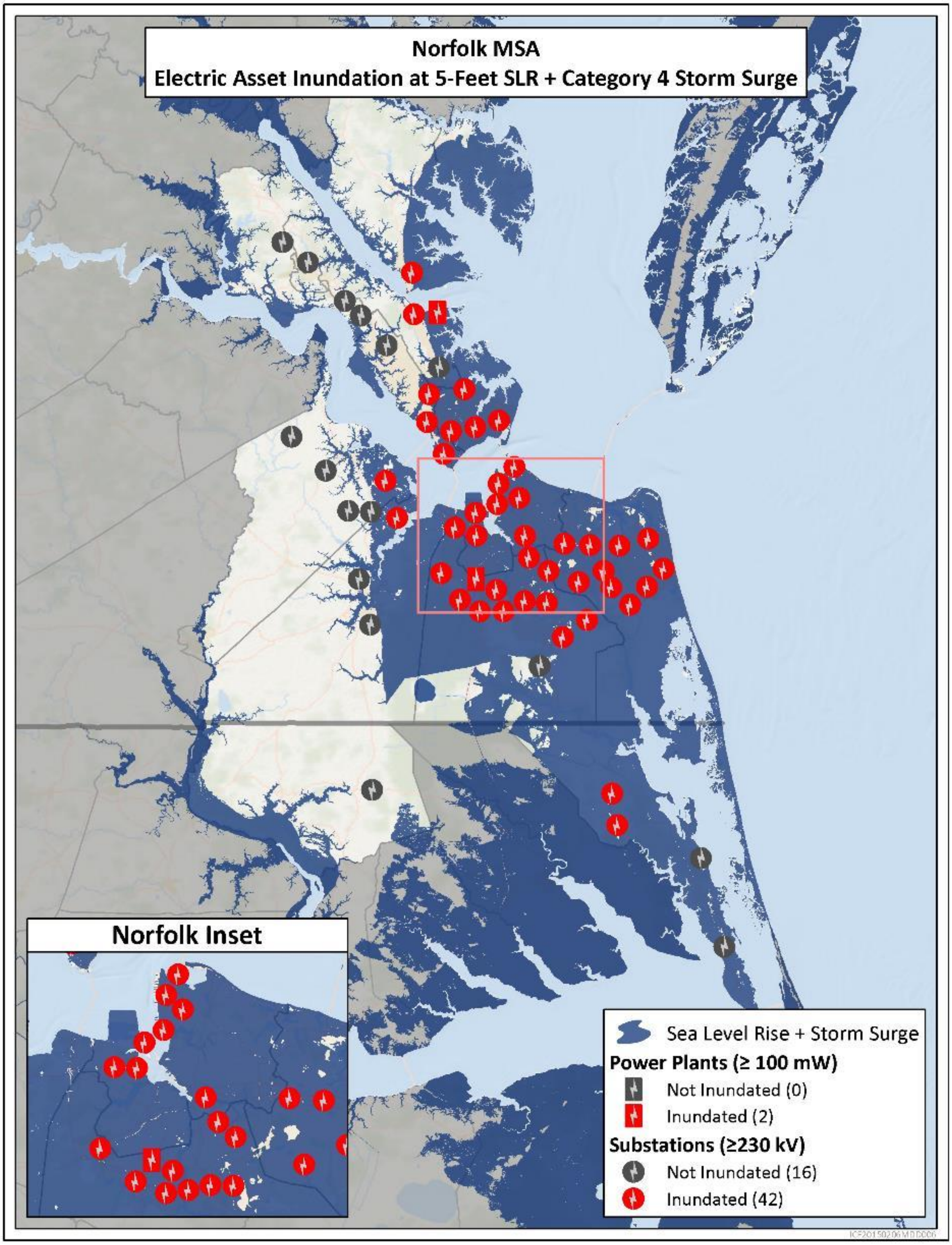
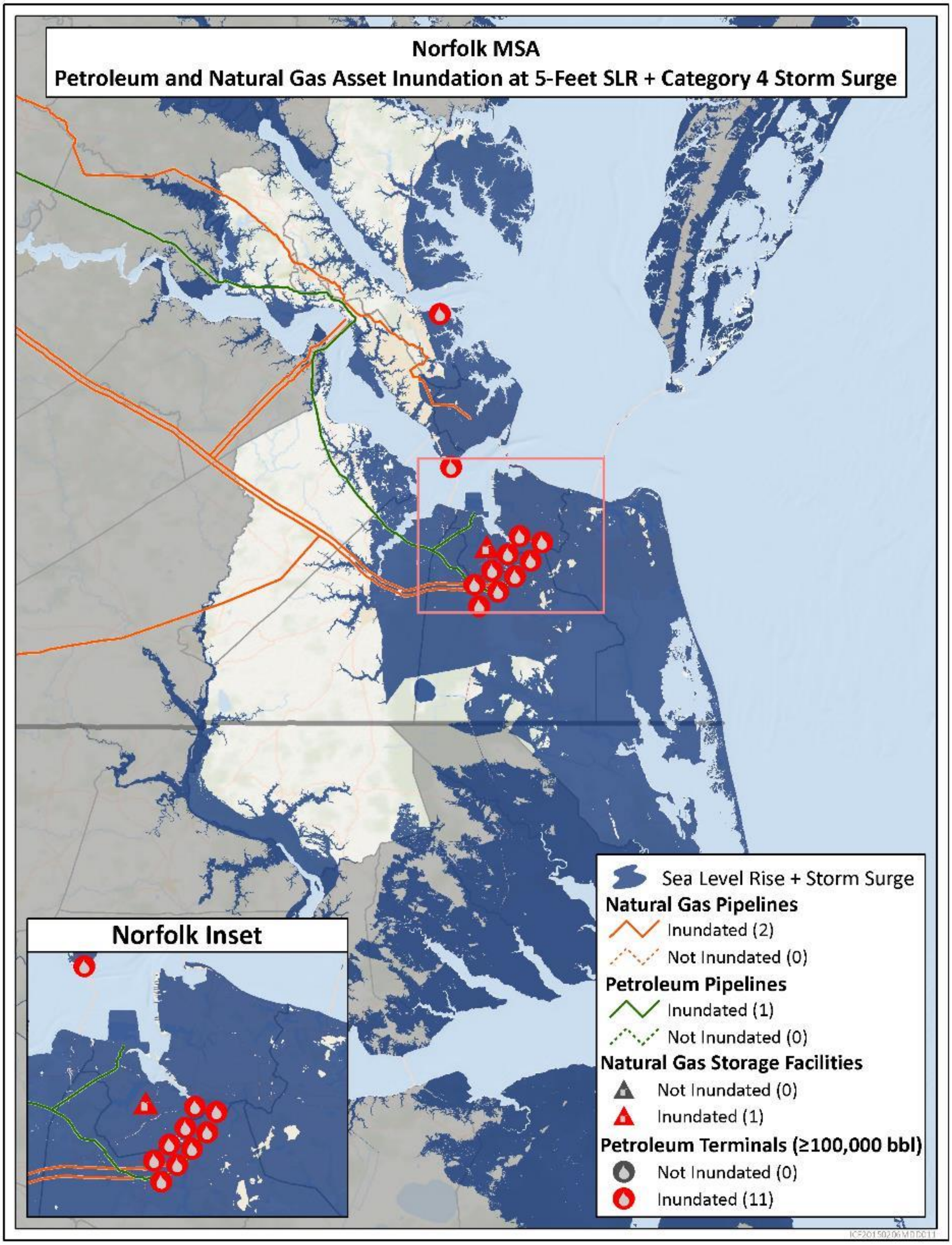


Figure 5b. Large Petroleum and Natural Gas Assets Inundated by 5-Feet SLR under the NCA Intermediate-High Scenario and Category 4 Storm Surge in Norfolk MSA



Appendix B: Method for Estimating Areas of Inundation from Sea Level Rise and Storm Surge Combined

The method described below builds on techniques used in a recent study by Oak Ridge National Laboratory.[15]

Data Sources

In order to estimate inundation of both sea level changes and areas inundated due to storm surge, several data sets were needed. This analysis made use of existing and well-established data sets where possible and only created new data where necessary. The data sets used include:

- **Sea Level Rise –** While many methods to create sea level rise scenarios are available using geospatial technologies, this report made use of the well-established and accepted data available from the NOAA Coastal Services Center (NOAA CSC).[16] NOAA CSC has created polygons representing the coastline at mean high higher water (MHHW)[17] as sea level changes over time. These are available at 1-foot intervals from zero (present sea level) to 6 feet. The 1- and 5-foot increments were used for this specific study.

- **Storm Surge –** NOAA's National Weather Service created the Sea, Lake and Overland Surges from Hurricanes (SLOSH)[18] model used to estimate storm surge heights associated with hurricanes by simulating the effects of storm size, forward speed, track, wind speed, and atmospheric pressure on water heights in the coastal zone. Data products from the SLOSH model are available for 39 basins along the coasts of the Atlantic Ocean, Gulf of Mexico, Caribbean Sea, and Hawaii that are exposed to hurricanes. SLOSH basins consist of a grid definition as well as various geographic features that route and impede the flow of water. Storm surge within a basin can be represented using a polar, elliptical, or hyperbolic grid with a variable resolution, with the higher resolutions associated with the area of interest. For example, the grid used in the current study for the Norfolk MSA had a horizontal resolution of approximately 1.2 miles at its furthest point offshore, 0.4 miles at the Navy Station in Norfolk, and 0.1 miles at its most inland point.

  Surge is estimated in these regions by running the model several thousand times with hypothetical hurricanes of varying storm characteristics. A composite of these runs is then used to determine a Maximum Envelope of Water (MEOW), which shows the highest surge values at each grid location for a given storm category, forward speed, and general track direction. This study uses the Maximum of MEOWs, or MOM, for estimates of storm surge heights. This provides the "worst case" estimate for a particular storm category, rather than the specific flooding from a particular storm (http://www.nhc.noaa.gov/surge/momOverview.php).

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[15] Maloney and Preston 2014. A geospatial dataset for U.S. hurricane storm surge and sea-level rise vulnerability: Development and case study applications. *Climate Risk Management*, 2, 26-41.

[16] Available at: http://coast.noaa.gov/slrdata/.

[17] NOAA describes MHHW as "The average of the higher high water height of each tidal day observed over the National Tidal Datum Epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the National Tidal Datum Epoch" (http://tidesandcurrents.noaa.gov/datum_options.html).

[18] Available at: http://www.nhc.noaa.gov/surge/slosh.php.

Although the latest science indicates that the intensity of the strongest storms may increase in the future,[19] the potential increase in intensity is difficult to quantify. This analysis includes storms that are stronger than previously experienced in Norfolk, which has primarily experienced Category 1 and 2 hurricanes over the last century.[20] To account for potentially stronger storms in the future, the study analyzes Category 4 storms. Category 1 storms are also analyzed to illustrate the effects of exacerbation from SLR on smaller storms.

- **Elevation –** Land elevation data was used to calculate the sea level and storm surge inundation. The USGS produces the National Elevation Dataset (NED)[21] nationwide. This digital elevation model (DEM) is available in the Norfolk area at a horizontal scale of 1 arc-second (~30 meters) and was used for this study. The NED also includes a more detailed 10-meter resolution for many areas of the country including Norfolk, but the coarser elevation data were used to improve processing time and because the increase in elevation resolution would not enhance the results given the coarser resolution of the SLOSH model.

Approach to Estimating Storm Surge Inundation

In order to explore the effects of increased storm surge levels due to sea level changes, an estimate of the areas of potential inundation was made. Generally, and as illustrated in Figure 6 below, the method starts by using the MHHW Coastline from the specific NOAA SLR scenario. The depth inundation from the SLOSH model scenario was added to the depth of inundation from the sea level rise scenario to find the elevation of the storm surge above the SLR scenario. This calculated elevation was then extended toward the coast to find the extent of the possible inundation. These data could then be compared to the infrastructure to determine facilities that may be affected by such a combined scenario (for example, which power plants might be inundated by a Category 4 storm occurring after 5 feet of sea level rise).

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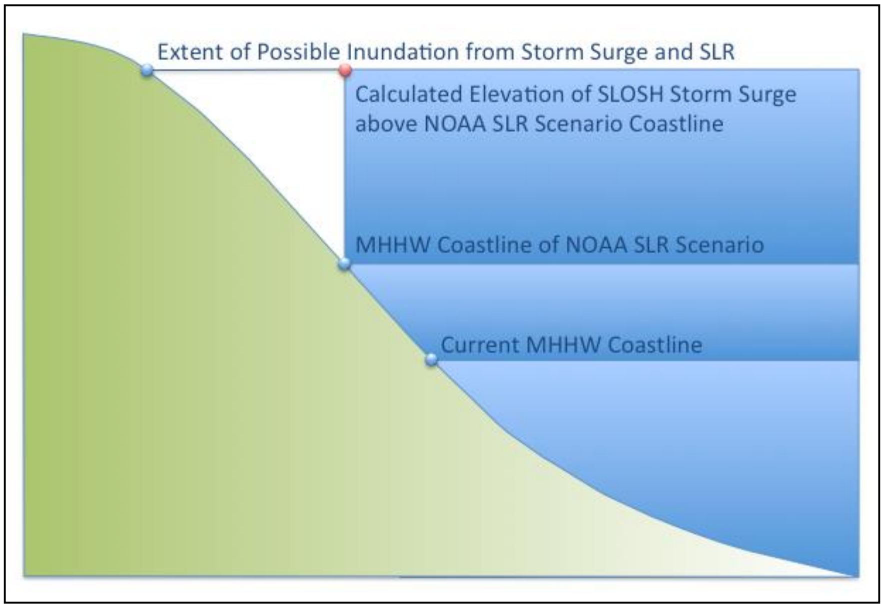
[19] Melillo et al., 2014.

[20] Available at: http://www.aoml.noaa.gov/hrd/hurdat/UShurrs_detailed.html

[21] Available at: http://ned.usgs.gov/.

Figure 6. Schematic of Sea Level Rise Plus Storm Surge Analysis



Specifically, the analysis goes through the following steps:

- Using ArcGIS 10.2 (Esri) to perform the spatial analysis functions, a series of observation points were created from the polygons of the specific NOAA CSC sea level rise scenario (1 and 4 foot).
- These points were spatially overlaid on the SLOSH model output for a specific Saffir-Simpson category of storm (Category 1 and Category 4) to join the depth of inundation at that location to the observation points.
- Those same points were compared with the NED elevation model to join the elevation to the observation points. Then, the elevation and depth of inundation values were added to get a height of water for that particular scenario at that observation point.
- With the series of points now having an estimate of inundation an Inverse Distance Weighting[22] was calculated from the observation points to create a continuous surface, modeling the given sea level and storm surge scenario. The output was set to same resolution as the DEM – 30m.
- The resulting output surface was compared to the elevation of the DEM. Given that the vertical accuracy of NED elevation model is expressed as a root mean square error of 2.44 m [23] and the various uncertainties associated with the SLOSH model, the resulting inundation grids did not maintain any depth of inundation data. Instead, areas where the scenario was higher than the DEM elevation were considered inundated and conversely, areas where the scenario were lower than the DEM elevation were considered dry – or not inundated.

[22] Inverse distance weighted (IDW) interpolation determines cell values using a linearly weighted combination of a set of sample points (Esri – 2014).

[23] D.B. Gesch, The national elevation dataset, D. Maune (Ed.), Digital Elevation Model Technologies and Applications: The DEM Users Manual (second ed.), American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland (2007), pp. 99–118

- The inundated cells were converted to polygons representing areas of inundation. These polygons were then used to identify which energy infrastructure facilities could be at risk of inundation based on the specific sea level rise and storm surge scenario.