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Future Sea Level and Recurrent Flooding Risk for Coastal Virginia

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FUTURE SEA LEVEL AND RECURRENT FLOODING RISK FOR COASTAL VIRGINIA

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EXECUTIVE SUMMARY

A report developed in response to a request from the Secretary of Natural Resources and Special Assistant to the Governor for Coastal Adaptation and Protection to assist with meeting the Executive Order No. 24 (2018), Increasing Virginia's Resilience to Sea Level Rise and Natural Hazards directive set forth in Section 2 Part A requiring the development of a Coastal Resilience Master Plan.

The report presents analysis of the best available existing data on coastal land elevation, sea level rise projections, vertical land motion (subsidence), and building and transportation assets. Sea level rise (SLR) projections are analyzed as Relative SLR (RSLR), combining the effects of vertical water rise (or "eustatic" change) with regional trends in vertical land motion, or subsidence. The study made use of available Commonwealth LiDAR elevation data, buildings, and roads as well as several sources of federal data, including sea level trends, tidal flooding and datums, and peer-reviewed and government reports. Maps of potential future inundation provided here represent a baseline assessment of impacts to land areas, including wetlands, parcels and development, roadways and buildings within the Commonwealth.

> The report presents analysis of the best available existing data on coastal land elevation, sea level rise projections, vertical land motion (subsidence), and building and transportation assets.

The total area at risk with RSLR in coastal Virginia is 424 square miles in 2040, 534 square miles in 2060, and 649 square miles in 2080. An additional 144 square miles will be vulnerable to minor tidal flooding by the year 2040, with similar areas of impact for 2060 and 2080. The total length of roadway potentially affected by RSLR and tidal flooding is 545 miles in 2040, 972 miles in 2060, and 1762 miles in 2080. The total number of buildings potentially affected by RSLR and tidal flooding is 30,795 in 2040, 57,740 in 2060, and 111,545 in 2080. Hampton Roads, the Eastern Shore, and the Middle Peninsula are the most severely and critically impacted. Additional metrics describing the potential risk from RSLR, minor (tidal) flooding, and moderate flood events can be found in the body of this report.

Impacted parcels, buildings, and roads are tabulated and presented in a series of charts, tables, and maps delimited by Planning District Commissions across coastal Virginia. The maps and related digital data promote sub-regional comparison and provide these organizations and municipalities a spatial product for first-order risk assessment and planning. Maps and tables are provided digitally in this report are also available as digital geospatial data for local spatial planning. The report further outlines inherent limitations and future improvements in the available data and emerging methods and scientific understanding to reduce uncertainty.

BACKGROUND

This report provides information in furtherance of the objectives of Executive Order No. 24 (2018) Increasing Virginia's Resilience to Sea Level Rise and Natural Hazards and at the request of the Special Assistant to the Governor for Coastal Adaptation and Protection.

Inundation modeling was conducted to determine the extent of permanent flooding due to relative sea level rise for the years 2040, 2060, and 2080

Inundation modeling was conducted to determine the extent of permanent flooding due to relative sea level rise for the years 2040, 2060, and 2080 in support of the Commonwealth's initial Coastal Resilience Master Plan.These benchmark timelines were selected to closely coincide with common planning time horizons, similar to the Hampton Roads Coastal Resilience Working Group's adopted Sea Level Rise Planning Policy[1]. Following the recommendation of the Commonwealth Center for Recurrent Flooding Resiliency (CCRFR)[2], the National Oceanic and Atmospheric Agency (NOAA) 2017 Intermediate-High curve was used to model flood surfaces. Values for these flood surfaces were obtained by examining the NOAA Intermediate-high curve at tide stations throughout coastal Virginia. The US Army Corps of Engineers Sea Level Rise Calculator (USACE)[3] was used to derive the relative SLR heights of tidal flooding, combining a NOAA SLR projection (Intermediate-High) for eustatic water level rise with local subsidence taken from regional measurements. The graph shown in **FIGURE 1** details sea level rise predictions for the Sewells Point tide gauge in Norfolk, Virginia.

For any given scenario, sea level rise estimates vary slightly throughout coastal Virginia and the Chesapeake Bay. Accordingly, inundation modeling was conducted independently for the following four geographically contiguous coastal study areas: (1)southern Bay and Atlantic (Hampton Roads), (2) Middle Peninsula, (3) Northern Neck and Northern Virginia, and (4) the Eastern Shore.

The examined geographic regions include the member cities and counties that comprise the following 8 coastal planning districts: Northern Virginia Regional Council (NVRC), George Washington Regional Council (GWRC), Northern

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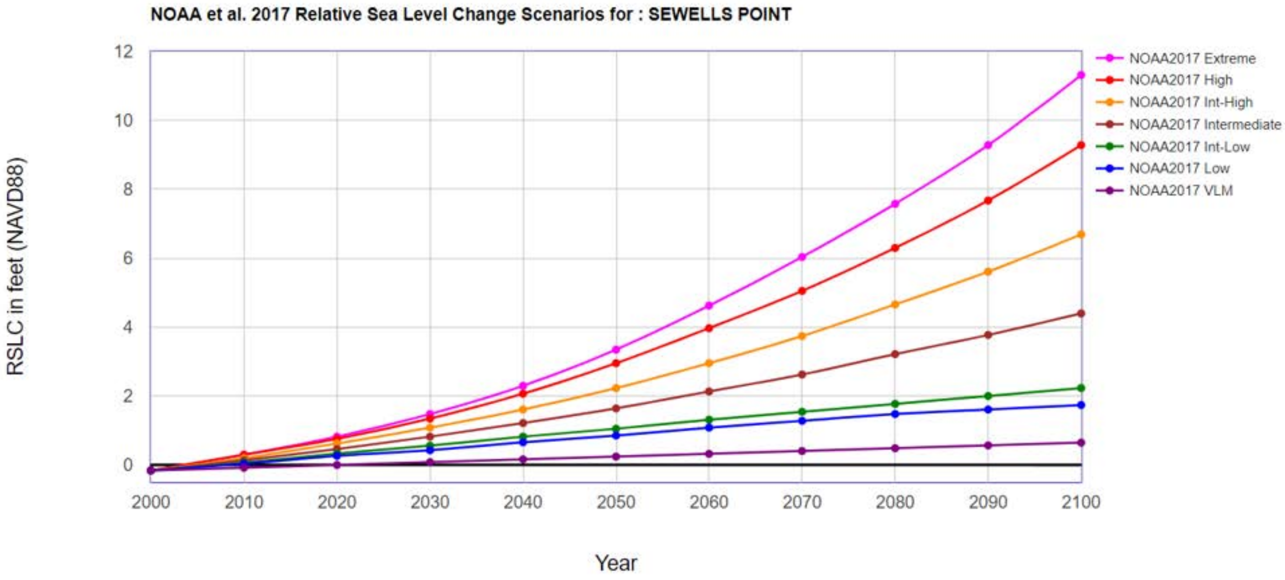
[1] Hampton Roads Planning District Commission. Resolution Adopted October, 18, 2018. HRPDC Sea Level Rise Planning Policy and Approach. https://www.hrpdcva.gov/uploads/docs/05A_Attachment%20-%20HRPDC%20Sea%20Level%20Rise%20Planning%20Policy%20and%20Approach%20-%20Adopted%20101818.pdf

[2] Considine, C., Seek, M., Erten-Unal, M., McLeod, G., and E. Steinhilber. October 23, 2019. Old DominionUniversity –Commonwealth Center for Recurrent Flooding Resiliency. Recommendations for Freeboard Standards for State-Owned Buildings in the Commonwealth of Virginia, Version 1.5. https://www.naturalresources.virginia.gov/media/governorvirginiagov/secretary-of-natural-resources/images/ODU-Freeboard-Recommendations-Ver-1.5-10_31_19-FINAL.pdf.

[3] US Army Corps of Engineers Sea-Level Change Curve Calculator(Version 2019.21). Last accessed January 21, 2020. http://corpsmapu.usace.army.mil/rccinfo/slc/slcc_calc.html

FIGURE 1

Relative Sea Level Rise Scenario Projections for Sewells Point, Norfolk, VA (NOAA 2017), including the projected Relative Sea Level Change (RSLC) for the selected NOAA 2017 Intermediate High scenario in this study. (Source: US Army Corps of Engineers Sea Level Rise Calculator, http://corpsmapu.usace.army.mil/rccinfo/slc/slcc_calc.html)



Neck Planning District Commission (NNPDC), Middle Peninsula Planning District Commission (MPPDC), Richmond Regional Planning District Commission (PlanRVA), Crater Planning District Commission (CPDC), Hampton Roads Planning District Commission (HRPDC), and Accomack-Northampton Planning District Commission (A-NPDC).

Inundation modeling was conducted utilizing methods modified from those outlined in the "Mapping Coastal Inundation Primer" produced by NOAA's Office for Coastal Management[4]. Future sea level surfaces for the years 2040, 2060, and 2080 were created using values derived from the NOAA (2017) Intermediate-high scenario. Each surface was adjusted to the mean higher high water (MHHW) datum to ensure that modeled inundation represents land area that would be inundated during normal tidal cycles. Digital depth models (DDMs) that define the areal extent and depth of flooding predicted by the model were developed using the best available LiDAR elevation data. All calculations for the impacts of RSLR for each modeled year (2040, 2060, 2080) are naturally inclusive of all prior years and not additive. However, calculations of the additional impacts of minor and moderate flooding are in addition to the impacts of RSLR.

To enhance their utility in ongoing planning efforts throughout the Commonwealth, these data were aggregated to the planning district level. The Appendix contains an expanded version of **FIGURE 2** and eight additional map figures that provide an overview of sea level rise inundation for each of the coastal planning districts.

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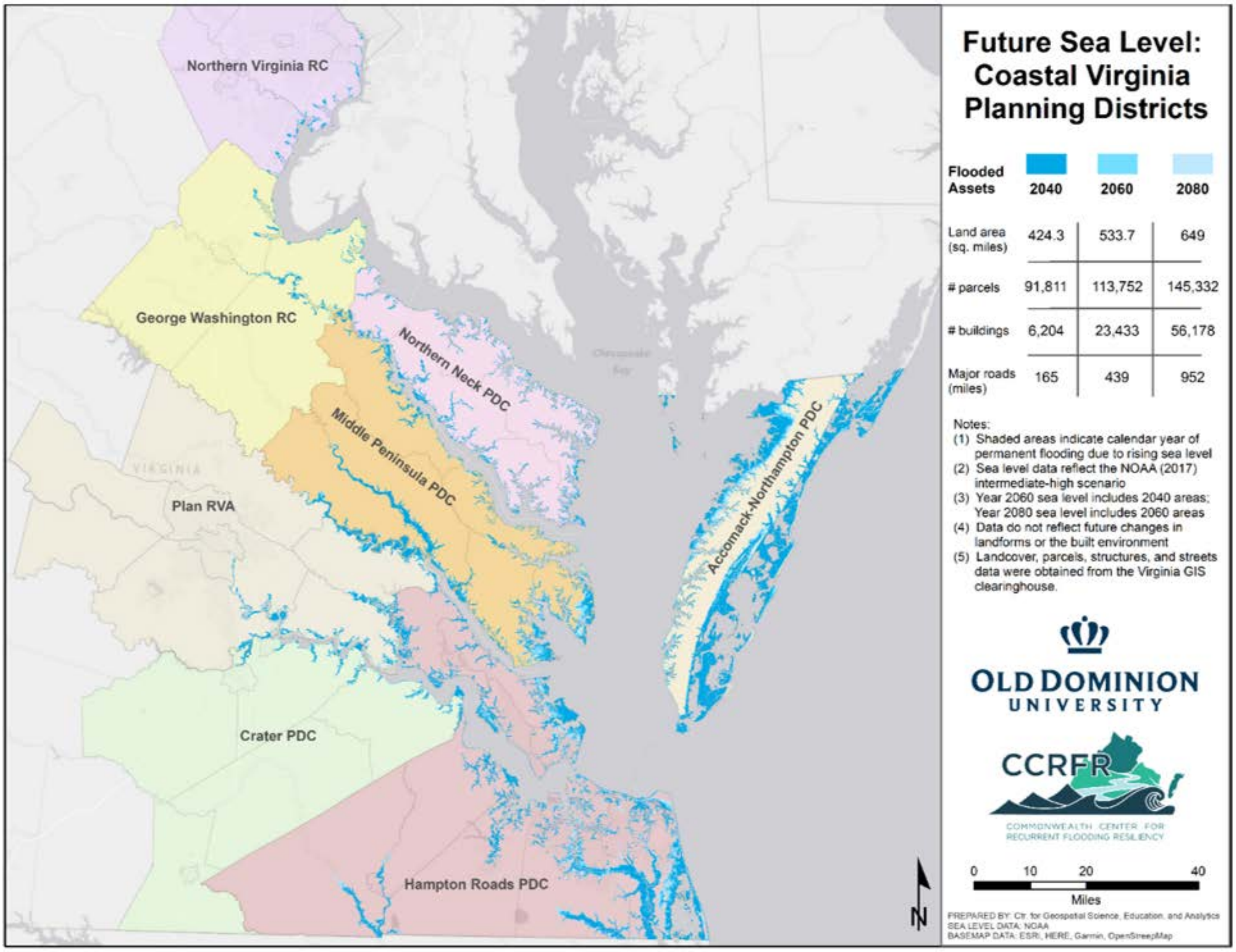
[4] NOAA Office for Coastal Management (formerly Coastal Services Center). April 2012. Mapping Coastal Inundation Primer.

FIGURE 2

Future Sea Level: coastal Virginia planning districts. Shown larger in Appendix I. Gloucester was included in the Middle Peninsula PDC for this study.



Future Sea Level: Coastal Virginia Planning Districts

Flooded Assets	🟦 2040	🟦 2060	🟦 2080
Land area (sq. miles)	424.3	533.7	649
# parcels	91,811	113,752	145,332
# buildings	6,204	23,433	56,178
Major roads (miles)	165	439	952

Notes:
(1) Shaded areas indicate calendar year of permanent flooding due to rising sea level
(2) Sea level data reflect the NOAA (2017) intermediate-high scenario
(3) Year 2060 sea level includes 2040 areas; Year 2080 sea level includes 2060 areas
(4) Data do not reflect future changes in landforms or the built environment
(5) Landcover, parcels, structures, and streets data were obtained from the Virginia GIS clearinghouse.

PREPARED BY: Ctr. for Geospatial Science, Education, and Analytics
SEA LEVEL DATA: NOAA
BASEMAP DATA: ESRI, HERE, Garmin, OpenStreetMap

RELATIVE SEA LEVEL RISE MODELING

Land Area Vulnerable to Sea Level Rise:

> As RSLR impacts to wetlands include both loss and migration inland, these environmental resources are at great risk and require additional, careful study and monitoring.

Virginia statewide land cover data (2016) were analyzed in conjunction with modeled sea level to assess the amount of predicted inundated area for the following land cover classes: Open Water, Developed, Barren, Forested, Shrub/Scrub, Harvested/Disturbed, Turf Grass, Planted/Cultivated, Wetlands.[5]

Cumulative inundation for all land cover(open water excluded) for coastal Virginia was predicted to be 424 square miles in 2040, 534 square miles in 2060, and 649 square miles in 2080 (figures rounded to the nearest mile).

Calculation of dry land-only inundation (wetlands excluded) predicted a total combined flood extent for coastal Virginia of 40 square miles in 2040, 86 square miles in 2060, and 170 square miles in 2080. In comparison, the total areas of Alexandria, Norfolk, and Richmond are 15 square miles, 54 square miles, and 60 square miles, respectively.

For the purpose of examining and highlighting potential disparity of impact between coastal regions, the flooded area total for the entire coastal region was broken down to the planning district level. **FIGURES 3** and **4** provide graphical representation of permanent sea level inundation for each district.

It should be noted here that future analysis should also consider the geomorphological impacts of relative SLR on tidal and non-tidal wetlands. As RSLR impacts to wetlands include both loss and migration inland, these environmental resources are at great risk and require additional, careful study and monitoring.

Further analysis was conducted to approximate the impact of future sea level inundation on real property parcels, buildings, and major roads throughout coastal Virginia and within each planning district. Data for these features were obtained through the Virginia GIS Clearinghouse data portal hosted by the Virginia Geographic Information Network (VGIN) through the Virginia Information Technologies Agency (VITA).[6]

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[5] VITA, VA DEQ. May 6, 2016. Technical Plan of Operations -Virginia Statewide Land Cover Data Development. https://www.vita.virginia.gov/media/vitavirginiagov/integrated-services/pdf/LandCover_TechnicalPlanOfOperations_v7_20160506.pdf

[6] VITA. Virginia GIS Clearinghouse. https://vgin.maps.arcgis.com/home/index.html. Last accessed 11/01/2019.

FIGURE 3

Present day land area (including wetlands) in each planning district that will be flooded by sea level rise

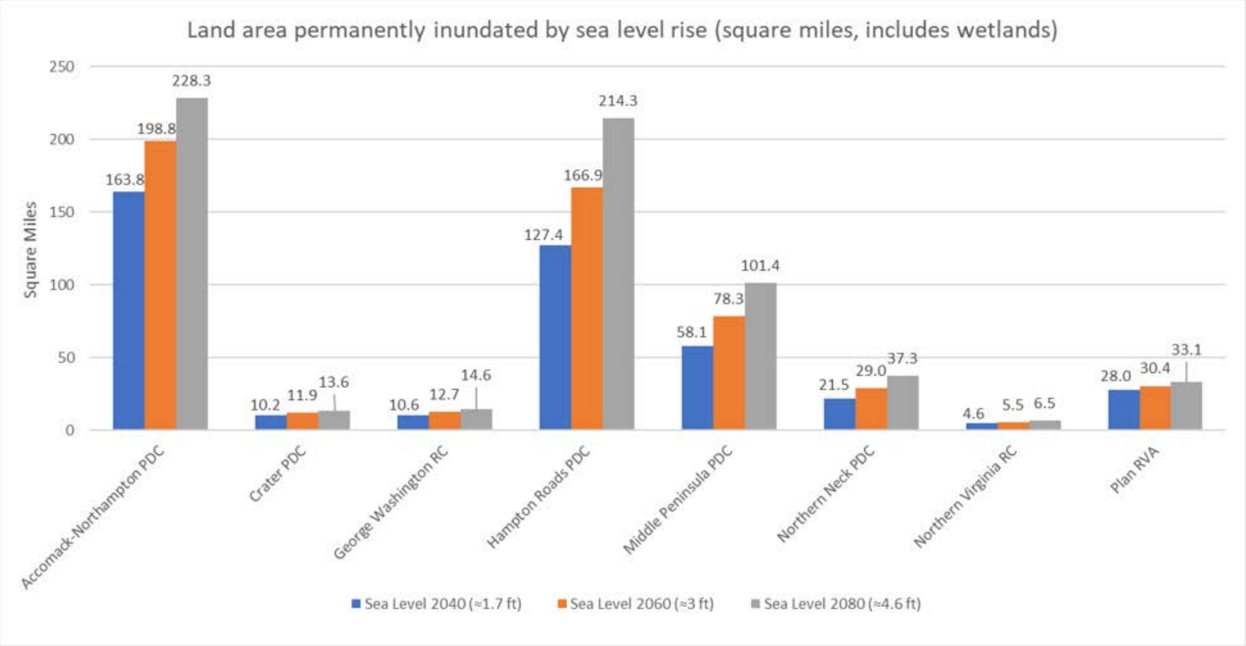
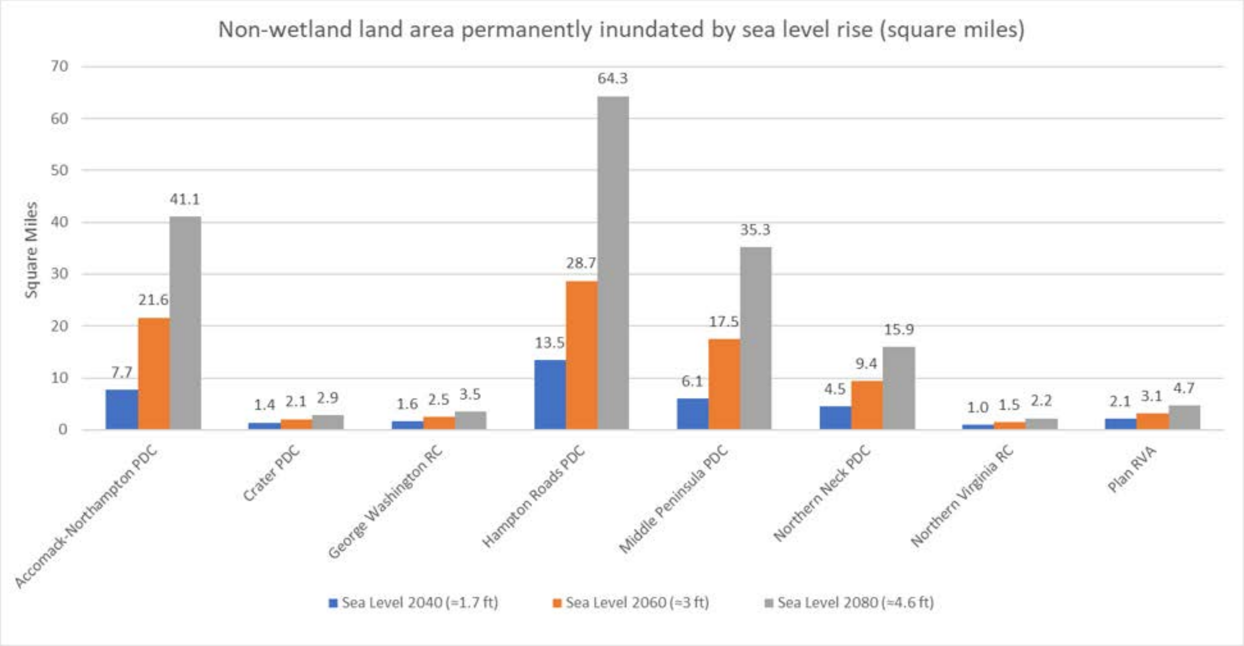


FIGURE 4

Present day land area (excluding wetlands) in each planning district that will be flooded by sea level rise



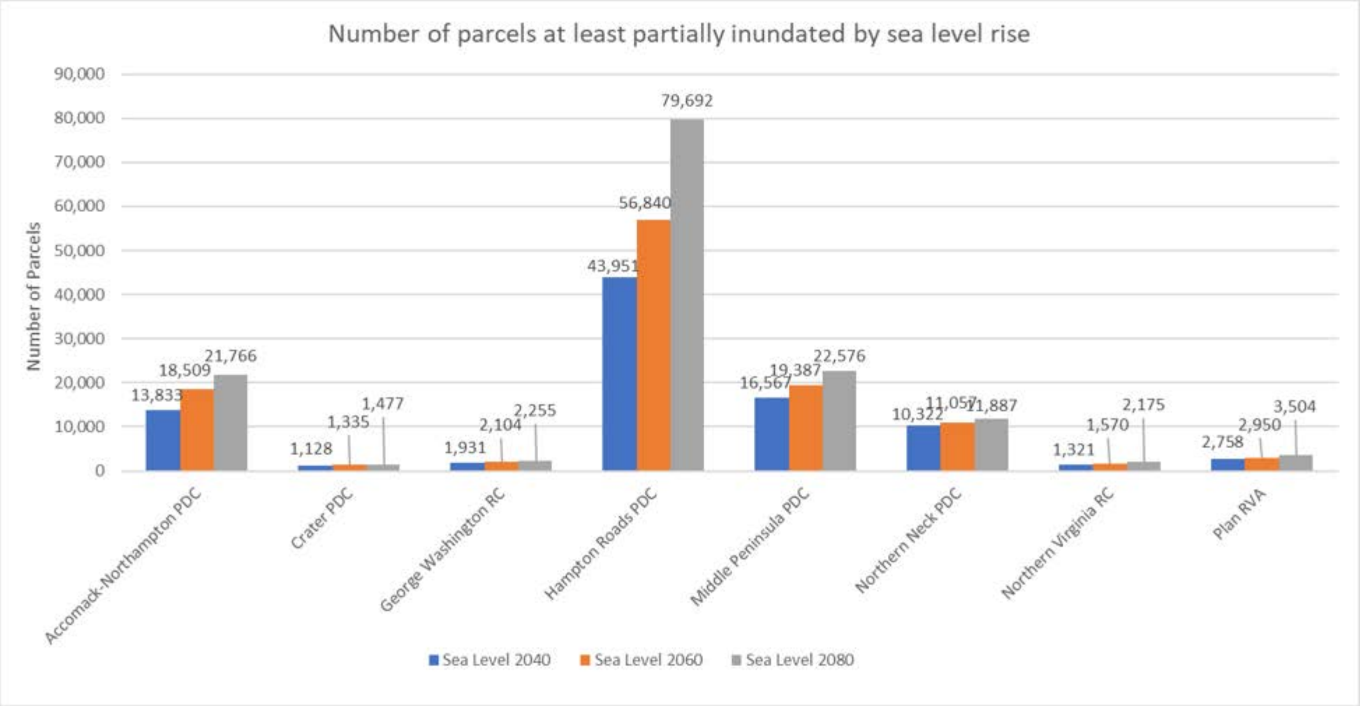
Real Property Parcels Impacted by Sea Level Rise:

Real property comprises land ownership boundaries (parcels) and the buildings on them. For the purpose of this assessment, we subdivide the analysis into potential parcel impacts and buildings.

For parcels, the study considers a potential impact any inundation that either wholly or partially overlays with the predicted relative sea level rise extent. Such parcels are tallied as "impacted" by future sea level rise. Hence, it provides a first approximation of exposure of a parcel, whereas more detailed vulnerability study would also incorporate susceptibility of a parcel flooding by functional use, assessed value, or damage, including acreage of land loss to permanent flooding. **FIGURE 5** enumerates the number of impacted parcels for each planning district at each modeled year. This overlay by intersection captures the extent that future high tide extends within the boundary of a parcel, thereby reducing or eliminating (in many cases) the land area available for use or development.

FIGURE 5

Existing Property Parcels in each planning district that will be impacted by sea level rise



Buildings Impacted by Sea Level Rise:

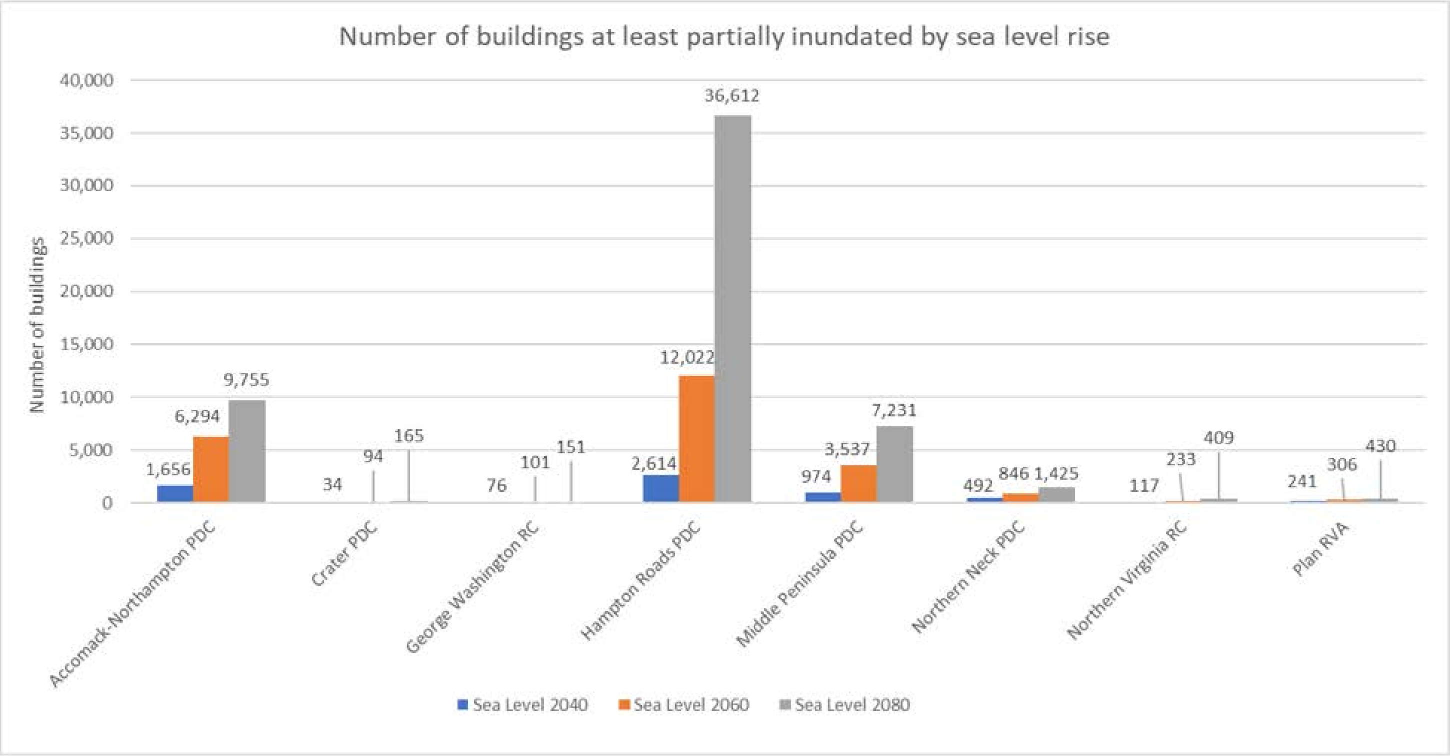
Impacts to existing buildings and other building-like structures were also modeled. The data supplied by VGIN for this analysis are described as follows, "Building footprints are polygon outlines of built structures digitized by Virginia Base Mapping Program's digital ortho-photogrammetry imagery, or digitizing of local government subdivision plats."[7] Those buildings that have a footprint either entirely within or intersecting the predicted future sea level boundary were considered to be impacted by sea level rise.

It is probable that buildings at or below the future high tide line will be rendered entirely unusable, necessitating relocation or demolition. **FIGURE 6** details the number of impacted buildings for each planning district at each modeled year.

It is unlikely that the building footprint data set captures 100% of buildings in the study area. However, the data are sufficiently complete to provide an indication of relative risk to buildings in the coastal planning districts.

FIGURE 6

Existing buildings in each planning district that potential impacted by sea level rise



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[7] VITA. Virginia GIS Clearinghouse. 2019 Q3Download: Building Footprint polygons (published quarterly). https://vgin.maps.arcgis.com/home/item.html?id=994d0afa44c046498f9774613671ce9a. Last accessed 11/01/2019.

Roadways Flooded by Sea Level Rise:

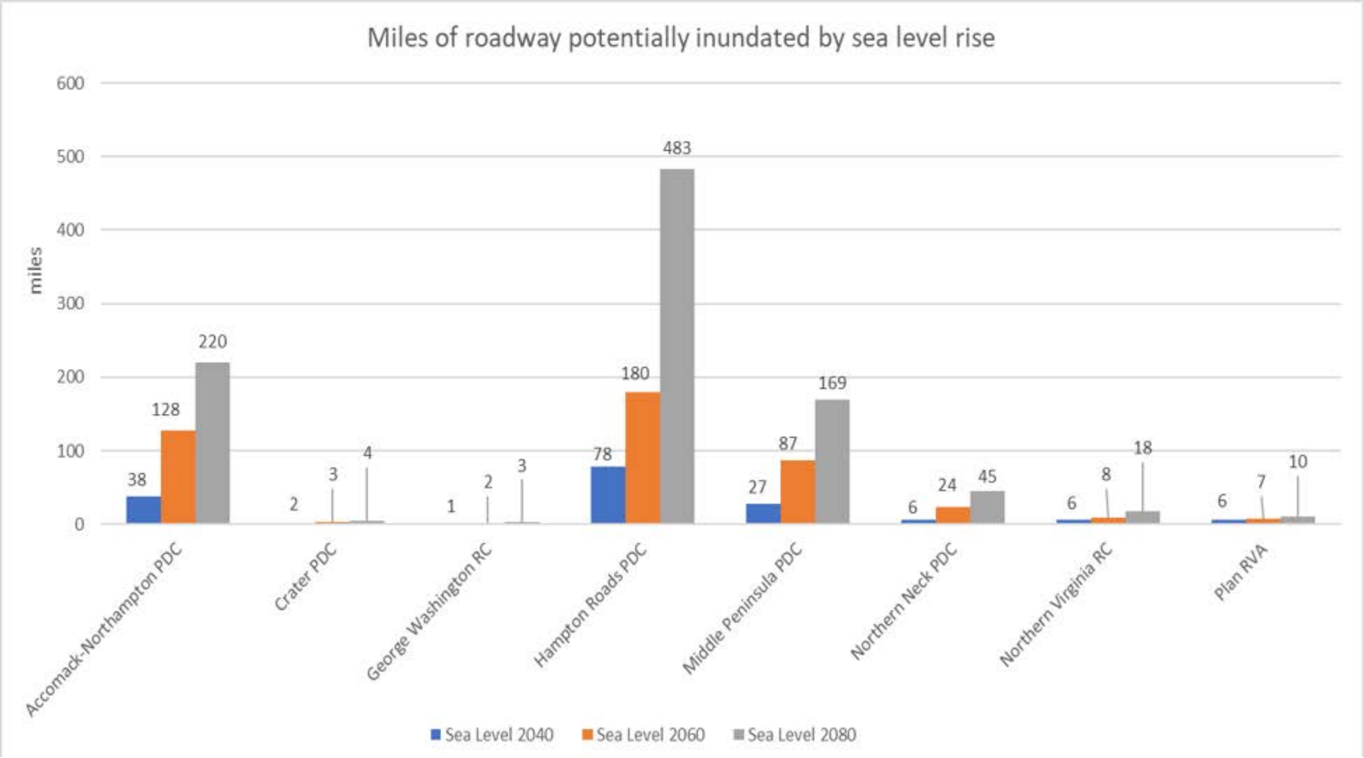
The impact of future sea level on roadways was also considered. Portions of the street centerline located within the boundaries of future predicted sea level, and therefore below the high tide line, were deemed to be impacted.

This preliminary, screening-level assessment does not differentiate among road type or function, USDOT classification, or vehicle miles traveled per day. Nonetheless, the spatial overlay of future flooding and existing roadways provides a baseline for further detailed transportation studies, including capturing vulnerability and susceptibility and structural adaptation or mitigation.

Many states, for instance, are conducting detailed transportation planning studies to inform future capital improvements, state and federal budget priorities, and identifying engineering alternatives for mitigation or roadway adaptation. Roadway impacts are also notable for potential underestimation, such as not considering the right of way and stormwater drainage conveyance, vegetated swales, or culverts and catch-basins bridges, etc. In addition, indirect impacts are not addressed here, including ecological flows, stormwater, fish passages, and other cascading impacts beyond this study. **FIGURE 7** details the total miles of roadway lost to sea level rise for each planning district at each modeled year.

FIGURE 7

Miles of roadway in each planning district that will be flooded by sea level rise



Cumulative Exposure of Relative Sea Level Rise:

TABLES 1 and **2** detail the exposure of sea level rise for each of the study area planning districts and the cumulative total for coastal Virginia.

TABLE 1

Total land and street flooding from sea level rise for coastal Virginia PDCs

	YEAR					
	2040		2060		2080	
PLANNING DISTRICT	LAND AREA (mi^2)	STREETS (mi)	LAND AREA (mi^2)	STREETS (mi)	LAND AREA (mi^2)	STREETS (mi)
Accomack-Northampton	164	38	199	128	228	220
Crater	10	2	12	3	14	4
George Washington	11	1	13	2	15	3
Hampton Roads	127	78	167	180	214	483
Middle Peninsula	58	27	78	87	101	169
Northern Neck	22	6	29	24	37	45
Northern Virginia	5	6	6	8	7	18
Richmond	28	6	30	7	33	10
TOTAL	**424**	**165**	**534**	**439**	**649**	**952**

TABLE 2

Total parcels and buildings impacted by SLR in coastal Virginia

	YEAR					
	2040		2060		2080	
PLANNING DISTRICT	PARCELS	BUILDINGS	PARCELS	BUILDINGS	PARCELS	BUILDINGS
Accomack-Northampton	13,833	1,656	18,509	6,294	21,766	9,755
Crater	1,128	34	1,335	94	1,477	165
George Washington	1,931	76	2,104	101	2,255	151
Hampton Roads	43,951	2,614	56,840	12,022	79,692	36,612
Middle Peninsula	16,567	974	19,387	3,537	22,576	7,231
Northern Neck	10,322*	492	11,057*	846	11,887*	1,425
Northern Virginia	1,321	117	1,570	233	2,175	409
Richmond	2,758	241	2,950	306	3,504	430
TOTAL	**91,811**	**6,204**	**113,752**	**23,433**	**145,332**	**56,178**

*NNPDC data excludes Northumberland County, for which no parcel data was available through the VA GIS Clearinghouse

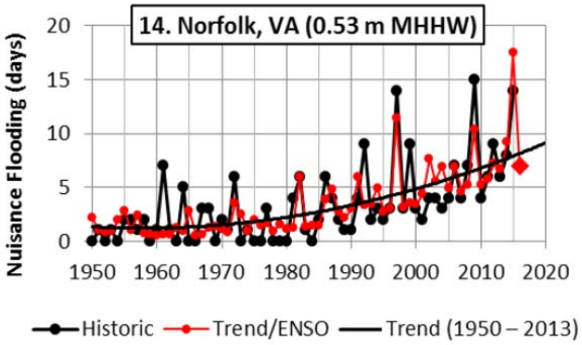
MINOR AND MODERATE FLOODING WITH RSLR MODELING

Reports of recurrent tidal flooding, often called “nuisance” flooding, in coastal Virginia have been increasing. Nuisance flooding is defined as a water level measured by NOAA tide gauges above the local NOAA National Weather Service (NWS) threshold for minor impacts established for emergency preparedness (Sweet and Marra, 2016).[8] A study by Fugro(2016) confirmed that tidal flooding in Norfolk’s Lafayette River watershed occurs frequently and is expected to worsen over time as sea level rises.[9]

A study by Fugro(2016) confirmed that tidal flooding in Norfolk’s Lafayette River watershed occurs frequently and is expected to worsen over time as sea level rises.

FIGURE 8

Annual flood frequencies (black circles) with 1950-2013 quadratic trends in Norfolk and bivariate regressions including ENSO effects and 2016 Outlook (adapted from Sweet and Marra, 2016)



In 2016, Sweet and Marra (2016) calculated the “nuisance flooding” threshold level for Norfolk, VA to be 0.53m above MHHW and predicted an accelerating trend of tidal flooding days per year (**FIGURE 8**).

NOAA has established three thresholds for coastal flood severity: (1) minor, (2) moderate, and (3) major. These thresholds are “based upon water level heights empirically calibrated to NOAA tide gauge measurements from years of impact monitoring.”[10] Minor refers to flooding which is more disruptive than damaging (includes tidal nuisance flooding), moderate refers to damaging flooding, and major is used to describe destructive flooding.

Concurrent with our analysis of SLR impacts using

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8. Sweet, W. and J. Marra. 2016. State of U.S. “Nuisance” Tidal Flooding. National Oceanic and Atmospheric Administration’s Center for Operational Oceanographic Products and Services and National Centers for Environmental Information. June 8, 2016. 5pp.

9. Fugro. 2016. Lafayette River Tidal Protection Alternatives Evaluation: City of Norfolk, City-wide Coastal Flooding Contract, Work Order No. 7. Fugro Project No. 04.8113009. 56pp.

10. Sweet, W., Dusek, G., Obeysekera, J., & Marra, J. (2018). Patterns and projections of high tide flooding along the U.S. coastline using a common impact threshold. NOAA technical report NOS CO-OPS, Vol. 86, National Oceanic and Atmospheric Administration, Silver Spring, Maryland, USA.

NOAA's intermediate-high curve, we have modeled the additional potential impacts of both minor (tidal) and moderate flood events for the entire study region for the years 2040, 2060, 2080.Tidal flooding water surface elevation data provided directly by NOAA were employed in these modeling efforts. Per NOAA staff, these experimental data are "based on interpolation from the NOAA report thresholds" (M. Pendleton, personal communication, September 17, 2019).[11]

Rather than relying only on a single tidal flooding threshold value (i.e. 0.53m), these surfaces establish a range of tidal water levels which would generate minor or moderate flooding throughout coastal Virginia. Predictive modeling using these data reveals which areas are at highest risk of being inundated during minor and moderate flooding events.

Land Area Vulnerable to Minor (Tidal) Flooding with RSLR:

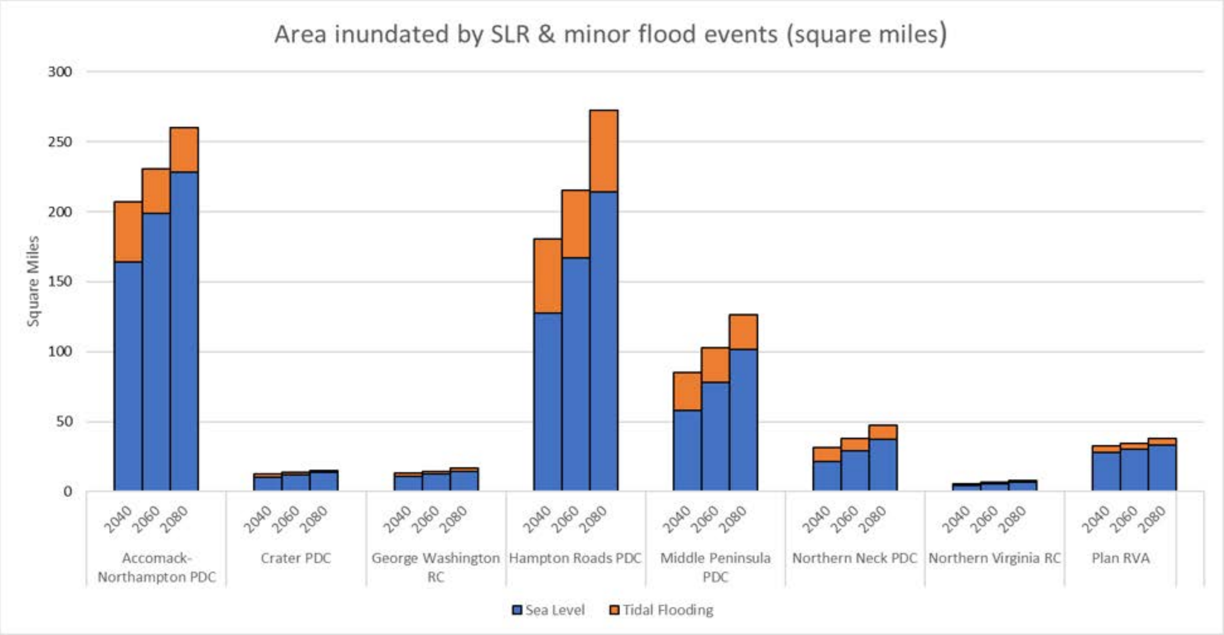
Our model predicts that over 140 square miles of land will be vulnerable to frequent recurrent tidal flooding, often called "nuisance" flooding by the year 2040. **FIGURE 9** shows the cumulative area of potential inundation from both sea level rise and minorflood events for each planning district. Hampton Roads, the Eastern Shore, and the Middle Peninsula display significant vulnerability to tidal and other minor recurrent flooding.

Buildings and Roadways impacted by Minor (Tidal) Flooding with RSLR:

FIGURES 10 & **11**, respectively, show the number of buildings and miles of roadway located within the area of highest risk during minor flooding events. Hampton Roads' high population density, coastal proximity, and low relief result in disproportionately elevated risk to infrastructure.

FIGURE 9

Present-day land area (including wetlands) in each planning district that will be flooded by sea level rise(blue) and at-risk during minor flooding events (orange). The stacked bars indicate that sea level rise progressively increases the extent of flooded areas.



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[11] 11. Pendleton, M. Lynker Technologies for NOAA OCM. September 17, 2019. Email communication.

FIGURE 10

Buildings potentially affected by relative sea level rise (blue) and at-risk during minor flooding events (orange)

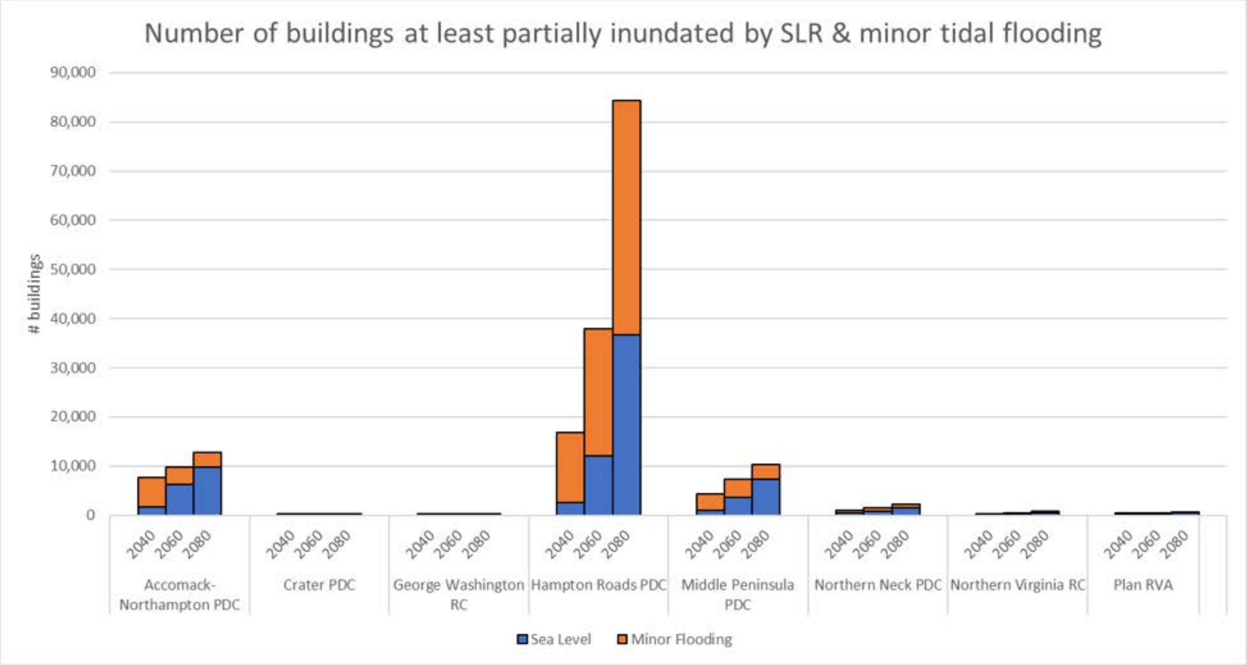
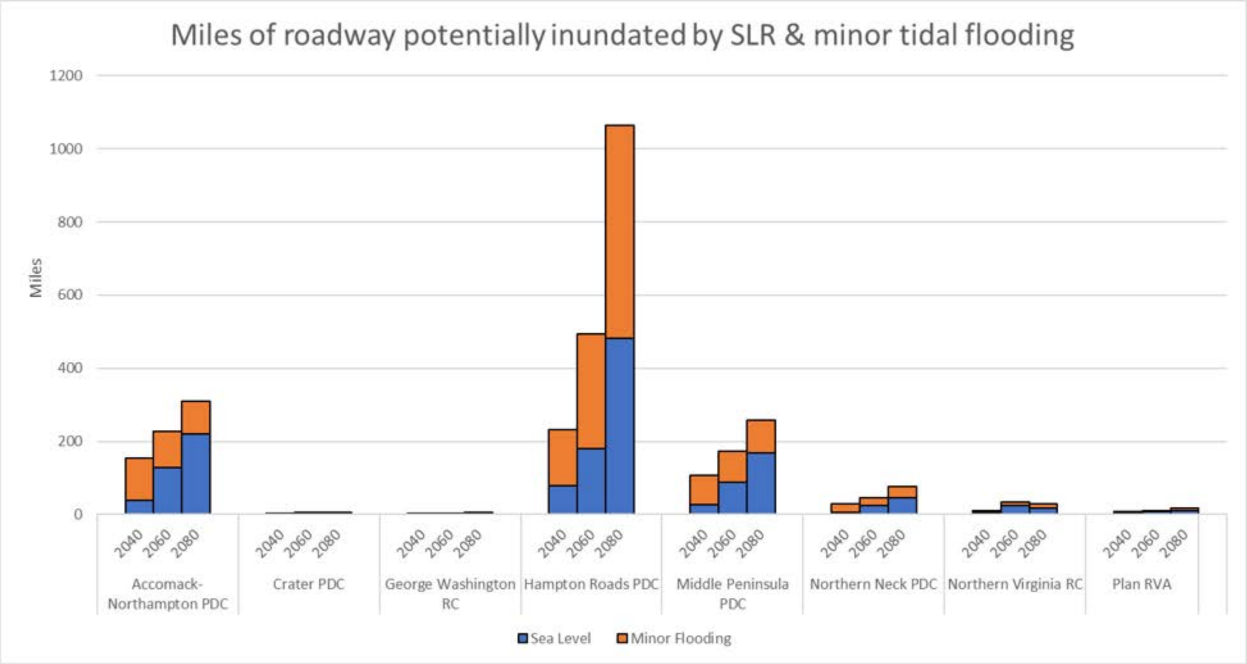


FIGURE 11

Streets potentially flooded by sea level rise (blue) and at-risk during minor flooding events (orange)



Cumulative Exposure of Minor (Tidal) Flooding with RSLR:

TABLES 3 and **4** detail the additional potential exposure of minor flooding with increasing relative sea level

TABLE 3

Total additional land and streets at-risk from minor flooding for coastal Virginia PDCs

YEAR

	2040		2060		2080	
PLANNING DISTRICT	**LAND AREA (mi^2)**	**STREETS (mi)**	**LAND AREA (mi^2)**	**STREETS (mi)**	**LAND AREA (mi^2)**	**STREETS (mi)**
Accomack-Northampton	44	116	32	99	32	90
Crater	2	1	2	1	2	1
George Washington	3	1	2	1	2	2
Hampton Roads	53	152	48	313	58	580
Middle Peninsula	27	79	24	85	25	90
Northern Neck	10	24	9	22	10	30
Northern Virginia	1	5	1	9	1	11
Richmond	4	2	4	3	5	6
TOTAL	**144**	**380**	**122**	**534**	**135**	**810**

TABLE 4

Total additional parcels and buildings at-risk from minor flooding for coastal Virginia PDCs

YEAR

	2040		2060		2080	
PLANNING DISTRICT	**PARCELS**	**BUILDINGS**	**PARCELS**	**BUILDINGS**	**PARCELS**	**BUILDINGS**
Accomack-Northampton	5,721	5,970	3,478	3,563	3,195	2,961
Crater	232	90	143	73	135	47
George Washington	233	35	165	53	186	65
Hampton Roads	15,795	14,200	23,939	25,858	39,106	47,734
Middle Peninsula	3,612	3,439	3,282	3,828	2,907	3,045
Northern Neck	919*	525	849*	613	1,020*	822
Northern Virginia	352	245	471	187	1,475	429
Richmond	287	87	599	132	1,041	264
TOTAL	**27,151**	**24,591**	**32,926**	**34,307**	**49,065**	**55,367**

*NNPDC data excludes Northumberland County, for which no parcel data was available through the VA GIS Clearinghouse

Land Area Vulnerable to Moderate Flooding with RSLR:

Areas at risk from moderate flood events are naturally inclusive of those that would also be impacted by minor tidal flooding. The threshold for moderate flooding, as defined by NOAA, is met when there is damaging flooding not associated with tropical storms (includes hurricanes). **FIGURE 12** shows the cumulative area of potential inundation from both sea level rise and moderate flood events for each planning district.

The additional areas of potential inundation by moderate flooding are significant, particularly in Hampton Roads, the Eastern Shore, and the Middle Peninsula. Examination of the potential impact to buildings and roadways once again underscores regional disparities and highlights the critical nature of the problem for Hampton Roads. **FIGURES 13** & **14** , respectively, show the number of buildings and miles of roadway located within the area of highest risk during moderate flooding events.

FIGURE 12

Present-day land area (including wetlands) in each planning district that will be flooded by sea level rise(blue) and at-risk during moderate flooding events (orange).

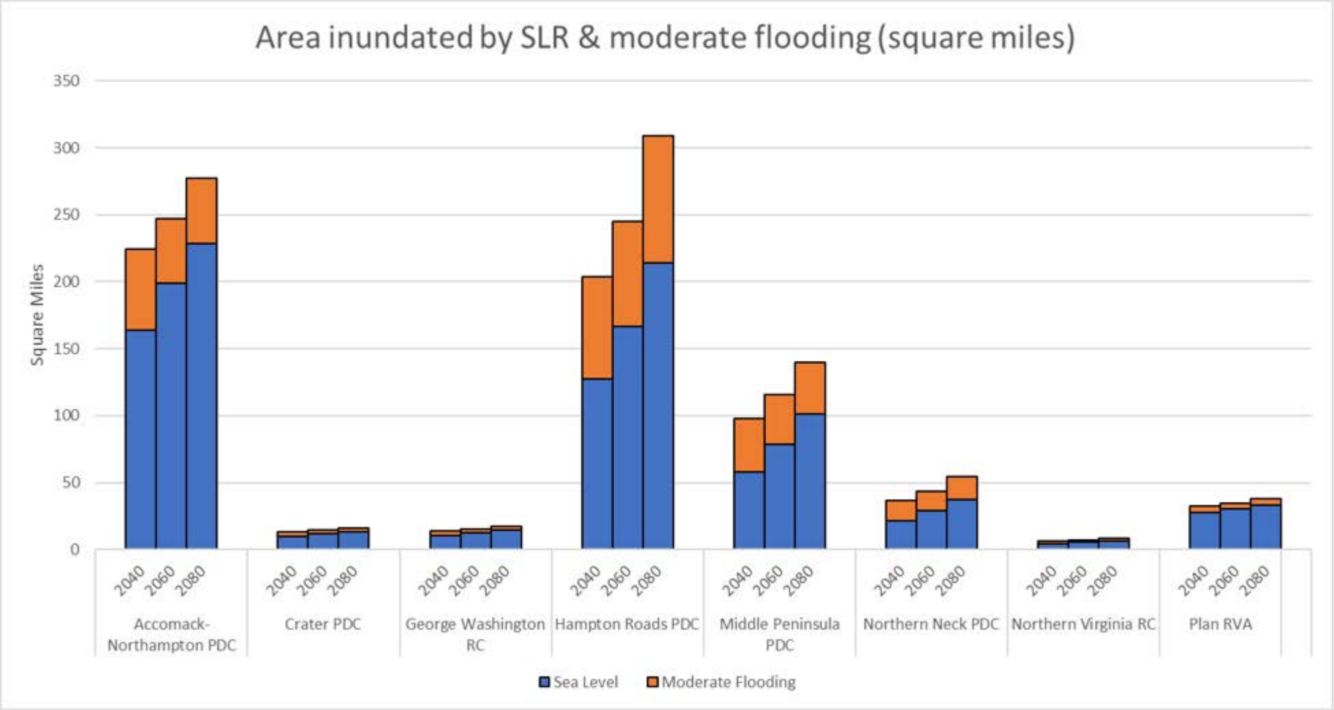


FIGURE 13

Buildings flooded by sea level rise (blue) and at-risk during moderate flooding events (orange)

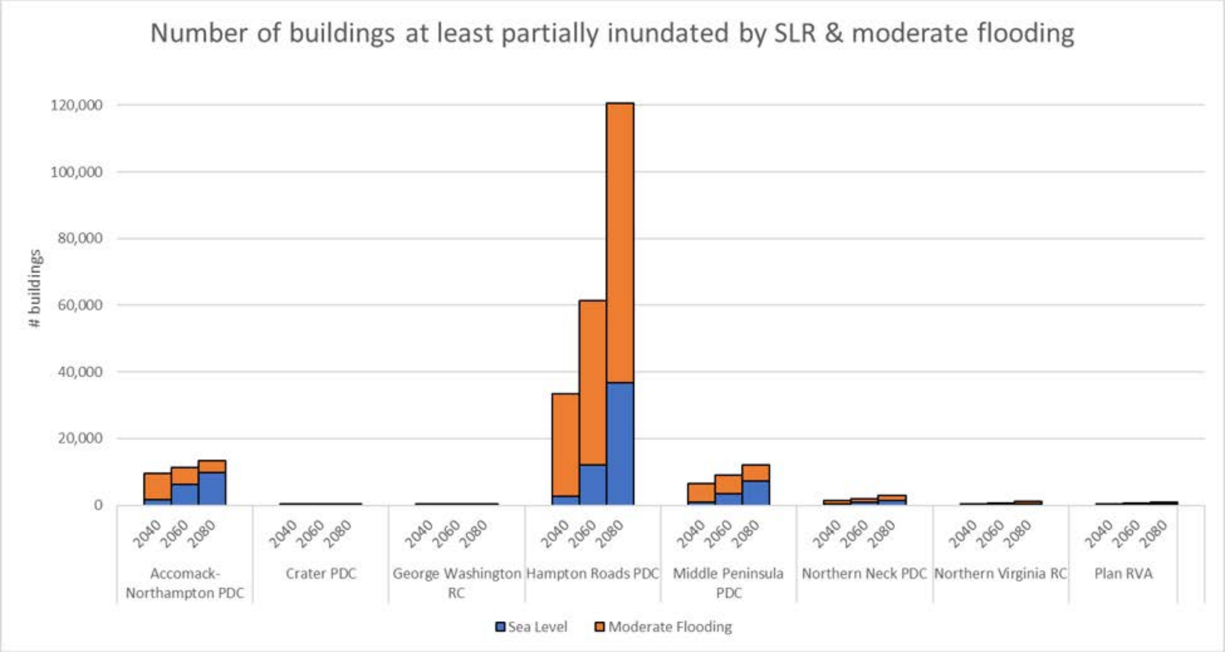
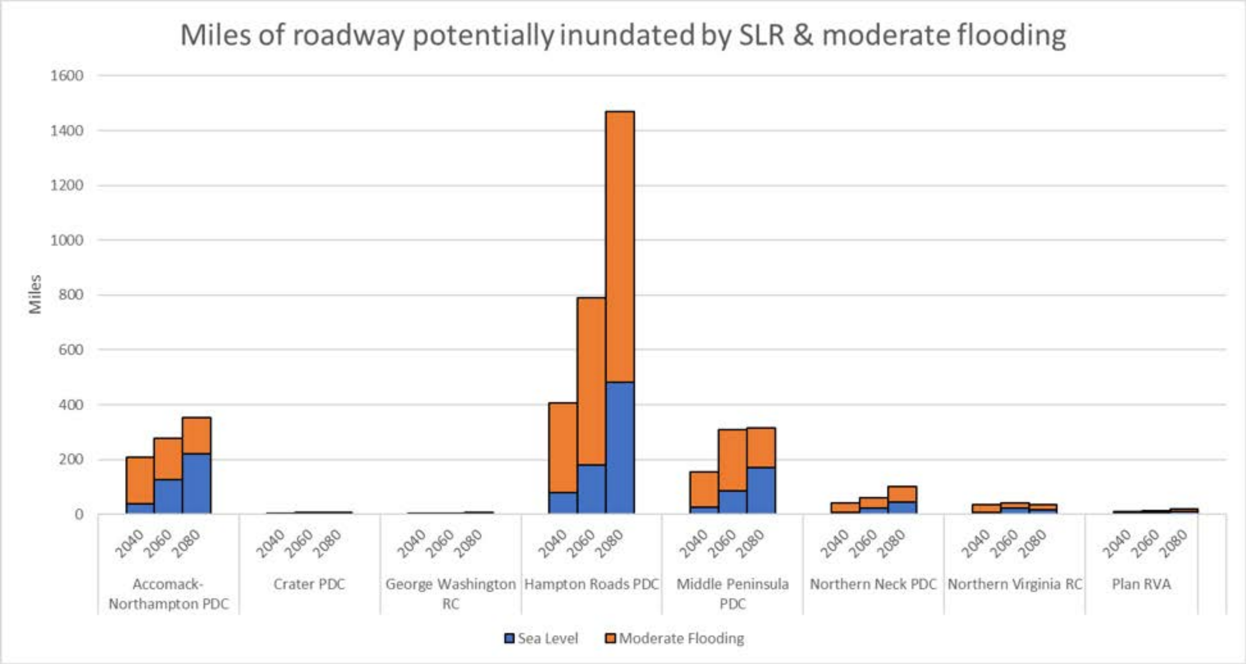


FIGURE 14

Roads flooded by sea level rise (blue) and at-risk during moderate flooding events (orange).



Cumulative Exposure of Moderate Flooding with RSLR:

TABLES 5 and **6** detail the cumulative exposure of moderate flooding with rising relative sea level for the entire study region.

TABLE 5

Total additional land and streets at-risk from moderate flooding for coastal Virginia PDCs

YEAR

	2040		2060		2080	
PLANNING DISTRICT	**LAND AREA (mi^2)**	**STREETS (mi)**	**LAND AREA (mi^2)**	**STREETS (mi)**	**LAND AREA (mi^2)**	**STREETS (mi)**
Accomack-Northampton	61	170	48	149	49	135
Crater	3	2	3	2	2	2
George Washington	4	2	3	2	3	4
Hampton Roads	77	328	78	610	95	987
Middle Peninsula	40	127	38	222	39	147
Northern Neck	15	37	14	38	18	57
Northern Virginia	2	30	2	17	2	18
Richmond	5	4	5	6	5	11
TOTAL	**207**	**700**	**191**	**1,046**	**213**	**1,361**

TABLE 6

Total additional parcels and buildingsat-risk from moderate flooding for coastal Virginia PDCs

YEAR

	2040		2060		2080	
PLANNING DISTRICT	**PARCELS**	**BUILDINGS**	**PARCELS**	**BUILDINGS**	**PARCELS**	**BUILDINGS**
Accomack-Northampton	7,561	7,808	5,279	5,068	4,089	3,638
Crater	315	121	221	94	222	78
George Washington	305	68	276	85	302	119
Hampton Roads	29,908	30,756	46,626	49,300	70,312	83,941
Middle Peninsula	5,432	5,575	4,922	5,569	4,832	4,836
Northern Neck	1,471*	870	1,469*	1,075	1,805*	1,404
Northern Virginia	792	272	1,594	415	2,050	669
Richmond	641	170	1,178	229	1,621	486
TOTAL	**46,425**	**45,640**	**61,565**	**61,835**	**85,233**	**95,171**

*NNPDC data excludes Northumberland County, for which no parcel data was available through the VA GIS Clearinghouse

This study focused on developing the future potential extent of various tidal and non-tidal flooding events, presented in the included maps and charts. In addition, recurrent tidal flooding will have impacts attributed to frequency and duration of flooding, particularly for wetlands and roadway not previously affected by increasingly higher tides and, especially, salinity.

Another compounding factor bearing on recurrent flooding is that of "combined flooding" owing to both extreme rainfall and tidal flooding. As tidal flooding increases in extent, frequency, and duration with sea level rise, rainfall runoff co-occurring with tidal flooding will exacerbate flood extent, depth, and impacts. Multiple recent studies also point to increasingly extreme rainfall events, evidenced in rainfall intensity and shorter return periods and affirming predicted regional climate change.[12,13] Thus, combined flooding bears further research and study, as rainfall hydrology is likely to co-occur and compound tidal flooding. In order to meet the need for an expedited assessment, this study was not able to include the rapidly developing scientific understanding of combined flooding and the interaction of extreme rainfall and increasing tidal water levels.

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12. Allen, Michael J. and Allen, Thomas R. 2019. "Precipitation Trends across the Commonwealth of Virginia (1947 –2016)," Virginia Journal of Science: Vol. 70 : No. 1 , Article 4. DOI: 10.25778/3cay-z849. https://digitalcommons.odu.edu/vjs/vol70/iss1/4

13. Dewberry. 2017. Joint Occurrence and Probabilities of Tides and Rainfall, City of Virginia Beach, Virginia. CIP 7-030, PWCN-15-0014, Work Orders 2 and 5A. Final Report. October 9, 2017. 55pp. https://www.vbgov.com/government/departments/public-works/comp-sea-level-rise/Documents/joint-occ-prob-of-tides-rainfall-4-24-18.pdf

WEB MAP AND DATA LAYER SHARING

Data developed by this study for land areas, buildings, and streets vulnerable to inundation by sea level rise and both minor (tidal) and moderate flooding are available for viewing in a web map at the below address (subject to future update).

Web Map: Coastal Virginia Sea Level with Minor and Moderate Flooding (NOAA Int-High Scenario2017)

URL: https://tinyurl.com/CoVA-SLR-Inundation-NOAA2017

Planners or other users can access the publicly shared map as streaming Web Map Services (WMS) layers or may email geovis@olddominion.onmicrosoft.com to request download access.

STUDY LIMITATIONS

The accuracy of inundation modeling is largely dependent upon the quality of digital elevation data used in the analysis. Errors in elevation surfaces will naturally propagate to final model results. Elevation discrepancies may result in shifts in the predicted flood boundary. These shifts may have the effect of either over-or under-predicting flooding extent depending on the direction (positive or negative) of elevation error.

The use of high-quality LiDAR-derived elevation surfaces for this study helps to minimize positional errors.

The use of high-quality LiDAR-derived elevation surfaces for this study helps to minimize positional errors. Further improvements could be developed to refine the areas of impact by applying fine scale hydrocorrection (Allen and Howard 2014), which would also improve roadway and drainage analyses and property susceptibility by reducing areas of omission of flooding impacts.[14]

In addition to the accuracy of underlying elevation data, some variables were not modeled and require further research, such as dynamic geomorphology and the developing data on vertical land motion and subsidence, infrastructure improvements, storm water system connectivity, groundwater hydrology, and other local factors may all impact future flooding severity and connectivity.

Local land subsidence data are very limited and presented a constraint to this study, which relied on long-term, high-precision tide gage data.

The study did not address storm surges and changes in storminess associated with climate change that will co-occur with sea level rise. Integrating climate change more widely into sea level rise risk assessment requires highly computational modeling and consideration of multiple, , interacting probabilistic changes (increasing tidal flooding, increasing storm energy, potential increase frequency of storms) well beyond the scope of tidal flooding in this project.

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[14] 14. Allen,T. and R. Howard. 2015. Improving Low-Relief Coastal LiDAR DEMs with Hydro-Conditioning of Fine-Scale andArtificial Drainages. Front. Earth Sci. 3:72. doi: 10.3389/feart.2015.00072

CONCLUSIONS AND FUTURE WORK

Model results and related graphics clearly illustrate that the Hampton Roads, Accomack-Northampton, and Middle Peninsula planning districts will be the most severely and disproportionally impacted.

Broad studies such as this should be used to inform and assist with the prioritization of more detailed, fine-scale analyses.

Map data and graphics are included in both the online web map and in the Appendix to provide more detailed illustrations of the localized impacts of sea level rise and tidal flooding. Hydrologically disconnected areas of potential inundation were preserved to highlight areas of increased, yet uncertain, vulnerability. Identifying these potential vulnerabilities provides opportunity for further analyses needed to better define localized flooding risk.

Broad studies such as this should be used to inform and assist with the prioritization of more detailed, fine-scale analyses. The final maps in the Appendix provide examples of how the implications of sea level rise can be examined at local scales for areas of critical risk and/or high value. Localized impacts analysis allows for the inclusion of comprehensive and highly specific asset inventories,which are unique to each study area. Highly developed asset inventories, combined with sea level and tidal flooding modeling, are necessary for identifying and quantifying the level of risk and potential cost of response.

It is recommended that this work be extended, and additional analysis performed to quantify the regional impacts of SLR in smaller geographic areas. Areas of potential critical impact should be identified for high-resolution development of asset inventories and focused analyses of physical and economic impacts of SLR.

This screening-level assessment is distinctly different from narrow spatial and feature-based risk assessments driven by land or resource managers, engineers,or planners. The limitations noted above should not detract from the potential to utilize the products and GIS data for planning today. Nonetheless, a series of prioritized enhancements are provided below, which could increase resilience to coastal hazards associated with sea level rise, especially flooding.

1. ***Need for Fine-Scale Elevation Data***
   This study used the best available elevation, tidal projections, and subsidence data, yet additional research has illustrated new techniques can further refine these data. Even higher resolution LiDAR, fine-scale hydrocorrection, digitally mapping ditches and low-relief drainage features, and expanding the availability of these improved GIS datasets could a) reduce the uncertainty that areas at risk are accidentally or unknowingly missed or omitted in flood risk mapping and b) provide more accurate data for detailed flooding modeling, stormwater engineering, and road or other construction, potentially reducing costs for adaptation and mitigation.

2. ***Assess Compounding Risk from Combined Flooding***
   Only a few very recent studies have quantitatively verified the increases in extreme rainfall, corroborating global and regional climate models. Yet, few spatial risk assessments have been conducted that identify these risks and impacts (primarily in larger cities with the capacity to fund them). Projects that could support more extensive regional rainfall study and climatology could inform stormwater engineering and drainage planning as well as coupling dynamic rainfall interactions with tidal flooding and sea level rise.

3. ***Assimilating Real Property, Building,and Infrastructure Data***
   Some data gaps were revealed in the analysis of coastal parcels. Building structures almost universally lack detailed First Floor Elevations (FFEs) which areessential to assessing susceptibility and mitigating flood risks. Future studies might develop cost-effective techniques to capture FFEs as well as building structural characteristics (e.g., foundation types) that are critical to damage assessment, flood insurance costs, and other floodplain policy and emergency management.

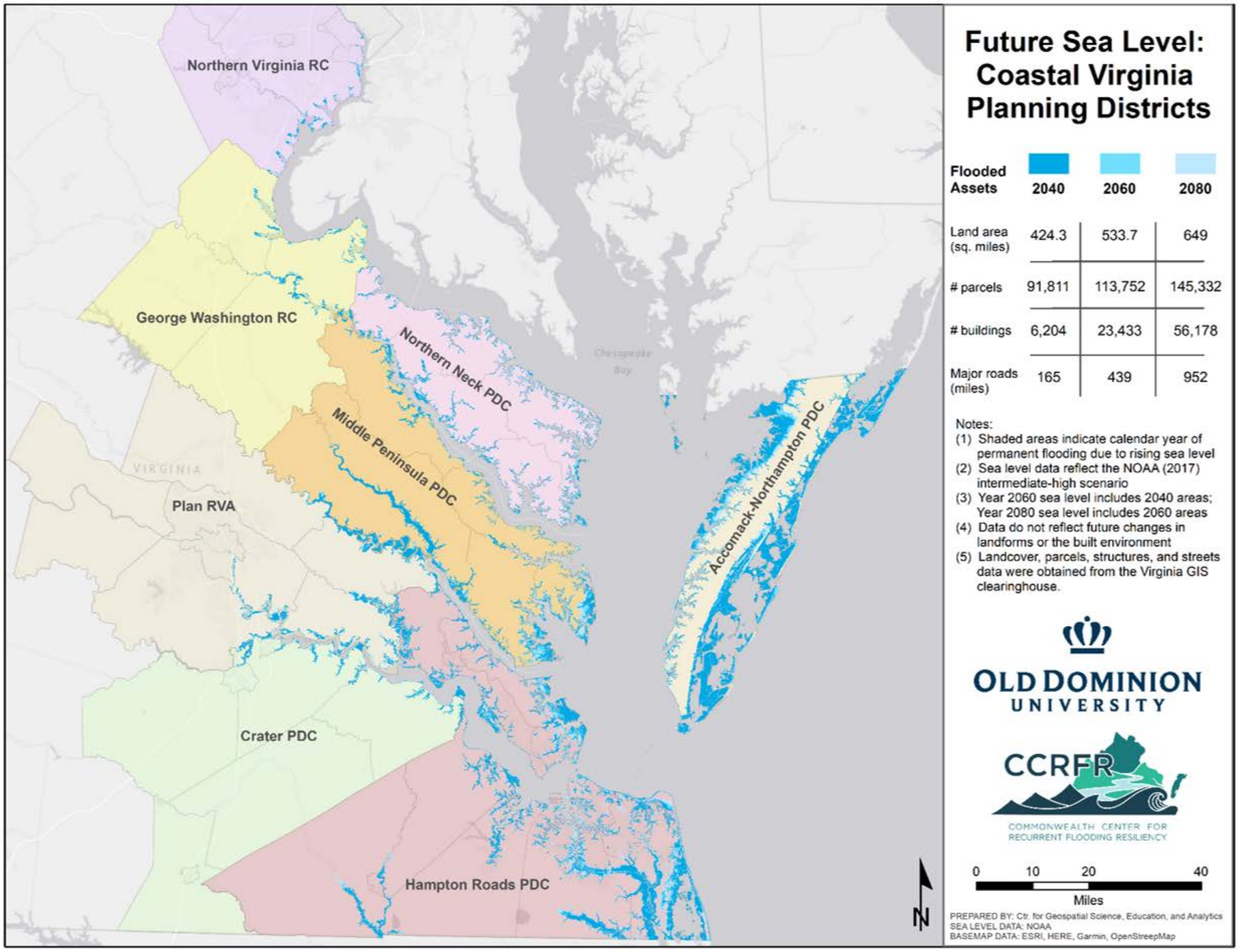
4. ***Assessing Emerging Risks and Cascading Impacts***
   This project assessed potential SLR impacts in unique features, land areas, parcels, buildings and roads. However, interacting, indirect, and even cumulative impacts may affect vulnerability. Wetlands loss or migration, also not a focus of this study, could lead to increasing inundation and loss of flood protection and ecosystem services. Ground water inundation could reduce storage during tides and rainfall flooding, resulting in increased surface flooding and damage to underground septic systems and utilities.

5. ***Storm Surge and Flood Modeling***
   Whereas this study focused on dynamic changes in sea level rise and tidal flooding, additional research is critically necessary to capture future storm surge flood risk. This would entail the inclusion of multiple, joint probabilities, including storminess, storm tracks and frequency, strength, and other meteorological dynamics with climate change (e.g., extreme rainfall, tropical storms, and extra tropical or nor'easter storms.)

APPENDIX

MAP 1

All Planning Districts



Future Sea Level: Coastal Virginia Planning Districts

Flooded Assets	2040	2060	2080
Land area (sq. miles)	424.3	533.7	649
# parcels	91,811	113,752	145,332
# buildings	6,204	23,433	56,178
Major roads (miles)	165	439	952

Notes:

(1) Shaded areas indicate calendar year of permanent flooding due to rising sea level
(2) Sea level data reflect the NOAA (2017) intermediate-high scenario
(3) Year 2060 sea level includes 2040 areas; Year 2080 sea level includes 2060 areas
(4) Data do not reflect future changes in landforms or the built environment
(5) Landcover, parcels, structures, and streets data were obtained from the Virginia GIS clearinghouse.

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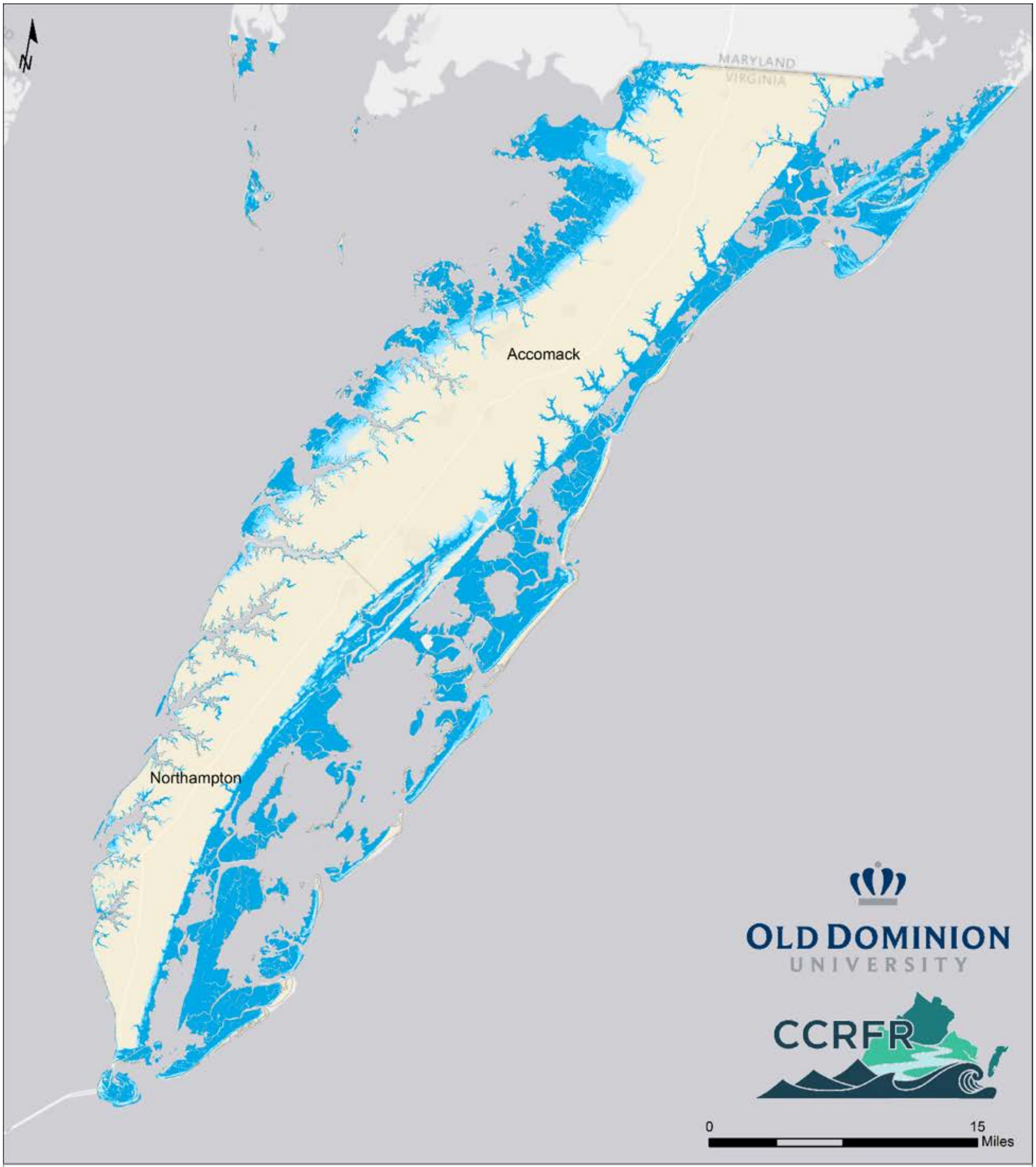
PREPARED BY: Ctr. for Geospatial Science, Education, and Analytics
SEA LEVEL DATA: NOAA
BASEMAP DATA: ESRI, HERE, Garmin, OpenStreepMap

MAP 2

Accomack-Northampton PDC



Future Sea Level: Accomack-Northampton Planning District

	Land area impacted (sq.mi.)$_3$	Number Parcels impacted	Number Structures impacted	Streets impacted (miles)
2040	164	13,833	1,656	38
2060	199	18,509	6,294	128
2080	228	21,766	9,755	220

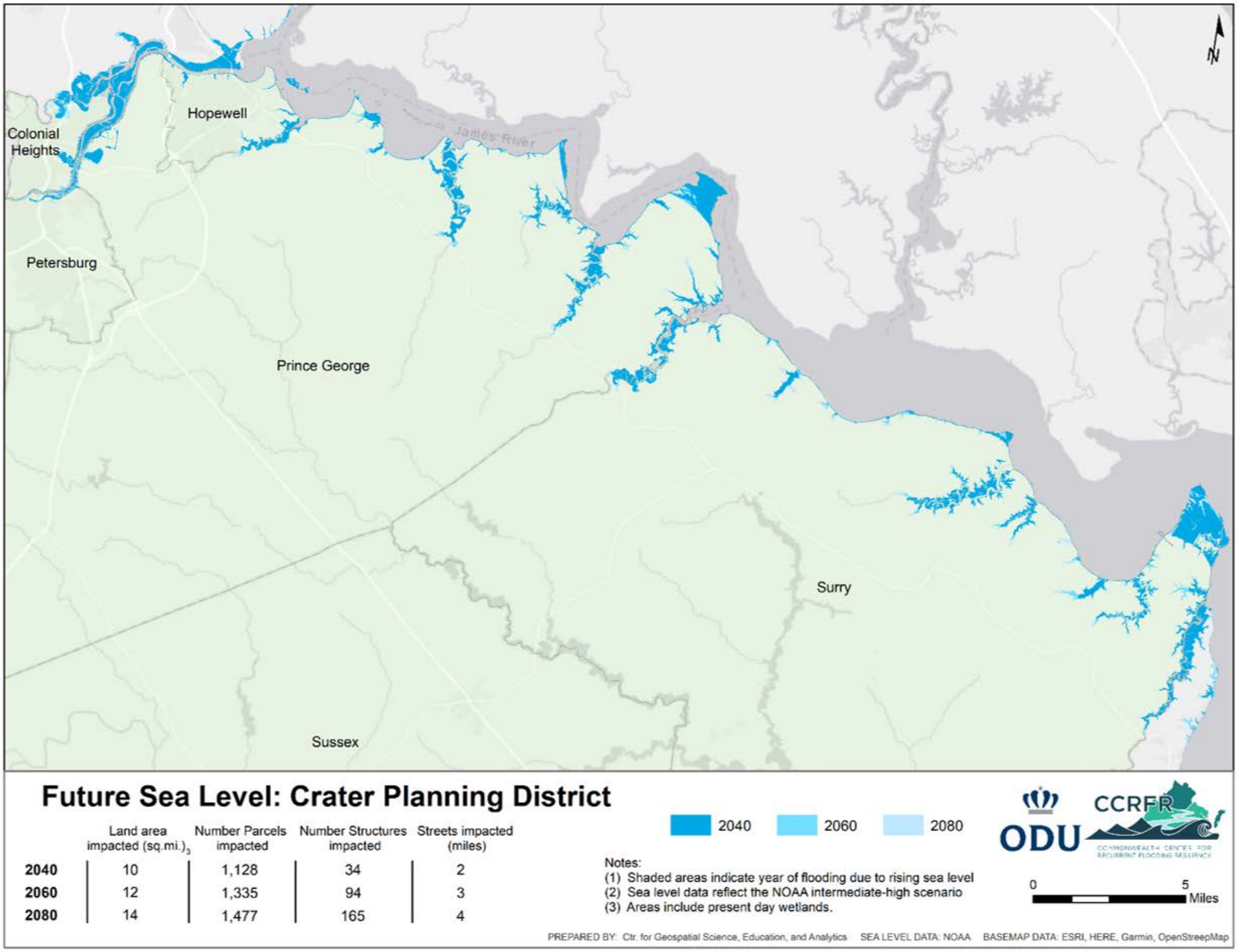
🟦	2040
🟦	2060
🟦	2080

Notes:
(1) Shaded areas indicate year of flooding due to rising sea level
(2) Sea level data reflect the NOAA intermediate-high scenario
(3) Areas include present day wetlands.

PREPARED BY: Ctr. for Geospatial Science, Education, and Analytics SEA LEVEL DATA: NOAA BASEMAP DATA: ESRI, HERE, Garmin, OpenStreepMap

MAP 3

Crater PDC



Future Sea Level: Crater Planning District

	Land area impacted (sq.mi.)$_3$	Number Parcels impacted	Number Structures impacted	Streets impacted (miles)
2040	10	1,128	34	2
2060	12	1,335	94	3
2080	14	1,477	165	4

Notes:
(1) Shaded areas indicate year of flooding due to rising sea level
(2) Sea level data reflect the NOAA intermediate-high scenario
(3) Areas include present day wetlands.

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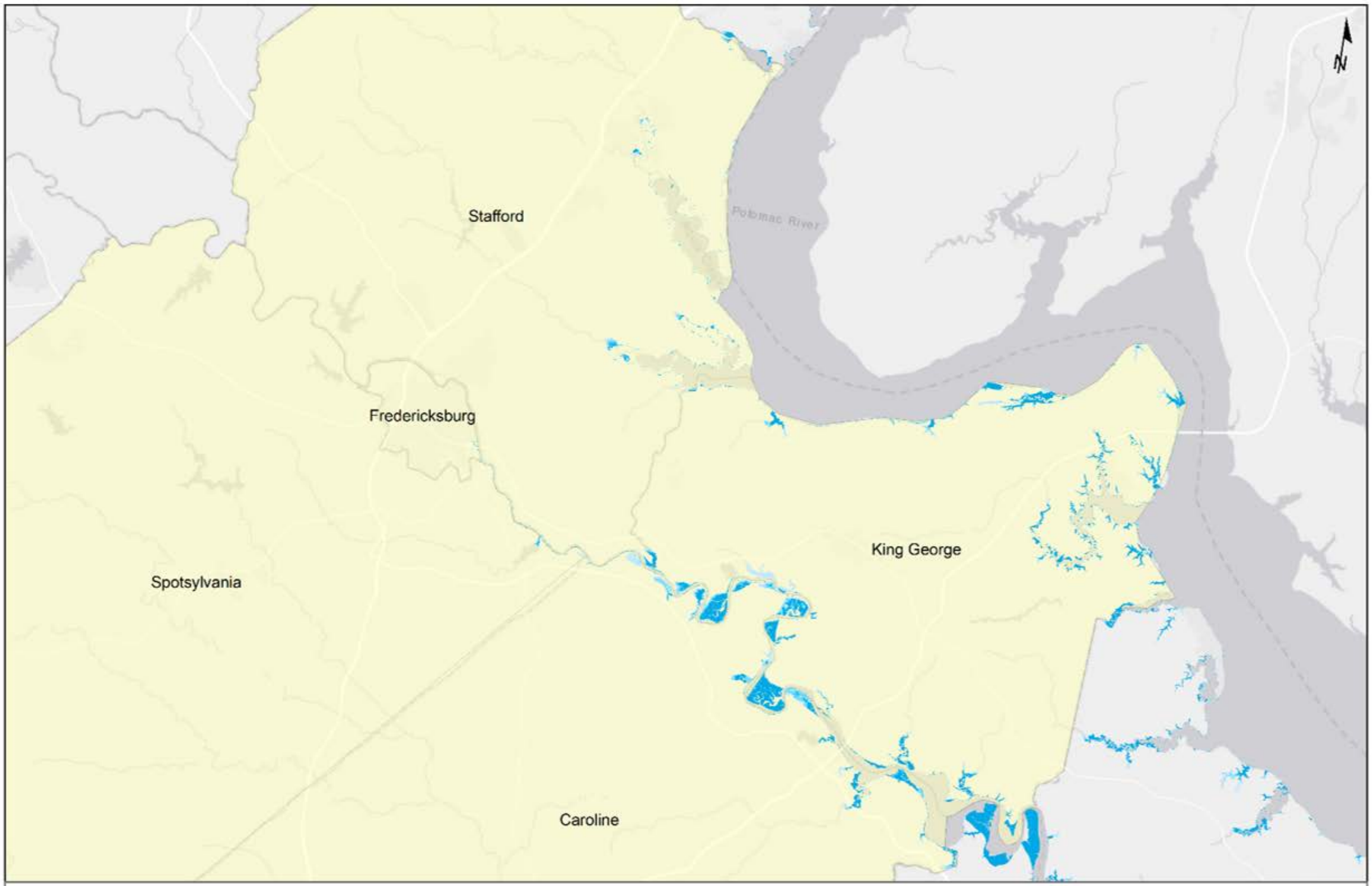
MAP 4

George Washington RC



Future Sea Level: George Washington Regional Commission

	Land area impacted (sq.mi.)$_3$	Number Parcels impacted	Number Structures impacted	Streets impacted (miles)
2040	11	1,931	76	1
2060	13	2,104	101	2
2080	15	2,255	151	3

🟦 2040 🟦 2060 🟦 2080

Notes:
(1) Shaded areas indicate year of flooding due to rising sea level
(2) Sea level data reflect the NOAA intermediate-high scenario
(3) Areas include present day wetlands.

0 10 Miles

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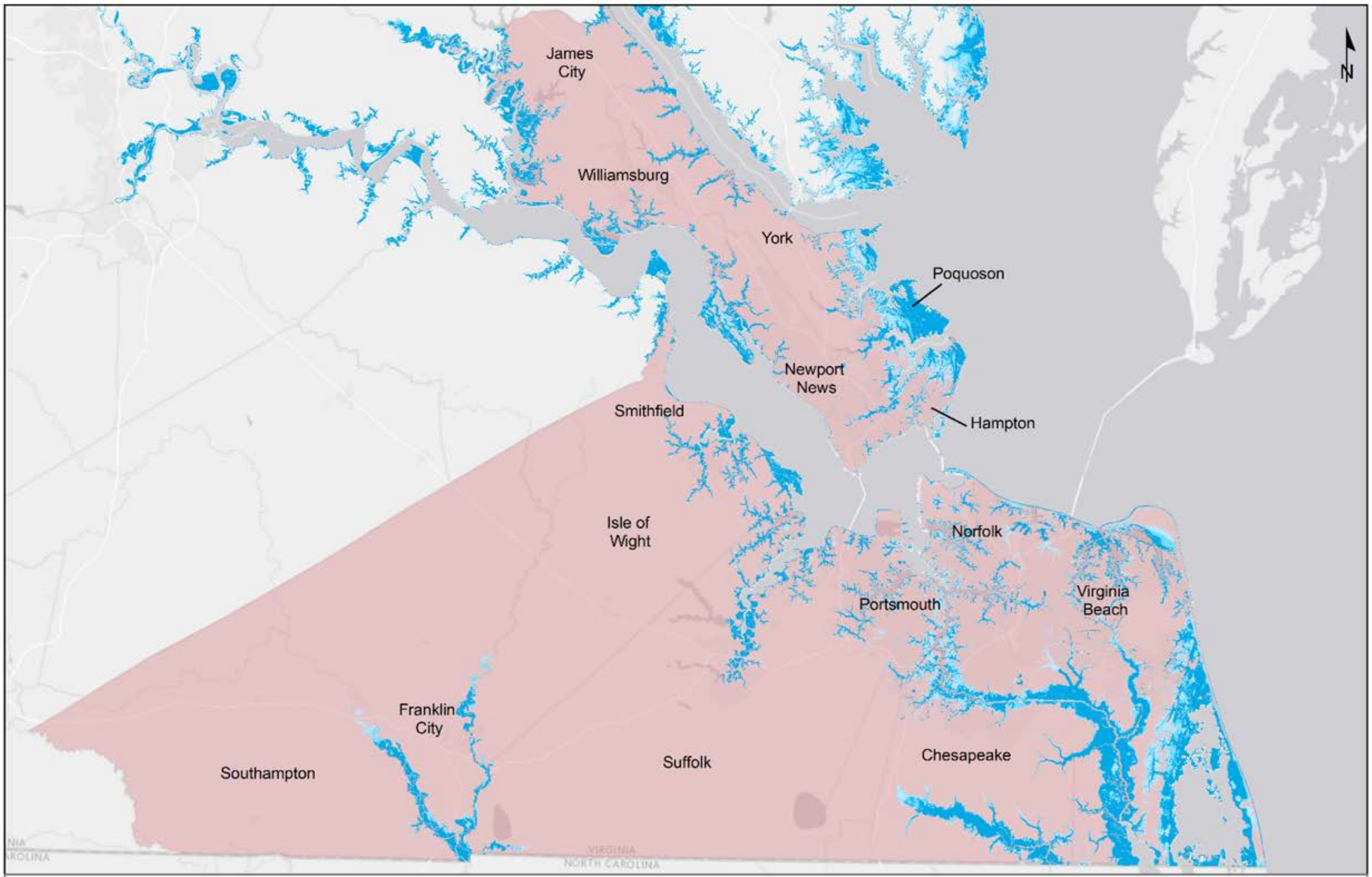
MAP 5

Hampton Roads PDC



Future Sea Level: Hampton Roads Planning District

	Land area impacted (sq.mi.)[3]	Number Parcels impacted	Number Structures impacted	Streets impacted (miles)
2040	127	43,951	2,614	78
2060	167	56,840	12,022	180
2080	214	79,692	36,612	483

▨ 2040 ▨ 2060 ▨ 2080

Notes:
(1) Shaded areas indicate year of flooding due to rising sea level
(2) Sea level data reflect the NOAA intermediate-high scenario
(3) Areas include present day wetlands.

0 20
Miles

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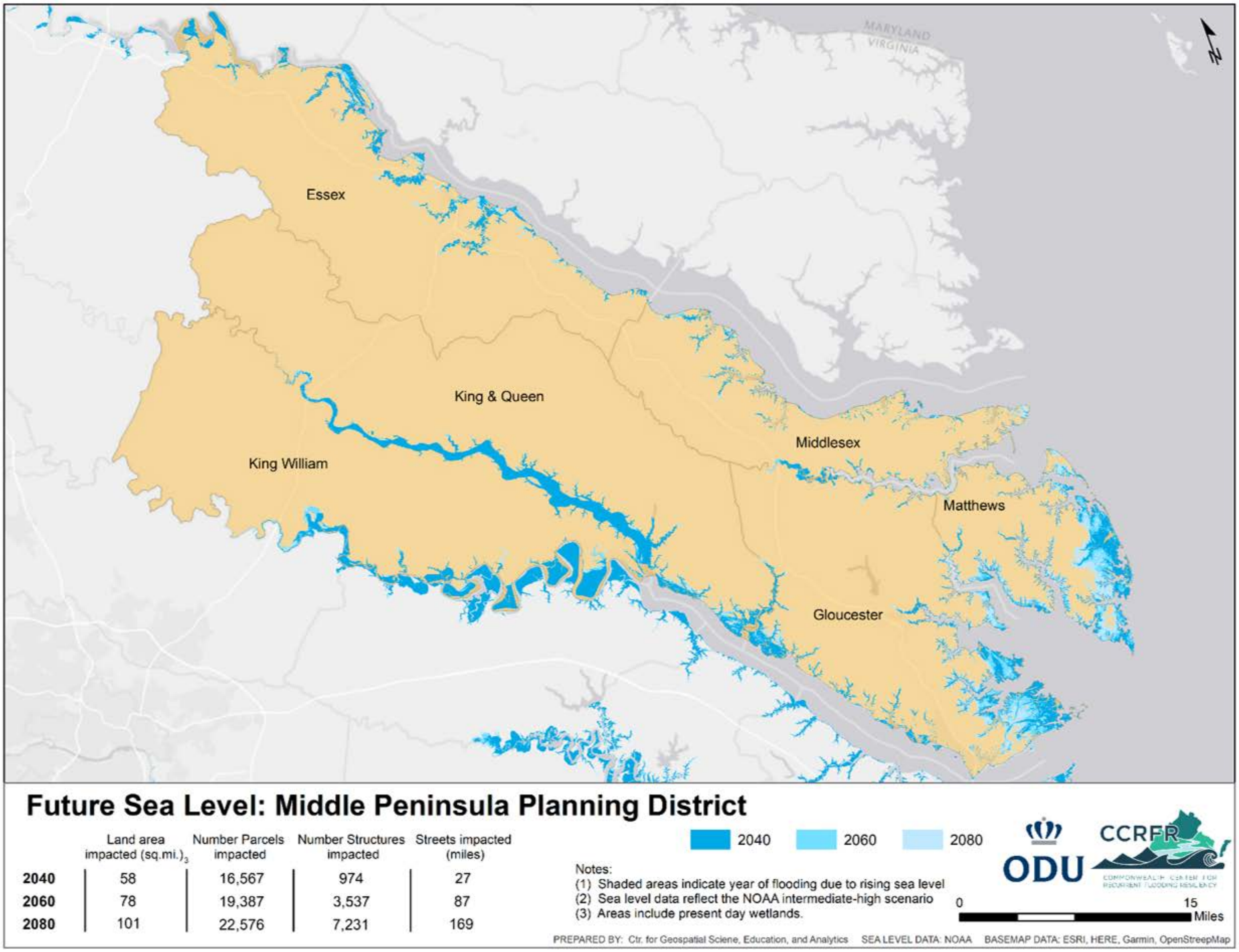
MAP 6

Middle Peninsula PDC



Future Sea Level: Middle Peninsula Planning District

	Land area impacted (sq.mi.)[3]	Number Parcels impacted	Number Structures impacted	Streets impacted (miles)
2040	58	16,567	974	27
2060	78	19,387	3,537	87
2080	101	22,576	7,231	169

Notes:
(1) Shaded areas indicate year of flooding due to rising sea level
(2) Sea level data reflect the NOAA intermediate-high scenario
(3) Areas include present day wetlands.

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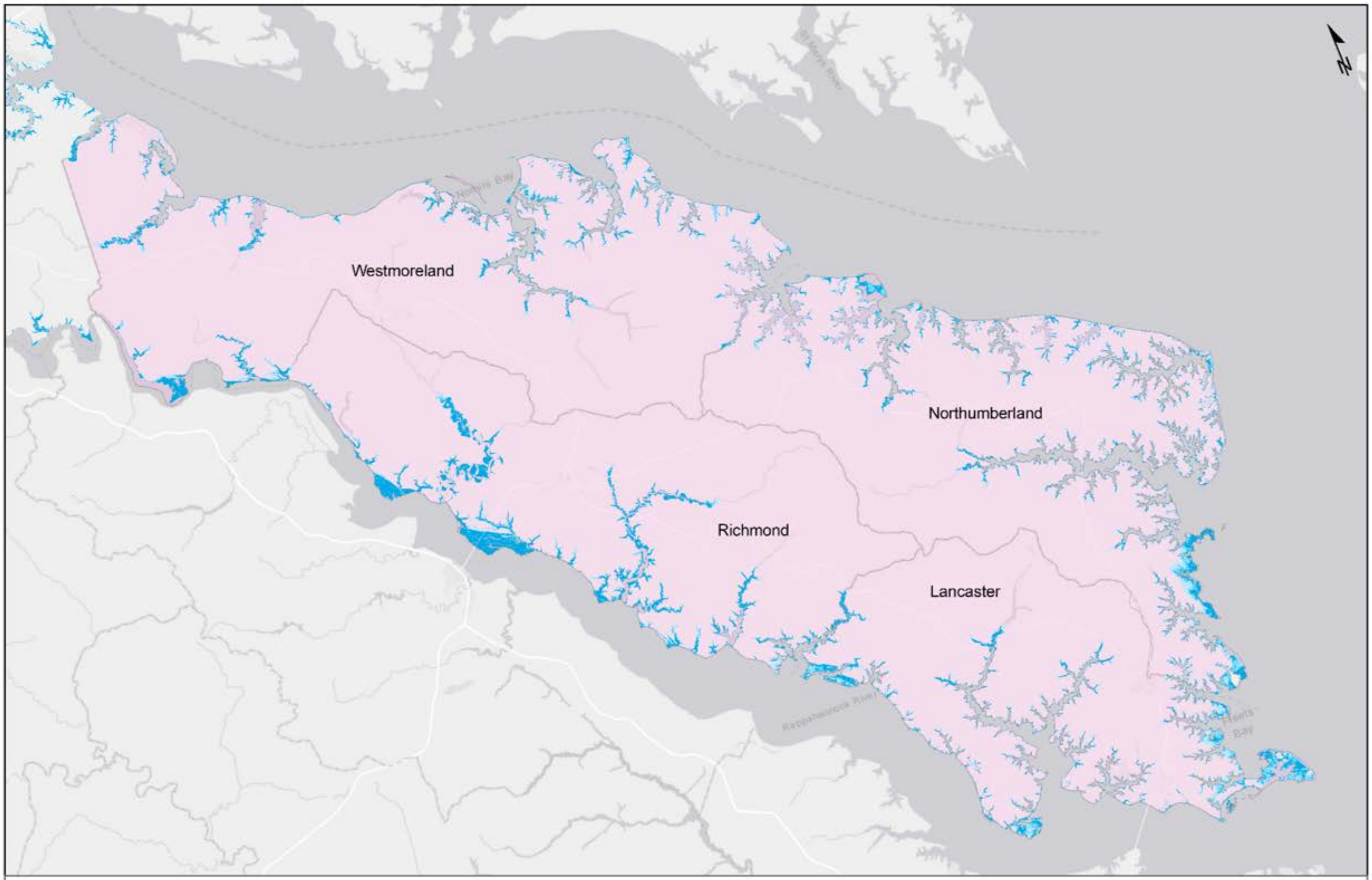
MAP 7

Northern Neck PDC



Future Sea Level: Northern Neck Planning District

	Land area impacted (sq.mi.)[3]	Number Parcels impacted[4]	Number Structures impacted	Streets impacted (miles)
2040	22	10,322	492	6
2060	29	11,057	846	24
2080	37	11,887	1,425	45

🟦 2040 🟦 2060 🟦 2080

Notes:
(1) Shaded areas indicate year of flooding due to rising sea level
(2) Sea level data reflect the NOAA intermediate-high scenario
(3) Areas include present day wetlands.
(4) Northumberland Co. parcel data unavailable

0 10 Miles

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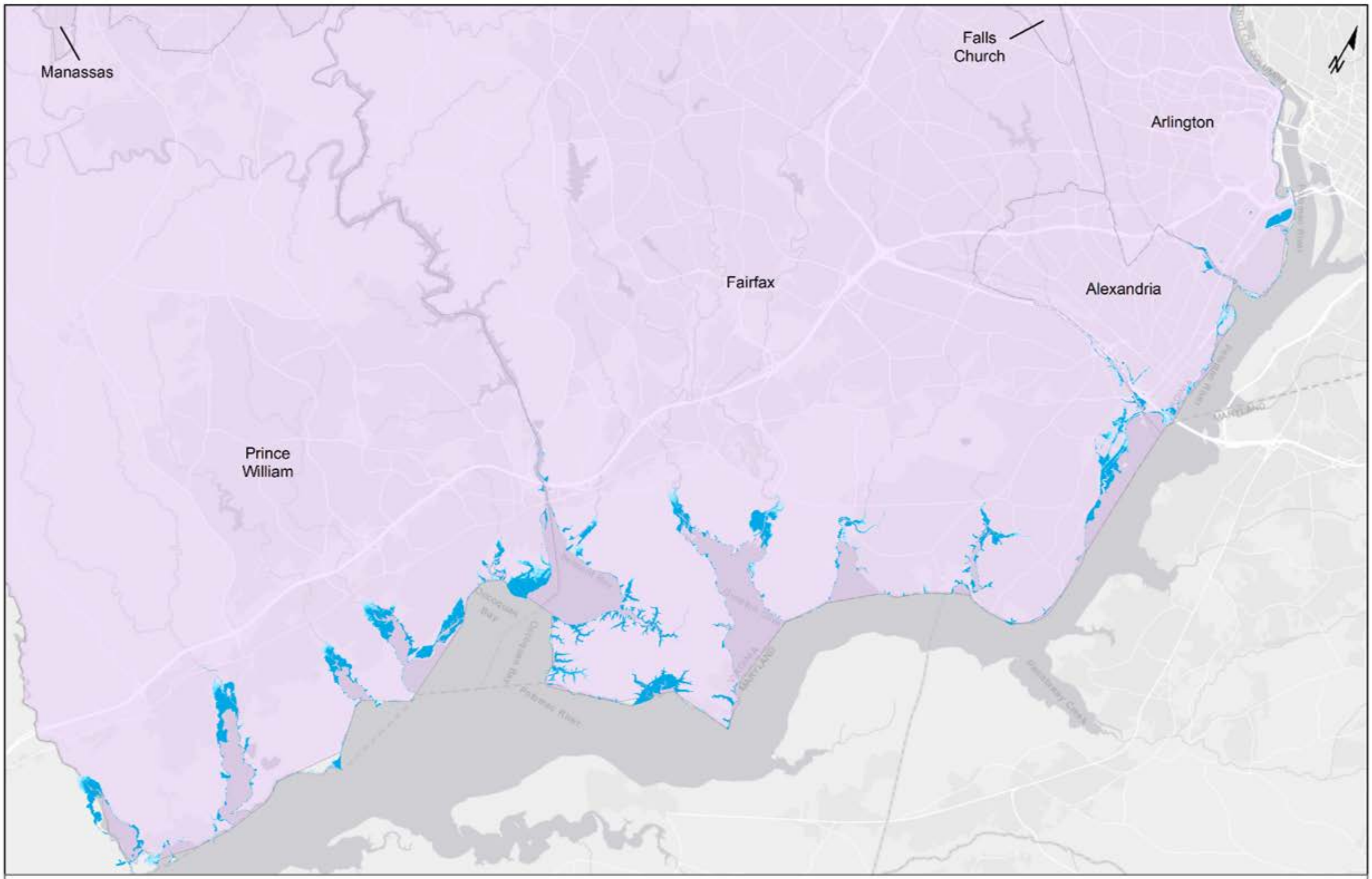
MAP 8

Northern Virginia RC



Future Sea Level: Northern Virginia Regional Commission

	Land area impacted (sq.mi.)$_3$	Number Parcels impacted	Number Structures impacted	Streets impacted (miles)
2040	5	1,321	117	6
2060	6	1,570	233	8
2080	7	2,175	409	18

2040 2060 2080

Notes:
(1) Shaded areas indicate year of flooding due to rising sea level
(2) Sea level data reflect the NOAA intermediate-high scenario
(3) Areas include present day wetlands.

0 5 Miles

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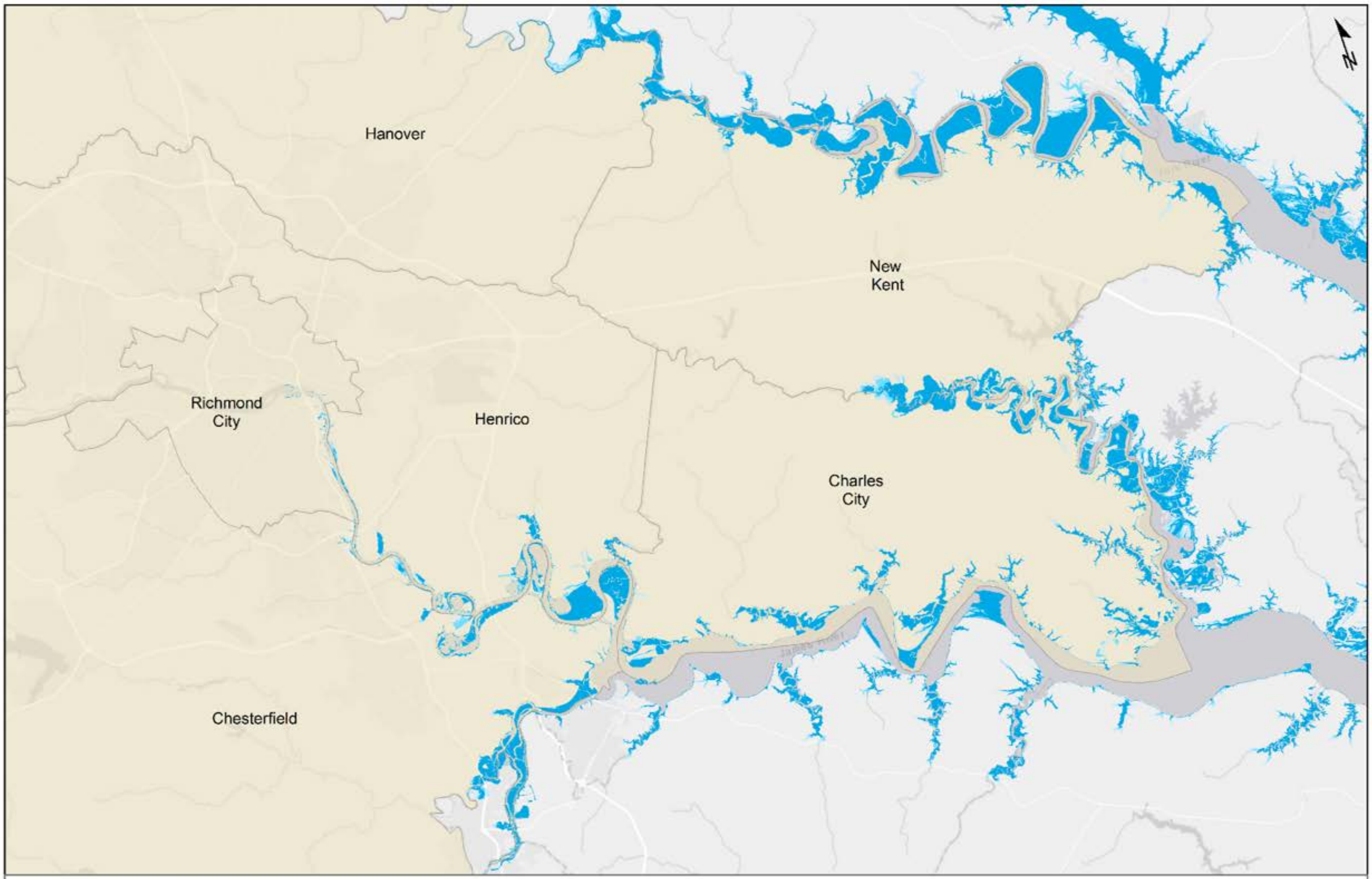
PREPARED BY: Ctr. for Geospatial Sciene, Education, and Analytics SEA LEVEL DATA: NOAA BASEMAP DATA: ESRI, HERE, Garmin, OpenStreepMap

MAP 9

Plan RVA (Richmond VA Regional PDC)



Future Sea Level: Plan RVA Regional Commission

	Land area impacted (sq.mi.)$_3$	Number Parcels impacted	Number Structures impacted	Streets impacted (miles)
2040	28	2,758	241	6
2060	30	2,950	306	7
2080	33	3,504	430	10

🟦 2040 🟦 2060 🟦 2080

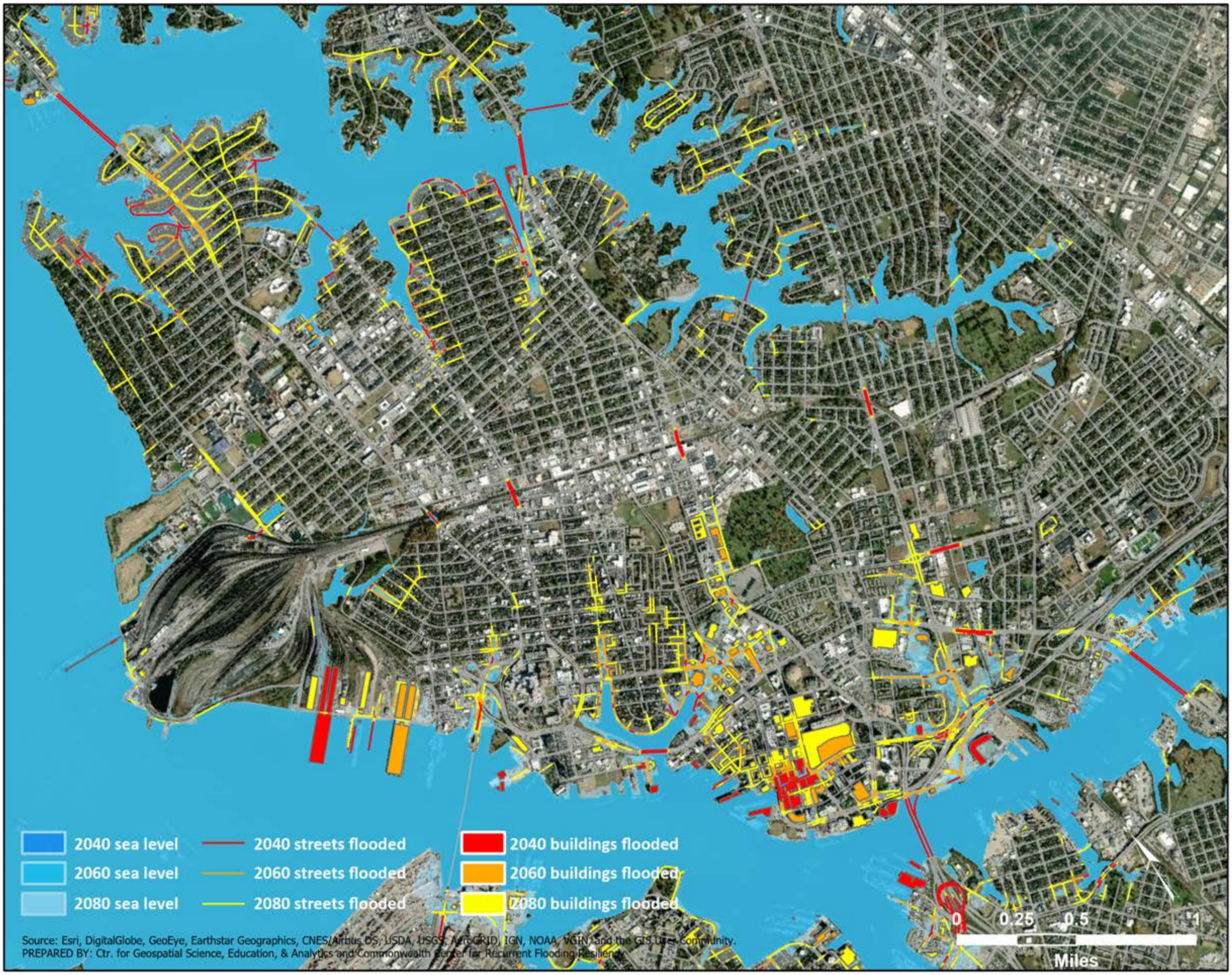
Notes:
(1) Shaded areas indicate year of flooding due to rising sea level
(2) Sea level data reflect the NOAA intermediate-high scenario
(3) Areas include present day wetlands.

0 10 Miles

PREPARED BY: Ctr. for Geospatial Sciene, Education, and Analytics SEA LEVEL DATA: NOAA BASEMAP DATA: ESRI, HERE, Garmin, OpenStreepMap

MAP 10

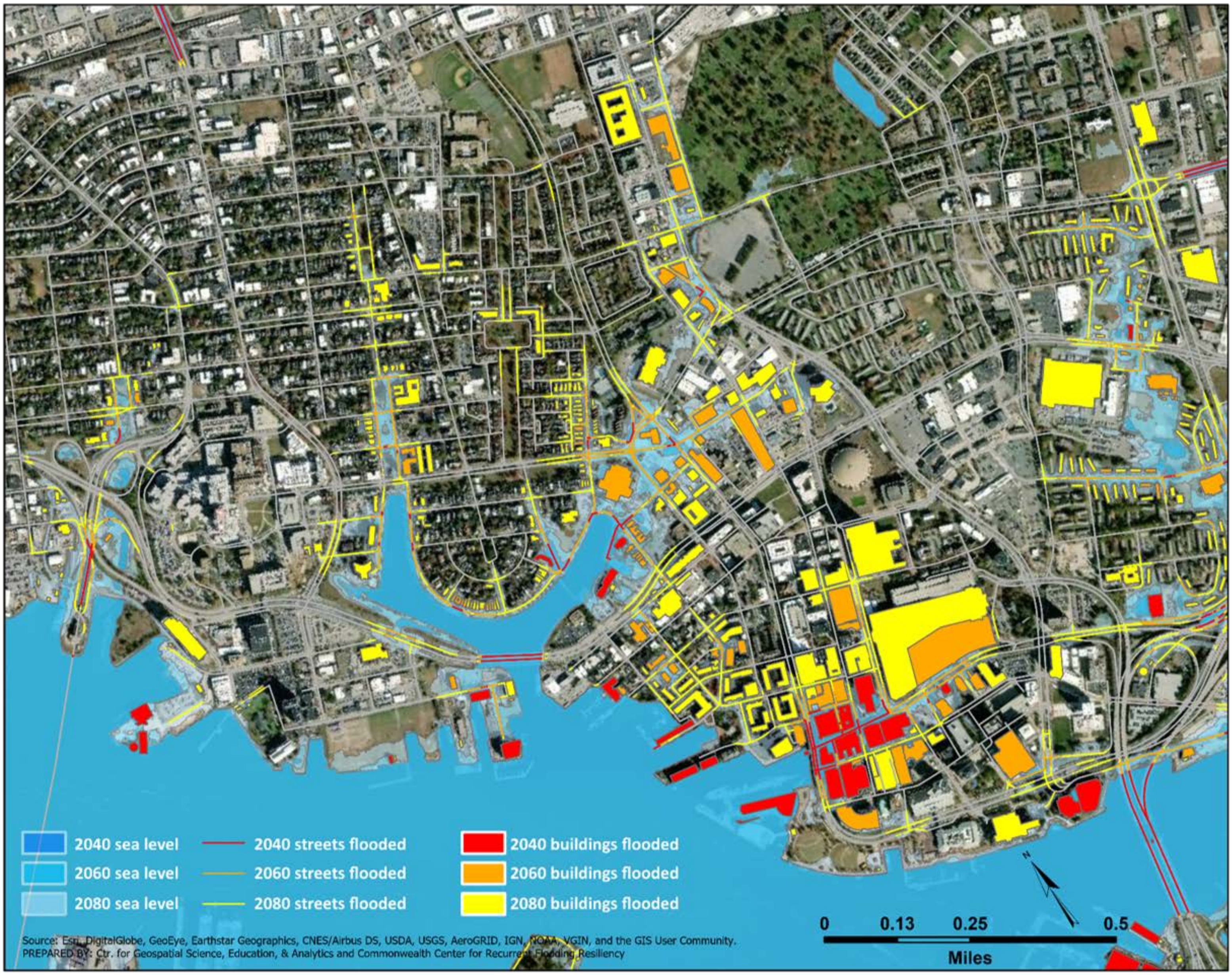
Norfolk



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, NOAA, VGIN, and the GIS User Community.
PREPARED BY: Ctr. for Geospatial Science, Education, & Analytics and Commonwealth Center for Recurrent Flooding Resiliency

MAP 11

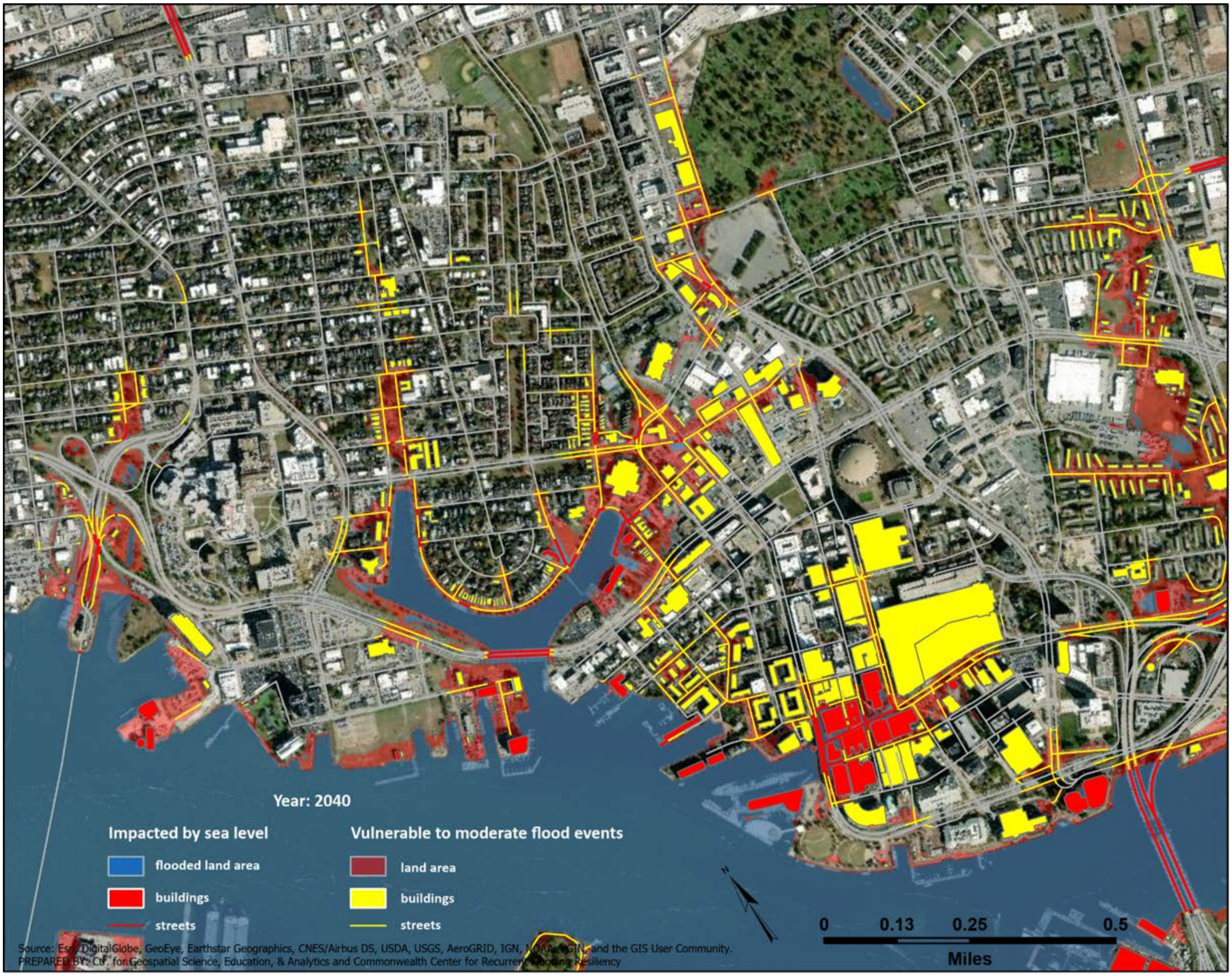
Norfolk



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, NOAA, VGIN, and the GIS User Community.
PREPARED BY: Ctr. for Geospatial Science, Education, & Analytics and Commonwealth Center for Recurrent Flooding Resiliency

MAP 12

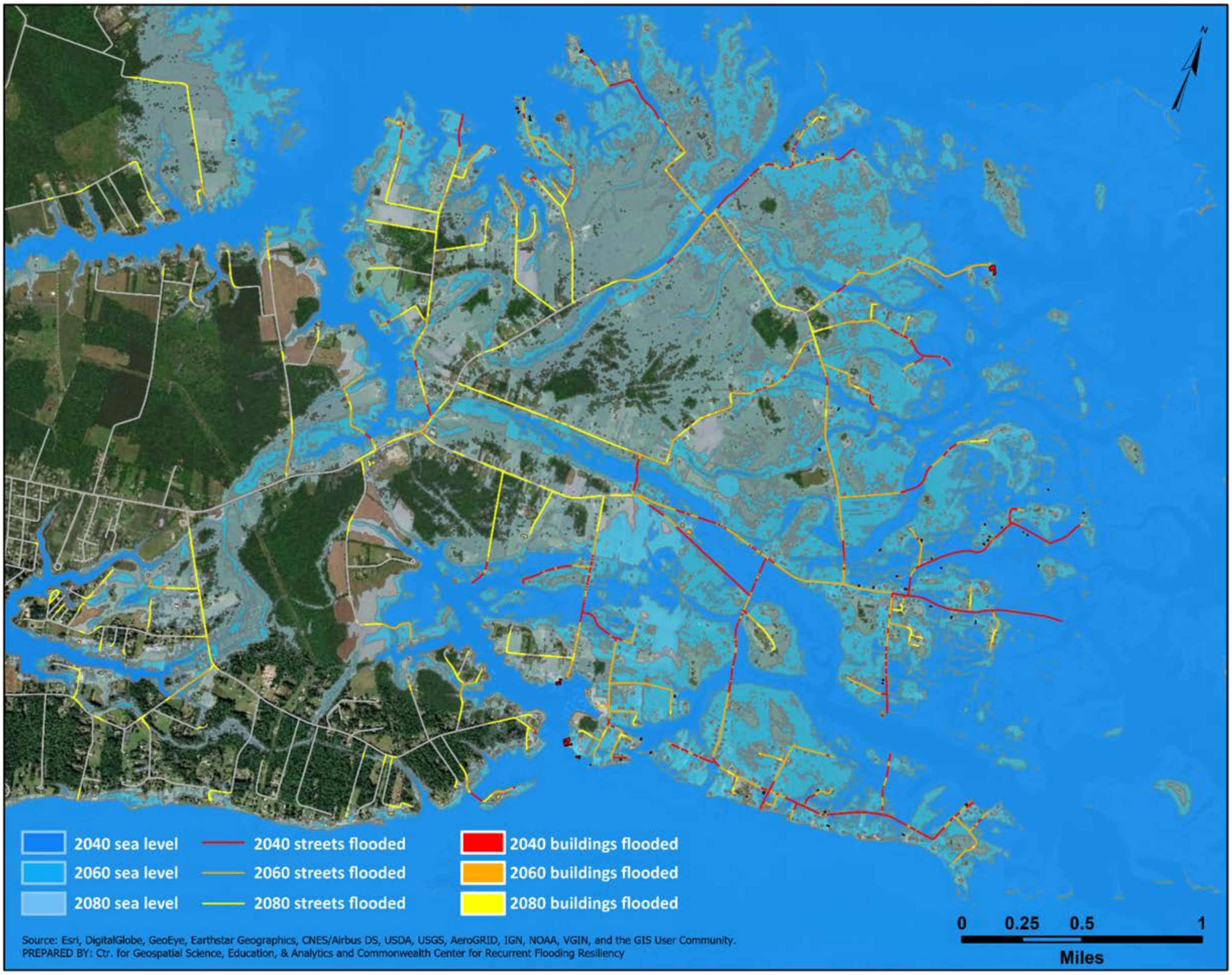
The Hague, Norfolk, including SLR and Moderate Flood Events for year 2040



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, NOAA, [illegible], and the GIS User Community.
PREPARED BY: Ctr. for Geospatial Science, Education, & Analytics and Commonwealth Center for Recurrent Flooding Resiliency

MAP 13

Guinea



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, NOAA, VGIN, and the GIS User Community.
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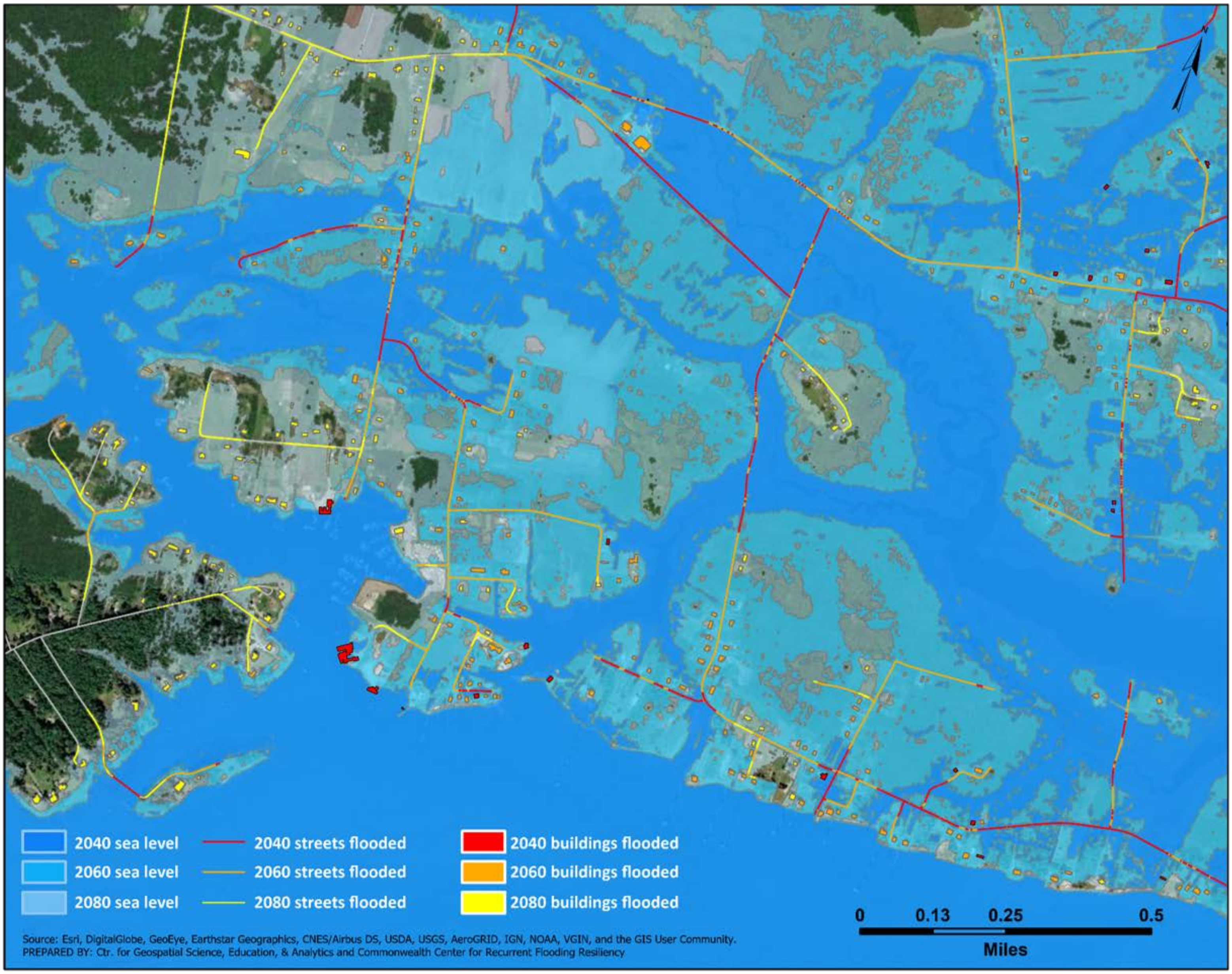
MAP 14

Guinea



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, NOAA, VGIN, and the GIS User Community.
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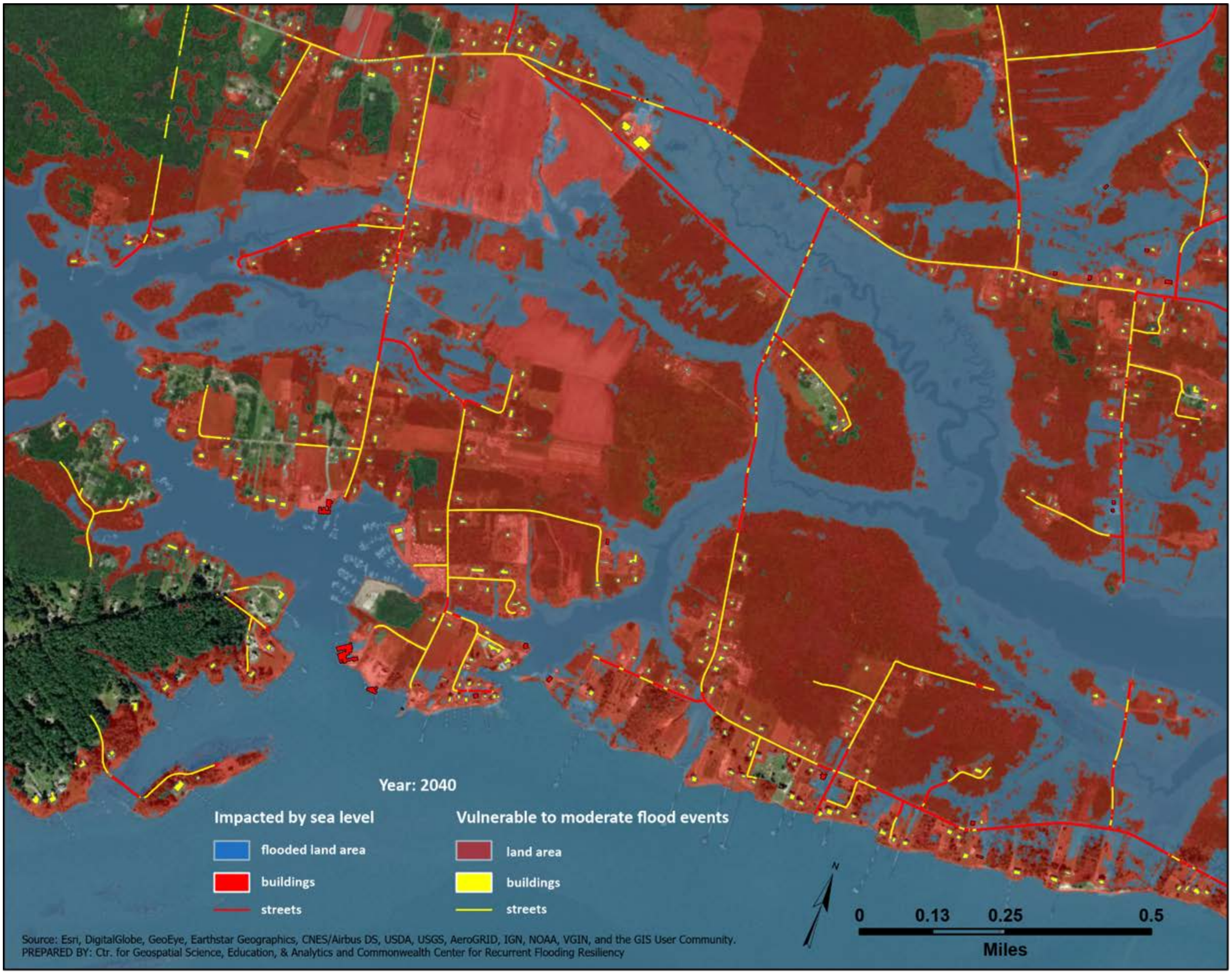
MAP 15

Guinea (subset), including SLR and Moderate Flood Events for year 2040



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, NOAA, VGIN, and the GIS User Community.
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