Worst Case Effects of Hurricanes, Fluvial Flooding, High Tides, and Sea Level Rise on DelDOT Assets

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Chapter 1 – Introduction

Problem Statement

What are the worst case effects of hurricanes, riverine flooding, high tides, and sea level rise inundation on Delaware Department of Transportation (DelDOT) assets? The University of Delaware Water Resources Center (UDWRC) and Center for Applied Demography and Survey Research (CADSR) utilized climatic, hydrologic, hydraulic, and geographic information systems (GIS) data to document and map the worst case effects of hurricane, fluvial flooding, high tide, and sea level rise inundation on the highway, railroad, transit, and pedestrian/bicycle transit assets of the DelDOT.

Project Narrative

On March 2, 2015 in Delaware City, Governor Jack Markell together with DelDOT Secretary Jennifer Cohan, DNREC Secretary David Small, University of Delaware Dean of the College of Earth, Ocean and Environment Dr. Nancy Targett, and others announced a new Climate Framework for Delaware. In September 2013, Governor Markell signed Executive Order 41 that created the Cabinet Committee on Climate and Resiliency to address climate change at the state level. On June 5, 2017, Governor John Carney announced that Delaware was among 10 states to join the U.S. Climate Alliance to adhere to the Paris Climate Agreement. The climate coalition is chaired by the governors of California, New York, and Washington and includes Connecticut, Delaware, Hawaii, Massachusetts, Minnesota, Oregon, Puerto Rico, Rhode Island, Vermont, and Virginia.

Delaware's Climate Framework is based on the Delaware Sea Level Rise Vulnerability Assessment (DNREC 2012) and Climate Change Impact Assessment (DNREC 2014). The 2014 climate assessment forecasts that the frequency of heavy precipitation events will increase during the 21st century (Figure 1.1). The 2012 assessment concludes that many DelDOT highways are vulnerable to 1 meter of sea level rise (Figure 1.2). Low lying Delaware is increasingly vulnerable to climate change and sea level rise and the Governor has directed that state agencies such as DelDOT plan to address the future impacts of flooding and coastal storms on infrastructure.

Research Approach

The University of Delaware conducted the analysis of the impact of severe storm and flooding scenarios on DelDOT assets according to the following scope of work.

1. **GIS Mapping and Database:** Construct GIS base mapping of DelDOT assets from centerline files including highways, bridges, dams, railroads, bus routes, pedestrian/bicycle trails, etc.

2. **Climatic/Hydrologic Analysis:** Conduct a climatic and hydrologic analysis of storms that have struck Delaware during the period of record with worst case combinations of coastal and riverine flooding based on National Oceanic and Atmospheric Service (NOAA) National Weather Service (NWS), Delaware Earth Observation System (DEOS), USGS stream gage, and NOAA tidal gages.

3. **Bridge Hydraulic Analysis:** Evaluate the hydraulics of bridges and culverts based on various flood velocities and discharges that occur during the most severe, worst case storm scenarios benchmarked to the 10-, 50-, 100-, and 500-year events. Utilizing Federal Emergency Management Agency (FEMA) flood profiles and floodplain mapping, identify DelDOT bridges/culverts that do not have the hydraulic capacity to pass the 10-, 50-, 100-, and 500- year flood events or are where the roadway is overtopped.

4. **Flood Inundation Analysis:** Using GIS mapping, overlay simulations of worst case flood events with base map of DelDOT assets utilizing FEMA Flood Insurance Study flood inundation mapping and NOAA NWS SLOSH model using an EPA mapper tool for 100- and 500-year floods coupled with Category 1 and 3 coastal storm surge scenarios. Map future flood scenarios that combine estimates of sea level rise (0.5 m) with 100- and 500-year storms and SLOSH Category 1-3 storm surge scenarios.

5. **Historic Storm Analysis:** Consult with DelDOT and from an evaluation of the most severe storm and flood events, analyze worse case scenarios for flood inundation based on Superstorm Sandy (October 2012) impacts on the Delaware coast as: (a) the storm actually occurred where the eye passed to the north of Delaware through Atlantic City, New Jersey and (b) a simulation where the eye of the storm passes (as originally forecast) through Lewes, Delaware.

6. **Flood Inundation Website:** Create a website where the flood inundation and impact on DelDOT asset mapping and data base will be mounted on a web based server at the University of Delaware and DelDOT where engineers and managers could obtain data such as number of road miles inundated and plan for future storms or evacuations and construction, operation, and, maintenance needs. The University of Delaware will assist DelDOT with training sessions on use of flood inundation software.

7. **Report:** Summarize the research and analysis of impacts of worst case storms and floods on DelDOT assets in a report including flood inundation mapping.

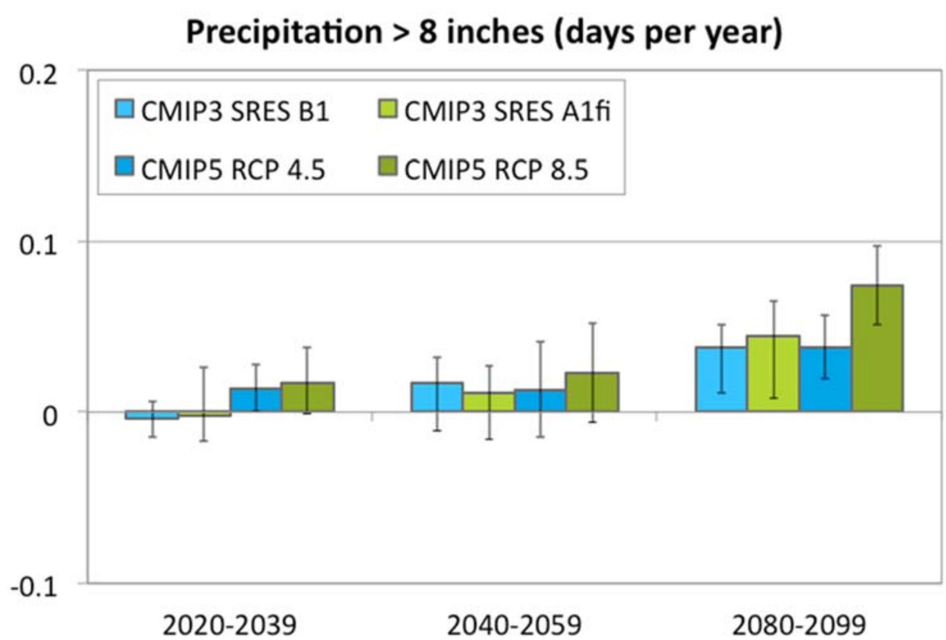


Figure 1.1. Future precipitation events greater than 8 inches in Delaware (Delaware Climate Change Impact Assessment 2014)

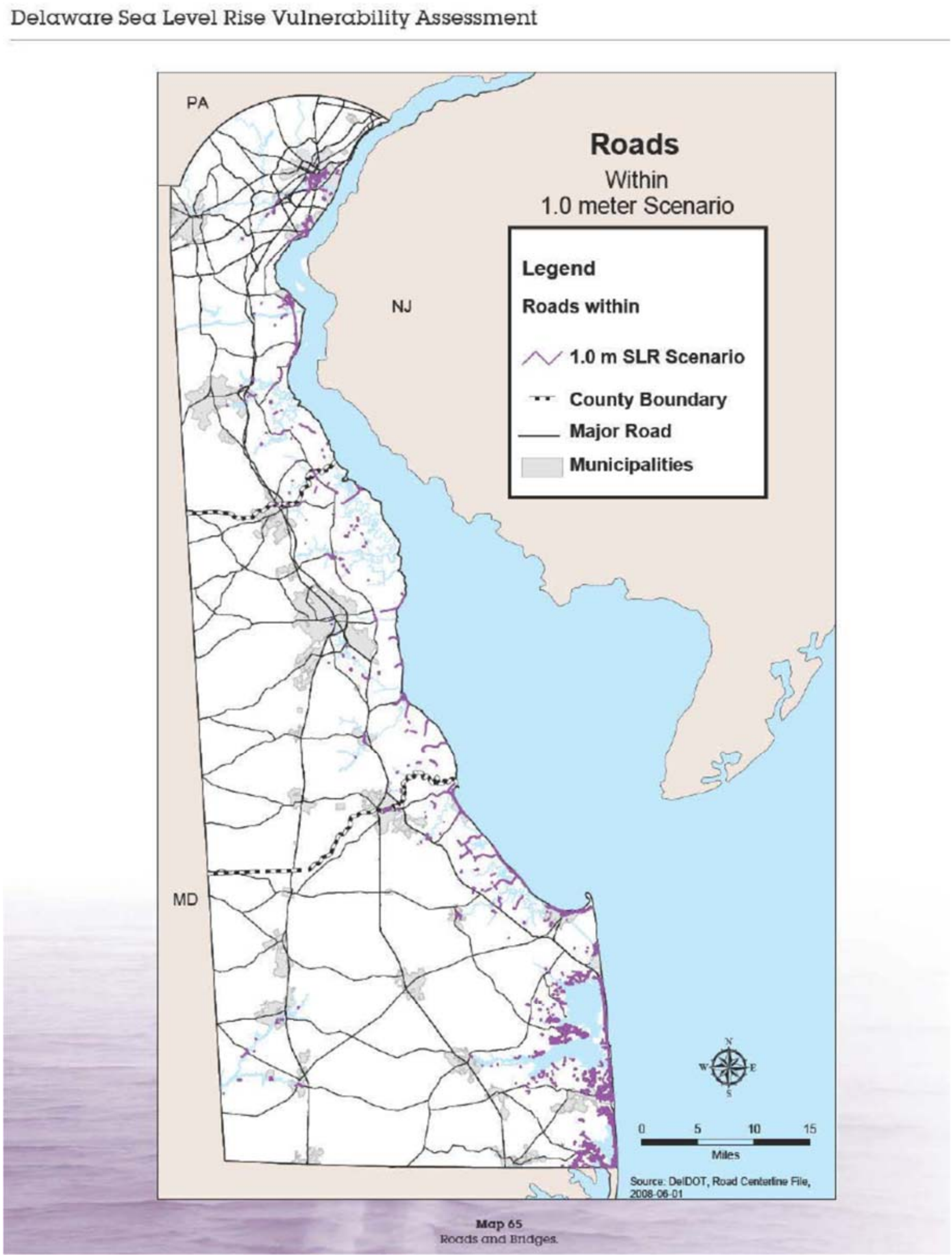


Figure 1.2. Delaware roads with one-meter sea level rise scenario (Delaware Sea Level Rise Vulnerability Assessment 2012)

Chapter 2 - GIS Mapping and Database

CADSR and the UDWRC constructed GIS base mapping of DelDOT assets from centerline files including the highway network, bridges, dams, maintenance yards, railroads, bus routes, pedestrian/bicycle trails according to the following approach:

1. Compile LiDAR data and derived data products for modelling and overlay

2. Work with Delaware Geological Survey (DGS) on procedures to process point cloud for ground and first-return information to derive bridge elevations.

3. Explore use of EPA Storm Surge and NOAA SLOSH models

4. Generate model runs for Category 1, 2, and 3 storms, for slow (10 MPH) and fast (40 MPH) moving storms, traveling NW and NNE

5. Explore other data sources, including NOAA inundation models (derived from SLOSH output and USGS DEM elevations), FEMA flood zones, etc.

6. Obtain storm inundation information including Category 1-5 coastal inundation worst-case scenario datasets, flood zone information (100-year and 500-year), plus flood frequency data.

7. Process the above data to derive a layer of combined coastal flood hazard for Category 1, 2, and 3 hurricanes (worst case at high tide) and the riverine and tidal tributary flooding from rainfall.

8. Process DelDOT roads (centerline file) and major routes to create a raster of roads including LiDAR-based road elevations above MHHW.

9. Combine road layers with inundation and flooding threat data to derive roads and major routes potentially affected under various storm surge and rain scenarios.
   - DelDOT buildings
   - Drainage structures
   - Maintenance yards and areas
   - Bus Stops
   - DTC Facilities
   - Fire Stations, Hospitals
   - Park and Pool, Park and Ride
   - Signals
   - Road Inventory

10. Compile other data such as for paving, capacity, traffic counts, evacuation routes, and multi-modal facilities were also compiled from other sources and community data on populations at risk, vulnerabilities, community assets, and response capabilities was compiled including:
    - Shelters
    - Critical facilities: hospitals, police, fire, medical, EOC, utility
    - Daycares, assisted living, nursing homes

- Trailer parks
- Retirement communities
- Prisons
- Apartments, condominiums, and other multi-unit
- EOC
- National Guard and military
- Store basics, hardware and materials
- Taxi, limo, and other transportation providers

11. CADSR created mapping applications to bring this information to develop throughout the project. The web address is www.cadsrgis2.org/hurricane . The mapping site and data within it requires a login when first entering the site. Data is not for redistribution outside of the project team. Numerous tools are incorporated within the interface.

Chapter 3 - Climatic/Hydrologic Analysis

Introduction

Situated at a mean elevation of 60 feet above sea level, Delaware is the lowest lying state in the U.S. and therefore is especially vulnerable to coastal and riverine flooding accentuated by changes in the climate and sea level rise (Figure 3.1). Preliminary GIS analysis by the UDWRC (2012) indicates that 17 percent of the First State is in the 100-year floodplain (Table 3.1) that would inundate 44 road miles in the Christina River watershed in New Castle County and 106 road miles in the Indian River Bay watershed in Sussex County, Delaware (Figure 3.2). DelDOT operates a transportation system of 6,280 road miles and thousands of bridges, railroads, bus routes, and bicycle trails. The analysis contained herein summarizes the data and information needed by transportation managers to plan for worst case scenarios of hurricane, fluvial flooding, high tide, and sea level rise inundation on DelDOT assets.

After a relatively tranquil period during the droughts of 1995, 1999, and 2002, Delaware has experienced a sequence of increasingly powerful storms and floods over the last decade and a half (Table 3.2 and Figure 3.3). The drought emergency of 1999 ended with Hurricane Floyd on September 16, 1999 that deposited 9 to 11 inches of rain, caused 100- to 500-year flooding, and peaked as the most severe flood on record along the Christina River, White Clay Creek, and Blackbird Creek. Tropical Storm Henri on September 15, 2003 exceeded the 500-year flood (Table 3.3) and is by far the most extreme flood on record along the Red Clay Creek (Figure 3.4) and led to the relocation of 200 homes in the Glenville neighborhood. Just a year later the remnants of Tropical Storm Jeanne brushed Delaware on September 28, 2004 as a 100-year flood as the second highest flood along Red Clay Creek. Tropical Storm Irene passed by Delaware on September 28, 2011 which exceeded the 100-year flood and was the worst flood on record in the St. Jones River watershed. Originally forecast to hit near Lewes, the eye of Superstorm Sandy hit Atlantic City, New Jersey coast just 60 miles north of the Delaware beaches (and then passed through Wilmington) and caused the highest flood tide on record at the Route 1 bridge over the Indian River inlet (Figure 3.5). A rare spring storm on April 30, 2014 caused school closing as the 3rd highest flood on record at the Brandywine Creek.

Under a low-range sea level rise scenario, Delaware is likely to see record-breaking coastal floods within the next 20 years, and near certain to see floods more than 5 feet above the high tide line by 2100 (Climate Central 2014). Under a rapid rise scenario, the state is near certain to see floods above 9 feet by end of century. Approximately 62,000 acres of land lie less than 5 feet above the high tide line in Delaware. Some $1.1 billion in property value, and 20,000 homes sit on this area. These figures jump to more than $2 billion and nearly 40,000 homes on 104,000 acres of land under 9 feet. More than 19,000 people are residents in the homes below 5 feet, and more than 41,000 are residents below 9 feet. The state has 428 miles of road below 5 feet and 9 houses of worship; 2 power plants; and 87 EPA-listed sites, such as hazardous waste dumps and sewage plants. At 9 feet, these numbers grow to 782 miles of road; 36 houses of worship; 4 power plants; and 135 EPA-listed sites.

Flood and Storm Surge Mapper

The DWRC conducted a hydraulic analysis to simulate historic worst case flood events and compare to the 100-year (1%) and 500-year (0.2% chance) flood events. We overlaid the worst case flood events with the base map of DelDOT assets utilizing FEMA Flood Insurance Study flood inundation mapping and the NOAA NWS SLOSH model using an EPA mapper tool that simulates the 100-year and 500-year riverine floods coupled with SLOSH Category 1 through 3 hurricane coastal storm surge scenarios. We mapped future flood scenarios that combine 0.5-meter sea level rise with the 100- and 500-year storms and SLOSH storm surge scenarios. Using GIS mapping, we illustrated the worst case scenario of a direct hit of a Category 3 hurricane or a repeat of a Superstorm Sandy on the Delaware coast with 0.5 meter of future sea level rise. The UDWRC researched several Federal/State storm surge mapper models that are used to assess the impacts of hurricanes and severe storms on DelDOT assets:

Federal

- Climate Central Surging Seas Risk Zone Map (Fig. 3.7)
- EPA Storm Surge Inundation Mapper (Fig. 3.8)
- NOAA Coastal Flood Exposure Mapper (Fig. 3.9)
- National Weather Service (NWS) SLOSH Inundation Model (Fig. 3.10)

Delaware

- Delaware Coastal Resilience Risk Explorer Map (Fig. 3.11)
- Delaware Seal Level Rise Inundation Map (Fig. 3.12)

Of the Federal/state interactive models, the EPA Storm Surge Mapper proves to be most useful for the inundation analysis as it combines fluvial (riverine) flooding based on return intervals (100-year/500-year flooding) with coastal storm surge flooding from the SLOSH model for Category 1 through 5 hurricanes. The Delaware coastal models map static sea level rise was used to map future storm surge scenarios. We utilized the GIS data from the EPA Storm Surge Inundation mapper for this inundation analysis of DelDOT assets because this hydraulic model is the only one that assesses hybrid flooding - riverine flooding in combination with coastal hurricane storm surge flooding. Future flood scenarios will incorporate 0.5 m sea level rise from the Delaware Sea Level Rise Inundation Mapper.

Table 3.1. Assessment of storm surge and sea level rise inundation models

Hydraulic Model	**Riverine Flooding/Storm Return Interval**	**Coastal Flooding/ Cat 1- 5 Hurricane**	**Static Sea Level Rise**
Climate Central Surging Seas Risk Zone Map			
EPA Storm Surge Inundation Mapper			
NOAA Coastal Flood Exposure Mapper			
National Weather Service (NWS) SLOSH Inundation Model			
Delaware Coastal Resilience Risk Explorer			
Delaware Seal Level Rise Inundation Map			

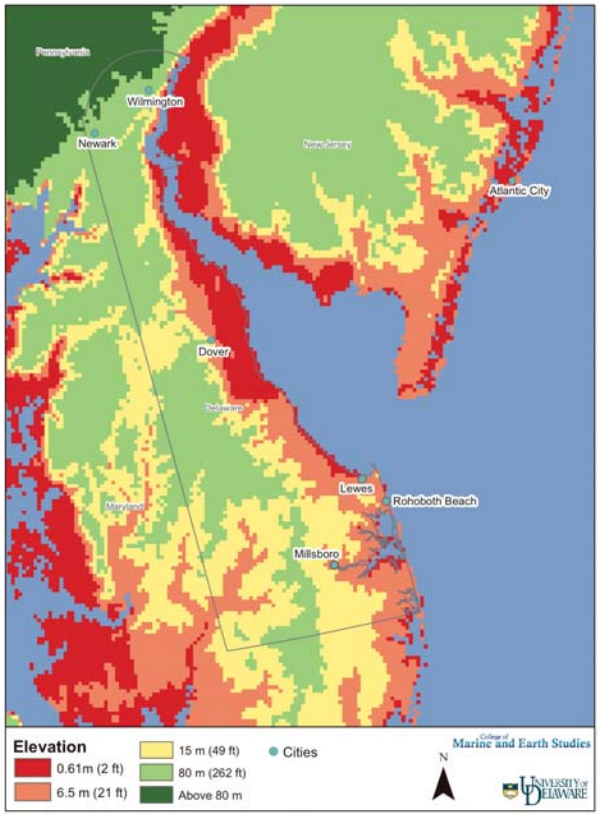


Figure 3.1. Low lying Delaware and environs impacted by sea level rise

Table 3.2. Area of the 100-year floodplain in Delaware

County	Land Area (mi²)	100-yr Floodplain (mi²)	% Floodplain
New Castle	432	67	16%
Kent	599	94	16%
Sussex	976	170	18%
Total	**2,007**	**331**	**17%**

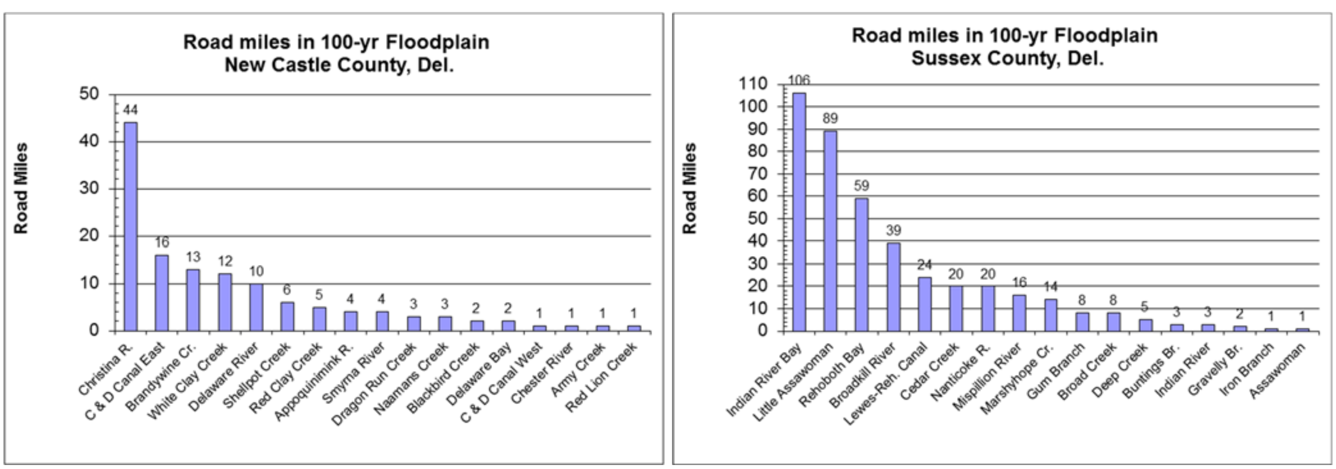


Figure 3.2. Roads in the 100-year floodplain in Delaware

Table 3.3. Top floods in Delaware watersheds
(Ries and Dillow 2006, www.usgs.gov)

USGS Gage	Date	Storm	Top Peak Flows (cfs)	Return Interval
White Clay Creek near Newark, Del.	9/16/99	Floyd	19,500	>200 year
01479000	8/28/11	Irene	16,700	>100 year
1943-present	5/01/14		14,600	100-year
	9/15/03	Henri	13,900	>50-year
	7/05/89	4th of July	11,600	>25 year
	1/19/96		9,150	25 year
	7/22/72	Agnes	9,080	25 year
Red Clay Creek at Wooddale, Del.	9/15/03	Henri	16,000	>500 year
01480000	9/28/04	Jeanne	8,280	>100 year
1943-present	8/28/11	Irene	7,680	50 year
	9/16/99	Floyd	7,650	50 year
	4/30/14		5,840	>10 year
	6/28/06		5,490	>10 year
	7/21/75		5,010	>10 year
Brandywine Creek at Wilmington, Del.	6/23/72	Agnes	29,000	100 year
01481500	9/17/99	Floyd	28,700	>50 year
1946-present	5/01/14		24,000	>25 year
	8/28/11	Irene	23,000	>25 year
	1/25/79		22,400	>25 year
	9/13/71		21,300	25 year
	9/29/04	Jeanne	20,800	25 year
St. Jones River at Dover, Del.	8/28/11	Irene	2,390	>100 year
01483700	9/13/60		1,900	100 year
1958-present	2/24/98		1,400	25 year
	2/26/79		1,340	25 year
	8/26/58		1,260	>10 year
	6/23/72	Agnes	996	5 year
Nanticoke River near Bridgeville, Del.	2/26/79		3,020	100 year
01487000	8/05/67		2,360	25 year
1943-present	8/26/58		2,300	25 year
	3/03/94		1,970	>10 year
	8/28/11	Irene	1,830	10 year
	9/17/99	Floyd	1,760	10 year

Table 3.4. Flood frequency along streams in Delaware watersheds
(Ries and Dillow 2006)

USGS Gage	10-yr (cfs)	25-yr (cfs)	50-yr (cfs)	100-yr (cfs)
Shellpot Creek at Wilmington Del. 01477800	4,320	5,560	6,650	7,880
Christina River at Cooches Bridge, Del. 01478000	3,430	4,410	5,220	6,080
White Clay Creek near Newark, Del. 01479000	7,840	10,400	12,600	15,000
Red Clay Creek at Wooddale, Del. 01480000	4,560	6,170	7,600	9,220
Brandywine Creek at Wilmington, Del. 01481500	16,100	21,300	25,700	30,400
Blackbird Creek at Blackbird, Del. 01483200	371	529	670	831
St. Jones River at Dover, Del. 01483700	1,100	1,420	1,660	1,910
Nanticoke River near Bridgeville, Del. 01487000	1,780	2,290	2,720	3,200

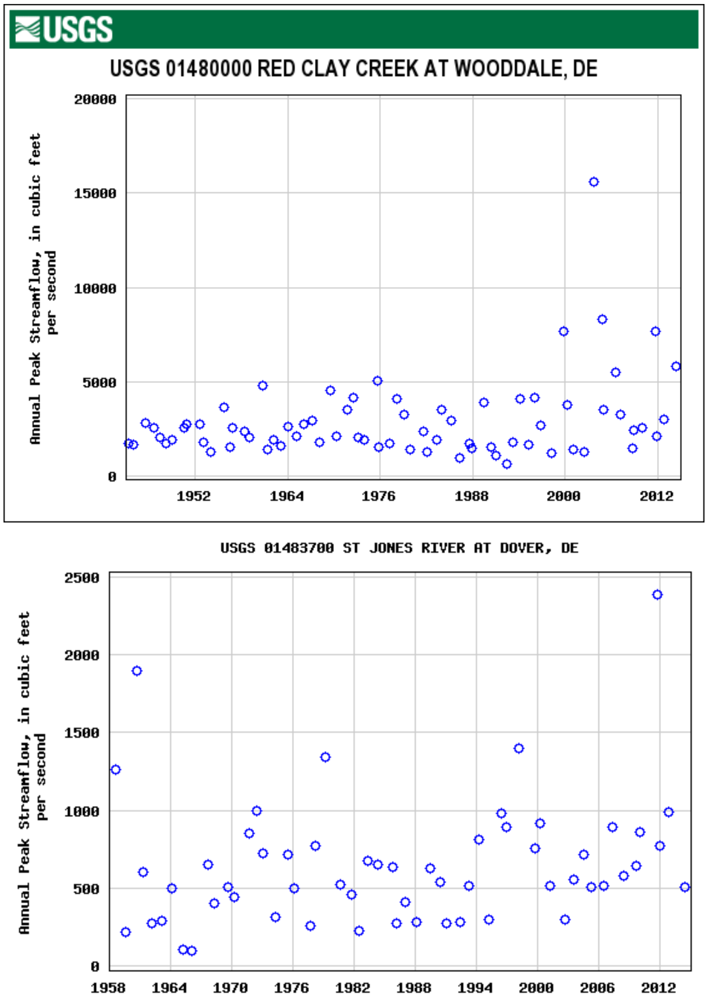


Figure 3.3. Peak flood events along Delaware streams (www.usgs.gov)

Figure 3.4. Highway damage along Red Clay Creek during September 2003 Tropical Storm Henri

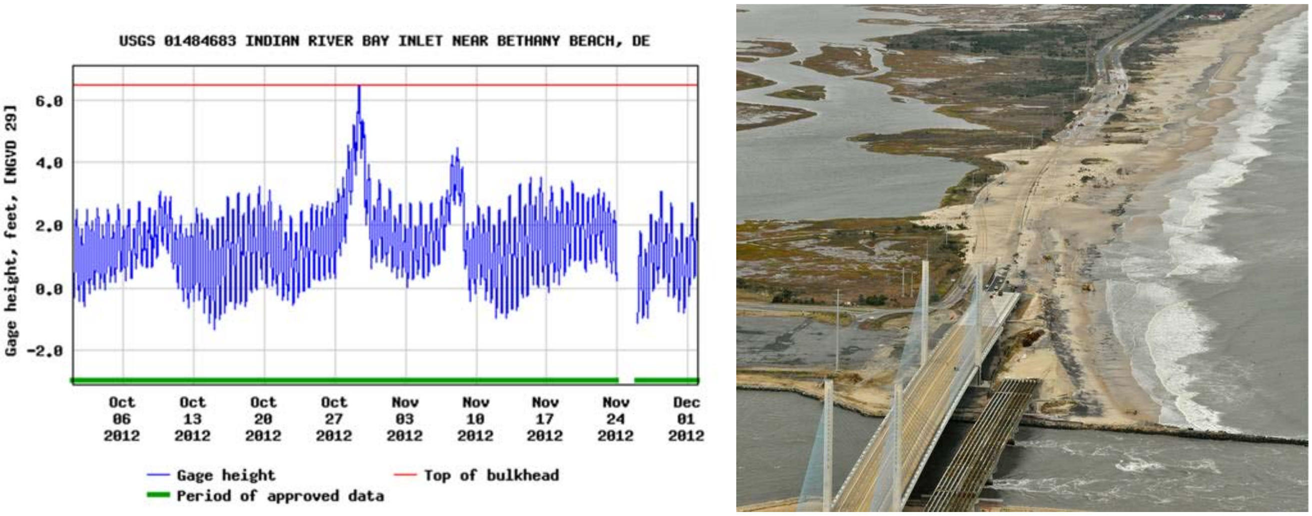


Figure 3.5. Historic peak flood tide at Indian River Bay Inlet, Superstorm Sandy October 29, 2012

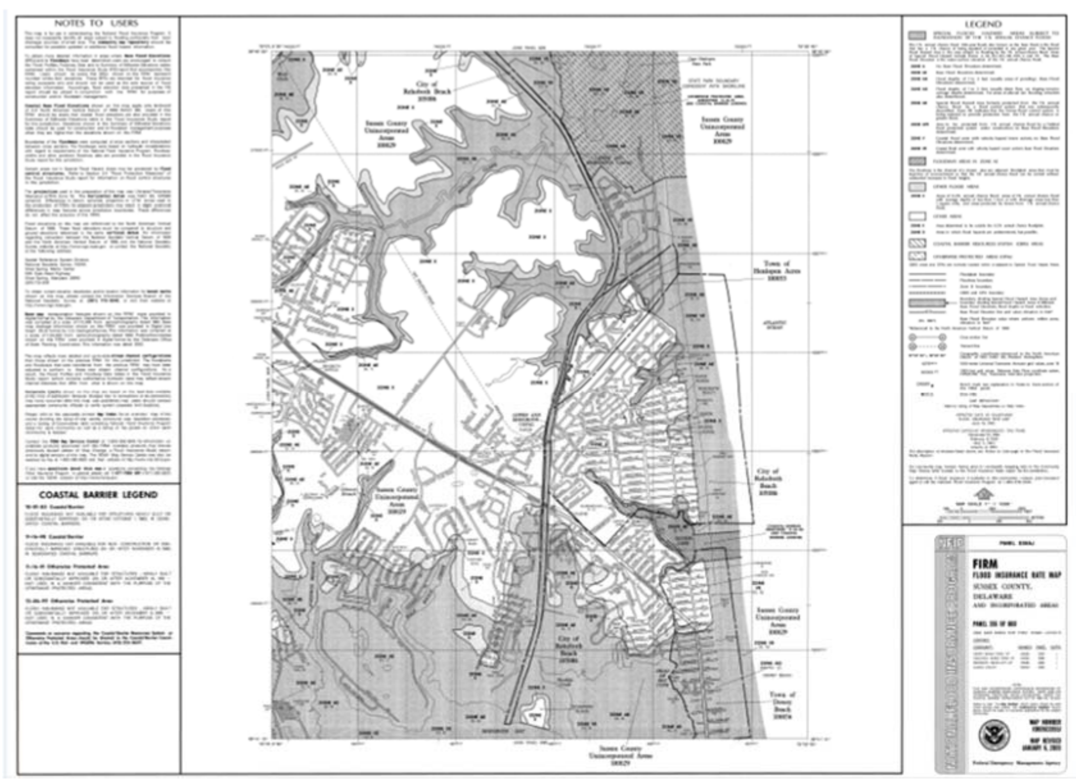


Figure 3.6. FEMA floodplain mapper

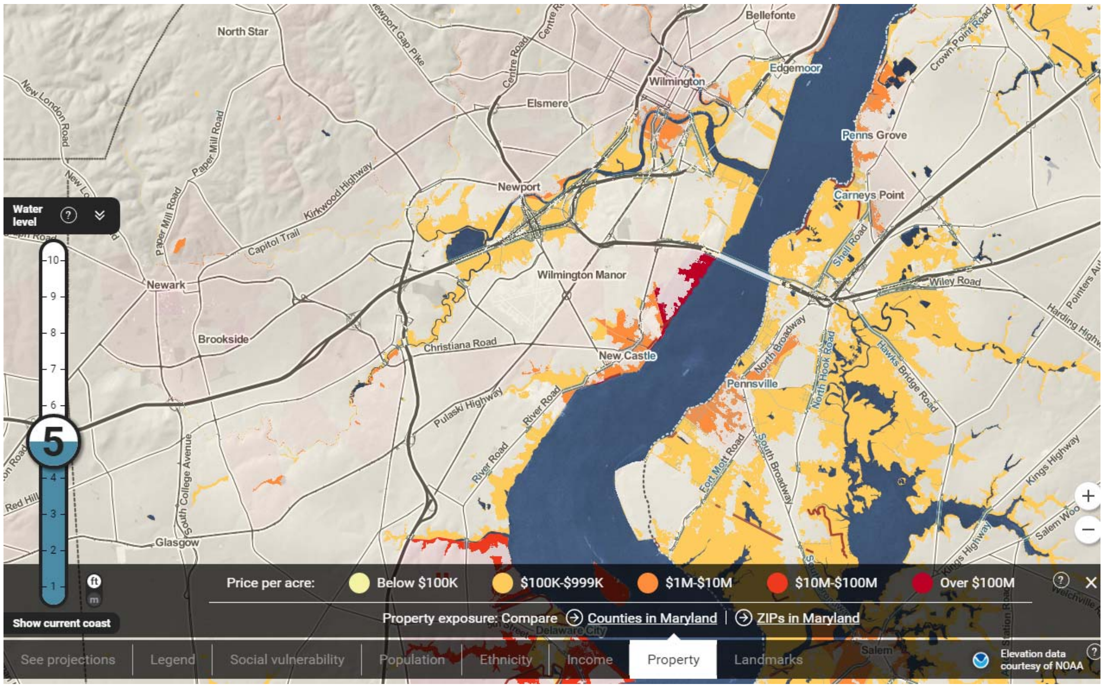


Figure 3.7. Climate Central Surging Seas Risk Zone Map, City of Wilmington

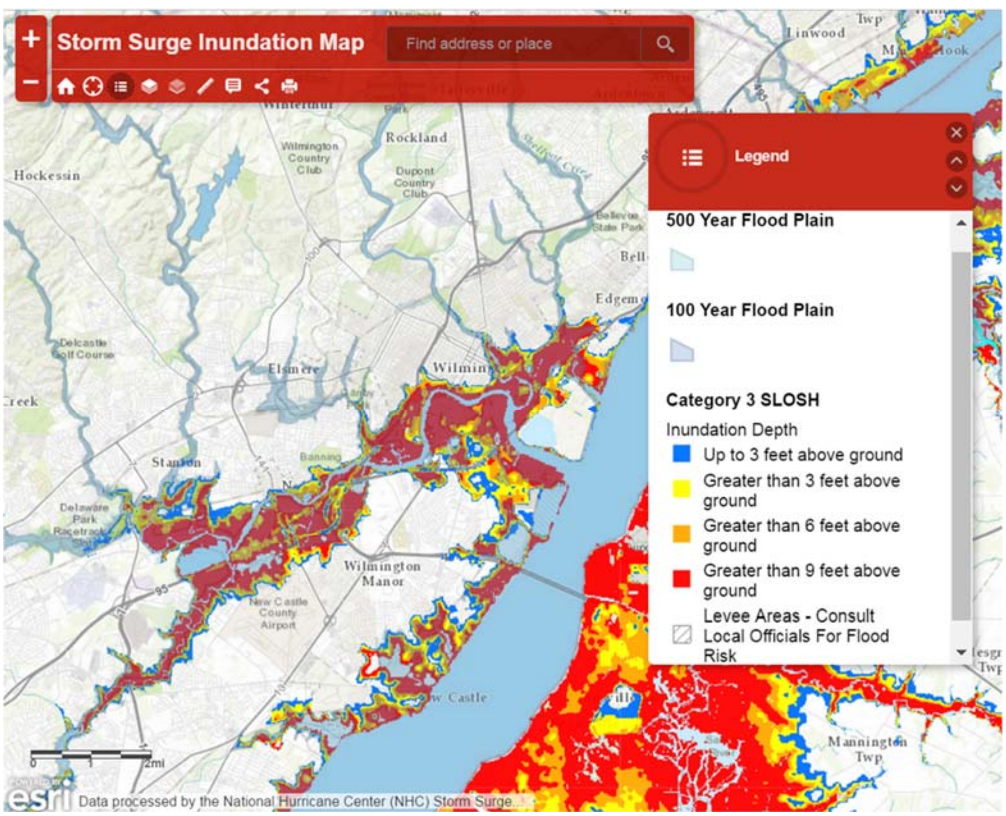


Figure 3.8. EPA Storm Surge Inundation Map, 100- and 500-year floodplain and Category 3 storm

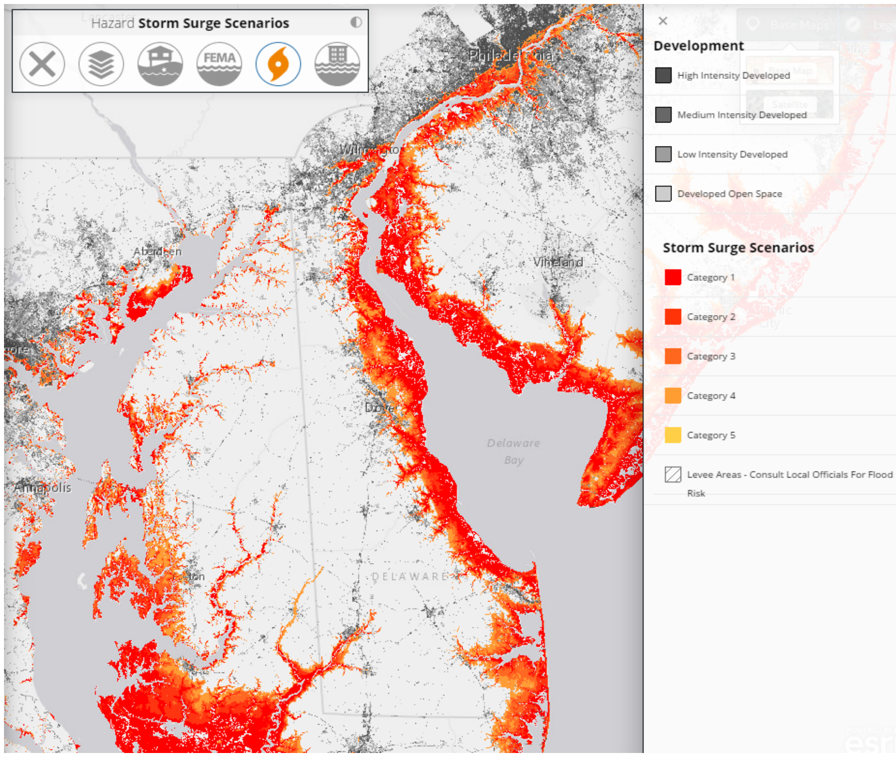


Figure 3.9. NOAA Coastal Flood Exposure Mapper, Category 1 through 5 storm surge scenarios

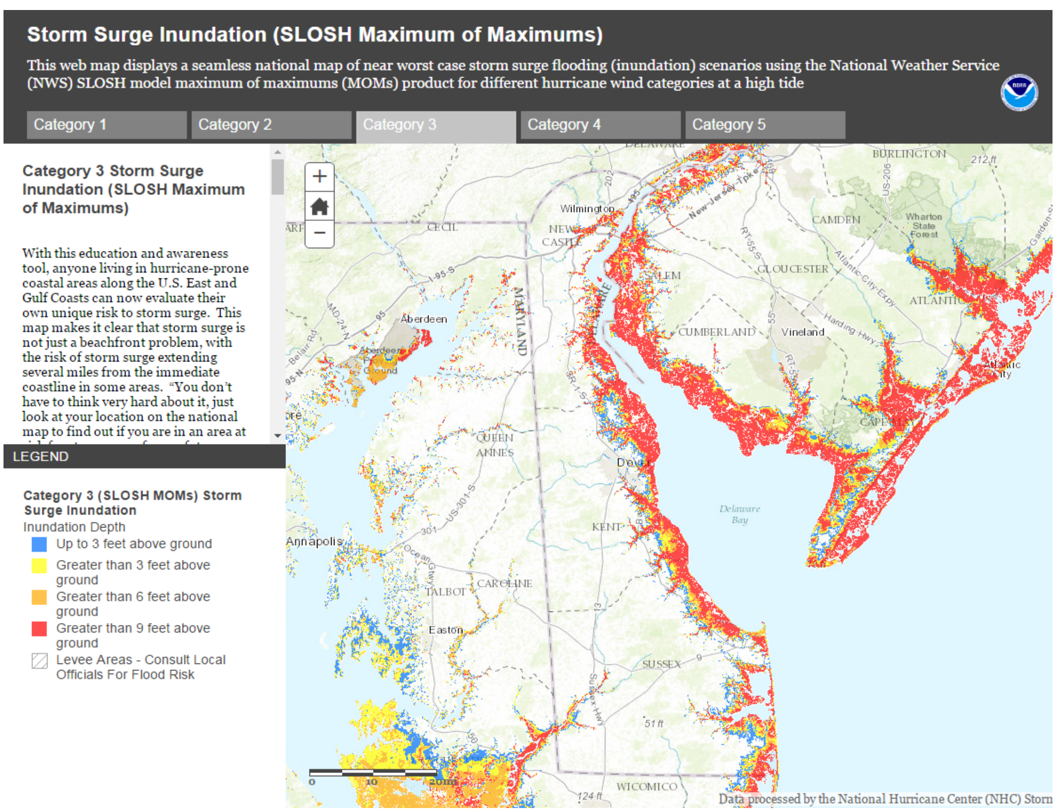


Figure 3.10. NOAA National Weather Service SLOSH Model Data Mapper

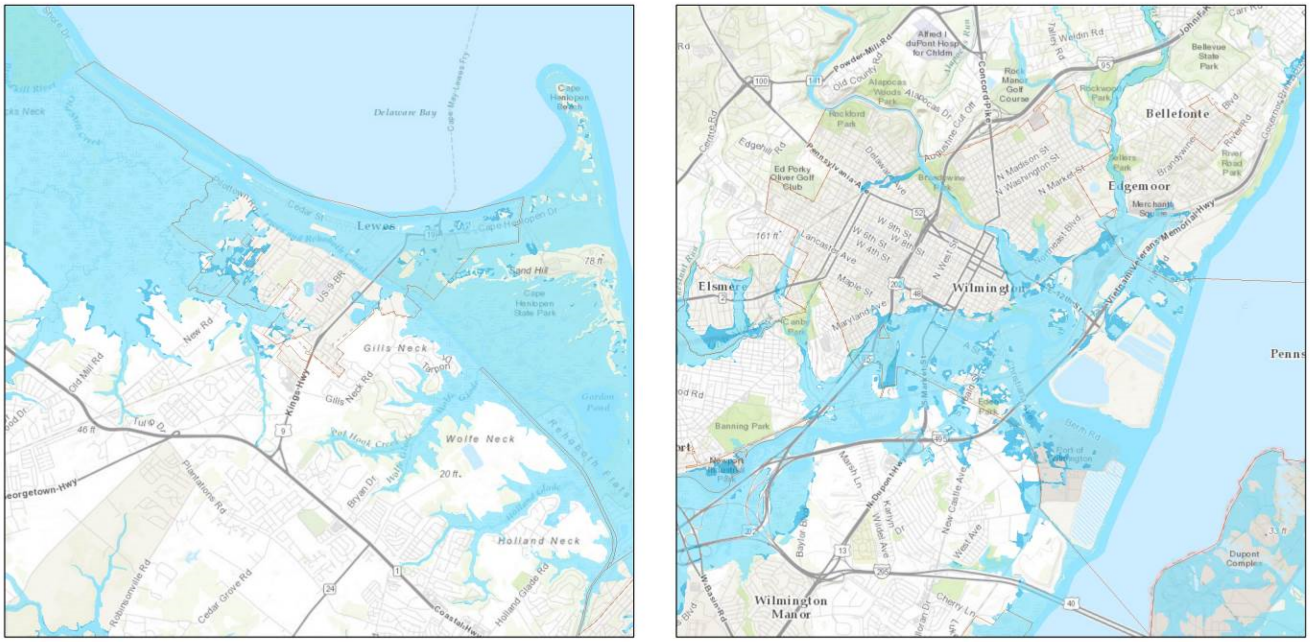


Figure 3.11. Coastal Resilience Risk Explorer Map in Delaware, Category 1 storm + 0.5 m SLR

DNREC Sea Level Rise Inundation Map: MHWH, 0.5m, 1.0, and 1.5m SLR – State of Delaware

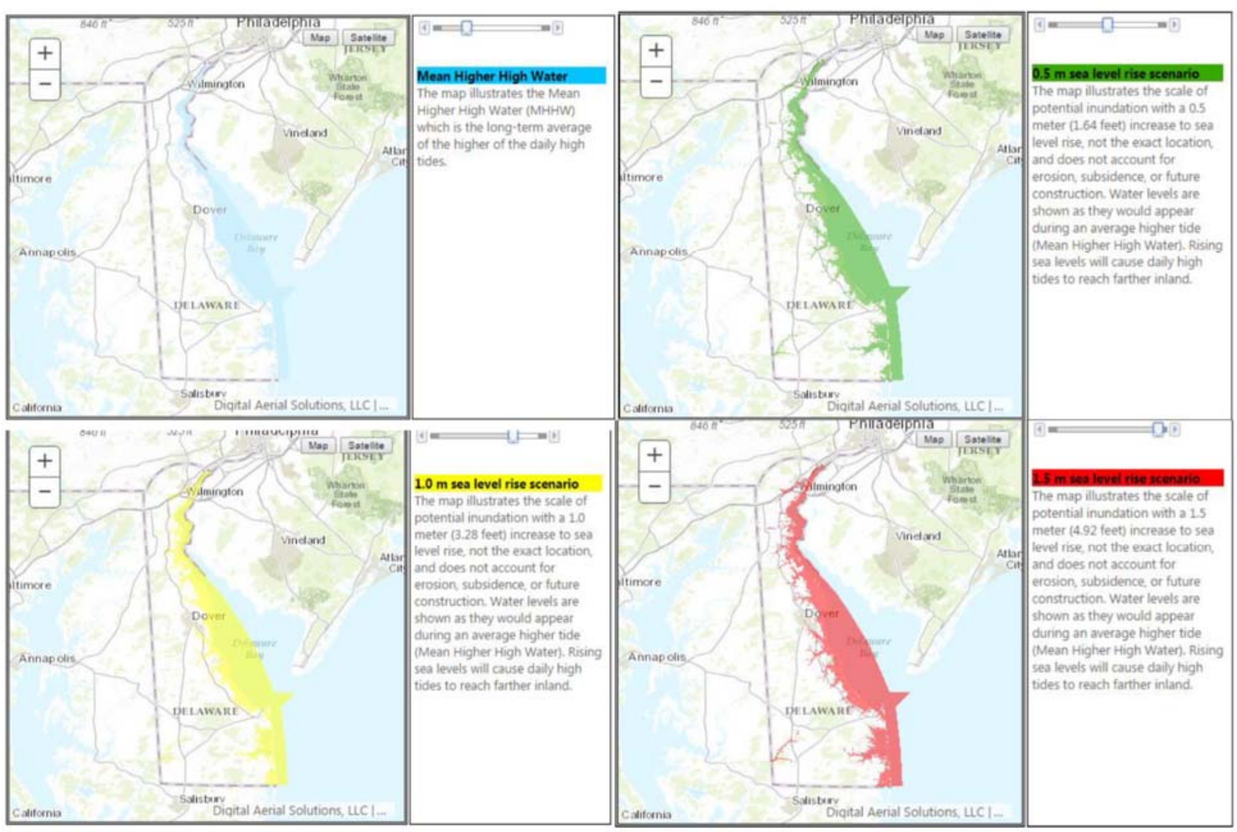


Figure 3.12. Delaware Sea Level Rise Inundation Map

Chapter 4 - Bridge Hydraulic Analysis

The DelDOT roadway design manual requires design of pipe culverts to passes the 50-year flood (Figure 4.1). The DelDOT bridge design manual requires that interstate, principal, and major arterial bridges to pass the 50-year flood. Local roads and streets are designed to pass the 25-year flood (Figure 4.2). The DelDOT road design and bridge design manuals ought to be reviewed to consider increasing the hydraulic design criteria for bridges and culverts to safely pass the 100-year frequency flood discharge. A systematic review of the DelDOT system should be conducted to enlarge bridges and culverts to adequately pass the 100-year flood and raise bridge deck elevations above the 100-year flood elevation with at least 2 feet of freeboard.

The UDWRC evaluate the hydraulic capacity of DelDOT bridges and culverts based on flood discharges that occur during the most severe and worst case storm scenarios benchmarked to the 10-, 50- and 100-year events. Utilizing FEMA flood profiles and floodplain mapping (Figure 4.3), we identified bridges and culverts that: (1) do not have the hydraulic capacity to pass the 10-, 50-, or 100-year flood events caused by an increase of more than 0.5 feet in the water surface elevation or (2) where the roadway is overtopped by the flood water surface elevation. For instance, at the Red Mill Road bridge along White Clay Creek in New Castle County (Figure 4.3), the water surface elevation increases by more than 0.5 feet therefore the bridge has inadequate capacity to convey the 10-, 50-, and 100-year floods but the bridge deck is not overtopped by these flood events. The Kirkwood Highway bridge along White Clay Creek shows no increase in flood elevation therefore it has adequate capacity to convey the flood discharge and the bridge deck is safely above the 100-year flood elevation.

FEMA FIS flood profiles have been developed for streams that are known flood hazards in areas currently developed or likely to be developed within New Castle, Kent, and Sussex counties. For the streams profiled in the FEMA study, a total of 547 bridges and culverts, we assessed whether these hydraulic structures are: (1) adequate to convey the 10-, 50-, and 100-year flood discharges, and (2) whether the bridge decks are overtopped (or inundated) by 10-, 50-, and 100-year floods. We linked this bridge hydraulic data to the DelDOT GIS layer of bridges delineated on the map layer. Note that there are many more bridges (nearly 2,450 bridges in total including highway overpasses) in DelDOT bridge inventory layer than were considered in the flood profile documents. Approximately 19% of these bridges were included in the flood insurance study documents, and were therefore assessed in the current study.

Of the 547 bridges analyzed in Delaware, 42% have inadequate hydraulic capacity to convey the 10-year flood, 64% are inadequate for the 50-year flood, and 74% do not safely convey the 100-year flood (Figure 4.4 and Table 4.1). In New Castle, Kent, and Sussex counties, 74%, 79%, and 67% of the bridges do not adequately convey the 100-year flood, respectively

Of the 547 bridges statewide, 14% of the bridge decks are overtopped by the 10-year flood, 32% are overtopped by the 50-year flood, and 45% are topped by the 100-year flood (Figure 4.5 and Tables 4.2-4.4). In New Castle, Kent, and Sussex counties, 41%, 58%, and 34% of the bridge decks would be overtopped by the 100-year flood, respectively

Design Criteria — Frequency
(Return Period in Years)

Functional Classification	Type of Drainage Installation [1]			
	Pipe Culverts	Storm Drains	Roadside Ditches	Median Drains
Interstate, Freeways and Expressways	50	10 [2]	50	50
Arterials	50	10 [2]	25	25 [2]
Collectors	50 [3]	10 [2]	25 [4]	10 [2]
Local Roads and Streets including Subdivision Streets	25	10 [5]	10	10 [5]

Figure 4.1. DelDOT road design manual culvert design frequency

Functional Classification	Design Frequency (Years)	
	Bridges and Culverts (Over 20-feet clear span)[1]	Bridges under 20 feet, Pipes and Culverts[2]
Interstates, Freeways and Expressways	50	50
Principal Arterials and Minor Arterials	50	50
Major Collectors and Minor Collectors	50	50/25 rural collector
Local Roads and Streets and Subdivision Streets	25	25
Evacuation Routes[3]		

[1] Rigid frames greater than 20-feet span are considered bridges.

[2] Greater than 20 square feet.

[3] Design of bridges and culverts on evacuation routes should be coordinated with DelDOT's Transportation Management Team Evacuation data.
http://www.deldot.gov/information/projects/tmt/evac_map.shtml

Figure 4.2. DelDOT road design manual bridge design frequency

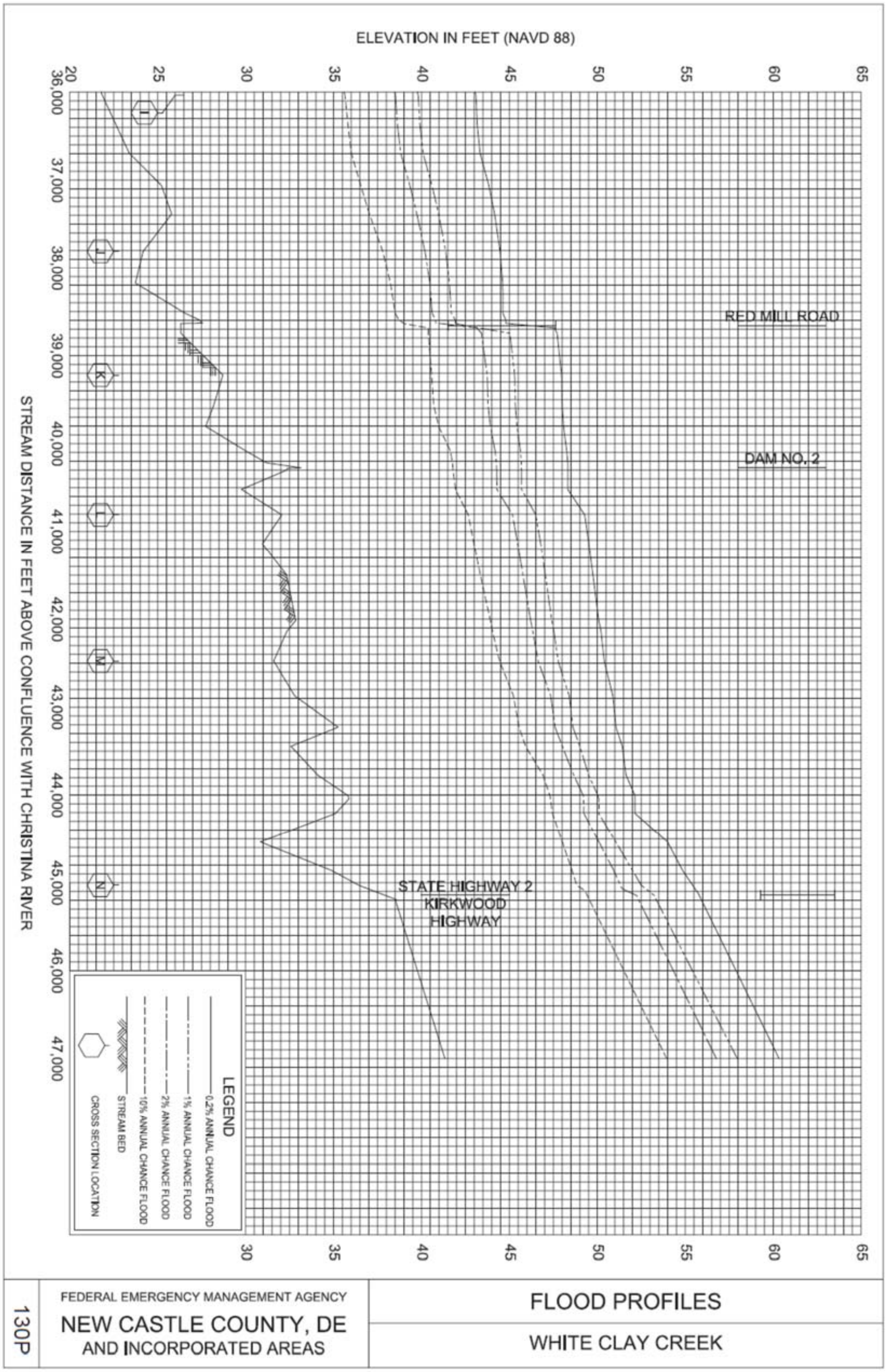


Figure 4.3. FEMA flood profile in along White Clay Creek in New Castle County

Table 4.1. Summary of bridge hydraulic analysis in Delaware

	Inadequate Bridge/Culvert capacity to convey:			
County	**10-year flood**	**50-year flood**	**100-year flood**	**Total Bridges**
New Castle	121	177	204	276
Kent	71	116	135	172
Sussex	36	59	66	99
Statewide	228	352	405	547
	Inadequate Bridge/Culvert capacity to convey:			
County	**10-year flood**	**50-year flood**	**100-year flood**	**Total Bridges**
New Castle	44%	64%	74%	276
Kent	41%	67%	79%	172
Sussex	36%	60%	67%	99
Statewide	42%	64%	74%	547
	Bridge deck overtopped by:			
County	**10-year flood**	**50-year flood**	**100-year flood**	**Total Bridges**
New Castle	47	74	112	276
Kent	19	74	99	172
Sussex	11	26	34	99
Statewide	77	174	245	547
	Bridge deck overtopped by:			
County	**10-year flood**	**50-year flood**	**100-year flood**	**Total Bridges**
New Castle	17%	27%	41%	276
Kent	11%	43%	58%	172
Sussex	11%	26%	34%	99
Statewide	14%	32%	45%	547

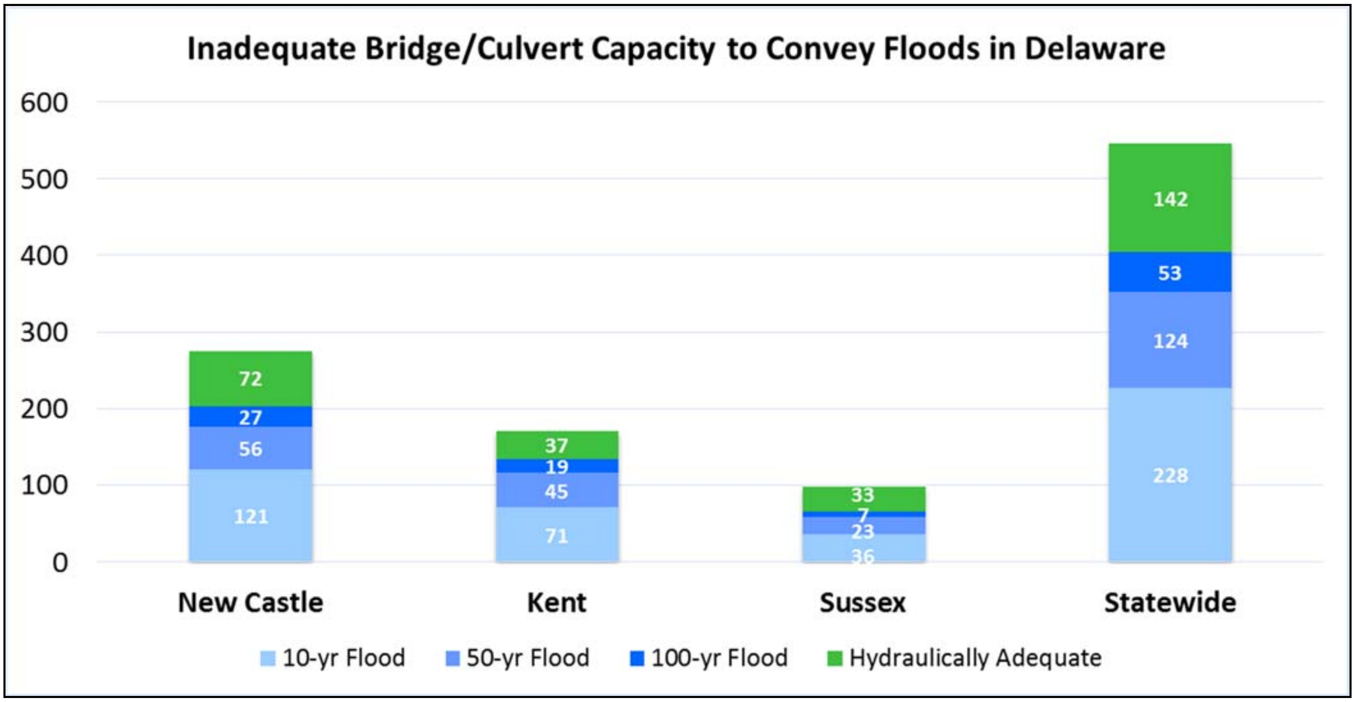


Figure 4.4. Inadequate bridge/culvert capacity to convey floods in Delaware

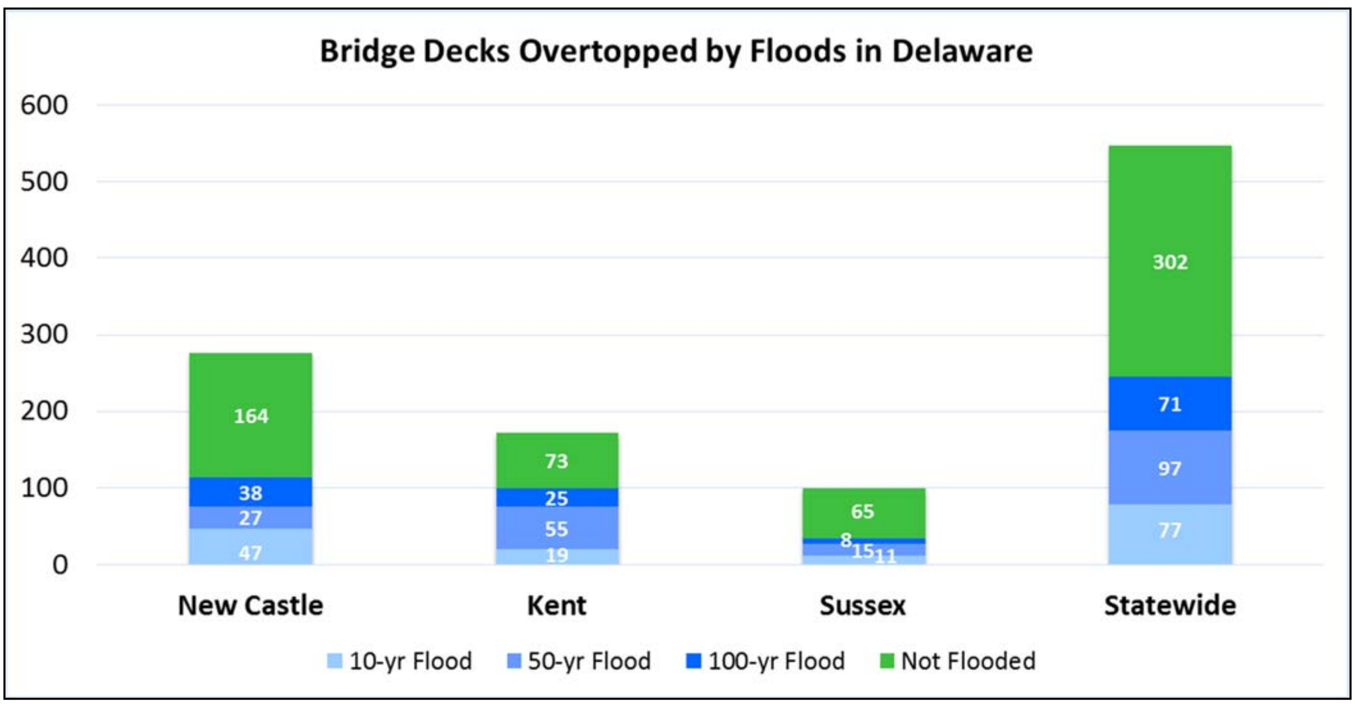


Figure 4.5. Bridge decks overtopped by floods in Delaware

Table 4.2. Bridge hydraulic analysis in New Castle County

			Inadequate Bridge capacity to convey:			Bridge deck overtopped by:		
River Name	**Road Name**	**Station (ft.)**	**10-yr Flood**	**50-yr Flood**	**100-yr Flood**	**10-yr Flood**	**50-yr Flood**	**100-yr Flood**
Appoquinimink River	DuPont Highway	41,000	Y	Y	Y	N	N	Y
Appoquinimink River	State Highway 1	41,850	N	N	N	N	N	N
Appoquinimink River	State Highway 71	62,800	N	N	Y	N	N	N
Appoquinimink River	Railroad	63,950	N	N	N	N	N	N
Appoquinimink River	Wiggins Mill Road	65,350	Y	Y	Y	Y	Y	Y
Appoquinimink River	Grears Corner Road	73,000	Y	Y	Y	Y	Y	Y
Appoquinimink River	State Highway 15	79,450	Y	Y	Y	Y	Y	Y
Appoquinimink Trib. 2	Private Road	1,400	-	-	Y	-	-	Y
Belltown Run	Railroad	6,750	N	Y	Y	N	N	N
Belltown Run	Route 72	7,550	N	Y	Y	N	N	N
Belltown Run	US Highway 40	11,200	Y	Y	Y	N	N	N
Belltown Run	Footbridge	15,050	N	N	N	N	N	N
Belltown Run	Caravel Drive	16,850	N	Y	Y	N	N	N
Belltown Run	Porter Road	20,600	Y	Y	Y	N	N	N
Brandywine Cr LR	Railroad	6,336	N	N	N	N	N	N
Brandywine Cr LR	US Highway 13	7,814	N	N	Y	N	N	N
Brandywine Cr LR	Jessup Street	9,821	N	N	N	N	N	N
Brandywine Cr LR	Market Street	11,299	N	N	N	N	N	N
Brandywine Cr LR	Van Buren Street	14,678	N	N	N	N	N	N
Brandywine Cr LR	Foot Bridge	16,632	N	N	N	N	N	N
Brandywine Cr LR	Private Road	21,014	N	N	N	N	N	N
Chestnut Run	Maple Avenue	845	Y	Y	Y	N	N	N
Chestnut Run	Forest Avenue	2,350	Y	Y	Y	N	Y	Y
Chestnut Run	State Highway 2	6,019	Y	Y	Y	N	N	N
Chestnut Run	Jefferson Avenue	14,890	Y	Y	Y	Y	Y	Y
Chestnut Run	Faukland Road	25,450	N	N	Y	N	N	N
Christina River	Railroad	2,000	N	N	Y	N	N	N
Christina River	Railroad	2,200	N	N	Y	N	N	N
Christina River	I-95	9,200	N	N	N	N	N	N
Christina River	State Highway 141	19,400	N	N	N	N	N	N
Christina River	South James Street	19,500	N	Y	Y	N	N	N
Christina River	I-95	27,000	N	Y	Y	N	N	N
Christina River	Churchmans Road	33,400	N	Y	Y	N	N	N
Christina River	State Rt. 7 (Main St)	52,600	Y	Y	Y	N	Y	Y
Christina River	Smalleys Dam Road	58,900	Y	Y	Y	Y	Y	Y
Christina River	Walther Road	69,400	N	N	N	N	N	N
Christina River	Salem Church Road	80,900	Y	Y	Y	N	Y	Y
Christina River	State Highway 72	94,400	N	N	N	N	N	N
Christina River	Railroad	94,800	N	N	N	N	N	N
Christina River	Old Baltimore Pike	97,600	N	N	N	N	N	N
Christina River	I-95	100,900	N	N	N	N	N	N
Christina River	I-95	101,200	N	N	N	N	N	N
Christina River	State Highway 896	102,800	Y	Y	Y	N	N	N
Christina River	I-95 Ramp	103,000	Y	Y	Y	N	N	Y
Christina River	State Highway 896	103,000	N	Y	Y	N	N	Y
Christina River	Welsh Tract Road	104,000	N	Y	Y	N	N	Y
Christina River	Chestnut Hill Road	105,350	Y	Y	Y	N	Y	Y
Christina River	Railroad	113,900	N	N	N	N	N	N
Christina River	Christina Parkway	115,000	N	N	N	N	N	N
Christina River	Route 2 (Elkton Rd)	117,350	Y	Y	Y	N	N	Y
Christina River	Railroad	121,450	N	N	N	N	N	N
Christina River	Church Road	128,100	Y	Y	Y	N	Y	Y

Christina River	Nottingham Rd (278)	128,800	N	N	Y	N	N	N
Christina River	Wedgewood Road	135,900	Y	Y	Y	N	N	Y
Deep Creek	State Highway 71	10,400	N	N	N	N	N	N
Deep Creek	Railroad	12,250	N	N	N	N	N	N
Deep Creek	State Route 15	20,500	Y	Y	Y	N	Y	Y
Derrickson Run	Maple Avenue	200	Y	Y	Y	N	N	N
Derrickson Run	Railroad	225	Y	Y	Y	N	N	N
Derrickson Run	Baltimore Avenue	1,675	Y	Y	Y	Y	Y	Y
Derrickson Run	State Highway 2	2,150	Y	Y	Y	Y	Y	Y
Derrickson Run	New Road	2,625	Y	Y	Y	Y	Y	Y
Derrickson Run	Junction Street	3,100	Y	Y	Y	Y	Y	Y
Doll Run	Lower Twin Lane	990	-	-	Y	-	-	Y
Doll Run	State Highway 7	1,340	-	-	Y	-	-	Y
Dragon Creek	US Highway 13 N	40	-	-	Y	-	-	N
Dragon Creek	US Highway 13 S	120	-	-	Y	-	-	Y
Dragon Creek	State Highway 1	360	-	-	N	-	-	N
Dragon Creek	McCoy Road	3,000	-	-	Y	-	-	N
Drawyer Creek Trib. 1	Brick Mill Road	9,850	N	N	N	N	N	N
Drawyer Creek Trib. 1	Cedar Lane Road	18,150	N	Y	Y	N	N	N
Drawyer Creek Trib. 1	Dirt Road	20,800	Y	Y	Y	Y	Y	Y
Drawyer Creek Trib. 1	Dirt Road	21,400	Y	Y	Y	Y	Y	Y
Drawyer Creek Trib. 1	Railroad	21,800	Y	Y	Y	Y	Y	Y
Drawyer Creek Trib. 1	Summit Bridge Road	22,400	Y	Y	Y	N	N	Y
Duck Creek	Smyrna Landing Rd	1,675	N	N	N	N	N	N
Duck Creek	State Highway 1	2,900	N	N	N	N	N	N
Duck Creek	US Highway 13	8,200	N	Y	Y	N	N	Y
Duck Creek	Duck Creek Road	12,250	Y	Y	Y	N	Y	Y
Duck Creek	Railroad Bridge	19,050	N	Y	Y	N	N	N
Duck Creek	State Highway 15	19,600	Y	Y	Y	Y	Y	Y
Duck Creek	Private Road	22,150	Y	Y	Y	Y	Y	Y
Providence Creek	Alley Mill Road	29,200	N	Y	Y	N	Y	Y
EB Christina River	Covered Bridge Lane	260	Y	Y	Y	N	N	N
EB Christina River	Wedgewood Road	2,520	Y	Y	Y	N	Y	Y
Little Mill Creek	I-95	3,600	N	N	N	N	N	N
Little Mill Creek	Railroad Spur	4,000	Y	Y	Y	N	N	N
Little Mill Creek	Railroad	4,050	Y	Y	Y	N	N	N
Little Mill Creek	Maryland Avenue	7,880	Y	Y	Y	Y	Y	Y
Little Mill Creek	DuPont Road	10,650	Y	Y	Y	N	N	Y
Little Mill Creek	DuPont Relocated	10,800	N	N	N	N	N	N
Little Mill Creek	Railroad	16,360	Y	Y	Y	N	N	N
Little Mill Creek	Kirkwood Highway	19,120	Y	Y	Y	Y	Y	Y
Little Mill Creek	State Highway 141	23,040	N	N	Y	N	N	N
Matson Run	Lea Boulevard	1,214	N	N	Y	N	N	Y
Matson Run	Washington Street	2,059	N	Y	Y	N	N	N
Mill Creek	Stanton-Christiana Road	200	N	N	N	N	N	N
Mill Creek	Del. Park Cart Path	1,080	Y	Y	Y	Y	Y	Y
Mill Creek	Delaware Park Blvd	1,160	Y	Y	Y	N	N	N
Mill Creek	Del. Park Cart Path	2,520	Y	Y	Y	Y	Y	Y
Mill Creek	Del. Park Cart Path	4,240	N	Y	Y	N	N	N
Mill Creek	Railroad	4,560	N	N	N	N	N	N
Mill Creek	Old Capitol Trail	6,280	Y	Y	Y	N	N	N
Mill Creek	State Highway 2	8,920	N	N	N	N	N	N
Mill Creek	Old Mill Town Road	13,720	Y	Y	Y	N	N	Y
Mill Creek	Mill Town Road	13,960	N	N	N	N	N	N
Mill Creek	Limestone Road	16,360	N	Y	Y	N	N	N
Mill Creek	Stoney Batter Road	24,800	N	N	Y	Y	N	N
Mill Creek	Camp Wright Road	30,320	Y	Y	Y	Y	Y	Y

Mill Creek	Mill Creek Road	30,800	Y	Y	Y	N	N	N
Mill Creek	Access Road	34,000	Y	Y	Y	Y	Y	Y
Mill Creek	Access Road	35,400	N	Y	Y	N	N	N
Mill Creek	Brackenville Road	37,320	Y	Y	Y	N	N	N
Mill Creek	Mill Creek Road	40,640	N	Y	Y	N	N	N
Mill Creek	Evanson Road	43,080	N	Y	Y	N	N	N
Mill Creek	Grant Avenue	43,920	Y	Y	Y	N	N	N
Mill Creek	Railroad	44,760	N	N	N	N	N	N
Mill Creek	Old Lancaster Pike	46,000	N	Y	Y	N	N	N
Mill Creek	Lancaster Pike	46,200	N	Y	Y	N	N	N
Mill Creek	McGovern Road	50,160	Y	Y	Y	Y	Y	Y
Muddy Run	Glascow Avenue	250	-	-	Y	-	-	Y
Naaman Creek	Access Road	2,550	Y	Y	Y	N	N	Y
Naaman Creek	Railroad	2,850	N	N	N	N	N	N
Naaman Creek	US Highway 13	3,200	N	N	N	N	N	N
Naaman Creek	Abandoned Railroad	3,800	N	N	Y	Y	N	N
Naaman Creek	Railroad Spur	4,950	Y	Y	Y	N	Y	Y
Naaman Creek	State Highway 92	5,000	N	N	N	N	N	N
Naaman Creek	Shopping Center	6,400	Y	Y	Y	N	N	Y
Persimmon Run	Sandy Brae Road	1,680	Y	Y	Y	Y	Y	Y
Persimmon Run	Access Road	1,960	Y	Y	Y	Y	Y	Y
Pike Creek	State Highway 2	2,120	N	N	N	N	N	N
Pike Creek	Upper Pike Creek Rd	4,120	Y	Y	Y	Y	Y	Y
Pike Creek	Henderson Road	7,120	N	Y	Y	N	N	Y
Pike Creek	New Linden Hill Rd	10,480	N	Y	Y	N	N	N
Pike Creek	Golf Cart Road	14,440	Y	Y	Y	N	N	Y
Pike Creek	Golf Cart Road	15,400	Y	Y	Y	N	Y	Y
Pike Creek	Access Road	16,200	N	Y	Y	N	Y	Y
Pike Creek	Granville Road	19,400	N	Y	Y	N	N	Y
Pike Creek	State Highway 72	22,480	N	Y	Y	N	Y	Y
Red Clay Creek	Newport Pike	4,200	Y	Y	Y	N	N	Y
Red Clay Creek	Newport Pike	4,400	Y	Y	Y	N	N	Y
Red Clay Creek	Kiamengi Road	9,000	N	Y	Y	N	N	N
Red Clay Creek	Old Capitol Trail	10,800	Y	Y	Y	N	N	Y
Red Clay Creek	Newport Road	11,400	Y	Y	Y	N	N	Y
Red Clay Creek	Access Road	12,500	Y	Y	Y	N	Y	Y
Red Clay Creek	Newport Gap Pike	15,100	N	Y	Y	N	N	N
Red Clay Creek	Greenbank Road	15,700	Y	Y	Y	N	N	N
Red Clay Creek	Access Road	15,800	N	Y	Y	N	Y	Y
Red Clay Creek	W&W Railward	16,000	N	Y	Y	N	Y	Y
Red Clay Creek	W&W Railward	18,800	N	Y	Y	N	N	Y
Red Clay Creek	Faukland Road	19,700	Y	Y	Y	N	Y	Y
Red Clay Creek	Railroad	23,500	N	Y	Y	N	N	N
Red Clay Creek	Golf Cart Path	26,200	N	N	N	N	N	N
Red Clay Creek	Lancaster Pike	26,400	N	N	N	N	N	N
Red Clay Creek	W&W Railward	27,100	N	N	N	N	N	N
Red Clay Creek	W&W Railward	32,100	N	Y	Y	N	Y	Y
Red Clay Creek	Fox Hill Lane	32,300	N	Y	Y	N	N	N
Red Clay Creek	Barley Mill Road	36,900	Y	Y	Y	N	N	Y
Red Clay Creek	Mount Cuba Road	41,500	N	Y	Y	N	N	N
Red Clay Creek	W&W Railward	43,000	N	Y	Y	N	N	N
Red Clay Creek	W&W Railward	44,700	Y	Y	Y	N	Y	Y
Red Clay Creek	Access Road	48,800	Y	Y	Y	N	N	Y
Red Clay Creek	Creek Road	50,200	N	Y	Y	N	N	N
Red Clay Creek	Creek Road	51,400	N	Y	Y	N	N	N
Red Clay Creek	W&W Railward	51,500	Y	Y	Y	N	Y	Y
Red Clay Creek	Barley Mill Road	53,300	Y	Y	Y	N	N	N

Red Clay Creek	Sharpless Road	55,800	Y	Y	Y	N	N	N
Red Clay Creek	W&W Railward	58,200	Y	Y	Y	N	Y	Y
Red Clay Creek	Yorklyn Road	61,800	Y	Y	Y	N	N	N
Red Clay Creek	Benge Road	63,900	N	N	Y	N	N	N
Red Clay Creek	Access Road	64,900	Y	Y	Y	Y	Y	Y
Shellpot Creek	Gov Prince Blvd (13)	8,650	Y	Y	Y	Y	Y	Y
Shellpot Creek	Lea Boulevard	8,950	Y	Y	Y	Y	Y	Y
Shellpot Creek	Colony Boulevard	10,300	Y	Y	Y	N	Y	Y
Shellpot Creek	US 13 Market Street	12,900	N	Y	Y	N	N	N
Shellpot Creek	Washington Street	16,000	Y	Y	Y	N	N	N
Shellpot Creek	Shipley Road	16,700	Y	Y	Y	N	Y	Y
Shellpot Creek	Carr Road	17,600	Y	Y	Y	N	N	N
Shellpot Creek	Carr Road	20,800	Y	Y	Y	Y	Y	Y
Shellpot Creek	I-95	21,100	Y	Y	Y	N	N	N
Shellpot Creek	Railroad	21,450	N	N	N	N	N	N
Shellpot Creek	Baynard Boulevard	23,450	Y	Y	Y	Y	Y	Y
Shellpot Creek	Wilson Road	28,400	Y	Y	Y	N	N	N
Shellpot Creek	Coachman Road	33,200	Y	Y	Y	N	Y	Y
Shellpot Creek	Silverside Road	37,300	Y	Y	Y	Y	Y	Y
Shellpot Creek	Walkway	38,650	Y	Y	Y	Y	Y	Y
Shellpot Creek	Private Road	39,750	Y	Y	Y	Y	Y	Y
Shellpot Creek	Kennedy Road	40,450	Y	Y	Y	Y	Y	Y
Silverbrook	Chestnut Hill Road	440	Y	Y	Y	Y	Y	Y
Silverbrook	Park Lane	1,620	Y	Y	Y	Y	Y	Y
Silverbrook Run	Taylor Road	800	N	Y	Y	N	N	Y
Silverbrook Run	Access Road	1,450	Y	Y	Y	Y	Y	Y
Silverbrook Run	Railroad	1,750	N	N	N	N	N	N
Silverbrook Run	Railroad Spur	1,825	N	N	Y	N	N	N
Silverbrook Run	State Highway 2	2,125	N	N	N	N	N	N
Silverbrook Run	New Road	2,175	Y	Y	Y	Y	Y	Y
Silverbrook Run	Access Road	2,625	Y	Y	Y	Y	Y	Y
Silverbrook Run	Access Road	2,925	Y	Y	Y	Y	Y	Y
SB Naaman Creek	Railroad Bridge	250	N	N	Y	N	N	N
SB Naaman Creek	Access Road	450	N	Y	Y	N	N	N
SB Naaman Creek	Interstate 495	3,100	N	Y	Y	N	N	N
SB Naaman Creek	Darley Road	4,200	N	Y	Y	N	N	N
SB Naaman Creek	Darley Road	5,050	N	Y	Y	N	N	N
SB Naaman Creek	Darley Road	5,900	N	N	N	N	N	N
SB Naaman Creek	I-95	10,100	N	Y	Y	N	N	N
SB Naaman Creek	Glenrock Road	10,400	N	N	Y	N	N	N
SB Naaman Creek	Railroad	12,850	N	N	N	N	N	N
SB Naaman Creek	Marsh Road	18,900	N	Y	Y	N	N	N
SB Naaman Creek	Harvey Mill Park	21,400	N	Y	Y	N	N	N
SB Naaman Creek	Decatur Road	22,400	N	Y	Y	N	N	N
SB Naaman Creek	Acme Entrance	23,400	N	N	Y	N	N	N
SB Naaman Creek	Rt. 92 Naamans Rd	23,600	Y	Y	Y	N	N	N
SB Naaman Creek	Rt. 261 Foulk Rd	24,650	Y	Y	Y	N	N	N
SB Naaman Creek	Culver Drive	24,850	N	Y	Y	N	N	N
Drawyer Creek Trib.	Cleaver Farms Road	3,500	N	Y	Y	N	N	N
Drawyer Creek Trib.	Cedar Lane Road	7,900	Y	Y	Y	Y	Y	Y
Drawyer Creek Trib.	Summit Bridge Road	9,350	Y	Y	Y	N	N	N
Belltown Run Trib.	Culvert	3,120	Y	Y	Y	N	Y	Y
Belltown Run Trib.	Beck's Woods Drive	3,560	Y	Y	Y	N	N	Y
Belltown Run Trib.	US Highway 40	5,280	Y	Y	Y	Y	Y	Y
Belltown Run Trib.	Culvert	6,600	Y	Y	Y	Y	Y	Y
Belltown Run Trib.	Scotland Drive	6,880	Y	Y	Y	N	N	N
Belltown Run Trib.	Railroad	7,680	Y	Y	Y	N	N	N

Belltown Run Trib. 1	US Highway 40	920	N	N	N	N	N	N
Belltown Run Trib. 2	Culvert	1,000	Y	Y	Y	N	N	N
White Clay Tributary	Railroad	4,600	Y	Y	Y	N	N	N
White Clay Tributary	State Highway 4	8,120	Y	Y	Y	Y	Y	Y
Mill Creek Tributary	Private Road	1,360	-	-	Y	-	-	Y
Mill Creek Tributary	Private Road	1,560	-	-	Y	-	-	Y
Mill Creek Tributary	Star Road	1,920	-	-	Y	-	-	N
Mill Creek Tributary	Slashpine Court	2,820	-	-	Y	-	-	Y
Mill Creek Tributary	Loblolly Court	3,320	-	-	Y	-	-	Y
WB Christina River	Swim Club Access	700	Y	Y	Y	Y	Y	Y
WB Christina River	Railroad	5,650	N	N	N	N	N	N
WB Christina River	Sandy Brae Road	6,200	N	Y	Y	N	N	N
WB Christina River	Rt. 2 Elkton Rd	7,200	N	Y	Y	N	N	N
White Clay Creek	Railroad	12,800	Y	Y	Y	N	N	N
White Clay Creek	Old State Highway 7	15,900	Y	Y	Y	N	N	N
White Clay Creek	State Highway 7	16,300	N	N	N	N	N	N
White Clay Creek	*Unlabeled Road*	16,800	Y	Y	Y	Y	Y	Y
White Clay Creek	Del. Park Cart Path	20,300	Y	Y	Y	N	Y	Y
White Clay Creek	Del. Park Cart Path	21,800	Y	Y	Y	N	N	Y
White Clay Creek	Del. Park Cart Path	23,300	Y	Y	Y	N	N	N
White Clay Creek	DE Park Track South	25,800	N	Y	Y	N	N	Y
White Clay Creek	Del. Park Cart Path	26,200	Y	Y	Y	N	N	Y
White Clay Creek	Railroad	28,150	N	Y	Y	N	N	N
White Clay Creek	Old Harmony Road	32,200	Y	Y	Y	N	N	Y
White Clay Creek	Harmony Road	32,600	N	N	N	N	N	N
White Clay Creek	Red Mill Road	38,700	N	Y	Y	N	N	N
White Clay Creek	State Highway 2	45,100	N	N	N	N	N	N
White Clay Creek	Rt. 72 Papermill Rd	53,200	Y	Y	Y	N	N	N
Yorkshire Ditch	Cooch's Bridge Road	240	Y	Y	Y	Y	Y	Y
Yorkshire Ditch	Bellview Road	700	Y	Y	Y	N	Y	Y

Table 4.3. Bridge hydraulic analysis in Kent County

			Inadequate Bridge capacity to convey:			Bridge deck overtopped by:		
River Name	**Road Name**	**Station (ft)**	**10-yr Flood**	**50-yr Flood**	**100-yr Flood**	**10-yr Flood**	**50-yr Flood**	**100-yr Flood**
Andrews Lake	Andrew's Lake Road	-	N	N	N	N	N	N
Beaverdam Ditch	State Route 8	1,350	N	N	Y	N	N	N
Beaverdam Ditch	Strauss Avenue	3,250	N	Y	Y	N	N	N
Beaverdam Ditch	Conrail	4,100	N	Y	Y	N	Y	Y
Beaverdam Ditch	Taraila Road	5,375	N	Y	Y	N	Y	Y
Browns Branch Trib. 1	US Highway 13 NB	4,640	N	Y	Y	N	N	N
Browns Branch Trib. 1	US Highway 13 SB	5,000	N	Y	Y	N	N	N
Browns Branch Trib. 1	Benjamin Street	6,080	Y	Y	Y	N	Y	Y
Browns Branch Trib. 1	Private Road	6,780	N	Y	Y	N	N	N
Browns Branch Trib. 1	Foot Bridge	6,860	N	Y	Y	N	Y	Y
Browns Branch Trib. 1	Del Ave. (Simmons St.)	7,480	N	Y	Y	N	N	Y
Cahoon Branch	Kenton Drive	2,200	Y	Y	Y	N	Y	Y
Cahoon Branch	Chestnut Grove Road	4,550	Y	Y	Y	N	Y	Y
Cahoon Branch	Sharon Hill Road	10,450	Y	Y	Y	N	Y	Y
Cahoon Branch	Rt. 8 (Forrest Avenue)	11,850	Y	Y	Y	N	Y	Y
Cahoon Branch	Rose Valley School Road	18,650	Y	Y	Y	N	Y	Y
Cahoon Branch	Farm Bridge	25,200	Y	Y	Y	Y	Y	Y
Choptank River	Still Road	6,050	N	Y	Y	N	N	N
Choptank River	Mud Mill Road	14,250	N	N	N	N	N	N
Choptank/Tidy Island Cr	Westville Road	19,225	N	Y	Y	N	N	N
Tidy Island Creek	Main Street	33,800	N	N	N	N	N	N
Coursey Pond	Canterbury Road	6,800	N	N	N	N	N	N
Coursey Pond	Killens Ponds Road	13,950	N	N	N	N	N	N
Murderkill River	US Highway 13 NB	27,100	N	N	N	N	N	N
Murderkill River	US Highway 13 SB	27,200	N	N	N	N	N	N
Murderkill River	Reeves Crossing Road	32,300	Y	Y	Y	N	Y	Y
Murderkill River	Railroad	34,750	N	N	N	N	N	N
Murderkill River	Little Mastens Corner Rd	36,450	Y	Y	Y	N	Y	Y
Murderkill River	Marshyhope Road	38,550	Y	Y	Y	N	Y	Y
Murderkill River	Private Road	39,675	Y	Y	Y	N	Y	Y
Cow Marsh Creek	Mahan Corner Road	8,880	N	N	N	N	N	N
Cow Marsh Creek	Pony Track Road	18,640	N	Y	Y	N	N	N
Cow Marsh Creek	Hollering Hill Road	23,400	N	N	N	N	N	N
Cow Marsh Creek	Cow Marsh Creek Road	28,520	N	N	N	N	N	N
Cow Marsh Creek	Farm Road	34,560	N	Y	Y	N	N	Y
Willow Grove Prong	Mud Mill Road	38,000	Y	Y	Y	N	Y	Y
Willow Grove Prong	Honeysuckle Road	39,000	Y	Y	Y	Y	Y	Y
Culbreth Marsh Ditch	Shady Bridge Road	3,300	Y	Y	Y	N	Y	Y
Culbreth Marsh Ditch	Mahan Corner Road	7,350	N	N	Y	N	N	N
Culbreth Marsh Ditch	Private Drive	13,850	Y	Y	Y	N	Y	Y
Culbreth Marsh Ditch	Lucks Drive	17,950	Y	Y	Y	N	Y	Y
Duck Creek	Smyrna Landing Road	1,650	N	N	N	N	N	N
Duck Creek	State Highway 1	2,900	N	N	N	N	N	N
Duck Creek	US Route 13	8,225	N	Y	Y	N	N	N
Duck Creek	North Main Street	12,250	Y	Y	Y	N	Y	Y
Duck Creek	Conrail	19,075	N	N	Y	N	N	N
Duck Creek	State Route 15	19,600	Y	Y	Y	Y	Y	Y
Providence Creek	Private Drive	22,125	Y	Y	Y	Y	Y	Y
Providence Creek	Alley Mill Road	29,175	N	Y	Y	N	Y	Y
Fork Branch	State Route 15	2,100	Y	Y	Y	Y	Y	Y
Fork Branch	Conrail	2,350	Y	Y	Y	N	N	N
Fork Branch	McKee Road	7,050	N	Y	Y	N	Y	Y

Fork Branch	State Route 15	14,375	Y	Y	Y	N	Y	Y
Fork Branch	Pearsons Corner Road	21,400	N	Y	Y	N	N	N
Fork Branch	Rose Dale Avenue	23,850	Y	Y	Y	N	Y	Y
Fork Branch	Shaws Corner Road	32,250	Y	Y	Y	N	Y	Y
Green Branch	Gallo Road	4,575	N	N	Y	N	N	N
Green Branch	Greenville Road	14,200	Y	Y	Y	N	Y	Y
Green Branch	Vernon Road	15,975	Y	Y	Y	N	N	N
Green Branch	Layton Corners Road	21,650	Y	Y	Y	N	N	Y
Green's Branch	Main Street	-	N	N	N	N	N	N
Green's Branch	Foot Bridge	4,650	N	N	N	N	N	N
Green's Branch	Conrail	5,150	N	Y	Y	N	N	N
Green's Branch	Rodney Road	8,380	N	N	Y	N	N	N
Green's Branch	Bassett Street	8,800	N	N	N	N	N	N
Green's Branch	Conrail	8,890	N	N	N	N	N	N
Horsepen Arm	Whiteleysburg Road	4,200	Y	Y	Y	N	N	N
Horsepen Arm	Fox Hunters Road	8,850	Y	Y	Y	N	Y	Y
Horsepen Arm	Park Brown Road	13,750	Y	Y	Y	N	Y	Y
Isaac Branch	US Route 13	11,000	N	Y	Y	N	N	Y
Isaac Branch	Layton Avenue	18,700	N	N	N	N	N	N
Isaac Branch	Conrail	18,775	N	N	N	N	N	N
Isaac Branch	North Railroad Avenue	18,900	N	N	N	N	N	N
Little River	State Route 8	1,000	N	Y	Y	N	N	N
Little River	White Oak Road	9,700	Y	Y	Y	N	Y	Y
Little River	Farm Driveway	10,950	N	Y	Y	N	Y	Y
Little River	US Route 1	11,950	N	Y	Y	N	N	N
Little River	Culvert	13,250	Y	Y	Y	N	Y	Y
Little River	East Wind Drive	13,300	N	Y	Y	N	N	Y
Little River	Walkway Bridge	13,875	Y	Y	Y	N	Y	Y
Little River	West Wind Drive	14,300	Y	Y	Y	N	N	Y
Maidstone Branch	Conrail	300	N	Y	Y	N	N	N
Maidstone Branch	McKee Road	2,550	Y	Y	Y	N	Y	Y
Maidstone Branch	Kenton Drive 9900	9,900	Y	Y	Y	N	Y	Y
Maidstone Branch	Maidstone Branch Road	18,400	Y	Y	Y	Y	Y	Y
Maidstone Branch	Sharon Hill Road	22,400	Y	Y	Y	Y	Y	Y
Penrose Branch	Victory Chapel Road	30,350	N	Y	Y	N	Y	Y
Penrose Branch	Pearsons Corner Road	36,575	Y	Y	Y	Y	Y	Y
Marshyhope Creek	US Route 16	75	N	N	N	N	N	N
Marshyhope Creek	Fishers Bridge Road	8,100	N	Y	Y	N	Y	Y
Marshyhope Creek	Andrewville Road	18,275	N	N	Y	N	N	N
Marshyhope Creek	Rt. 14 Vernon Rd	26,775	N	N	N	N	N	N
Marshyhope Creek	Hemping Road	33,100	N	Y	Y	N	N	Y
Marshyhope Creek	Brownsville Road	37,850	Y	Y	Y	N	Y	Y
Marshyhope Ditch	Whiteleysburg Road	42,050	N	Y	Y	N	N	N
Marshyhope Ditch	Park Brown Road	47,100	Y	Y	Y	N	Y	Y
McColley Pond	Canterbury Road	1,325	N	N	N	N	N	N
Browns Branch	Sandbox Road	9,200	N	Y	Y	N	Y	Y
Browns Branch	Killens Pond Road	14,650	Y	Y	Y	N	Y	Y
Browns Branch	Jackson Ditch Road	21,350	N	Y	Y	N	Y	Y
Browns Branch	Jackson Ditch Road	27,600	Y	Y	Y	N	N	Y
Browns Branch	State Highway 14	31,000	Y	Y	Y	N	N	Y
Browns Branch	Doctor Smith Road	31,225	Y	Y	Y	Y	Y	Y
Browns Branch	Kathryn Drive	34,250	N	Y	Y	N	N	Y
McGinnis Pond	McGinnis Pond Road	-	N	Y	Y	N	N	Y
Mill Creek	US Route 13	14,000	N	N	N	N	N	N
Mill Creek	South Carter Road	19,250	N	Y	Y	N	N	N
Mill Creek	Railroad	24,500	N	Y	Y	N	N	N
Morgan Branch	Private Road	2,250	Y	Y	Y	Y	Y	Y

Morgan Branch	Little Creek Road	5,150	Y	Y	Y	Y	Y	Y
Puncheon Branch	Rt. 1 South State St.	2,550	Y	Y	Y	N	N	N
Puncheon Branch	US 13 DuPont Highway	3,150	Y	Y	Y	N	Y	Y
Puncheon Branch	US 13A S. Gov. Ave.	3,700	Y	Y	Y	Y	Y	Y
Puncheon Branch	New Burton Road	7,250	Y	Y	Y	N	Y	Y
Puncheon Branch	Conrail	7,350	N	N	N	N	N	N
St. Jones River	US Route 13	10,550	N	N	N	N	N	N
St. Jones River	Court Street	14,600	N	N	Y	N	N	N
St. Jones River	E. Loockerman Street	15,350	N	Y	Y	N	Y	Y
St. Jones River	Rt. 8 E. Division Street	17,050	N	Y	Y	N	Y	Y
St. Jones River	US Route 13 Alt.	22,975	N	N	Y	N	N	N
St. Jones River	West College Square	29,950	N	Y	Y	N	Y	Y
Stream 1	Sunnyside Road	600	N	Y	Y	N	N	N
Tantrough Branch	Northbound US Route 13	-	N	N	Y	N	N	N
Tantrough Branch	Southbound US Route 13	50	N	N	Y	N	N	N
Tantrough Branch	County Road 633	6,650	Y	Y	Y	N	N	N
Tantrough Branch	Dirt Road	13,500	Y	Y	Y	N	N	N
TappaHanna Ditch	Sandy Bend Road	4,700	N	Y	Y	N	Y	Y
TappaHanna Ditch	Tappahanna Bridge Road	9,050	N	Y	Y	N	N	Y
TappaHanna Ditch	Tuxward Road	14,150	N	Y	Y	N	N	Y
TappaHanna Ditch	Hourglass Road	19,300	N	N	N	N	N	N
TappaHanna Ditch	Private Road	22,950	Y	Y	Y	N	N	N
TappaHanna Ditch	Private Road	25,600	Y	Y	Y	Y	Y	Y
TappaHanna Ditch	Ray's Lane	26,450	Y	Y	Y	Y	Y	Y
TappaHanna Ditch	State Route 8	26,850	N	Y	Y	N	Y	Y
Tidbury Creek	Alt. 13 Upper King Rd	25,700	N	N	N	N	N	N
Tidbury Creek	Railroad	28,900	-	-	Y	-	-	N
Tidbury Creek	Dundee Road	33,000	-	-	Y	-	-	Y
Tidbury Creek	Steelers Ridge Road	34,300	-	-	Y	-	-	Y
Tidbury Creek	Steelers Ridge Road	37,000	-	-	Y	-	-	Y
Beaverdam Branch	Marshyhope Road	840	N	Y	Y	N	N	Y
Black Swamp Creek	Railroad	3,960	N	N	N	N	N	N
Black Swamp Creek	Little Mastens Corner	7,840	N	N	Y	N	N	N
Black Swamp Creek	Hills Market Road	11,920	Y	Y	Y	N	Y	Y
Black Swamp Creek	Marshyhope Road	16,640	Y	Y	Y	Y	Y	Y
Black Swamp Creek	Hopkins Cemetary Road	21,280	Y	Y	Y	Y	Y	Y
Double Run	Irish Hill Road	9,350	N	Y	Y	N	N	Y
Double Run	Rt. 106 Woodlytown Rd	14,550	Y	Y	Y	N	Y	Y
Double Run	County Highway 105	22,150	Y	Y	Y	N	Y	Y
Double Run	Barney Jenkins Road	27,650	Y	Y	Y	Y	Y	Y
Fan Branch	Little Mastens Corner Rd	5,400	Y	Y	Y	N	Y	Y
Hudson Branch	Fox Chase Road	6,500	N	Y	Y	N	Y	Y
Hudson Branch	Barratts Chapel Road	14,250	N	Y	Y	N	Y	Y
Hudson Branch	State Highway 15	16,200	N	Y	Y	N	N	Y
Hudson Branch	US Highway 13	18,600	N	Y	Y	N	N	Y
Hudson Branch	Turkey Point Road	23,950	N	Y	Y	N	N	Y
Andrew's Lake Road	Andrews Lake Road	3,600	N	N	N	N	N	N
Pratt Branch	State Highway 15	12,050	Y	Y	Y	N	Y	Y
Pratt Branch	Chimney Hill Road	21,550	Y	Y	Y	Y	Y	Y
Red House Branch	Lake Front Drive	2,070	-	-	Y	-	-	Y
Red House Branch	Railroad	2,080	-	-	Y	-	-	Y
Red House Branch	Rt. 234 Bison Road	3,040	-	-	Y	-	-	Y
Spring Branch	Scrap Tavern Road	3,250	Y	Y	Y	N	Y	Y
Spring Branch	Chimney Hill Road	7,600	Y	Y	Y	N	Y	Y
Spring Branch	US Highway 13	15,750	Y	Y	Y	Y	Y	Y
Tidbury Creek Trib. 3	Rt. 10 Henry Cowgill Rd	800	-	-	Y	-	-	Y

Table 4.4. Bridge hydraulic analysis in Sussex County

			Inadequate Bridge capacity to convey:			Bridge deck overtopped by:		
River Name	**Road Name**	**Station (ft)**	**10-yr Flood**	**50-yr Flood**	**100-yr Flood**	**10-yr Flood**	**50-yr Flood**	**100-yr Flood**
Bark Pond	Conrail	2,300	N	N	N	N	N	N
Bark Pond	County Road 328	2,900	N	N	N	N	N	N
Betts Pond	Conrail	1,250	N	N	N	N	N	N
Betts Pond	State Route 20	2,000	Y	Y	Y	Y	Y	Y
Betts Pond	US Route 13	4,600	N	N	N	N	N	N
Betts Pond	County Route 410	9,950	N	N	N	N	N	N
Shoals Branch	County Road 412	19,200	N	N	N	N	N	N
Shoals Branch	State Route 432	26,350	N	N	N	N	N	N
Bridgeville Branch	Rt. 13 Main Street	7,850	N	Y	Y	N	N	N
Bridgeville Branch	North Cannon Street	9,450	Y	Y	Y	N	N	Y
Bridgeville Branch	Conrail	9,500	N	N	N	N	N	N
Broad Creek	Bethel Bridge	25,150	N	N	N	N	N	N
Broad Creek	Railroad	40,550	N	N	N	N	N	N
Broad Creek	Rt. 28A North Poplar St.	41,225	N	Y	Y	N	N	N
Broad Creek	Alt. 13 N. Central Ave	41,550	N	N	N	N	N	N
Broad Creek	Rt. 486 Delaware Ave	42,200	Y	Y	Y	N	N	N
Broad Creek	Willow Street	42,750	Y	Y	Y	N	N	N
Broadkill River	State Route 5 Union St.	25,200	Y	Y	Y	N	N	N
Bunting's Branch	State Route 54	1,700	N	N	Y	N	N	N
Bunting's Branch	State Route 17	5,450	N	N	Y	N	N	N
Sandy Branch	Rt. 378 Main St.	7,900	N	N	Y	N	N	N
Sandy Branch	Covered Walkway	8,200	N	N	Y	N	N	N
Sandy Branch	Private Drive	8,300	N	Y	Y	N	N	Y
Sandy Branch	Selbyville Middle School	8,850	Y	Y	Y	N	Y	Y
Sandy Branch	Conrail	9,750	N	Y	Y	N	Y	Y
Sandy Branch	West Railroad Avenue	9,800	Y	Y	Y	N	Y	Y
Sandy Branch	US Route 113	11,350	N	Y	Y	N	N	N
Sandy Branch	US Route 113	11,550	N	Y	Y	N	N	N
Sandy Branch	State Route 54	13,000	Y	Y	Y	N	Y	Y
Sandy Branch	Rt. 80 Gumborc Rd	13,200	Y	Y	Y	N	Y	Y
Butler Mill Branch	Woodland Road	3,850	N	Y	N	N	N	N
Butler Mill Branch	Craigs Mill Road	6,700	N	Y	Y	N	N	N
Butler Mill Branch	Woodpecker Road	11,900	N	N	N	N	N	N
Butler Mill Branch	Rt. 20 Stein Highway	17,450	N	N	N	N	N	N
Cart Branch	US Route 13	1,750	N	Y	Y	N	N	Y
Cart Branch	County Road 583A	2,500	N	Y	Y	N	Y	Y
Cart Branch	Governors Avenue	6,650	Y	Y	Y	N	N	N
Cart Branch	Rt. 16 Market St.	7,150	Y	Y	Y	N	Y	Y
Cart Branch	Conrail	9,150	Y	Y	Y	Y	Y	Y
Cedar Creek	Cubbage Pond Road	4,000	Y	Y	Y	N	N	N
Cedar Creek	County Road 38	9,500	N	N	N	N	N	N
Cedar Creek	County Road 225	14,100	Y	Y	Y	N	Y	Y
Cedar Creek	Conrail	16,700	N	Y	Y	N	N	N
Cedar Creek	County Road 213	18,350	Y	Y	Y	Y	Y	Y
Cedar Creek	US Route 113	23,450	N	N	N	N	N	N
Chapel Branch	Woodland Road	3,650	N	N	N	N	N	N
Chapel Branch	Railroad	13,200	Y	Y	Y	N	N	N
Chapel Branch	Rt. 20 Stein Highway	13,900	N	Y	Y	N	N	Y
Chapel Branch	Chapel Branch Road	18,200	N	Y	Y	N	N	Y
Chapel Branch	Boyce Road	25,750	Y	Y	Y	Y	Y	Y
Church Branch	Cubbage Pond Road	4,150	N	Y	Y	N	N	N
Church Branch	County Road 38	13,850	N	Y	Y	N	N	N

Church Branch	County Road 226	22,500	Y	Y	Y	N	Y	Y
Church Branch	County Road 227	25,350	Y	Y	Y	Y	Y	Y
Clear Brook	High Street	675	N	N	N	N	N	N
Clear Brook	E. Poplar Street	1,200	Y	Y	Y	N	N	N
Clear Brook	US Route 13	6,100	N	N	N	N	N	N
Clear Brook	Tharp Road	10,150	N	N	N	N	N	N
Clear Brook	US Route 13	21,600	N	N	N	N	N	N
Clear Brook	Alternate Route 13	22,025	N	N	N	N	N	N
Clear Brook	Private Drive	22,300	Y	Y	Y	N	N	N
Clear Brook	County Road 46	28,025	Y	Y	Y	Y	Y	Y
Deep Branch	Unnamed Dirt Road	1,900	Y	Y	Y	Y	Y	Y
Deep Branch	Marshall Street	4,950	N	N	N	N	N	N
Deep Branch	McCoy Street	5,150	Y	Y	Y	N	N	N
Georgetown Road Branch	Rt. 446 Sycamore Rd	950	Y	Y	Y	N	N	N
Gravelly Branch	Coverdale Road	2,450	N	Y	Y	N	N	N
Gravelly Branch	Rt. 18 Seashore Highway	17,300	N	Y	Y	N	N	N
Gravelly Branch	Seashore Highway Weir	17,450	Y	Y	Y	Y	Y	Y
Gravelly Branch	Deer Forest Road	35,100	N	Y	Y	N	N	N
Gum Branch	Redder Road	7,775	N	N	N	N	N	N
Gum Branch	Sunnyside Road	9,500	Y	Y	Y	Y	Y	Y
Gum Branch	Oak Road	24,000	N	Y	Y	N	N	N
Gum Branch	B & R Road	31,350	Y	Y	Y	N	N	Y
Herring Creek	State Route 24	8,880	N	N	N	N	N	N
Herring Run	State Route 20	950	N	N	Y	N	N	N
Herring Run	Alt. US Route 13	3,350	Y	Y	Y	N	Y	Y
Hitch Pond Branch	Hitch Pond Road	3,000	N	N	N	N	N	N
Hitch Pond Branch	Trap Pond Road	10,850	N	N	N	N	N	N
Hitch Pond Branch	Wooten Road	20,000	N	N	N	N	N	N
Hopkins Prong	State Route 24	6,600	Y	Y	Y	N	Y	Y
Unity Branch	County Road 302	11,350	Y	Y	Y	Y	Y	Y
Unity Branch	Rt. 5 Indian Mission Rd	17,200	-	-	Y	-	-	Y
Ingram Branch	Conrail	2,450	N	N	N	N	N	N
Ingram Branch	County Road 319	2,900	Y	Y	Y	N	N	N
Iron Branch	Railroad	3,950	N	N	Y	N	N	N
Iron Branch	Rt. 83 Mitchell St.	5,250	N	Y	Y	N	Y	Y
Iron Branch	US Route 113	6,200	Y	Y	Y	N	N	Y
Iron Branch	Handy Road	9,000	Y	Y	Y	N	Y	Y
Iron Branch	Hickory Hill	15,850	N	Y	Y	N	N	N
James Branch	Laurel Road	2,250	N	N	N	N	N	N
James Branch	Wooten Road	19,150	N	N	N	N	N	N
James Branch	Arvey Road	26,900	N	N	Y	N	N	N
James Branch	Rt. 30 Whitesville Road	33,450	N	Y	Y	N	N	N
Little Creek	West Sixth Street	450	N	Y	Y	N	N	N
Love Creek	State Route 24	-	N	N	N	N	N	N
Love Creek	County Road 277	10,050	Y	Y	Y	N	Y	Y

Chapter 5 - Flood Inundation Analysis

Using GIS mapping, the UDWRC overlaid simulations of worst case flood events with the base map of DelDOT assets utilizing FEMA Flood Insurance Study floodplain mapping and the NOAA NWS SLOSH model using an EPA mapper tool that simulates 100-year and 500-year riverine flooding coupled with Category 1 and 3 coastal storm surge scenarios. We then mapped future flood scenarios that combine estimates of sea level rise (0.5 m) with 100- and 500-year floods and the SLOSH Category 1 and 3 storm surge scenarios. We assessed over 7,000 DelDOT total road miles and over 1,700 major route (Federal interstate/highway/state principal/major collector) miles and mapped and estimated the road miles inundated or flooded within the riverine floodplain (100- and 500-year flood) coupled with Category 1 and 3 coastal storm surge zone. We utilized the EPA Storm Surge Inundation mapper to assess the impacts of hurricanes and severe storms on DelDOT assets for the following storm scenarios in increasing order of flood risk for existing and future sea level rise conditions (Table 5.1):

Existing Scenario
1. 100-year Riverine Flood with Coastal Flooding from Category 1 Hurricane
2. 500-year Riverine Flood with Coastal Flooding from Category 1 Hurricane
3. 100-year River Flood with Coastal Flooding from Category 3 Hurricane
4. 500-year Riverine Flood with Coastal Flooding from Category 3 Hurricane

Future Scenario(w/ 0.5 m sea level rise)
5. 100-year Riverine Flood with Coastal Flooding from Category 1 Hurricane
6. 500-year Riverine Flood with Coastal Flooding from Category 1 Hurricane
7. 100-year River Flood with Coastal Flooding from Category 3 Hurricane
8. 500-year Riverine Flood with Coastal Flooding from Category 3 Hurricane

Table 5.1. DELDOT storm surge and sea level rise inundation scenarios

Riverine/Hurricane Flood Scenario	**Riverine 100-yr Flood**	**Riverine 500-yr Flood**
Existing Scenario		
Category 1 Hurricane	1	2
Category 3 Hurricane	3	4
Future 0.5 m Sea Level Rise		
Category 1 Hurricane	5	6
Category 3 Hurricane	7	8

Along all DelDOT roads, flooding would inundate 437 miles (6% of roads) in the 100-year floodplain, 533 miles (7%) in the 500-year floodplain, 212 miles (3%) during a Category 1 storm and 794 miles (11%) during a Category 3 storm (Figure 5.1 and 5.2 and Table 5.2). Along major Federal/state highways/roads, flooding would inundate 119 miles (7%) in the 100-year floodplain, 143 miles (8%) in the 500-year floodplain, 71 miles (4%) during a Category 1 storm and 229 miles (13%) during a Category 3 storm (Figure 5.3 and 5.4 and Table 5.3).

Table 5.2. Total road miles potentially inundated by flooding in Delaware

	New Castle	Kent	Sussex	Statewide
Miles inundated by				
100-year Flood	120	88	229	437
500-year Flood	161	114	258	533
Cat. 1 Storm	42	46	124	212
Cat. 2 Storm	113	83	253	450
Cat. 3 Storm	188	149	456	794
500-year Flood plus Cat 3 Storm	243	183	494	919
% of total miles				
100-year Flood	4%	5%	9%	6%
500-year Flood	6%	7%	10%	7%
Cat. 1 Storm	2%	3%	5%	3%
Cat. 2 Storm	4%	5%	10%	6%
Cat. 3 Storm	7%	9%	18%	11%
500-year Flood plus Cat 3 Storm	9%	11%	19%	13%

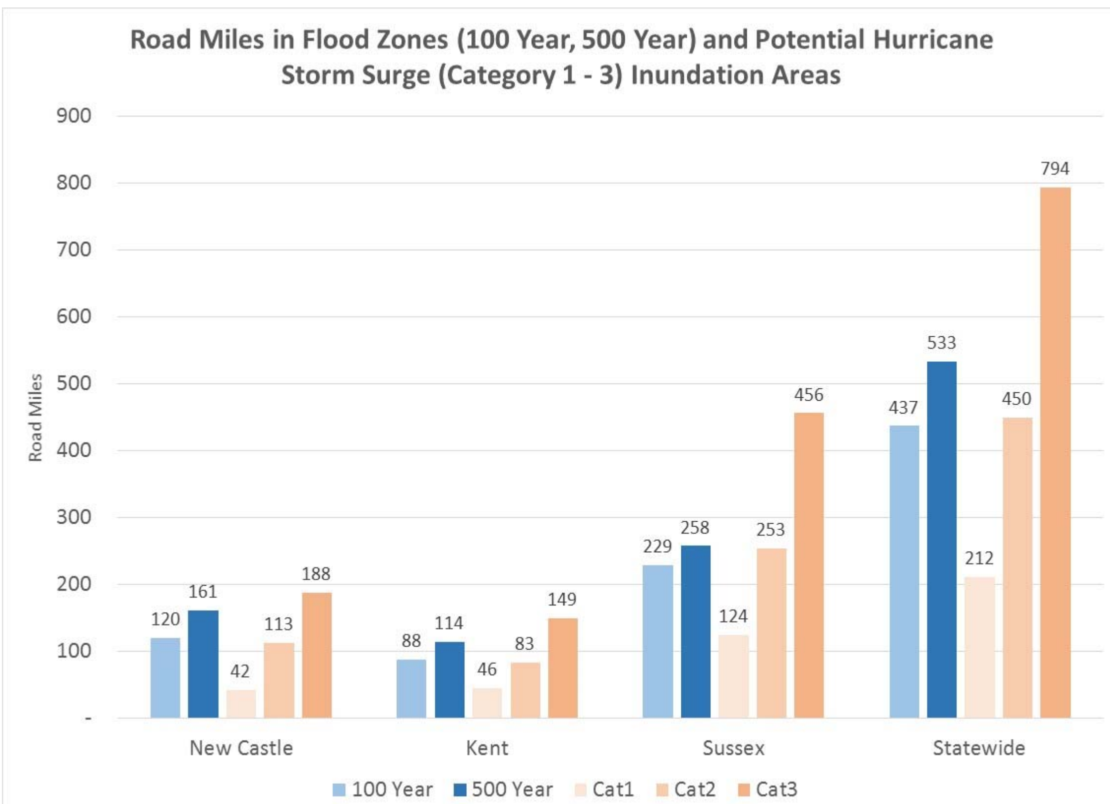


Figure 5.1. Total roads inundated by flooding in Delaware

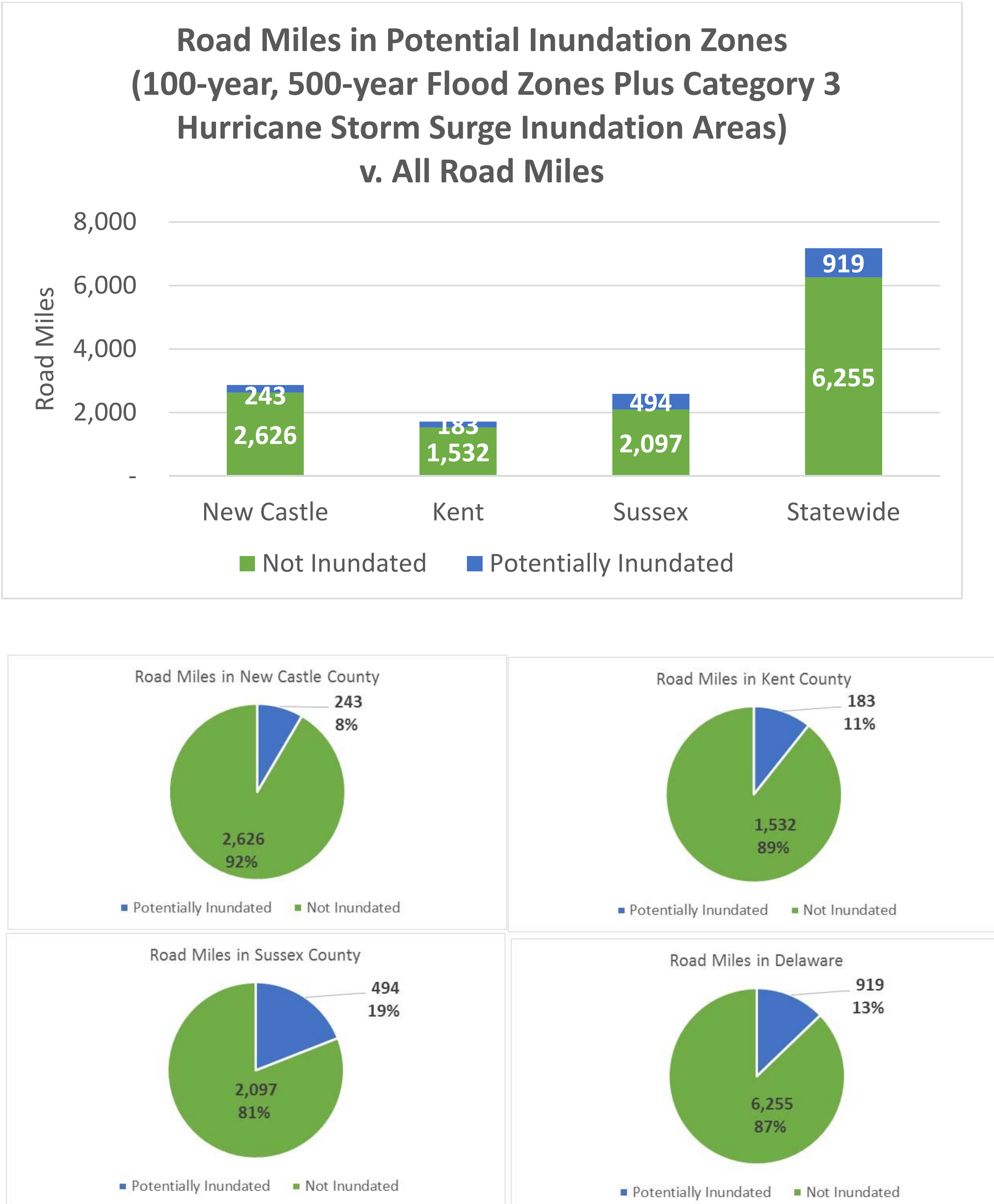


Figure 5.2. Total road miles inundated by flooding in Delaware

Table 5.3. Major route miles potentially inundated by flooding in Delaware

	New Castle	Kent	Sussex	State
Miles inundated by				
100-year Flood	43	18	58	119
500-year Flood	53	24	65	143
Cat. 1 Storm	20	10	41	71
Cat. 2 Storm	48	25	66	138
Cat. 3 Storm	79	48	102	229
500-year Flood plus Cat 3 Storm	95	55	108	258
% of major roads				
100-year Flood	6%	5%	10%	7%
500-year Flood	7%	6%	11%	8%
Cat. 1 Storm	3%	3%	7%	4%
Cat. 2 Storm	7%	6%	11%	8%
Cat. 3 Storm	11%	12%	17%	13%
500-year Flood plus Cat 3 Storm	13%	14%	18%	15%

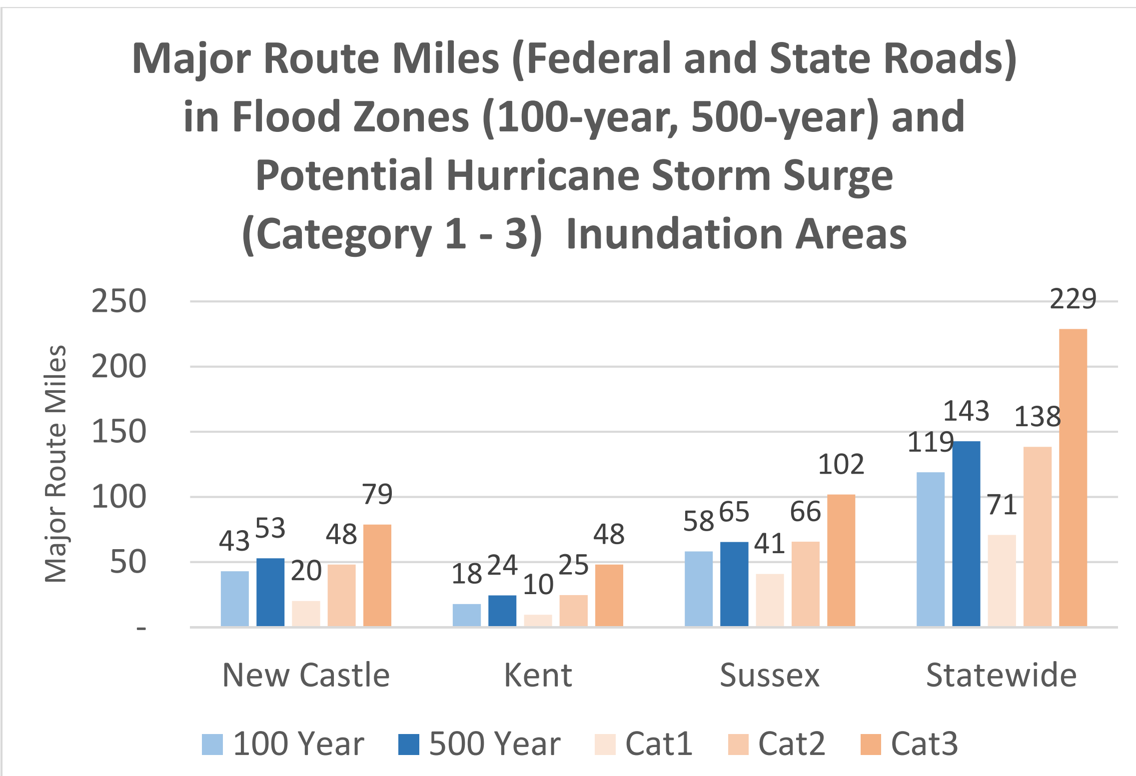


Figure 5.3. Major route miles inundated by flooding in Delaware

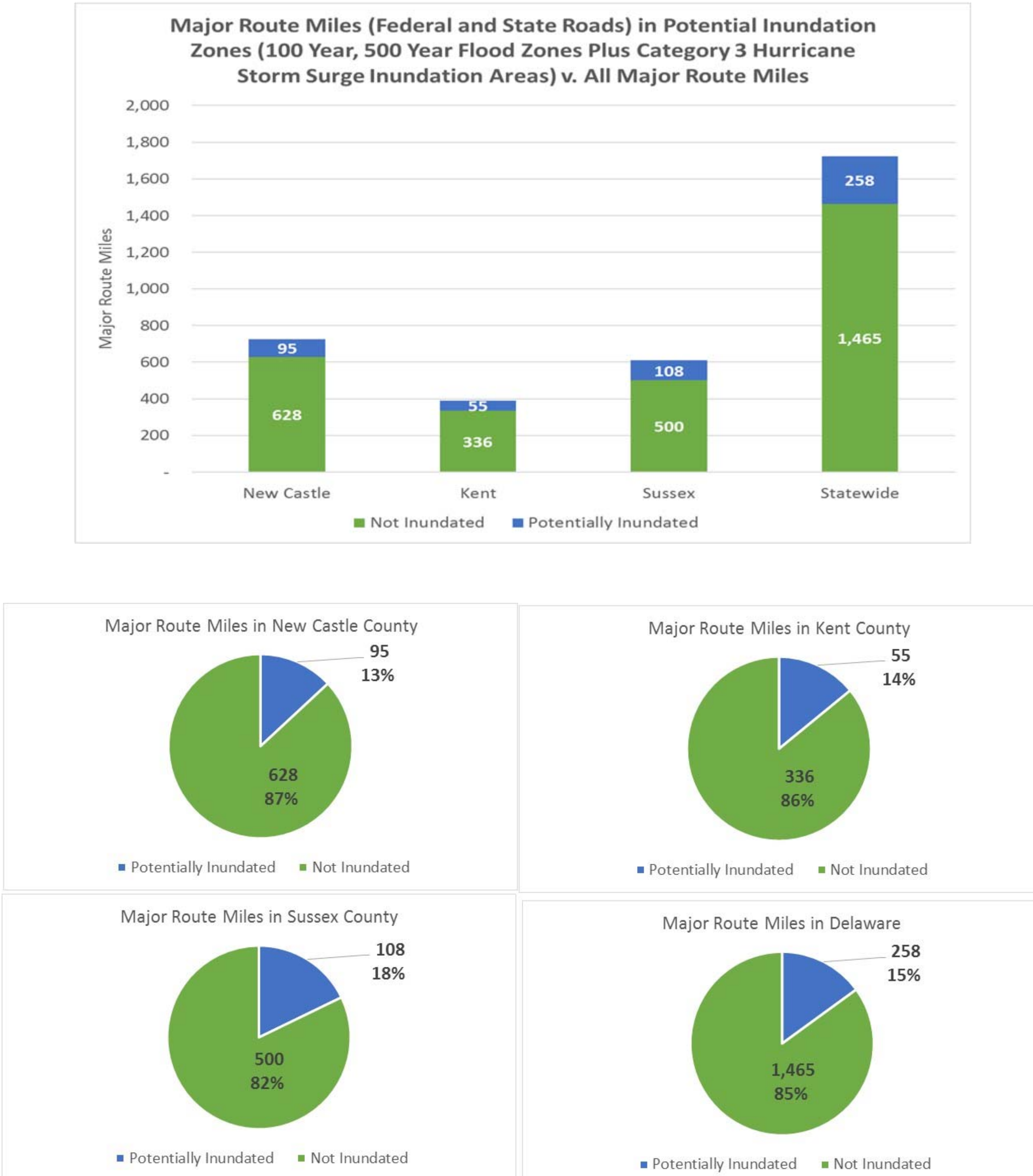


Figure 5.4. Major roads inundated by flooding in Delaware

Chapter 6 - Historic Storm Analysis

The UDWRC conducted an evaluation of the recent hurricane and severe storm events that impacted Delaware. We selected for analysis a worst case scenario for flood inundation based on Superstorm Sandy (October 29-30, 2012) impacts on Delaware coast as: (a) the storm actually occurred where the eye passed to the north of Delaware through Atlantic City, New Jersey and (b) a counterfactual (what if?) simulation where the eye of the storm passes (as originally forecast) through Lewes, Delaware.

The most severe hurricanes to pass near Delaware were unnamed Category 4 storms that occurred in 1944 (Table 6.1 and Figure 6.1). Hurricane Irene (August 28, 2011) and Sandy (October 29, 2012) were two of the most severe Category 1 storms to ever pass near Delaware causing significant flooding. Two of the more severe storms to cross over Delaware were Tropical Storm Bertha in 1996 with 58 mph winds and Tropical Storm Floyd on September 16, 1999 with winds up to 64 mph and 24-hour rainfall of 10.58 inches at Greenwood, Delaware, a state record that destroyed 33 homes in New Castle County.

According to the EPA storm surge inundation map utilizing NOAA data, there is a 10- to 30-year probability that a hurricane will impact Sussex County, Delaware and a 30- to 100-year probability that a hurricane will impact New Castle County and Kent County, Delaware (Figure 6.2)

Table 6.1. Hurricanes and tropical storm strikes in or near Delaware (EPA Storm Surge Inundation Map and NOAA)

Year	Name	Max. Wind (knots)	Max. Storm Category	Location Notes
1903	Unnamed	80	1	North 20 miles east of Sussex County, DE, west near Avalon, NJ, then north of Philadelphia
1904	Unnamed	75	1	Traveled diagonally through Sussex County, DE, tip of NJ beach coast across Delaware Bay
1924	Unnamed	65	1	Travelled through eastern Sussex County, upward across entire NJ coastline (inland)
1928	Unnamed	90	2	Path straight across Atlantic ocean, then turning southwest, travelling through OC, MD
1934	Unnamed	85	2	Traveled diagonally through central NJ and NCC, DE and through Baltimore, MD
1934	Unnamed	80	1	NE, 60 miles east of Sussex County, DE, 40 miles east along NJ coast, through Long Island
1936	Unnamed	85	2	traveling ~60 degrees NE, ending about 60 miles east of southern DE border
1939	Unnamed	65	1	Travelled East-West through Dover, DE
1944	Unnamed	70	1	Traveled diagonally through Sussex County, DE, tip of NJ coast across Delaware Bay
1944	Unnamed	115	4	Travelled south of Salisbury, MD, out to ocean, 10miles east of DE southern border
1944	Unnamed	115	4	Traveled ~45 degrees NE, passing through MD just south of OC, MD, ~45miles east of IR Inlet
1944	Unnamed	110	3	60 deg NE, 75 miles east of Sussex County, DE, 40 miles off NJ coast, east tip of Long Island
1945	Unnamed	115	4	Traveled diagonally through No. NJ, Southeast PA, NCC, DE, toward Fredericksburg
1953	Barbara	80	1	Off VA, then turned to travel ~30 degrees NE out to Ocean, >100 miles off DE shore
1959	Cindy	65	1	45 deg NE, Delmarva Peninsula, 90 mi east of Sussex Co., DE, 90 mi east of Atlantic City, NJ
1960	Donna	120	4	60 degrees NE, 60 miles east of Sussex County, DE, 40 miles off NJ, east tip of Long Island
1972	Agnes	75	1	85 degrees NW, 100 miles east of Sussex, west 20 miles east of Long Branch, NJ, through NYC
1976	Belle	95	2	85 deg NE, 60 miles east of Sussex County, DE, 30 miles east of NJ coast, through Long Island
1985	Gloria	90	2	25 miles east of Ocean City, MD, 40 miles east of IR Inlet, 20-25 miles off along NJ coast
1986	Charley	70	1	traveled ~30 degrees NE, ending ~100miles east of Sussex County, DE
1996	Bertha	90	2	Travelled diagonally through Kent County, DE as tropical storm, up to Long Island
1999	Floyd	90	2	Travelled NE just off Sussex County coast as tropical storm then intersecting Atlantic City.
2004	Jeanne	105	4	West from Atlantic Ocean toward Delaware bay, path stopping 20 miles east of Lewes, DE
2004	Gaston	65	1	30 degrees NE, crossing middle of VA tip of Delmarva Peninsula out to Atlantic Ocean
2011	Irene	75	1	Traveled north, ~15-20 miles east from IR Inlet, through Atlantic City, NJ, along NJ coast
2012	Sandy	80	1	Traveled NW Atlantic City through Southern NJ then crossed Wilmington, Delaware.

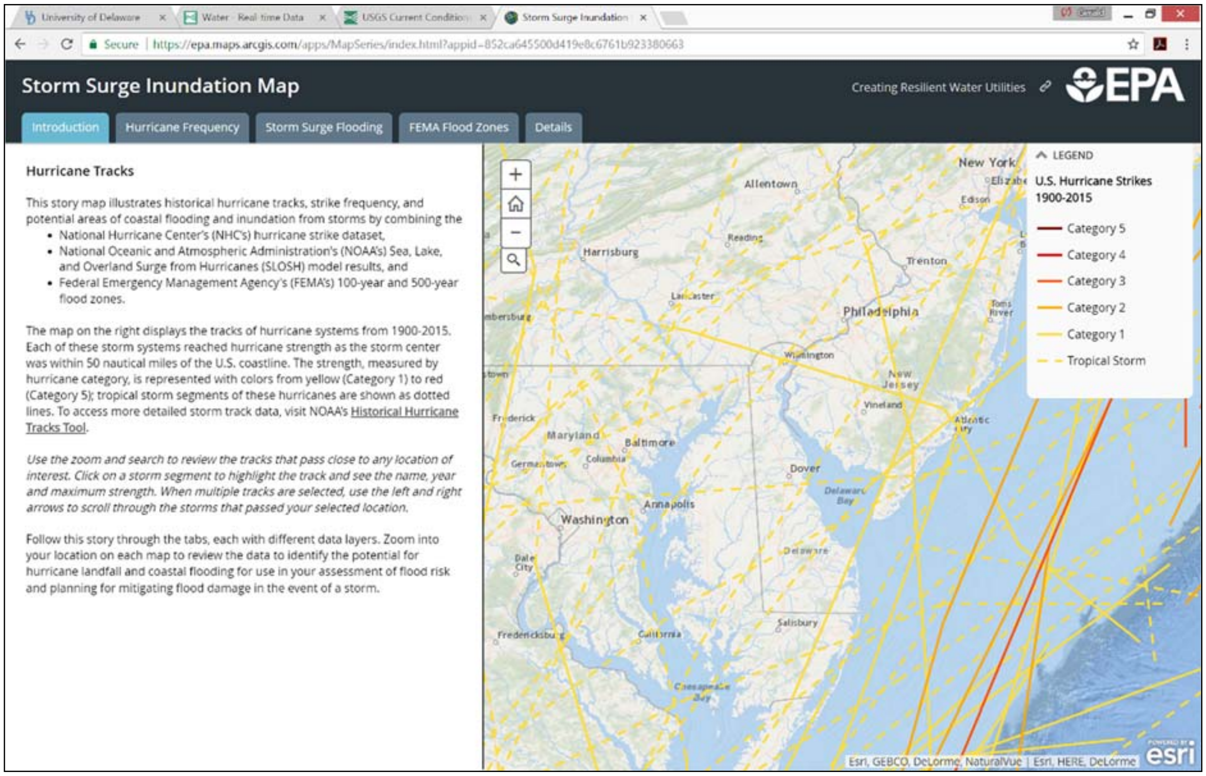


Figure 6.1. Hurricane and tropical storm strikes in or near Delaware

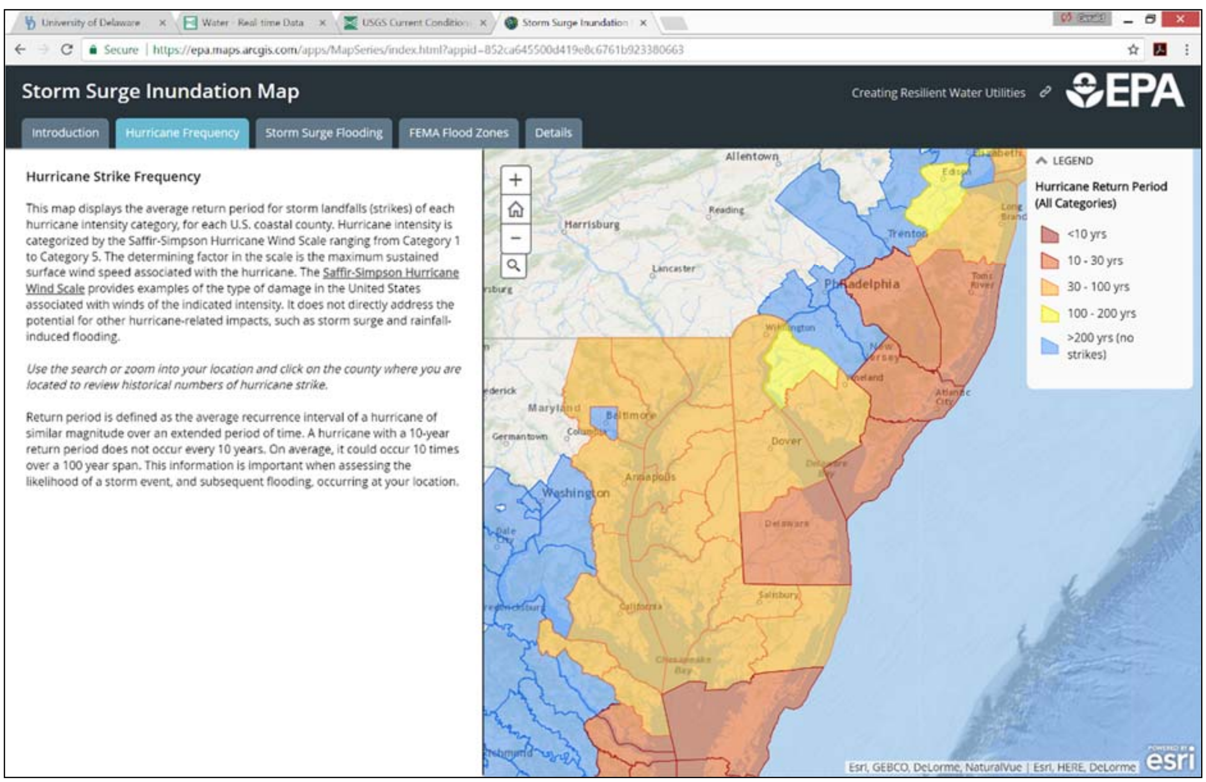


Figure 6.2. Hurricane return period for Delaware

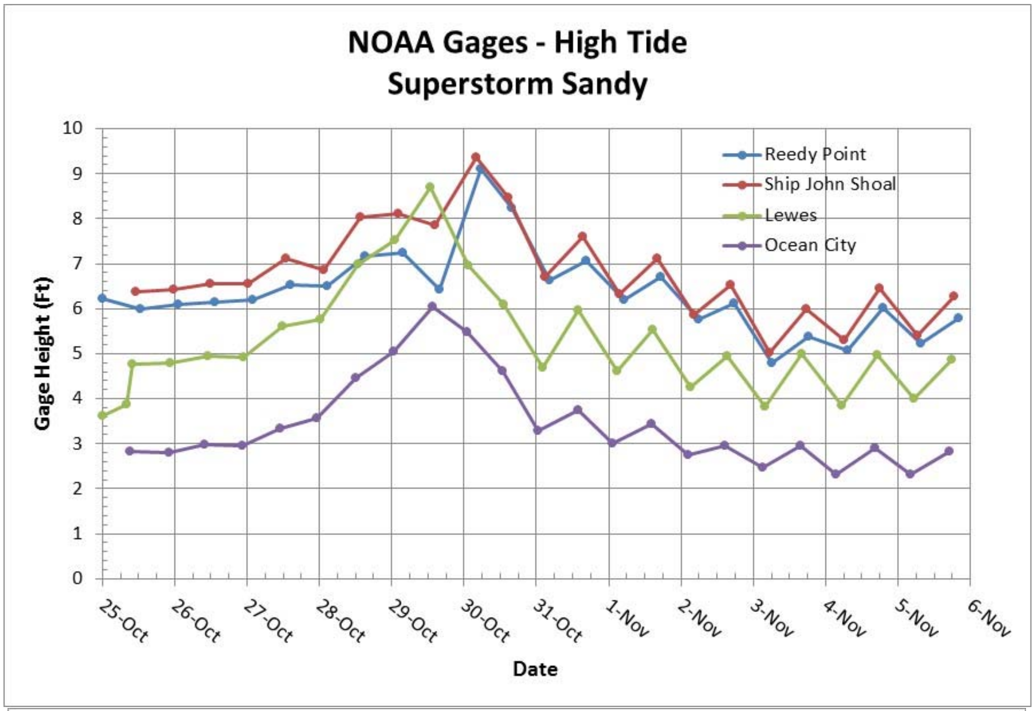
To conduct a simulation of the inundation of Superstorm Sandy in October 2012, we reviewed peak stages recoded by NOAA tide gages between Ocean City, Maryland and Reedy Point, Delaware and USGS gages between Little Assawoman Bay, Delaware and Christina River at Wilmington (Table 6.2 and Figures 6.3 and 6.4). The peak stage ranged from 6.51 feet at Indian River Bay at 9:00 hours on October 29, 2012 to 7.20 feet at 12:00 hours on October 30 at Delaware River at New Castle. The peak stages ranged from 4.82 feet at Little Assawoman Bay to 9.37 feet at Ship John Shoal, Delaware. From recorded peak stage data we mapped the inundation floodplain (Figures 6.5 - 6.8) during Superstorm Sandy where the eye crossed through Atlantic City, New Jersey then veered west through Wilmington, Delaware.

We also mapped the inundation floodplain for a hypothetical scenario where the eye of Superstorm Sandy crosses through Lewes, Delaware as originally forecast. This would have put much of Delaware in the more dangerous northwest quadrant of the storm with higher peak flood elevations. To simulate this scenario, we examined NOAA tide gages from Atlantic City, New Jersey and north to the Battery at the foot of Manhattan Island in New York City. We then translated these total flood peaks to Delaware as an estimate of probable flood heights in the event that Sandy would have passed through southern Delaware. The inundation maps illustrate that if the storm crossed Delaware to the south as originally forecast, flood peaks during Sandy would have increased from 6.1 feet to 15.8 feet at Delaware City and from 6.1 feet to 13.8 feet at Lewes, Delaware. The flood inundation area would have spread inland from Indian River and Rehoboth Bay, miles west along the Delaware Bay to Route 1in Sussex County and through Route 9 in Kent and New Castle counties.

Table 6.2. Peak stages recorded during Superstorm Sandy, October 29-30, 2012

Tidal Gage	No.	Time of Peak		Peak Stage
Indian River Bay Inlet Bethany, DE	USGS 01484683	9:00	10/29/2012	6.51
Murderkill River at Bowers, DE	USGS 01484085	9:30	10/29/2012	4.87
Lewes, DE	NOAA 8557380	13:00	10/29/2012	8.71
Ocean City, MD	NOAA 8570283	13:45	10/29/2012	6.04
Rehoboth Bay at Dewey, DE	USGS 01484670	21:30	10/29/2012	5.34
Little Assawoman Bay, DE	USGS 01484701	23:00	10/29/2012	4.82
Christina River at Wilmington, DE	USGS 01480120	1:30	10/30/2012	8.28
Ship John Shoal, NJ	NOAA 8537121	4:15	10/30/2012	9.37
Reedy Point, DE	NOAA 8551910	5:45	10/30/2012	9.10
Delaware River at New Castle, DE	USGS 01482170	12:00	10/30/2012	7.20

Mapping for the inundation from riverine flooding and coastal storms (Category 1-3) is included in a separate deliverable as a map analysis. This mapping consists of two series, one showing flooding, inundation and bridge flooding (overtopping) based on current Mean Higher High Water (MHHW), and one showing the same information based on a future 0.5 meter sea level rise scenario. Appendix A includes samples of these inundation maps.



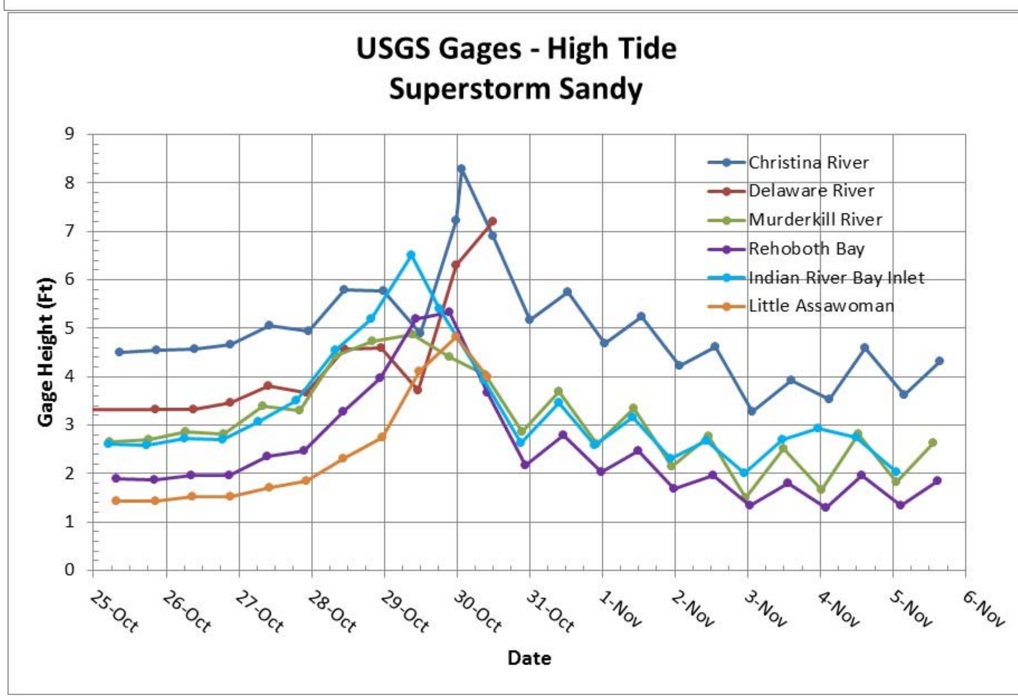


Figure 6.3. High tide elevations during Superstorm Sandy (October 2012)

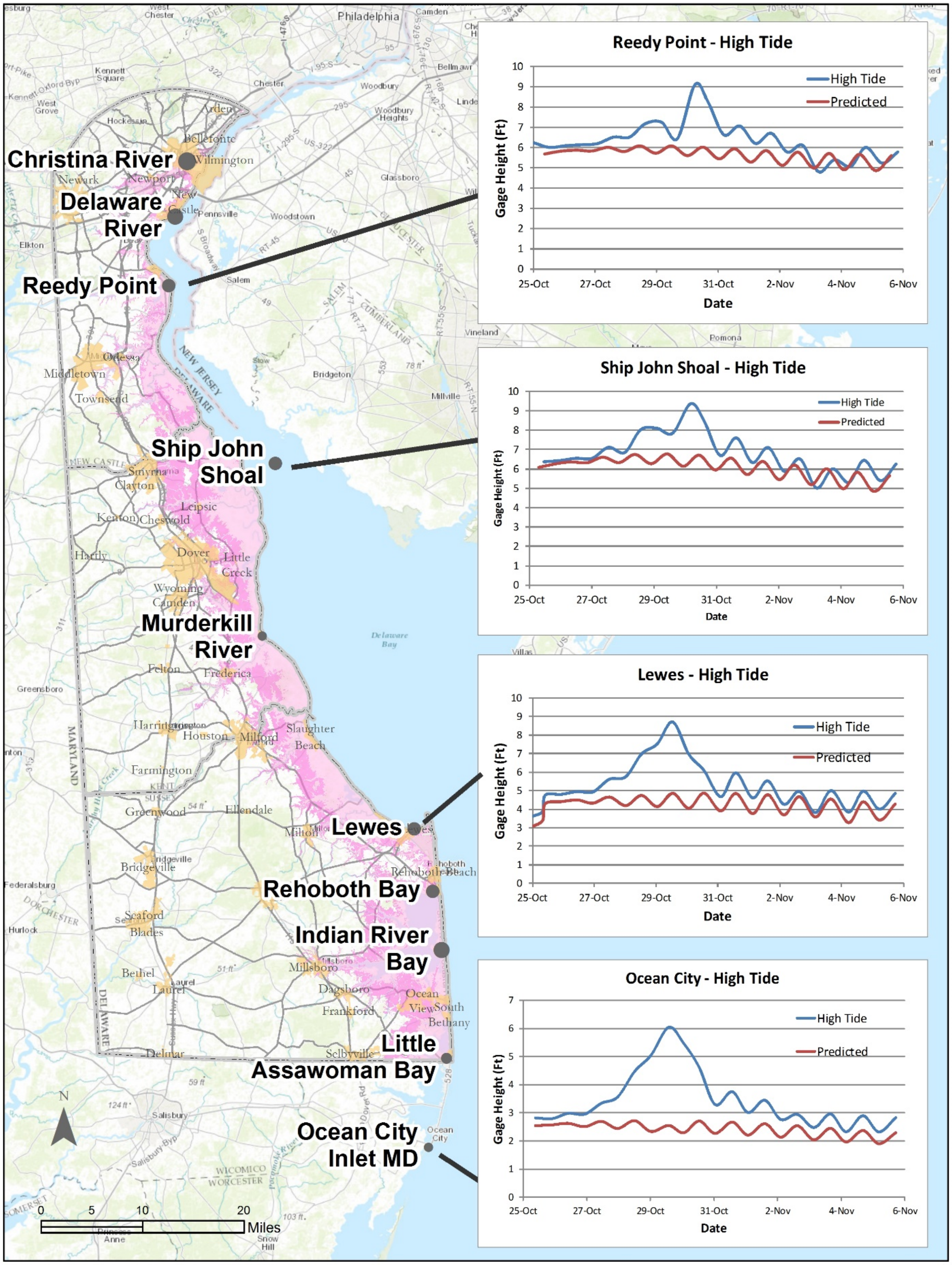


Figure 6.4. Tide levels at NOAA gages, Delaware Bay and River, Superstorm Sandy (October 2012)

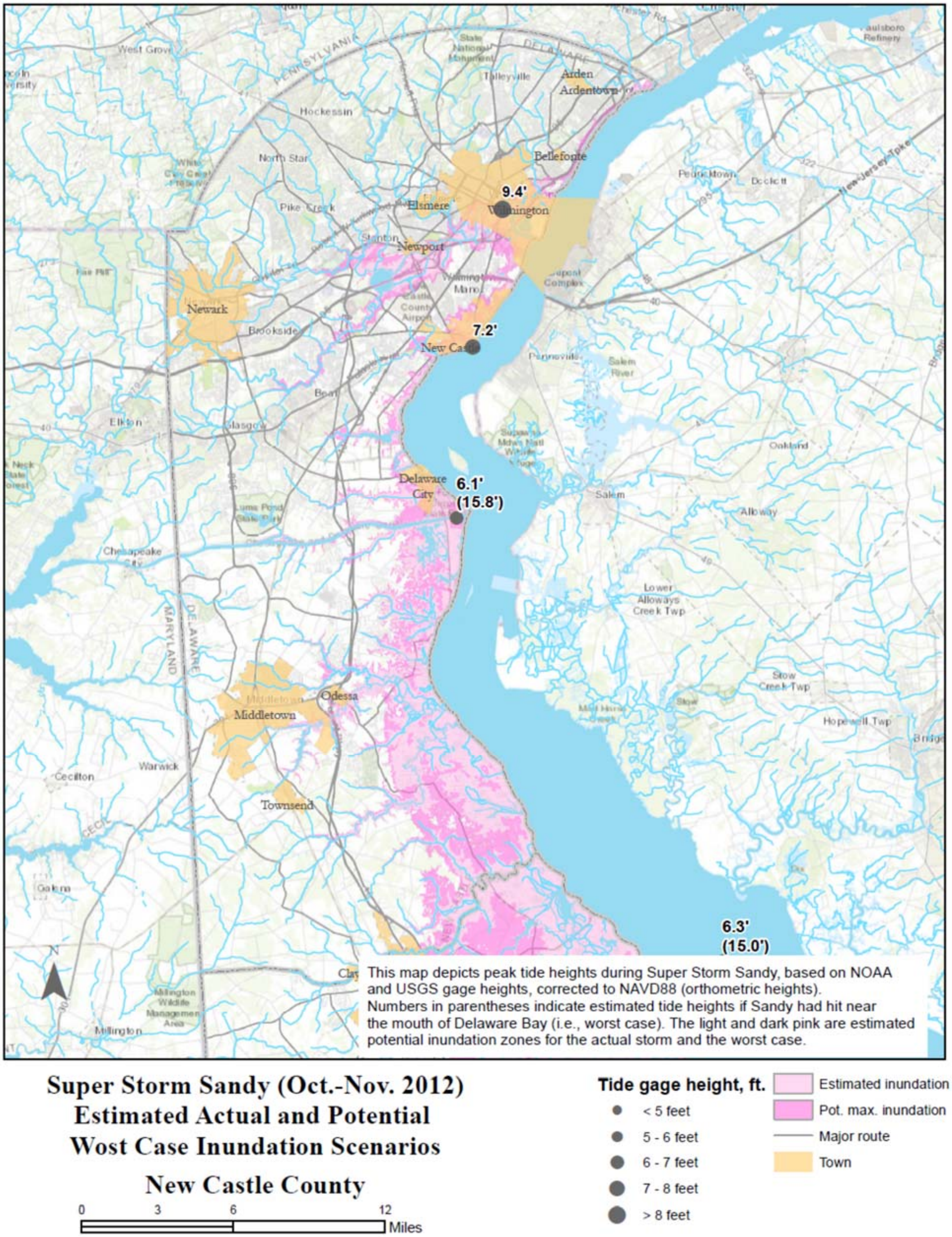


Figure 6.5. Inundation area of Superstorm Sandy in New Castle County (October 2012)

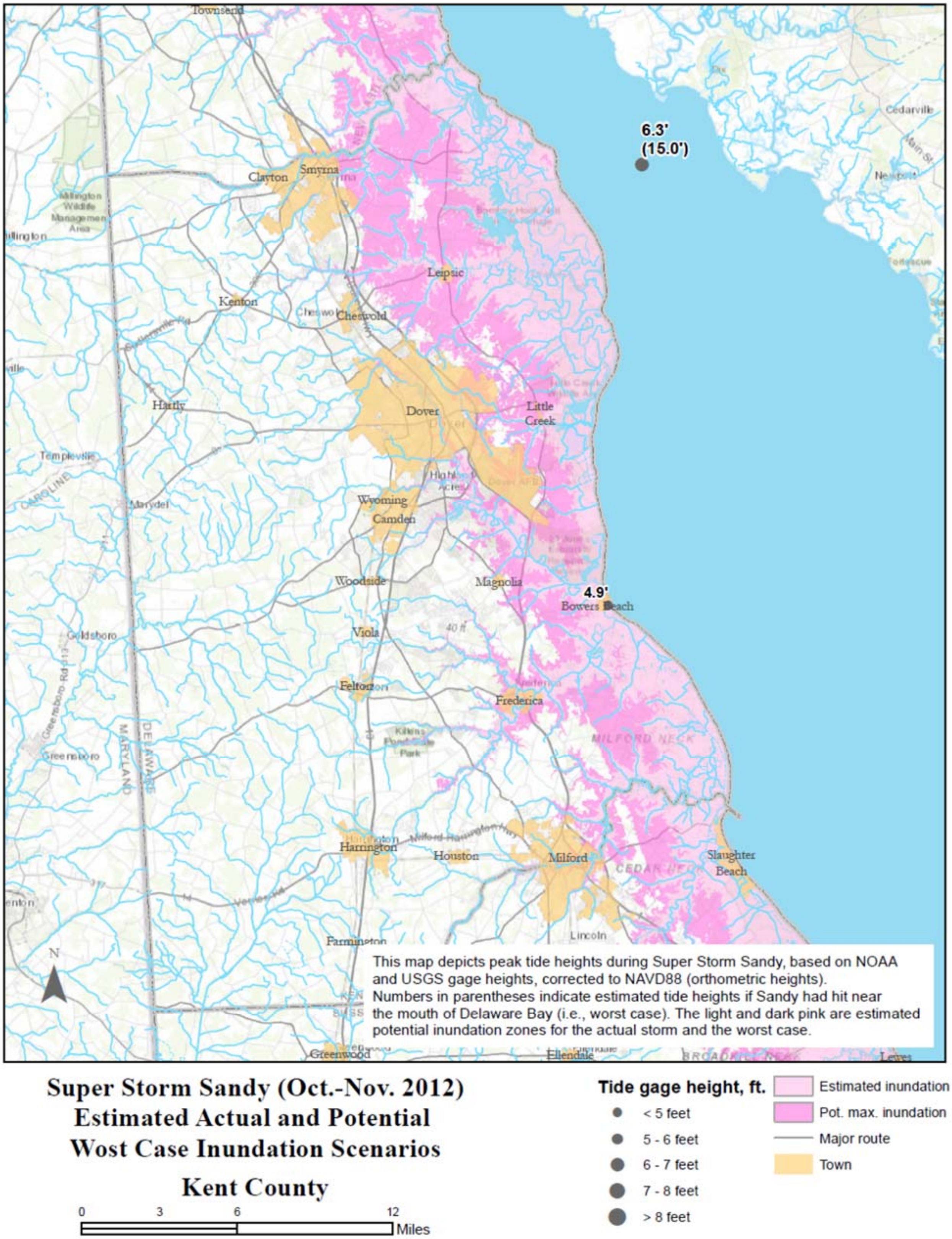


Figure 6.6. Inundation area of Superstorm Sandy in Kent County (October 2012)

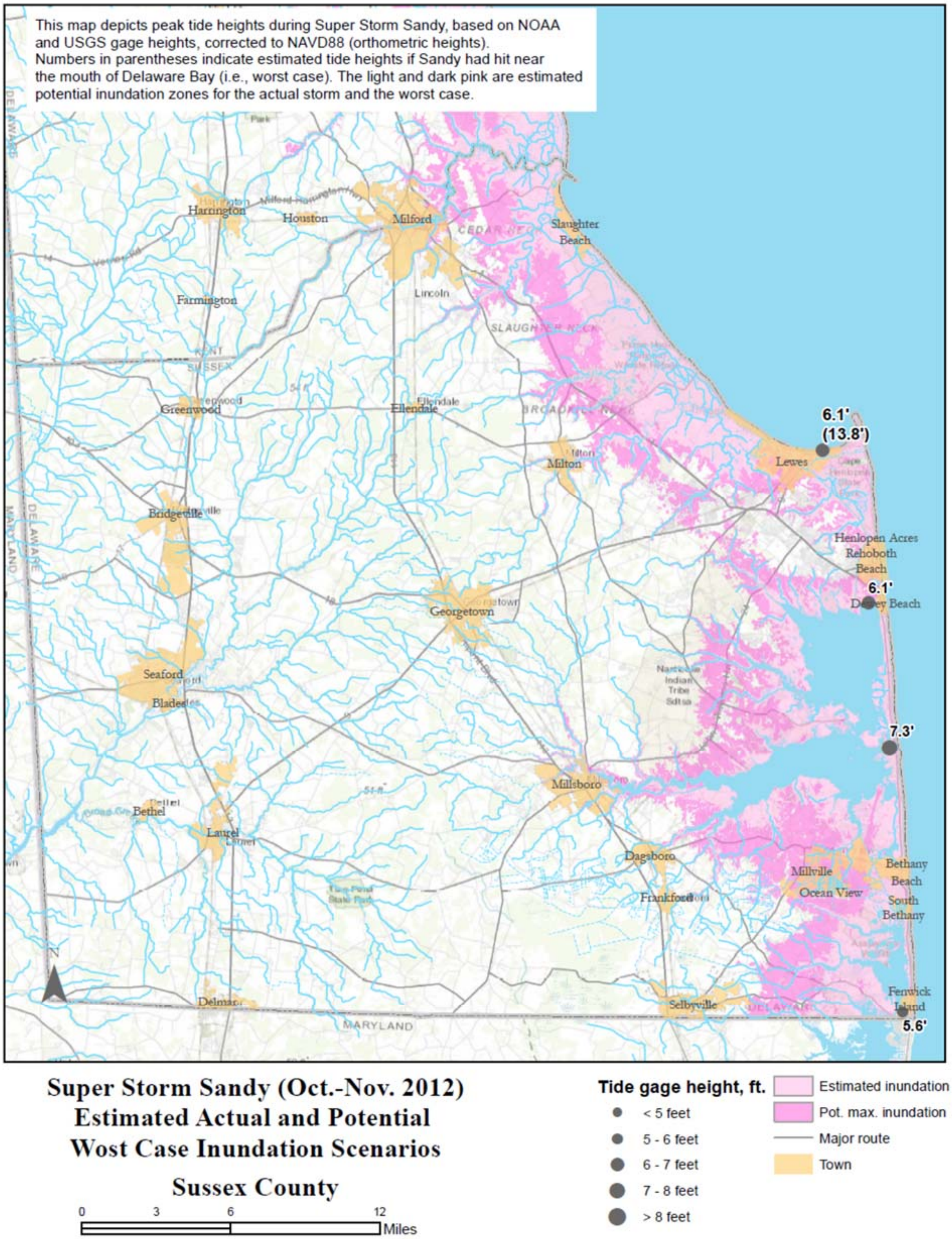


Figure 6.7. Inundation area of Superstorm Sandy in Sussex County (October 2012)

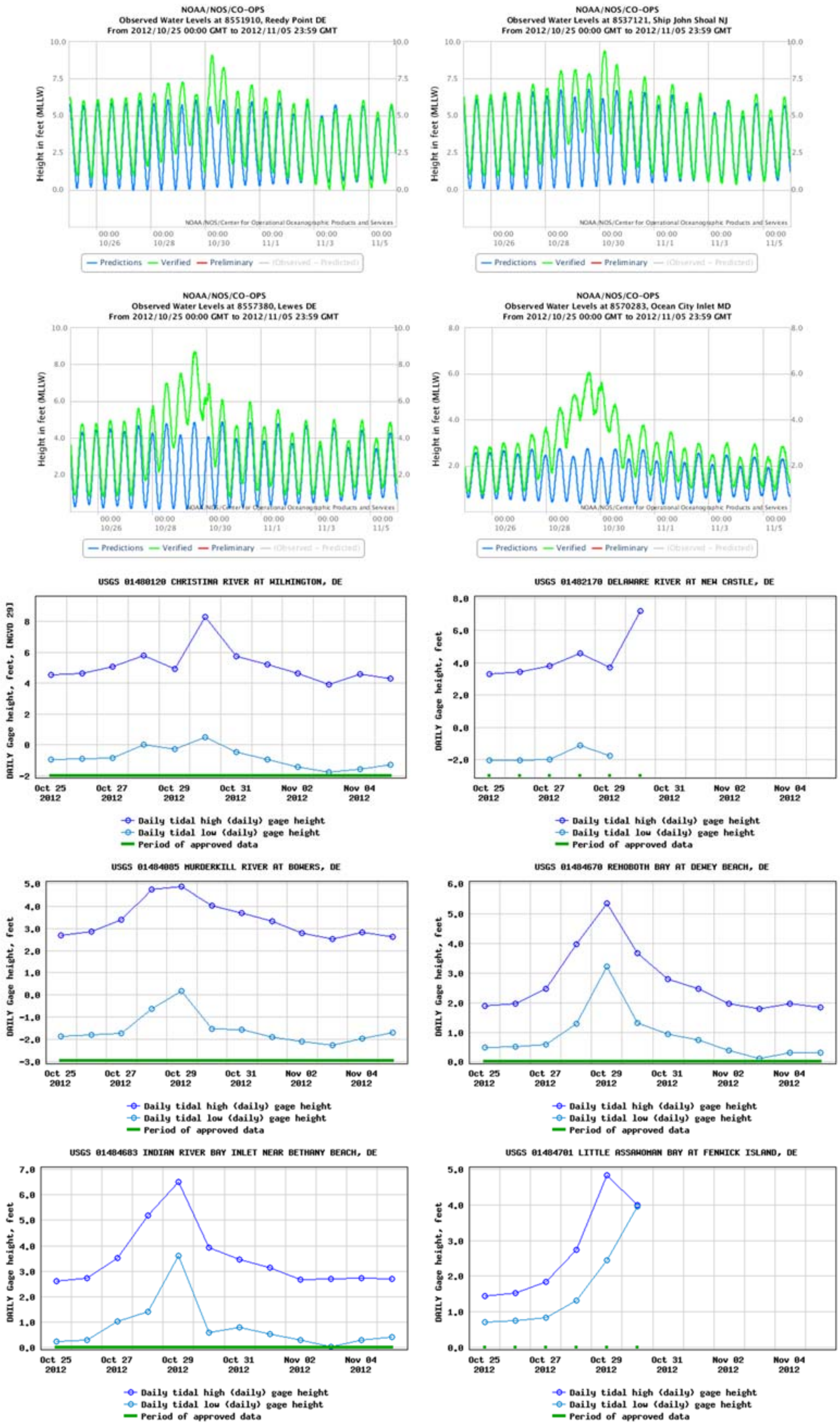


Figure 6.8. Flood hydrographs during Superstorm Sandy (October 2012)

Chapter 7 – DelDOT Facilities and Critical Facilities

The following sections detail types of data that can be analyzed with the interactive tool created for the project using the provided flood scenario layers and demographic data about Delaware. Details may change as the data set is continually updated. This report examines DelDOT managed and associated assets, demographics of areas inundated by flooding in scenarios, and wind damage as calculated by FEMA and USACE approved methods. The interactive tool created for the project is explained in detail.

DelDOT Buildings and Materials

There are no significant DelDOT facilities that would be directly inundated by floods in the provided worst-case scenario models. However, these buildings would likely experience wind damage as simulated by HAZUS and the USACE, and would experience capability reductions resulting from evacuation congestion and road network closures as modeled.

Hospitals

There is one hospital facility that would experience inundation in the Category 3 scenarios, the Nanticoke Memorial Hospital in Seaford, DE (Table 7.1). This facility is at risk during a significant hurricane event.

Table 7.1. Hospital facility inundation by scenario

Facility	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Nanticoke Memorial Hospital			Inundated	Inundated
Facility	**Scenario 1 SLR**	**Scenario 2 SLR**	**Scenario 3 SLR**	**Scenario 4 SLR**
Nanticoke Memorial Hospital			Inundated	Inundated

Non-Hospital Medical Facilities

There are a number of non-hospital medical facilities that would experience inundation in the modeled scenarios. These facilities are detailed in Tables 7.2 and 7.3 below.

Table 7.2. Non-hospital medical facility inundation by scenario

Facility	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Sussex County EMS (Future Site)			Inundated	Inundated
SCEMS Medic 105				
Mid-Sussex Rescue Squad, Millsboro	Inundated	Inundated	Inundated	Inundated
Station 106			Inundated	Inundated
Primary Care Center			Inundated	Inundated
Chesapeake Bay Orthopedics			Inundated	Inundated
Oncology and Hematology PA			Inundated	Inundated
La Red Health Center, Seaford			Inundated	Inundated
Compassionate Care Hospice		Inundated	Inundated	Inundated
Henrietta Johnson Medical Center, Wilm.			Inundated	Inundated
NCCEMS Medic 1		Inundated	Inundated	Inundated
Westside Family Healthcare		Inundated	Inundated	Inundated

Table 7.3. Non-hospital medical facility inundation by scenario with 0.5 m Sea Level Rise

Facility	Scenario 1 SLR	Scenario 2 SLR	Scenario 3 SLR	Scenario 4 SLR
Sussex County EMS (Future Site)			Inundated	Inundated
SCEMS Medic 105			Inundated	Inundated
Mid-Sussex Rescue Squad, Millsboro	Inundated	Inundated	Inundated	Inundated
Station 106			Inundated	Inundated
Primary Care Center			Inundated	Inundated
Chesapeake Bay Orthopedics			Inundated	Inundated
Oncology and Hematology PA			Inundated	Inundated
La Red Health Center, Seaford			Inundated	Inundated
Compassionate Care Hospice		Inundated	Inundated	Inundated
Henrietta Johnson Medical Center, Wilm.			Inundated	Inundated
NCCEMS Medic 1		Inundated	Inundated	Inundated
Westside Family Healthcare		Inundated	Inundated	Inundated

Fire Stations

There are a substantial number of fire stations that would experience inundation in the modeled scenarios (Tables 7.4 and 7.5). While most of the fire that would be inundated in Scenario 1 are aware that preventative measures have to be taken during a flood, the loss of fire station facilities can lead to a substantial hindrance in response during hurricane events, when fires are often a significant secondary hazard. Additionally, the increased use of fire departments as medical responders should be considered when discussing the reductions in capabilities of local fire companies during these flood events.

Table 7.4. Fire station facility inundation by scenario

Facility	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Bethany Beach Volunteer Fire Company	Inundated	Inundated	Inundated	Inundated
Roxana Volunteer Fire Company 90	Inundated	Inundated	Inundated	Inundated
Bethany Beach Volunteer Fire Company	Inundated	Inundated	Inundated	Inundated
Millville Volunteer Fire Company 84			Inundated	Inundated
Millville Volunteer Fire Company 84			Inundated	Inundated
Indian River Volunteer Fire Company 80	Inundated	Inundated	Inundated	Inundated
Lewes Fire Department - Station 82			Inundated	Inundated
Milton Fire Department			Inundated	Inundated
Memorial Volunteer Fire Company	Inundated	Inundated	Inundated	Inundated
South Bowers Fire Company	Inundated	Inundated	Inundated	Inundated
Frederica Volunteer Fire Company			Inundated	Inundated
Bowers Fire Company	Inundated	Inundated	Inundated	Inundated
Little Creek Volunteer Fire Company	Inundated	Inundated	Inundated	Inundated
Leipsic Volunteer Fire Company	Inundated	Inundated	Inundated	Inundated
Port Penn Volunteer Fire Company			Inundated	Inundated
Delaware City Fire Company	Inundated	Inundated	Inundated	Inundated
Christiana Fire Company	Inundated	Inundated	Inundated	Inundated
Good Will Fire Company	Inundated	Inundated	Inundated	Inundated
Delaware State Fire School	Inundated	Inundated	Inundated	Inundated
Wilmington Fire Dept. (New Castle Ave)	Inundated	Inundated	Inundated	Inundated
Wilmington Fire Dept. (500 Swedes Landing)	Inundated	Inundated	Inundated	Inundated

Table 7.5. Fire station facility inundation by scenario with 0.5 m Sea Level Rise

Facility	Scenario 1 SLR	Scenario 2 SLR	Scenario 3 SLR	Scenario 4 SLR
Bethany Beach Volunteer Fire Company	Inundated	Inundated	Inundated	Inundated
Roxana Volunteer Fire Company 90	Inundated	Inundated	Inundated	Inundated
Bethany Beach Volunteer Fire Co. – Sta. 70	Inundated	Inundated	Inundated	Inundated
Millville Volunteer Fire Co. 84 (Atlantic Ave)			Inundated	Inundated
Millville Volunteer Fire Co. 84 (Omar Rd)			Inundated	Inundated
Indian River Volunteer Fire Company 80	Inundated	Inundated	Inundated	Inundated
Lewes Fire Department - Station 82			Inundated	Inundated
Milton Fire Department			Inundated	Inundated
Memorial Volunteer Fire Company	Inundated	Inundated	Inundated	Inundated
South Bowers Fire Company	Inundated	Inundated	Inundated	Inundated
Frederica Volunteer Fire Company			Inundated	Inundated
Bowers Fire Company	Inundated	Inundated	Inundated	Inundated
Little Creek Volunteer Fire Company	Inundated	Inundated	Inundated	Inundated
Leipsic Volunteer Fire Company	Inundated	Inundated	Inundated	Inundated
Port Penn Volunteer Fire Company			Inundated	Inundated
Delaware City Fire Company	Inundated	Inundated	Inundated	Inundated
Christiana Fire Company	Inundated	Inundated	Inundated	Inundated
Good Will Fire Company	Inundated	Inundated	Inundated	Inundated
Delaware State Fire School	Inundated	Inundated	Inundated	Inundated
Wilmington Fire Department (New Castle Ave)	Inundated	Inundated	Inundated	Inundated
Wilmington Fire Dept. (500 Swedes Landing)	Inundated	Inundated	Inundated	Inundated

Police Stations

A few municipal police departments will experience inundation in modeled scenarios (Tables 7.6 and 7.7). The loss of station facilities should be considered before significant hurricane events.

Table 7.6. Police station facility inundation by scenario

Facility	Scenario 1	Scenario 2	Scenario 3	Scenario 4
City of Lewes Police Department (E 3rd St)				
Milton Police Department (Federal St)			Inundated	Inundated
Milford Police Department (NE Front St)		Inundated	Inundated	Inundated
Delaware City Police Department (Clinton)			Inundated	Inundated
City of New Castle Police Dept. (Mun. Blvd)	Inundated	Inundated	Inundated	Inundated

Table 7.7. Police station facility inundation by scenario with 0.5 m Sea Level Rise

Facility	Scenario 1 SLR	Scenario 2 SLR	Scenario 3 SLR	Scenario 4 SLR
City of Lewes Police Department (E 3rd St)			Inundated	Inundated
Milton Police Department (Federal St)			Inundated	Inundated
Milford Police Department (NE Front St)		Inundated	Inundated	Inundated
Delaware City Police Department (Clinton)			Inundated	Inundated
City of New Castle Police Dept. (Mun. Blvd)	Inundated	Inundated	Inundated	Inundated

Nursing Homes

The Governor Bacon Health Center complex is modeled to experience inundation in all Category 1 and Category 3 hurricane events (Tables 7.8 and 7.9). It is well known that this low-lying area is at risk during flood events. During the Category 3 hurricane scenarios, four nursing homes are modeled to experience inundation. Evacuation of these facilities would require a significant response from the state.

Table 7.8. Nursing home facility inundation by scenario

Facility	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Lifecare at Lofland Park			Inundated	Inundated
Lewes Convalescent Center			Inundated	Inundated
Harbor Healthcare and Rehab			Inundated	Inundated
Governor Bacon Health Center	Inundated	Inundated	Inundated	Inundated

Table 7.9. Nursing home facility inundation by scenario with 0.5 m Sea Level Rise

Facility	Scenario 1 SLR	Scenario 2 SLR	Scenario 3 SLR	Scenario 4 SLR
Lifecare at Lofland Park			Inundated	Inundated
Lewes Convalescent Center			Inundated	Inundated
Harbor Healthcare and Rehab			Inundated	Inundated
Governor Bacon Health Center	Inundated	Inundated	Inundated	Inundated

Mobile Homes

There are a large number of mobile homes around the state that would experience inundation in all of the modeled scenarios (Tables 7.10 and 7.11). While some of these homes are used for vacations there will still be a large response effort required to evacuate and shelter residents during worst-case scenarios.

Table 7.10. Mobile home inundation by scenario

Mobile Homes	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Number of Mobile Homes Inundated	3640	3897	8288	8371

Table 7.11. Mobile home inundation by scenario with 0.5 m Sea Level Rise

Mobile Homes	Scenario 1 SLR	Scenario 2 SLR	Scenario 3 SLR	Scenario 4 SLR
Number of Mobile Homes Inundated	3949	4135	8410	8493

Traffic Signals

There are several DelDOT managed traffic signals that will be inundated in the modeled scenarios, and additionally these intersections will not be navigable due to flooding (Tables 7.12 and 7.13). Total counts of inundated signals by scenario are included below. These tables do not include lost signals due to wind damage or power loss.

Table 7.12. Traffic signal inundation by scenario

Traffic Signals	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Number of Signals Inundated	69	93	143	148

Table 7.13. Traffic Signal Inundation by Scenario with 0.5M Sea Level Rise

Traffic Signals	Scenario 1 SLR	Scenario 2 SLR	Scenario 3 SLR	Scenario 4 SLR
Number of Signals Inundated	76	96	153	158

Drainage

Table 7.14. Drainage structure inundation by scenario

Drainage Structures	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Drainage Structures Inundated	1255	1429	1993	2062

Table 7.15. Drainage structure inundation by scenario with 0.5 m Sea Level Rise

Drainage Structures	Scenario 1 SLR	Scenario 2 SLR	Scenario 3 SLR	Scenario 4 SLR
Drainage Structures Inundated	1286	1449	2208	2275

Transit Facilities

A significant number of bus stops (and bus routes) will be unavailable in the modeled worst-case scenarios, leading to reduction in public transportation efficiency (Tables 7.16 and 7.17). These losses should be considered in evacuation planning and post storm recovery. Inundated counts are shown in tables ***.

Table 7.16. Transit facility inundation by scenario

Transit Facilities	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Park and Ride	0	0	1	1
Bus Stops	157	225	293	319

Table 7.17. Transit facility inundation by scenario with 0.5 m Sea Level Rise

Transit Facilities	Scenario 1 SLR	Scenario 2 SLR	Scenario 3 SLR	Scenario 4 SLR
Park and Ride	0	0	1	1
Bus Stops	165	288	317	342

Chapter 8 – Demographic Analysis of Wind Damage and At-Risk Areas

Wind Damage

There is significant wind damage predicted by direct hurricane hits to Delaware. This analysis includes threat models from the FEMA HAZUS ArcGIS extension and SimSuite output from the United States Army Corps of Engineers (USACE). Both the HAZUS and USACE models predict significant damages as detailed in Tables 8.1 – 8.6 and Figures 8.1 – 8.7.

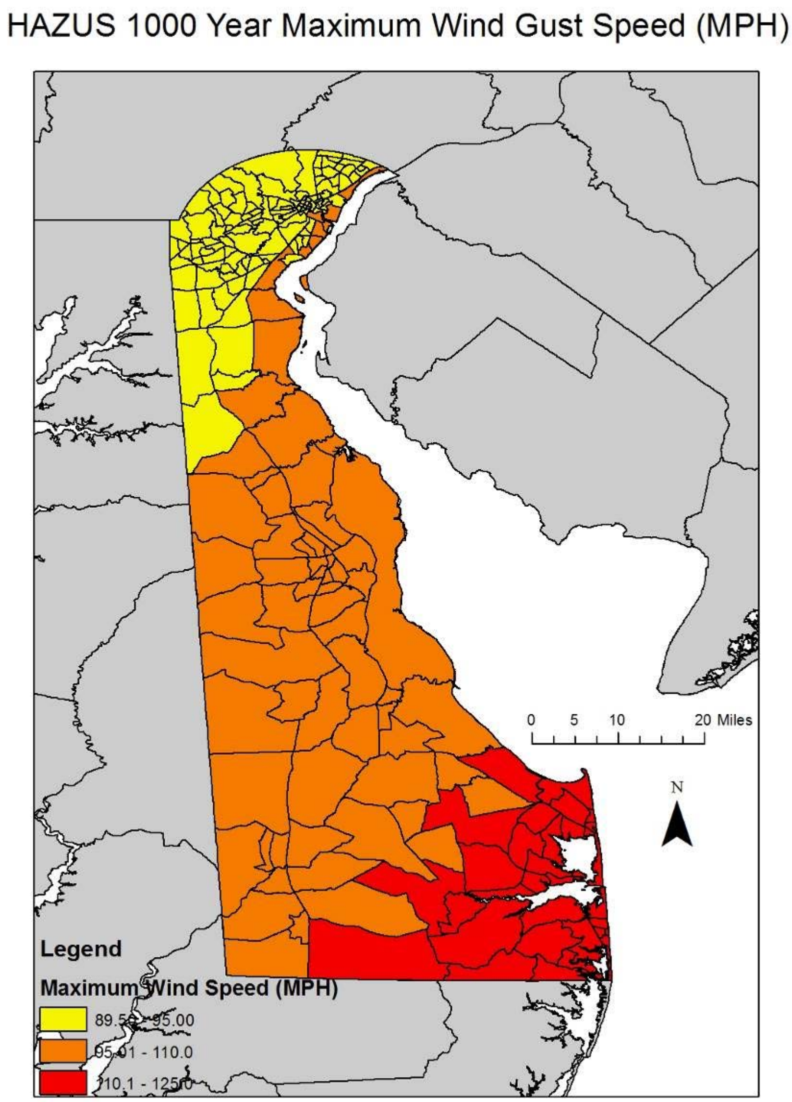


Figure 8.1. Maximum wind gust speed modeled by HAZUS

Table 8.1. HAZUS essential facility damage prediction

Essential Facility Damage	100-year Storm	200-year Storm	500-year Storm	1000-year Storm
EOC Moderate Damage	0	0	0	0
EOC Complete Damage	0	0	0	0
EOC Loss of Use < 1 Day	2	2	2	2
Fire Stations Moderate Damage	0	0	0	0
Fire Stations Complete Damage	0	0	0	0
Fire Stations Loss of Use < 1 Day	94	94	94	94
Hospitals Moderate Damage	8	2	8	8
Hospitals Complete Damage	0	0	0	1
Hospitals Loss of Use < 1 Day	11	10	10	8
Police Stations Moderate Damage	0	0	1	1
Police Stations Damage	0	0	0	0
Police Stations Loss of < 1 Day	36	36	36	36
Schools Moderate Damage	0	0	2	9
Schools Complete Damage	0	0	0	0
Schools Loss of Use < 1 Day	357	341	297	221

Table 8.2. HAZUS debris prediction

Debris Generation	100-year Storm	200-year Storm	500-year Storm	1000-year Storm
Total Tons of Debris	410,099	366,880	1,071,768	1,852,140
Removed Debris Truckloads Required	927	3,129	7,551	12,725

Table 8.3. HAZUS displacement and sheltering prediction

Sheltering	100 -year Storm	200-year Storm	500-year Storm	1000-year Storm
Households Displaced	8	360	1231	2438
People needing Sheltering	1	75	266	543

Table 8.4. HAZUS property damage prediction

Property Damage (Thousands $)	100-year Storm	200-year Storm	500-year Storm	1000-year Storm
Residential Building Property Damage	313,288.55	598,846.72	1,405,013.25	2,321,315.13
Residential Content Property Damage	72,422.92	205,872.13	518,919.77	852,011.13
Commercial Building Property Damage	6,493.19	21,356.96	61,370.19	112,609.73
Commercial Content Property Damage	313.90	9,352.87	29,212.50	54,073.21
Commercial Inventory Property Damage	9.55	192.19	589.84	1,108.66
Industrial Building Property Damage	1,694.68	3,853.89	13,344.67	28,189.51
Industrial Content Property Damage	366.46	2,314.21	8,687.71	19,173.08
Industrial Inventory Property Damage	61.18	274.58	1,077.57	2,471.87
Other Building Property Damage	1,465.97	4,094.30	12,831.17	25,714.33
Other Content Property Damage	89.17	1,819.61	5,976.38	11,980.95
Other Inventory Property Damage	7.70	78.43	238.75	445.61
Total Building Property Damage	322,942.38	628,151.86	1,492,559.28	2,487,828.70
Total Content Pr operty Damage	73,192.45	219,358.82	562,796.35	937,238.37
Total Inventory Property Damage	78.43	545.20	1,906.17	4,026.15

Table 8.5. HAZUS business interruption prediction

Business Interruption (Thousands $)	100-year Storm	200-year Storm	500-year Storm	1000-year Storm
Residential Income	0.00	12.25	167.37	332.92
Residential Relocation	11,174.01	61,134.04	159,854.09	264,255.82
Residential Rental	4,644.00	21,800.63	54,445.27	89,317.15
Residential Wage	0.00	28.68	392.00	779.80
Commercial Income	58.50	1,948.34	5,633.49	12,188.51
Commercial Relocation	196.67	3,508.51	9,763.23	17,929.60
Commercial Rental	23.11	1,834.40	5,173.92	9,323.83
Commercial Wage	20.76	2,059.28	5,799.34	13,065.00
Industrial Income	2.21	30.75	97.18	241.26
Industrial Relocation	20.23	380.89	1,134.67	2,245.50
Industrial Rental	1.92	37.34	126.57	275.49
Industrial Wage	3.65	52.33	163.19	402.31
Other Income	0.00	180.95	430.41	1,032.70
Other Relocation	22.50	726.62	2,244.44	4,664.28
Other Rental	0.03	49.06	169.21	404.95
Other Wage	0.00	1,617.76	3,383.37	8,136.07
Total Income	60.71	2,172.28	6,328.45	13,795.39
Total Relocation	11,413.41	65,750.05	172,996.43	289,065.19
Total Rental	4,646.75	23,721.43	59,914.97	99,321.43
Total Wage	24.40	3,758.06	9,737.91	22,383.17

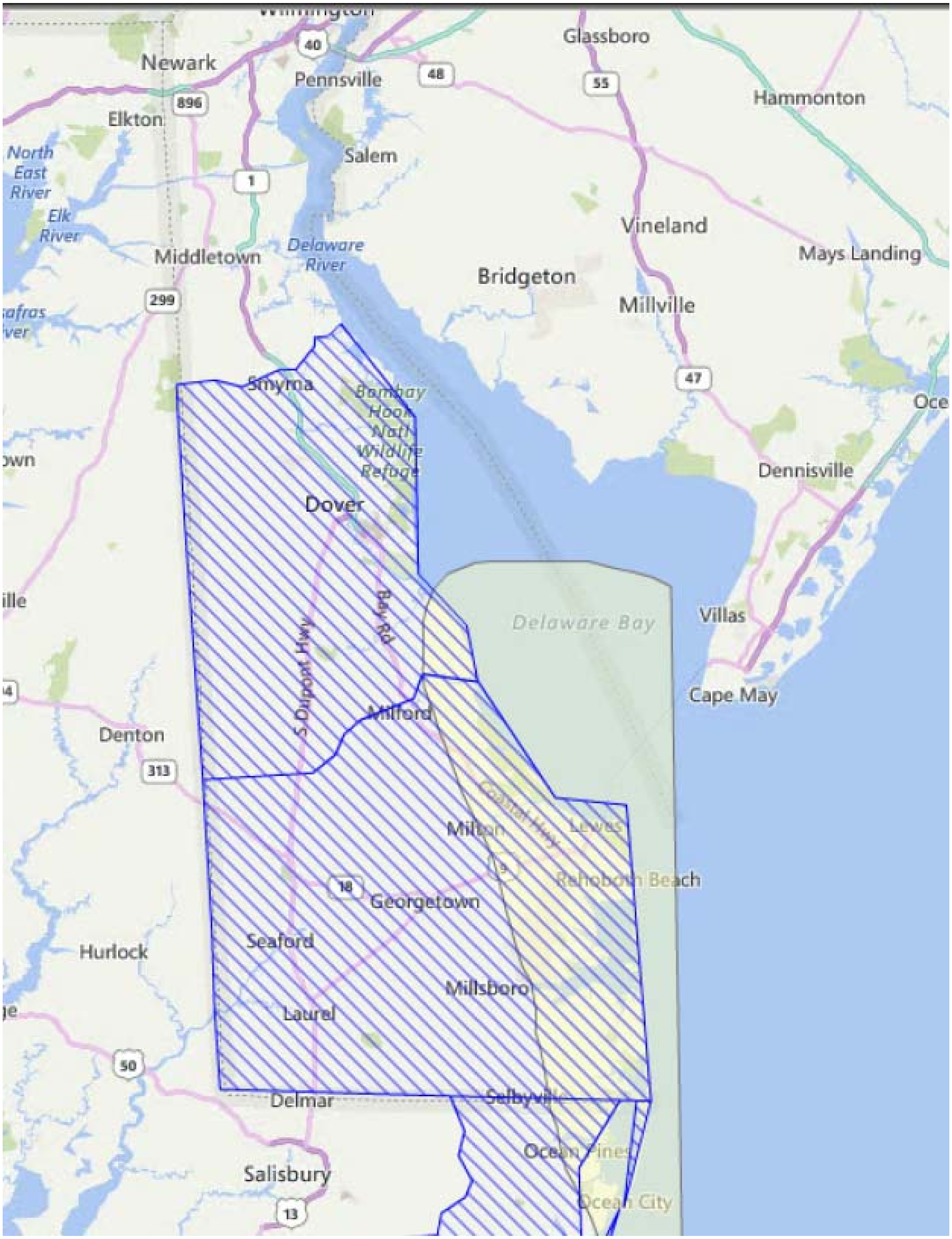


Figure 8.2. Hurricane damage modeled by USACE

Table 8.6. Army Corps of Engineers SimSuite Output Damage Calculations

USACE Model Data	Category 1	Category 3
Debris (Cubic Yards)	190,688	1,776,986
Temporary Roofing	1,207	2,415

Population Density

According to the U.S. Census taken in 2010, Delaware's population density is 460.8 people per square mile. Calculating by census tract, one can receive more detailed information about a certain region of the state. The most densely populated census tract is found in New Castle County and has a population density of 60,015.99 people per square mile. The ten tracts with the lowest population density are mainly located on the coast of the southern part of the state.

Scenario 1: 100-year Flood, Category 1 Hurricane: For Scenario 1, the average population density of the area covered is 215.08 people per square mile. This is well below the state average of 460.8. Overall, most of the flooded zones will have a low population density. The highest density will be found in the northern part of the state, at 3,255 people per square mile for one tract.

Scenario 1 SLR: 100-year Flood, Category 1 Hurricane. Includes Sea Level Rise: The majority of the potential flood zone does not include densely populated regions. In this scenario, most areas that will be covered have a fairly low population density. On average, the population density is 225.388 people per square mile. The most densely populated tract to be affected during this scenario has a density of 3,255 people per square mile.

Scenario 2: 500-year Flood, Category 1 Hurricane: In this scenario, very few highly populated areas will be affected. The average population density is 227.9 people per square mile. This is below Delaware's average population density. The most densely populated tract to be flooded in this scenario has a density of 3,255 people per square mile and is located in New Castle County, the northern part of the state.

Scenario 2 SLR: 500-year Flood, Category 1 Hurricane. Includes Sea Level Rise: When including Sea Level Rise for Scenario 2, the amount of land covered increases. Along with this increase, the average population density of the affected area increases too. In this scenario, the average amount of people per square mile is 228.647, a slight increase from the scenario without Sea Level Rise. Like in the previous studies, the area with the highest population density has 3,255 people per square mile.

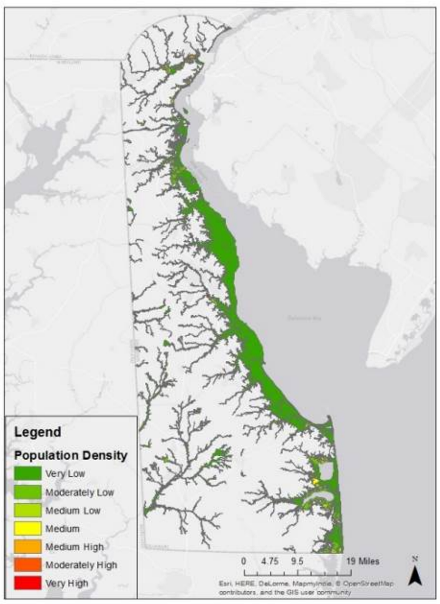
Scenario 3: 100-year Flood, Category 3: Here, the average population density of the affected area has increased to 229.77 people per square mile. Like the previous scenarios, this is below the average population density for the state of Delaware.

Scenario 3 SLR: 100-year Flood, Category 3. Includes Sea Level Rise: Accounting for Sea Level Rise, the average population density has risen to 230.65 people per square mile. This is less than a one percent difference from the previous scenario's calculation. Like former scenarios, the highest population density is 3,255 people per square mile.

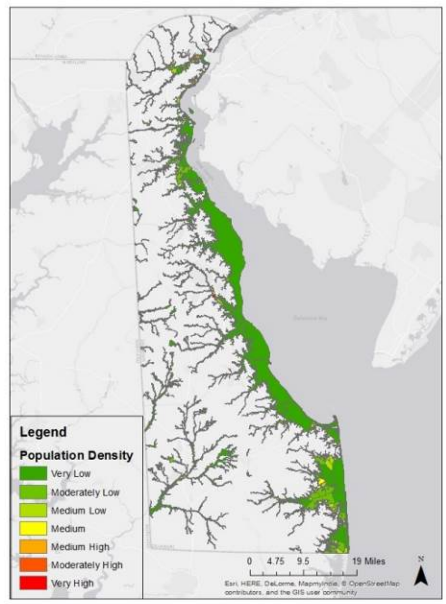
Scenario 4: 500-year Flood, Category 3: In this scenario, the population density of the area that will be covered is 232.6 people per square mile. This is an increase from other previous measurements. Like previous situations, most of the population is concentrated in the northern part of the state with the highest population density being 3,255 people per square mile.

Scenario 4: 500-year Flood, Category 3. With Sea Level Rise: Here, the population density increases to 233.47 people per square mile. Despite this being the highest population density for any of the scenarios, it is still 49.33% lower than the state average. Out of all the tracts covered by water, the measurement of the highest population density is still 3,255 people per square mile.

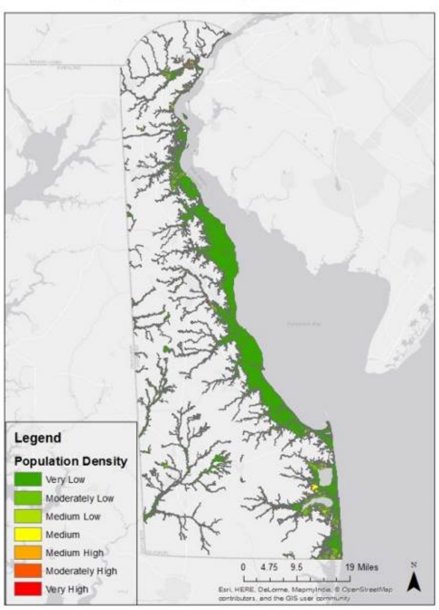
Population Density: Scenario 1



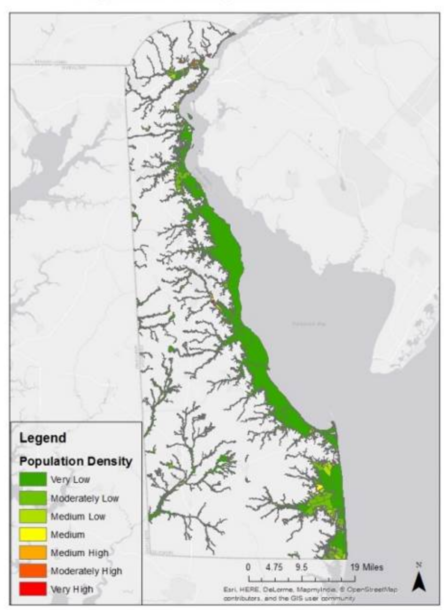
Population Density: Scenario 1 SLR



Population Density: Scenario 2



Population Density: Scenario 2 SLR



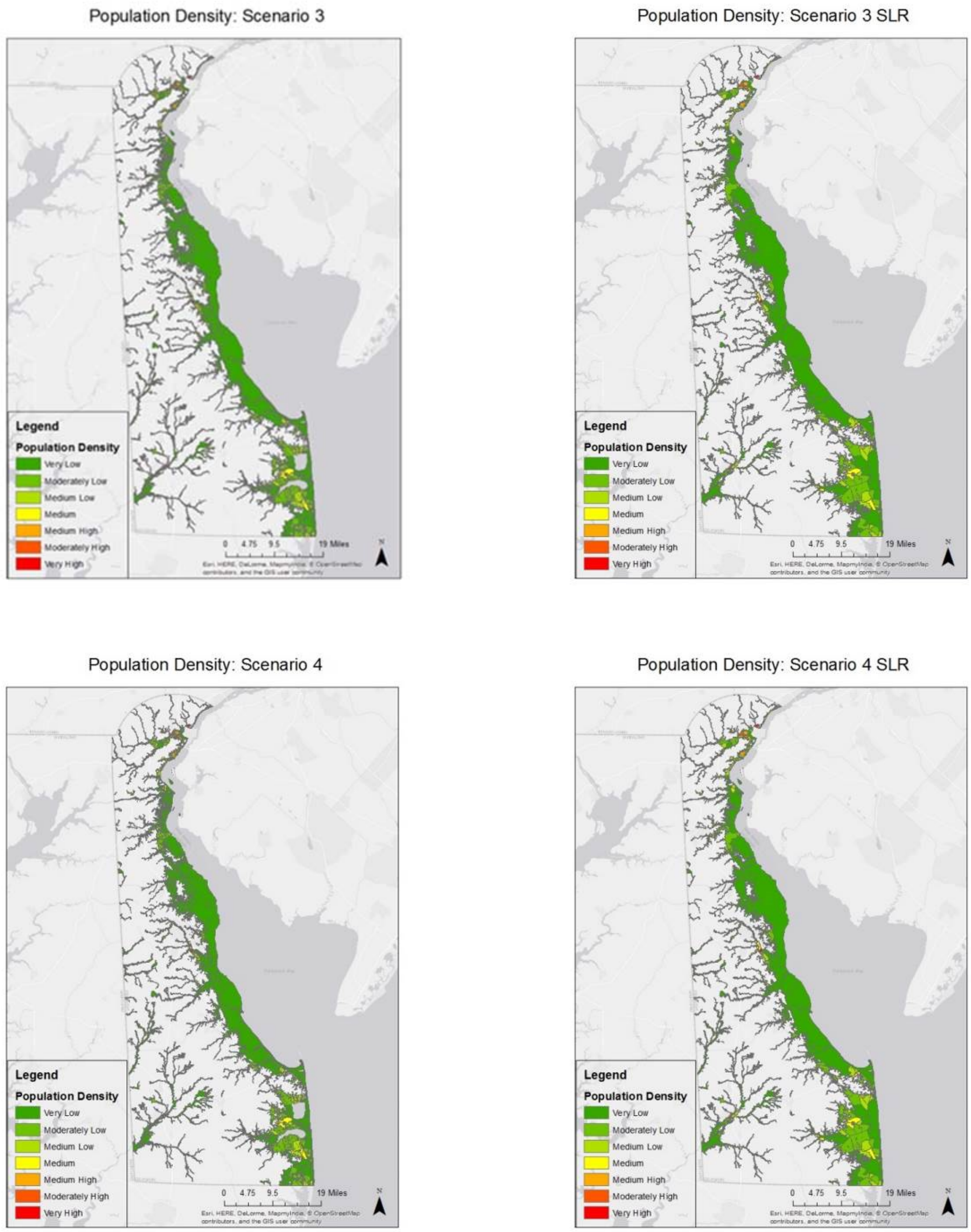


Figure 8.3. Population density - Delaware

Population Over 65

According to the U.S. Census taken in 2010, 15.89% of Delaware's population is made up of people 65 years or older. The census tracts with the highest percentages of this demographic are found along the coast of the southern section of the state. The tract with the highest percentage is at 83.07% and is located in this coastal region. It should be noted that in all the scenarios, the proportion of people over 65 affected is larger than the state average.

Scenario 1: 100-year Flood, Category 1 Hurricane: For the first scenario, people over 65 make up approximately 16.59% of the people affected by the flooding. This is a fairly significant figure. The regions with the highest percentages are located on the coasts of the southern section of Delaware. The highest ratio of people over 65 can be found near the coast of southern Delaware and make up about 83% of the population in the census tract.

Scenario 1 SLR: 100-year Flood, Category 1 Hurricane. Includes Sea Level Rise: When accounting for Sea Level Rise, the percentage of people over 65 in the affected area drops to around 16.41%. Like the previous situation, the regions with the higher percentages are concentrated in the southern part of the state. Also, like the previous situation, the highest percentage is around 83%.

Scenario 2: 500-year Flood, Category 1 Hurricane: In this scenario, people over the age of 65 make up 16.37% of the population affected by flooding. This is a very small decrease from the other scenarios. This is because more land is being flooded and more people (most who do not belong to the over 65 category) are being affected, adding to the denominator.

Scenario 2 SLR: 500-year Flood, Category 1 Hurricane. Includes Sea Level Rise: Here, the percentage of people over 65 is 16.39% in the flood zones. Like previous models, most of this is concentrated in the lower part of the state near the coast. Most of the new area covered has a lower percentage of people over 65.

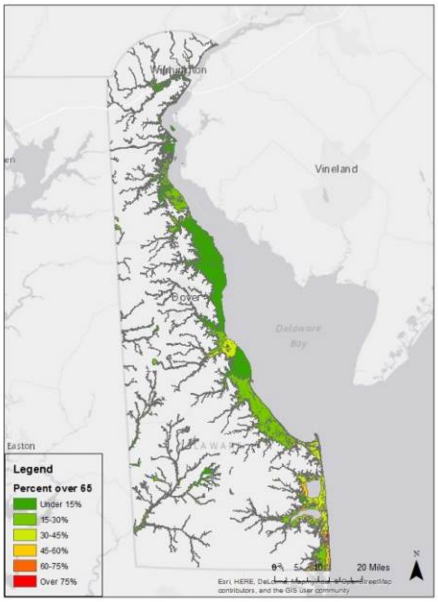
Scenario 3: 100-year Flood, Category 3: In this scenario, people over the age of 65 make up approximately 16.37% of those affected by the flooding. The tract with the highest percentage of people over 65 is currently made up of 83.07% of this demographic.

Scenario 3 SLR: 100-year Flood, Category 3. Includes Sea Level Rise: Consistent with the pattern, the percentage of those over 65 is decreasing as more land is covered. Now, this population makes up about 16.34% of the people affected by the flood. With the addition of Sea Level Rise, some of the areas with more of this demographic become even more flooded, showing that more are at risk.

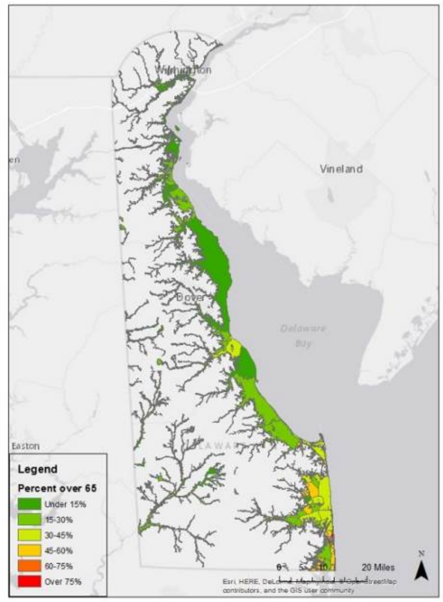
Scenario 4: 500-year Flood, Category 3: In this scenario, 16.33% of the affected population is over 65 years old. Like previous models, most of the flooding occurs in regions with a fairly low percentage of this demographic. The exception to this is the southern section of the state.

Scenario 4: 500-year Flood, Category 3. With Sea Level Rise: When accounting for Sea Level Rise in Scenario 4, 16.31% of the projected victims will be over 65 years old. As in the other scenarios, most of the communities with the higher proportion of this demographic are in the southern part of the state.

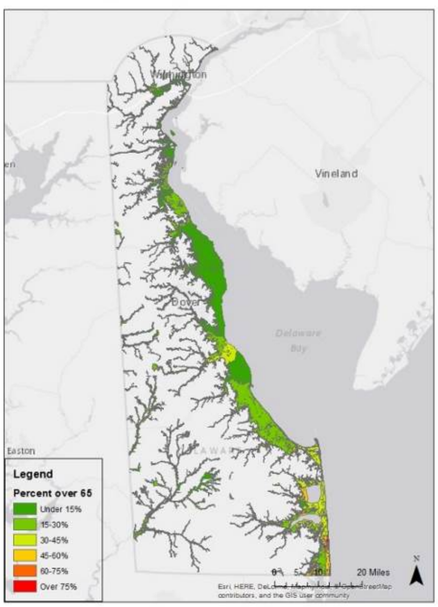
Percentage of Population over 65: Scenario 1



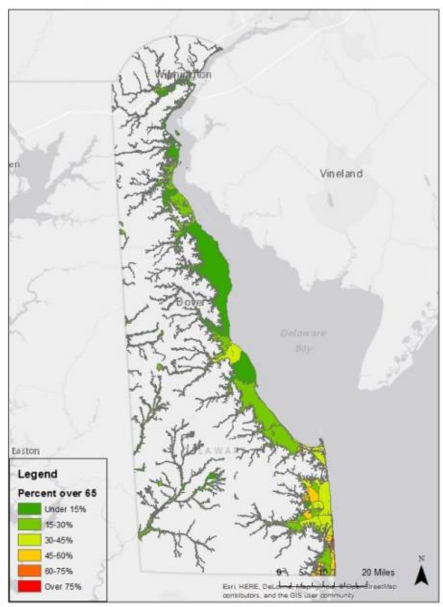
Percentage of Population over 65: Scenario 1 SLR



Percentage of Population over 65: Scenario 2



Percentage of Population over 65: Scenario 2 SLR



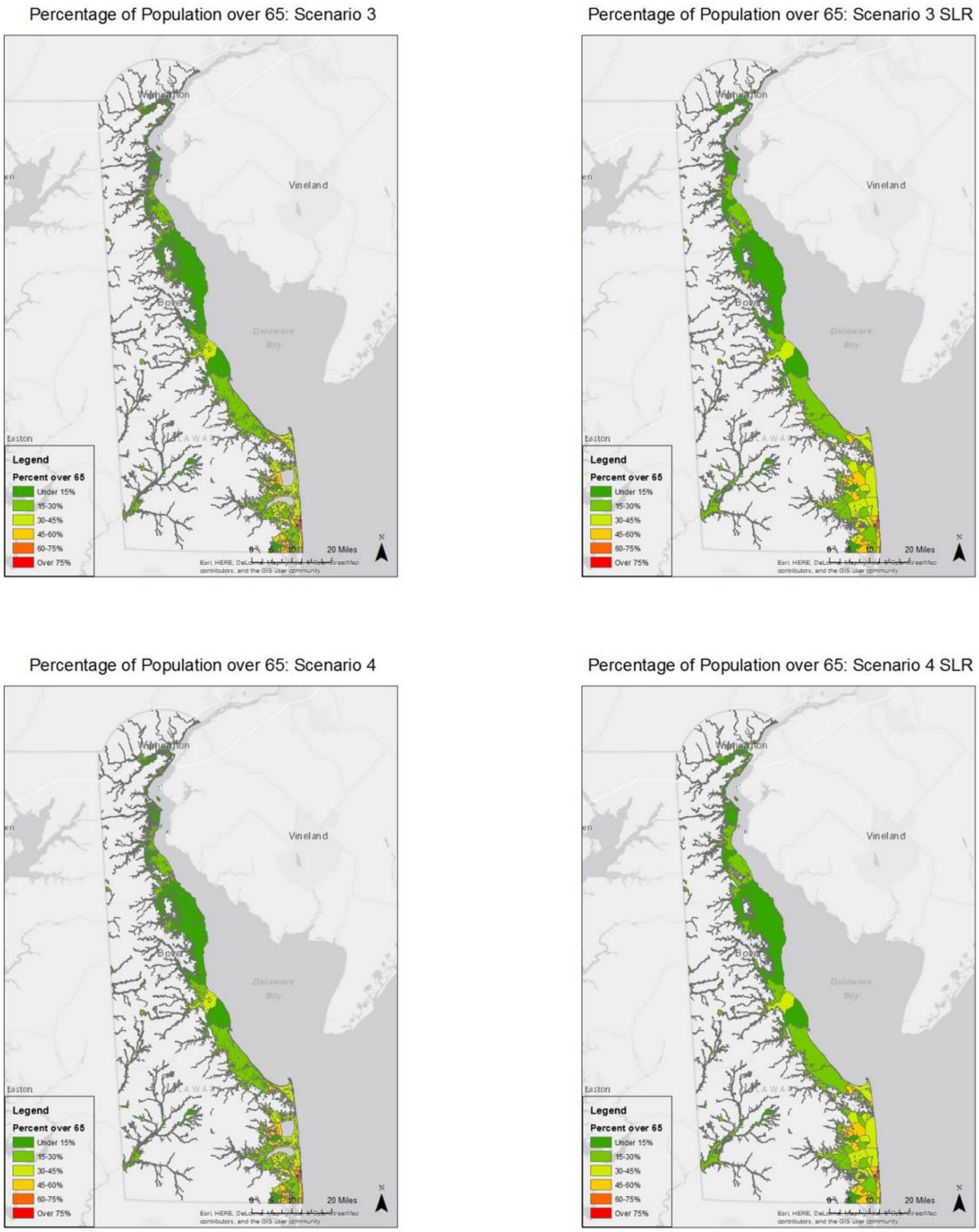


Figure 8.4. People over 65 – Delaware

Concentration of Poverty

According to the U.S. Census taken in 2010, 11.69% of the population of Delaware is below the poverty line. The census tracts with the highest amounts of poverty are found in the north, mainly near Wilmington. Other significant percentages can be found in Dover, along with in some of the southern areas of the state. The highest level of poverty is at 73.18% and is found in the upper region of the state.

In all scenarios, none of the poverty ratios of the flood zones exceed the state average. With all calculations being close to the state average, there are no significant deviations.

Scenario 1: 100-year Flood, Category 1 Hurricane: For this scenario, the amount of people below the poverty line makes up 10.72% of the affected population. While most of the census tracts covered have fairly low amounts of people below the poverty line, there are higher concentrations in some areas. This can be seen along the coast in the middle of the state and in some selected areas of the southern part of the state. The most notable area includes the northern part of the state. Here, the amount of people below the poverty line can make up 73.18% of the inhabitants.

Scenario 1 SLR: 100-year Flood, Category 1 Hurricane. Includes Sea Level Rise: Of the projected victims for this scenario, 11.11% of them are expected to be people from below the poverty line. This is higher than the scenario without the sea level rise. A lot of this can be attributed to the increase of flooding in the northern part of the state, especially in the Wilmington area. In this scenario, the census tract with the highest proportion of people below the poverty line is found in the northern part of the state, with this demographic making up 73.18% of the population.

Scenario 2: 500-year Flood, Category 1 Hurricane: Here, the amount of people below the poverty line will make up 11.09% of the people affected. Like previous scenarios, there are some significant proportions of this demographic in the flood zones near the middle and lower parts of the state. The most significant concentration is in the northern part of the state, especially near Wilmington.

Scenario 2 SLR: 500-year Flood, Category 1 Hurricane. Includes Sea Level Rise: When accounting for Sea Level Rise in Scenario 2, the percentage of people below the poverty line slightly increased to 11.11%. In this scenario, some of the previously uncovered territory from Scenario 2 is now covered by flood water. This is especially noticeable in cities like Wilmington, where a lot of the poverty is concentrated.

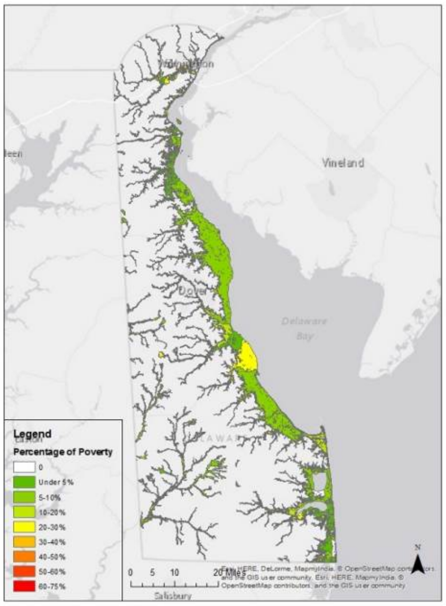
Scenario 3: 100-year Flood, Category 3*:* In this scenario, 11.11% of the potential victims will be below the poverty line. This number is very similar to Scenario 2 SLR. In this situation, some areas in the southern part of Delaware that have a higher concentration of poverty are covered by water. This is counteracted by some parts that have lower concentrations also being covered.

Scenario 3 SLR: 100-year Flood, Category 3. Includes Sea Level Rise: With Sea Level Rise, the percentage of those in the flooding zone who are below the poverty line increases to 11.17%. As in previous scenarios, the highest rates are found in the northern part of the state at 73.18%.

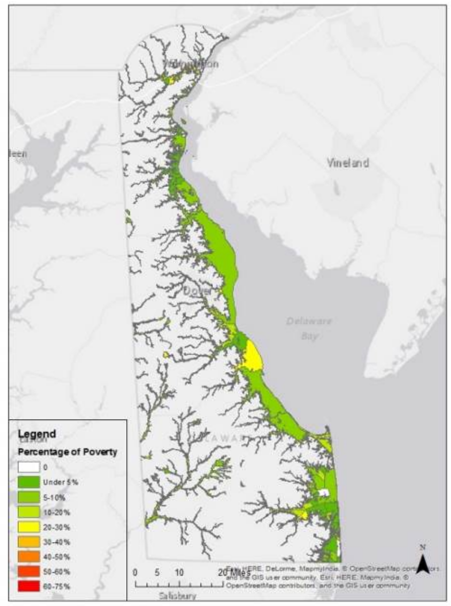
Scenario 4: 500-year Flood, Category 3: For this scenario, 11.08% of the population affected is below the poverty line. This is fairly consistent with estimates from other scenarios. Like previous scenarios, the census tract with the most poverty is found in the northern part of the state with 73.18% being below the poverty line.

Scenario 4: 500-year Flood, Category 3. With Sea Level Rise: When including area affected with sea level rise, 11.14% of the population will be below the poverty line. This is fairly consistent with the other calculations. In these regions, poverty does not exceed 73.18% of the population.

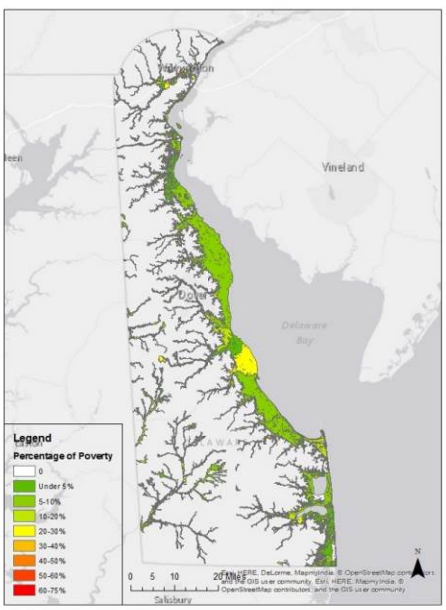
Concentration of Poverty: Scenario 1



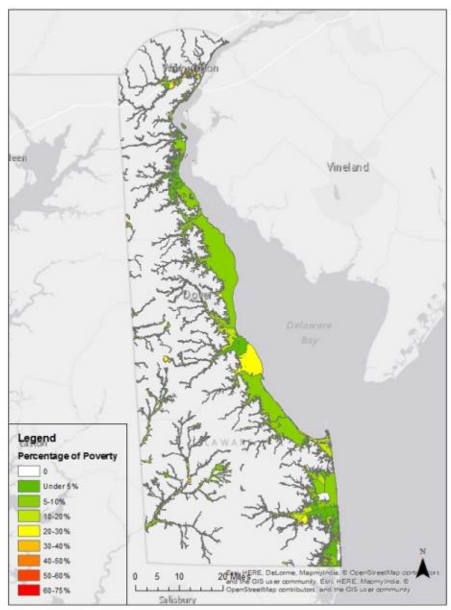
Concentration of Poverty: Scenario 1 SLR



Concentration of Poverty: Scenario 2



Concentration of Poverty: Scenario 2 SLR



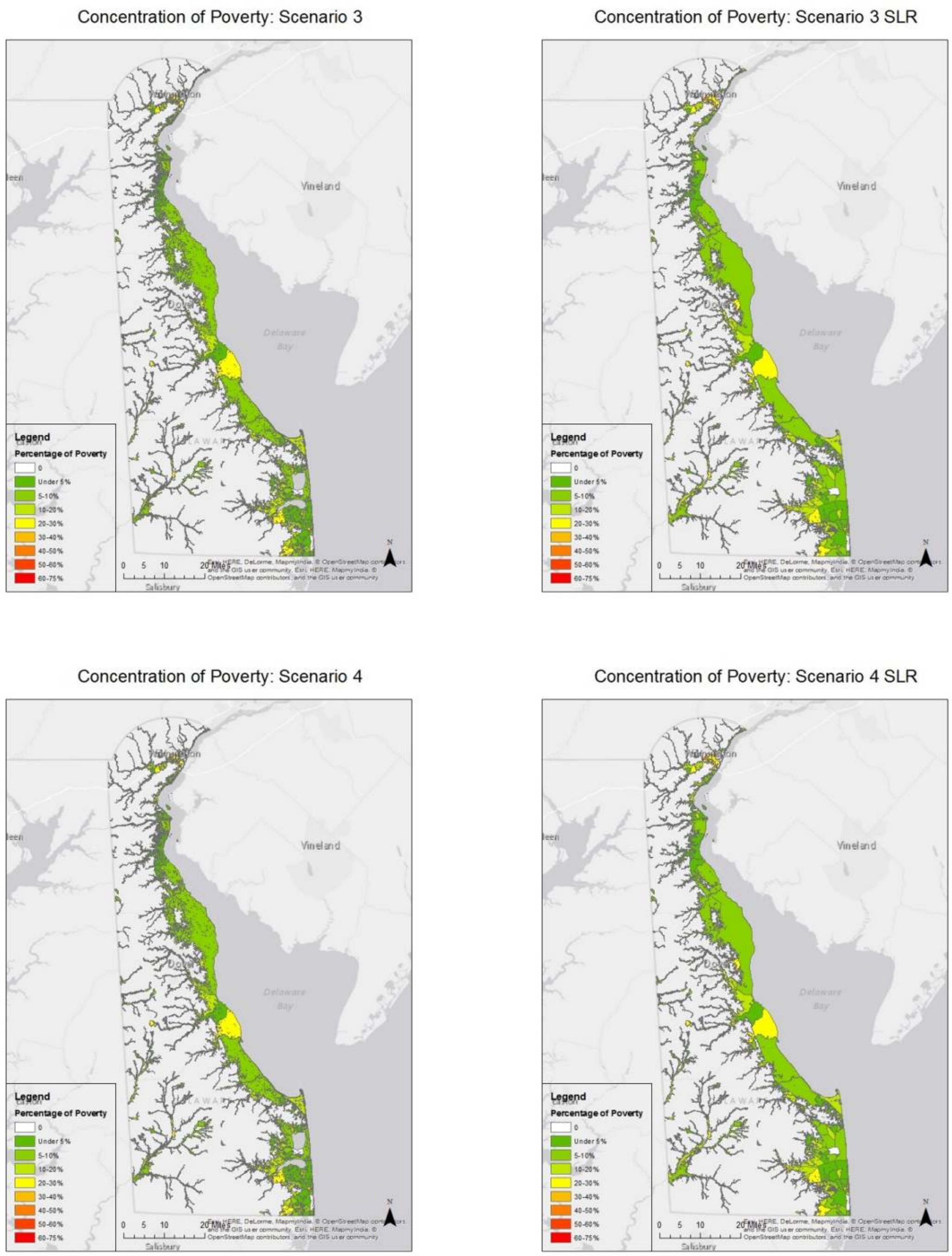


Figure 8.5. Concentration of poverty – Delaware

Households with Limited English Proficiency

According to the U.S. Census taken in 2010, 2.22% of households in Delaware have limited English capabilities. Limited English proficiency may hinder evacuation efforts, as it may be difficult to communicate with emergency personnel. Overall, the census tract with the highest percentage of households with limited English capabilities is found in Georgetown, Delaware at 27.04%. This is not in the flood zone.

Scenario 1: 100-year Flood, Category 1 Hurricane: In this scenario, 1.91% of the households affected by the flooding will have limited English proficiency. This is close to the state average of 2.22%. The highest percentage for a single tract is significantly over the state average at 23.11% of the current population. It is found in Milford, DE. Other significant concentrations can be found in the southern section of the state. In New Castle County, these concentrations of households with limited English proficiency are found near the cities of Newark and Wilmington.

Scenario 1 SLR: 100-year Flood, Category 1 Hurricane. Includes Sea Level Rise: With the addition of Sea Level Rise, the percentage of households with limited English proficiency increased to 2.09%. Even though the proportion increased, it is still below the state average.

Scenario 2: 500-year Flood, Category 1 Hurricane: Here, percentage of households with limited English proficiency is at 2.09%. This value is fairly close to the state average of 2.22%.

Scenario 2 SLR: 500-year Flood, Category 1 Hurricane. Includes Sea Level Rise: When including area affected by Sea Level Rise, the percentage of limited English proficient households increased to 2.1%. Still below the state average, this percentage is slightly higher than the same scenario minus the Sea Level Rise. In this scenario, flooding fills in sections that were previously untouched in Scenario 2 (no Sea Level Rise).

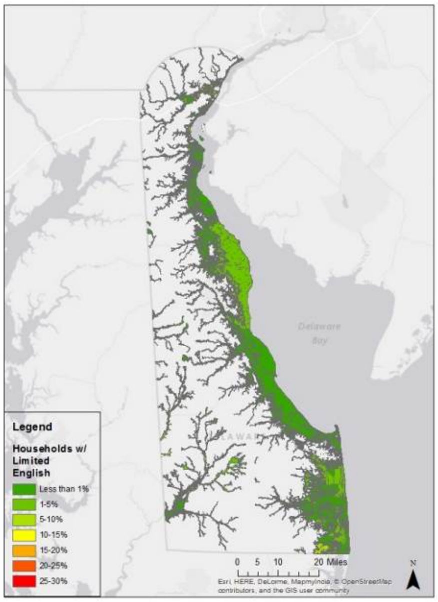
Scenario 3: 100-year Flood, Category 3: At 2.11%, the percentage of households with limited English is fairly normal when compared to other scenarios. This value can be expected and is actually a little bit less than the state average of 2.22%.

Scenario 3 SLR: 100-year Flood, Category 3. Includes Sea Level Rise: Under Sea Level Rise conditions, the percentage of households with limited English proficiency remains the same as Scenario 3 without Sea Level Rise. Even though flooding covers more land with Sea Level Rise, the contents of what is covered remains fairly similar to Scenario 3's coverage.

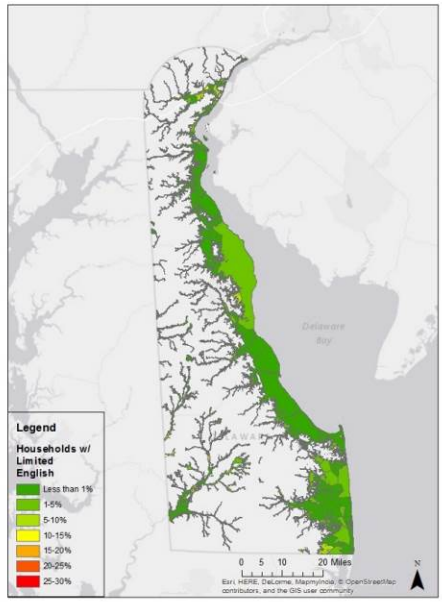
Scenario 4: 500-year Flood, Category 3: In this scenario, the percentage of households with limited English proficiency is 2.1%. This is fairly consistent with the other values calculated in the other scenarios. Like the other scenarios, the highest percentage that households with limited English proficiency make up of the tract's households is 23.11%.

Scenario 4: 500-year Flood, Category 3. With Sea Level Rise: Of the projected area affected, households with limited English proficiency will make up about 2.1% of the households affected. This figure is unchanged from Scenario 4 without Sea Level Rise.

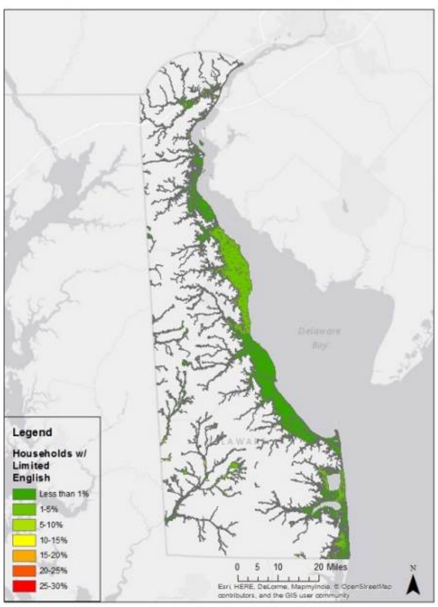
Percentage of Households with Limited English: Scenario 1



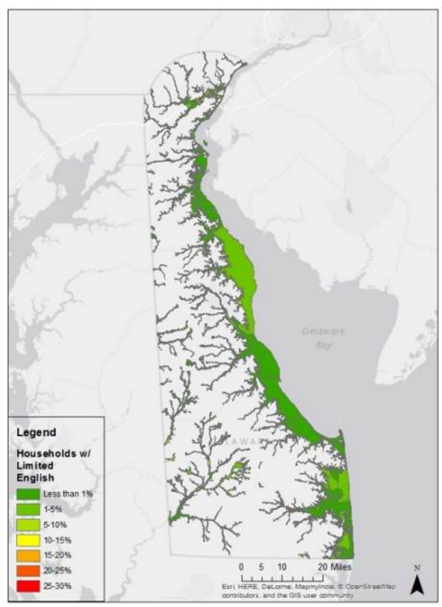
Percentage of Households with Limited English: Scenario 1 SLR



Percentage of Households with Limited English: Scenario 2



Percentage of Households with Limited English: Scenario 2 SLR



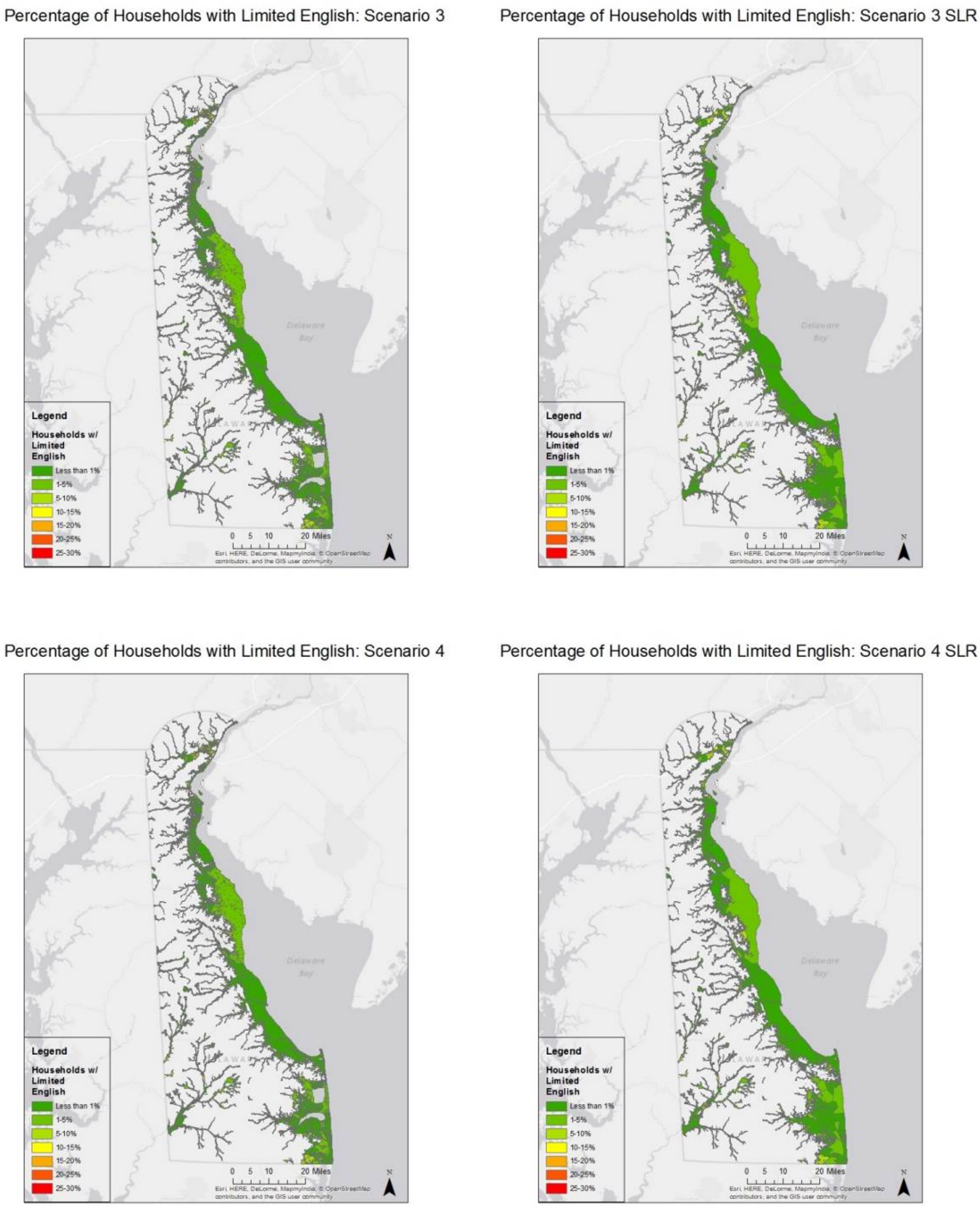


Figure 8.6. Households with limited English proficiency – Delaware

Age of Housing

For this section, the ages of housing will be split up into three different categories similar to housing stock classification in the HAZUS software, built before 1950, 1950 and 1970, and after 1970." Age of housing is important when considering the effects of natural disasters. This is because regulations and safety practices change over time, influencing the quality of the building. Also, as buildings get older, the more susceptible they are to damage brought on by flooding. According to the U.S. Census taken in 2010, 13.47% of housing units were built before 1950. In all the scenarios, the percentage of "Built Before 1950" does not exceed the state average. Statewide, "Built Between 1950 and 1970" makes up 21.43% of all housing units. In every scenario, "Built Between 1950 and 1970" does not exceed 19%.

Scenario 1: 100-year Flood, Category 1 Hurricane: Built Before 1950: Out of the housing units flooded in this scenario, 10.2% of them were built before 1950. This is the smallest category. Built Between 1950 and 1970: Housing built in between these years comprises 16.97% of all buildings in the flood zone. The areas with higher percentages of these buildings are along the coast in the south. Built After 1970: By far the largest category, housing built after 1970 makes up 72.83% of the housing in the state. As a result, it is very prevalent throughout the state.

Scenario 1 SLR: 100-year Flood, Category 1 Hurricane. Includes Sea Level Rise: Built Before 1950: With Sea Level Rise, the percentage of housing units built before 1950 has increased to 11.01%. Built Between 1950 and 1970: This is due to the increase of flooding in the northern part of the state. Built After 1970: Even though the percentage of this category dropped, it is still the dominant one, being at 69.99%. This is mainly due to the increase of housing built between 1950 and 1970.

Scenario 2: 500-year Flood, Category 1 Hurricane: Built Before 1950: Like previous scenarios, this category remains fairly low at 11.30%. Built Between 1950 and 1970: The second largest category, makes up 18.97% of housing units. Built After 1970: Once again the largest category, "Built After 1970" is currently at 69.72%.

Scenario 2 SLR: 500-year Flood, Category 1 Hurricane. Includes Sea Level Rise: Built Before 1950: As the smallest category, "Built Before 1950" is 11.4% of the housing in the affected region. Built Between 1950 and 1970 houses built account for 19.11% of the total houses in the flood zone. Built After 1970: At 69.48%, "Built After 1970" is the largest category.

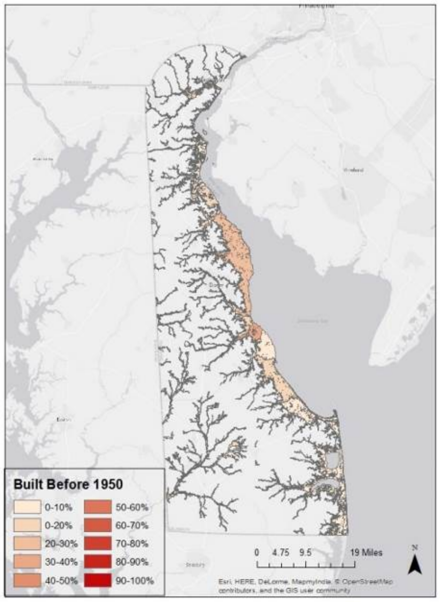
Scenario 3: 100-year Flood, Category 3: Built Before 1950: For this scenario, the percentage for "Built Before 1950" drops a little to 10.92%. Built Between 1950 and 1970: Like "Built Before 1950," this category dropped to 19.06%. Built After 1970: Because of the decreasing percentages of the other two categories the proportion of this one increased. It is now currently at 70.01%

Scenario 3 SLR: 100-year Flood, Category 3. Includes Sea Level Rise: Built Before 1950: This category makes up 10.93% of the housing units found in this region. Built Between 1950 and 1970: At 19.23%, this category is the second largest. Built After 1970: approximately 70% of the housing units and the largest category by far.

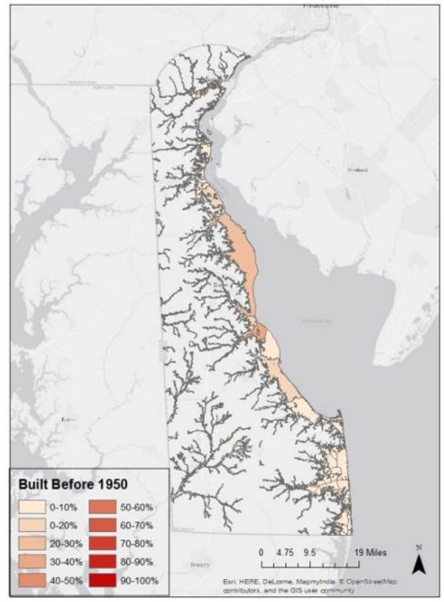
Scenario 4: 500-year Flood, Category 3: Built Before 1950 accounts for 11.28% of housing units in the flood zone. Built Between 1950 and 1970: This group is 19.08% of all housing units affected. Built After 1970: The largest category.

Scenario 4: 500-year Flood, Category 3. With Sea Level Rise: Built Before 1950: When accounting for Sea Level Rise, the percentage for "Built Before 1950" remains at 11.28%. Built Between 1950 and 1970: Bigger than Scenario 4 without SLR the percentage is 19.25%. Built After 1970: The largest category at 69.47%.

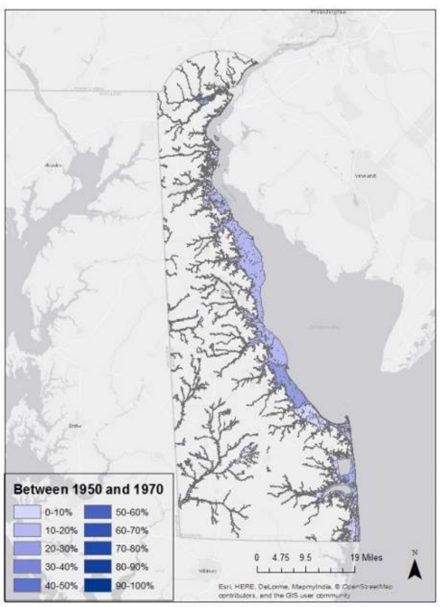
% of Housing Built Before 1950: Scenario 1



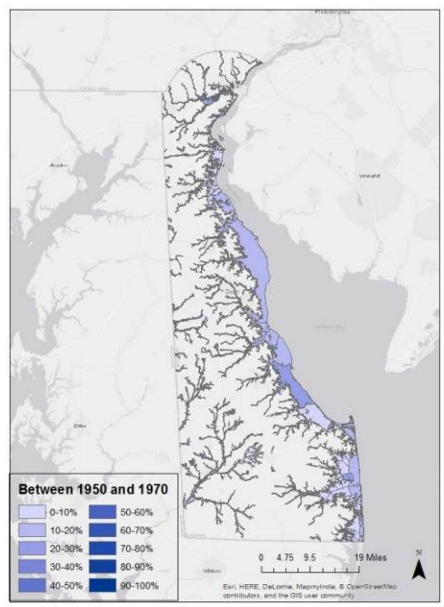
% of Housing Built Before 1950: Scenario 1 SLR



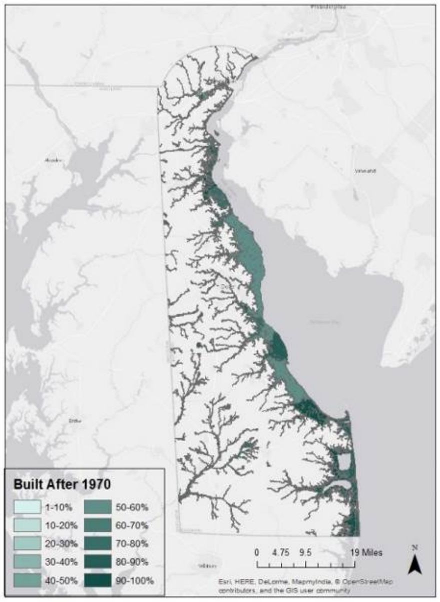
% of Housing Built Between 1950 and 1970: Scenario 1



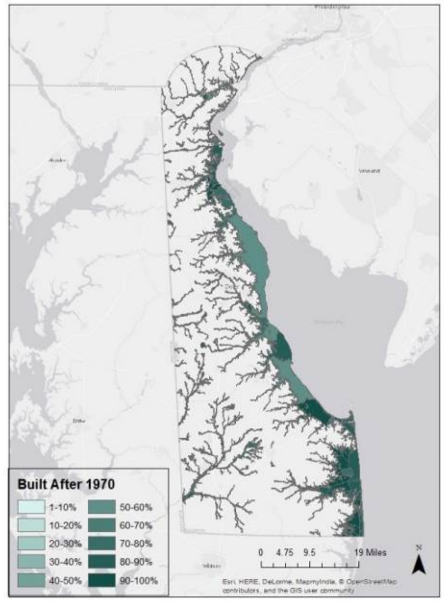
% of Housing Built Between 1950 and 1970: Scenario 1 SLR



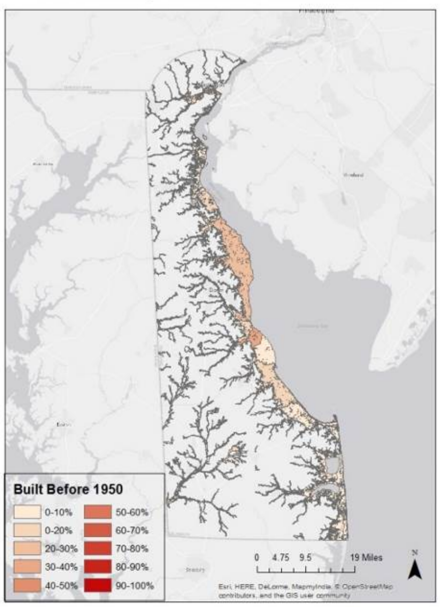
% of Housing Built After 1970: Scenario 1



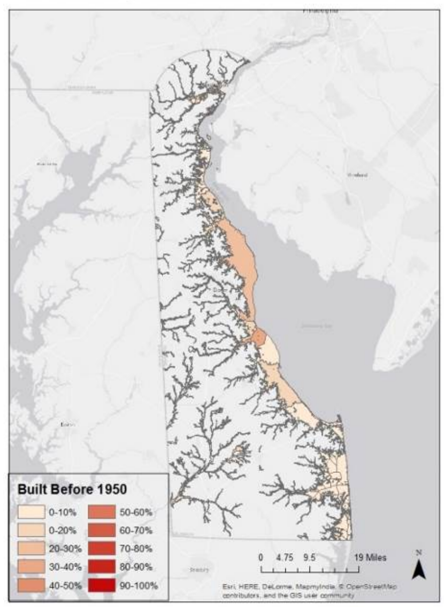
% of Housing Built After 1970: Scenario 1 SLR



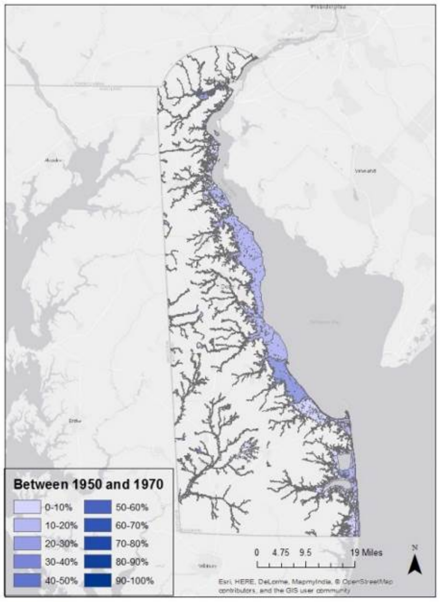
% of Housing Built Before 1950: Scenario 2



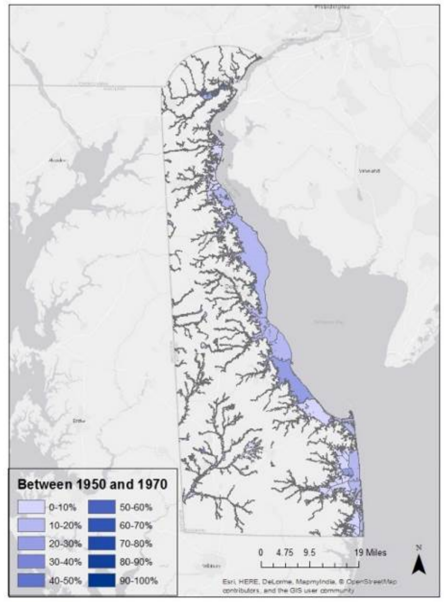
% of Housing Built Before 1950: Scenario 2 SLR



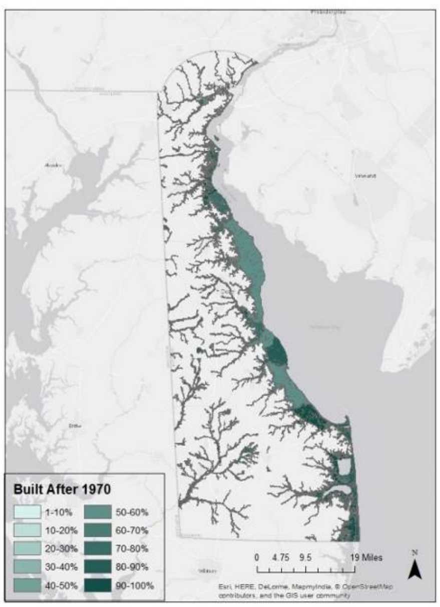
% of Housing Built Between 1950 and 1970: Scenario 2



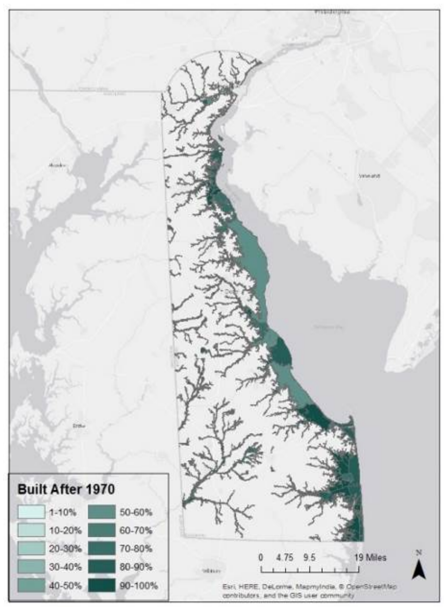
% of Housing Built Between 1950 and 1970: Scenario 2 SLR



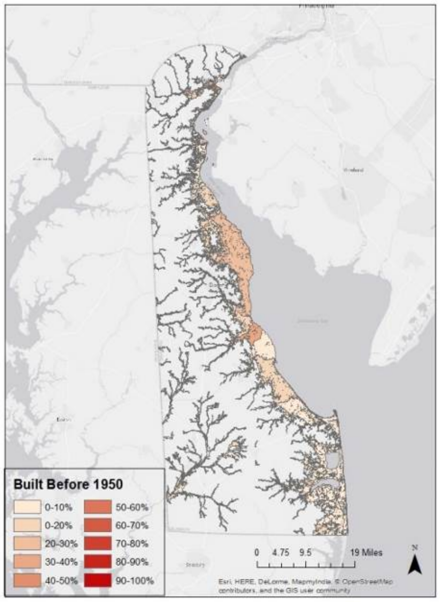
% of Housing Built After 1970: Scenario 2



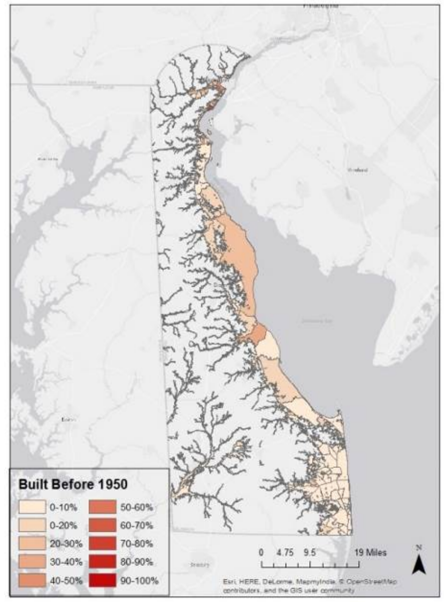
% of Housing Built After 1970: Scenario 2 SLR



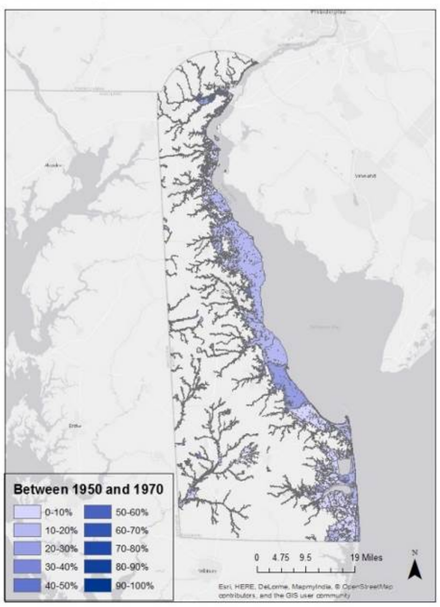
% of Housing Built Before 1950: Scenario 3



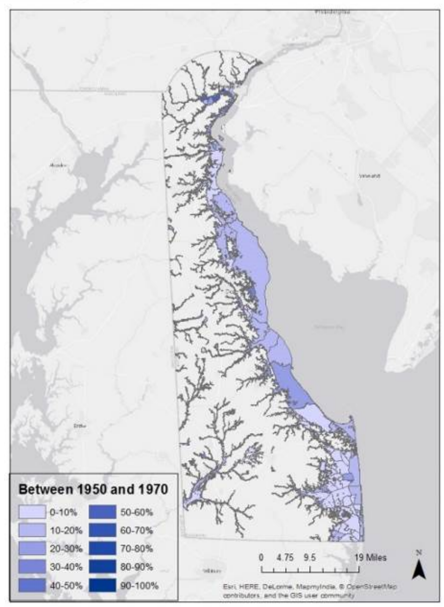
% of Housing Built Before 1950: Scenario 3 SLR



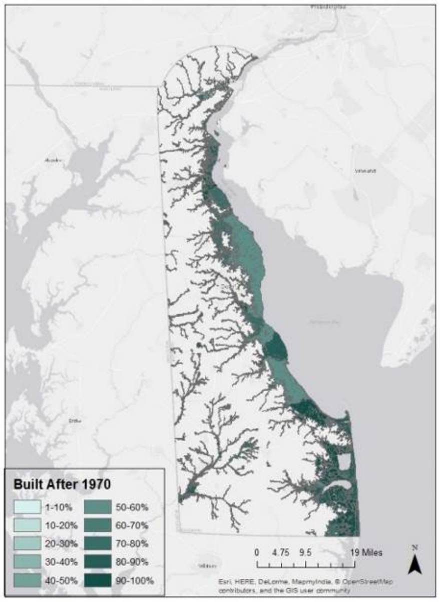
% of Housing Built Between 1950 and 1970: Scenario 3



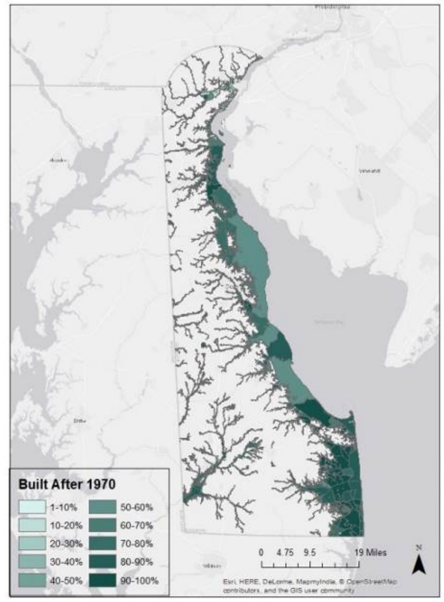
% of Housing Built Between 1950 and 1970: Scenario 3 SLR



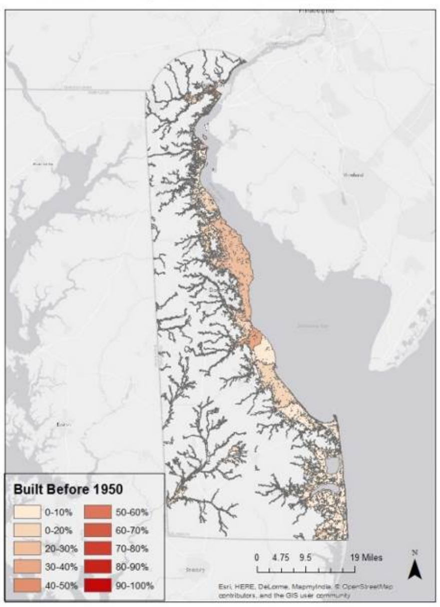
% of Housing Built After 1970: Scenario 3



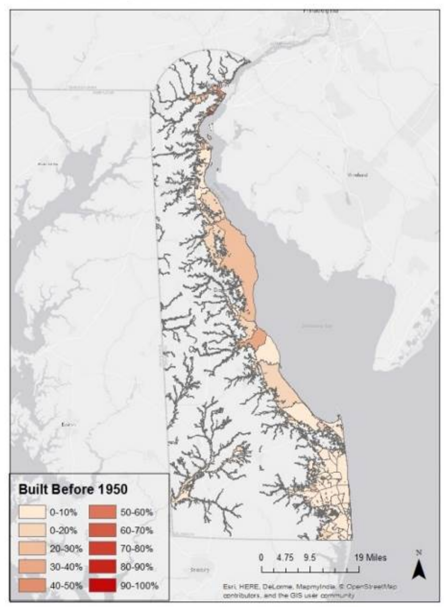
% of Housing Built After 1970: Scenario 3 SLR



% of Housing Built Before 1950: Scenario 4



% of Housing Built Before 1950: Scenario 4 SLR



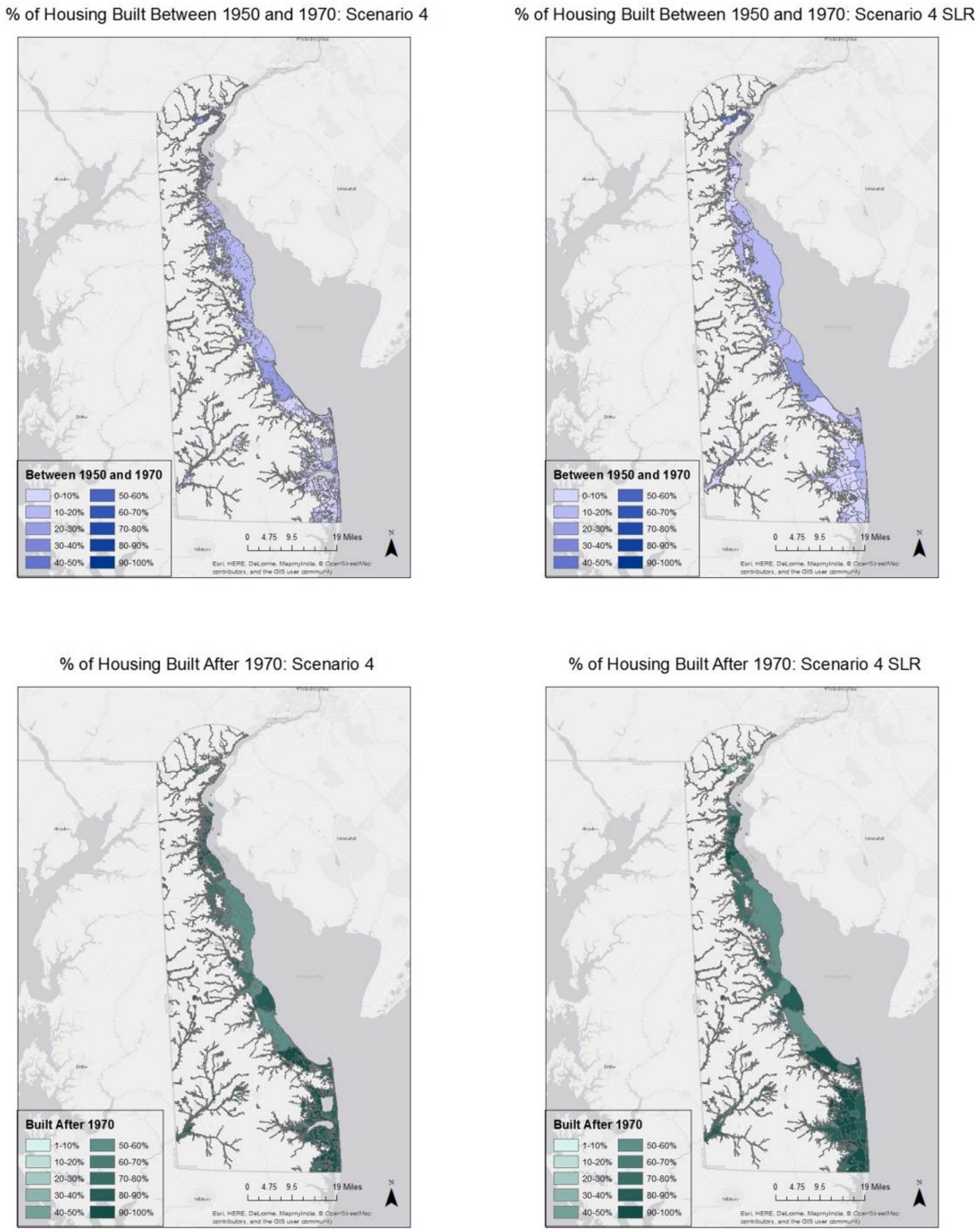


Figure 8.7. Age of housing - Delaware

Chapter 9 - Web Mapping Interface

As part of this project a web mapping interface was created to collect and view relevant data that is described below. Additional functionality and updates are being planned and the interface will be available for comment and improvement over the next year. This collection of data could serve as a demonstration and starting point for future improvements. Additional tools can be developed and easily incorporated into the framework. Critical facilities data were as obtained from Delaware Hazus data, State of Delaware connections, and CADSR GIS libraries

The current URL for the map is https://cadsrgis.org/hurricane
A backup site can be found at https://cadsrgis2.org/hurricane

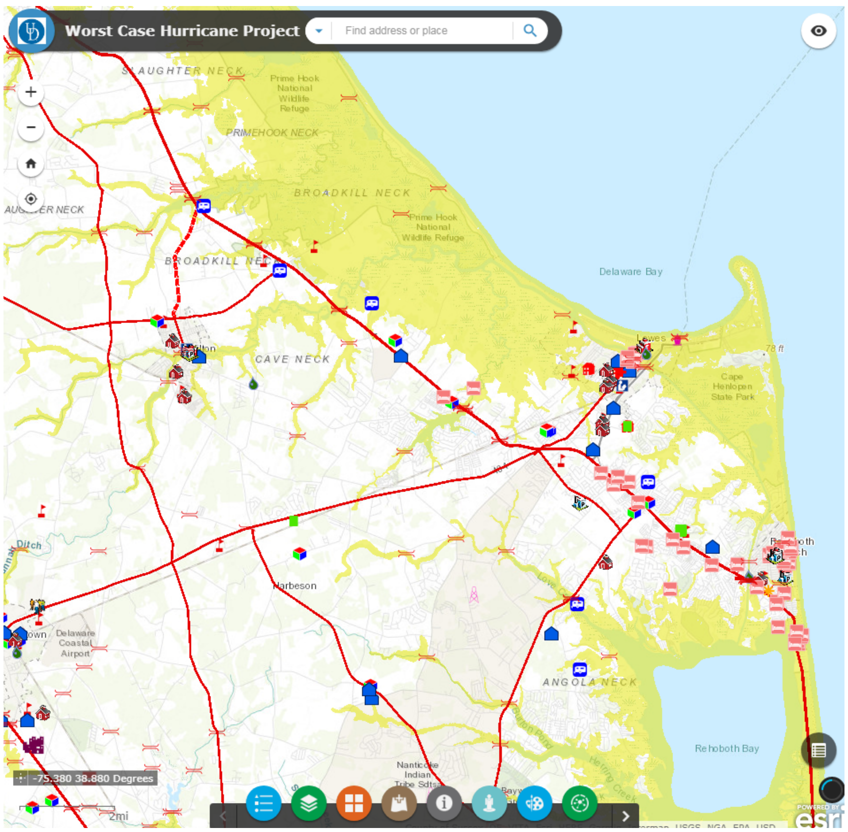


Figure 9.1. Worst case hurricane project mapping site

Software

The software used to create the site are ESRI products. Map layers are organized within ArcGIS Online map documents. Map functionality is provided by a set of map widgets, many of which are provided by ESRI and some developed through javascript programming or available as public domain utilities.

Security

Maps and map services employ SSL (https) encryption and data is password protected. For access contact David Racca (CADSR, email: dracca@udel.edu). Data is proprietary subject to DelDOT approval and user agreements.

Data Included

Table 9.1, below, lists map layers included in the site. Data for DelDOT assets is what was obtainable in January 2017. There is a very large amount of information presented, some of which can and does contain errors or omissions. CADSR has updated data for medical facilities, police, and fire stations, and has prioritized the review and update for many other layers.

Table 9.1. Data elements in worst case scenario project map

DelDOT Assets	Multimodal
Bridges	DTC Facilities (DART First State)
Signals	Bus Stops
DelDOT Buildings	Bus Routes
Drainage Structures	Park and Ride
Roads	Park and Pool
	Train Stations
Maintenance	Airports
DelDOT Maintenance Yards	Trails
Maintenance Responsibility	Sidewalks
Maintenance Districts	Bicycle Routes
	Bicycle Route Connectors
Critical Facilities	
Evacuation Routes	**Vulnerable Sites**
	Adult Day Care
Communications	Assisted Living
Electric Power	Nursing Homes
EOC Facilities	Daycares
Ferry Facilities	Educational
Port Facilities	Trailer Parks
Police Stations	Prisons
Medical Care Facilities	Retirement Communities
Waste Water Facilities	
Fire Stations	**Hurricane Scenarios**
	Category 1 with 100-year Flood
Response	Category 1 with 500-year Flood
Emergency Operations	Category 3 with 100-year Flood
Hardware and Materials	Catefory 3 with 500-year Flood
Military Facilities	Sea Level Rise (1 meter for above scenarios
Taxi and Limo	
Animal Resources	**Hurricane Inundation Areas (FEMA)**
Store Basics	Category 1
	Category 2
Shelters	Category 3
Shelters	Category 4
National Guard	FEMA Floodplains
Lodging	
Public Schools	
Community Centers	
YMCA	
Places of Worship	
Libraries	

Table 9.2. Data elements in worst case scenario projects due to flooding

Census Thematic Maps
Households
Population
Poverty
Population of 65
Places
Housing Units
Apartments and Condominiums
Housing Units
Destinations
Other Transportation Layers
Road Capacity
Traffic Counts
Pavement Type
Pavement Quality

Tools

A series of tools is available for users are available and described below. The development framework allows for the addition of other tools. A very wide range of complexity is accommodated allowing for very involved analysis and customization. Current tools are briefly described below.

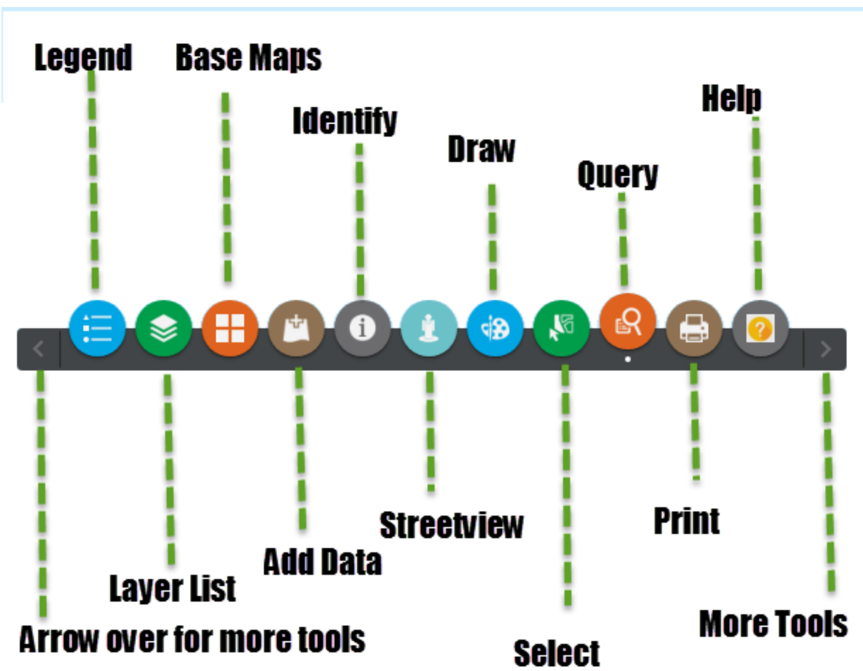


Figure 9.2. Tools available on web mapping interface

Legend: Shows symbology for map elements.

Layer List: View and turn on and off map layers.

Base Maps: Choice of a dozen or more different base maps.

Add Data: Add map layers from the web, ArcOnline, or local compute.r

Identify: When activated displays the information behind selected map elements.

Streetview: Implementation Google Streetview allows users movable 3-D image view of surroundings.

Draw: Draw and mark up tools.

Select: Selection of elements by forming rectangles or polygon boundaries. Information for selected features is available in tabular format.

Help: Links to help documens for the site.

Query: Complex queries can be created and performed on map layers. Spatial querries are also supported, so that for instance elements can be selected within a inundation area or other area of interest. Selected features are displayed and can be viewed in tabular format. An example of the use of this tool is below where destinations that were in the area inundated by a Category 3 hurricane with a 100-year flood were identified and then frequency of use categories were tabulated.

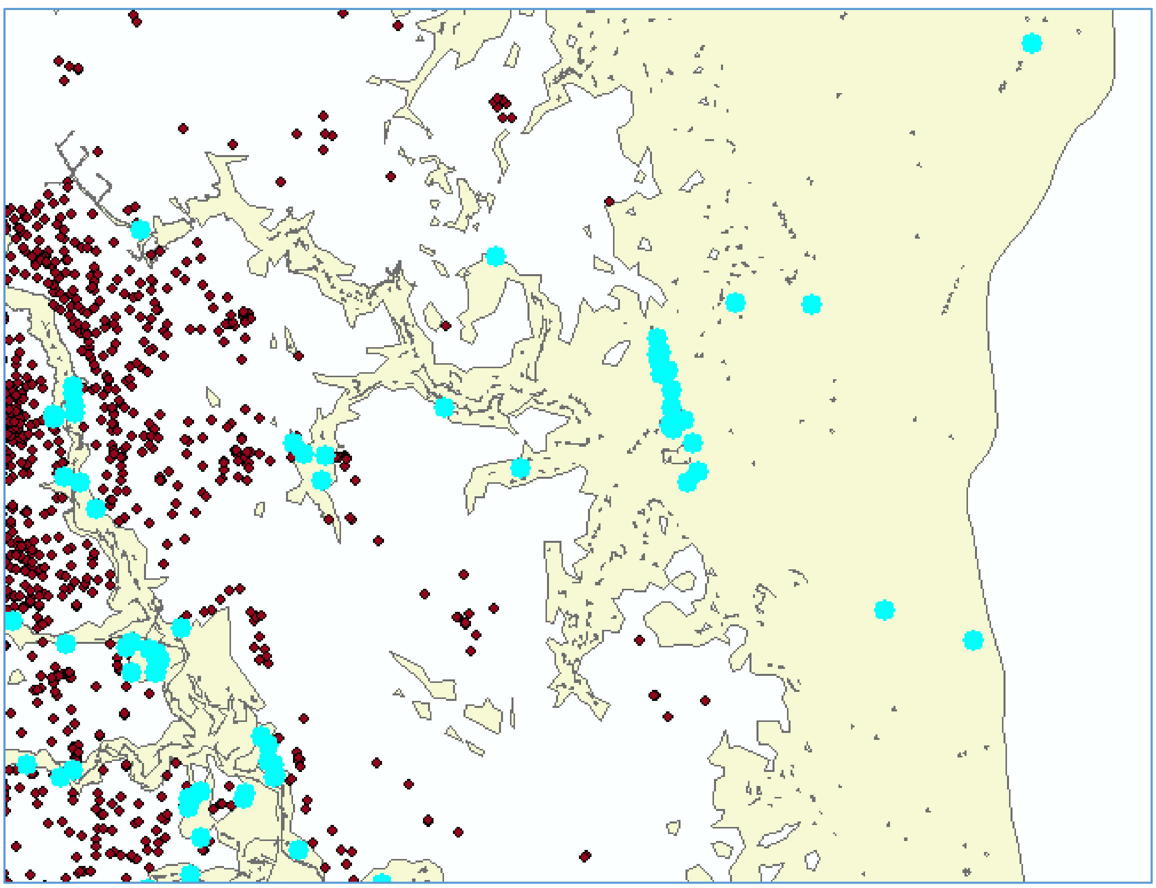


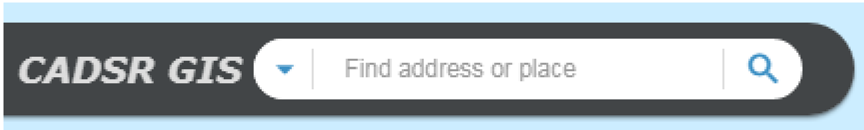
Figure 9.3. View of selected destinations falling in Category 3, 100-year Flood inundation areas.

Table 9.3. Frequency of destinations in Category 3, 100-year flood areas by Place category

Beauty	61
ChildCare	9
Community	217
Contractor	923
EatOut	219
Education	31
Energy	1
Finance	378
Food	6
Government	2
Historic	1
Housing	93
Industrial	1
Manufacturing	72
Media	8
Medical	167
PlaceofWorship	19
RealEstate	46
Recreation	123
Rental	43
Retail	559
Services	1,007
ShortStop	39
StoreBasics	76
Transportation	46
Utilities	20
Wholesale	99

Address and Place Search: At the top of the web site page is a search box (Figure 9.4) where an address or place (e.g. "Brandywine High School") can be typed in and searched.

Show Attribute Table: At the bottom right of the map is a tabular icon which when selected will show information in tabular form for map layers. All elements can be shown or just the selected set. Options for this tool include addition of a filter, showing and hiding columns, and the ability to export data to a spreadsheet.



FID	OBJECTID	ID	YARD_NO	NAME	ADDRESS	CITY	ZIP	PHONE_NO	GEOMETRY1_	COUNTY	DISTRICT
14	14	14	2	Seaford Yard	Bridgeville Highway	Seaford	19973	856-5485		3	South
15	15	15	3	Ellendale Yard	Route 16	Ellendale	19941	684-2760		3	South
16	16	16	4	Gravel Hill Yard (Back)	Route 30	Georgetown	19947	856-5205		3	South
20	20	20	20	Gravel Hill Yard (Front)	Seashore Highway	Georgetown	19947	856-5203		3	South

Figure 9.4. Address search box, attribute table icon, sample table view, question mark icon

Development

The mapping and data query interface provides a powerful collection of data relevant to hurricane concerns and can be developed further. There is certainly other information that would be of interest. This programming framework also allows for the addition of complex tools that can be developed within GIS systems including processing widgets and geoprocessing map services and tools. Custom made complex analysis steps, queries, and operations can be developed with Python programming or tools within ArcGIS, and then published to work in the web map. The web map will be provided to DelDOT staff for review and suggestions for further steps, and available for at least one year after the conclusion of the work.

Chapter 10 – Summary

Conclusions

Flood Vulnerability

1. Situated at a mean elevation of 60 feet above sea level, Delaware is the lowest lying state in the U.S. and therefore is especially vulnerable to coastal and riverine flooding accentuated by changes in the climate and sea level rise. With sea level rise, Delaware is likely to see record-breaking coastal floods within the next 20 years, and near certain to see floods more than 5 feet above the high tide line by 2100. Over 62,000 acres of land lie less than 5 feet above the high tide line in Delaware and $1.1 billion in property value and 20,000 homes sit on this area.

2. The Governor has directed that state agencies such as DelDOT plan to address the future impacts of flooding and coastal storms on infrastructure. In September 2013, Governor Markell signed Executive Order 41 that created the Cabinet Committee on Climate and Resiliency to address climate change at the state level. Delaware's Climate Framework is based on the 2012 Sea Level Rise Vulnerability Assessment and 2014 Climate Change Impact Assessment. In June 2017, Governor John Carney announced that Delaware was among 10 states to join the U.S. Climate Alliance to adhere to the Paris Climate Agreement.

Bridge Hydraulic Analysis

3. The DelDOT roadway design manual requires design of pipe culverts to pass the 50-year flood and the DelDOT bridge design manual requires that interstate, principal, and major arterial bridges pass the 50-year flood. Local roads and streets are designed to pass the 25-year flood.

4. Of the 547 bridges along streams with FEMA Flood Insurance Study floodplains in Delaware, 230 bridges (42%) have inadequate hydraulic capacity to convey the 10-year flood, 353 (65%) are inadequate to pass the 50-year flood, and 405 (74%) do not adequately convey the 100-year flood (Table 10.1). Of 547 bridges statewide, 78 bridges (14%) have bridge decks overtopped by the 10-year flood, 175 (32%) are overtopped by the 50-year flood, and 245 (45%) are overtopped by the 100-year flood.

Table 10.1. Summary of bridge hydraulic analysis in Delaware

	Inadequate bridge/culvert capacity to convey:			
	10-yr flood	**50-yr flood**	**100-yr flood**	**Total Bridges**
No. of Bridges	230	353	405	547
% of Bridges	42%	65%	74%	100%
	Bridge deck overtopped by:			
	10-yr flood	**50-yr flood**	**100-yr flood**	**Total Bridges**
No. of Bridges	78	175	245	547
% of Bridges	14%	32%	45%	100%

Highway Flood Inundation

5. We assessed over 7,000 DelDOT total road miles and over 1,700 major route (Federal

interstate/highway/state principal/major collector) miles and mapped the road miles flooded (inundated) within the riverine floodplain (100- and 500-year flood) and/or the Category 1, 2, and 3 coastal storm surge zone for the following scenarios

Existing Conditions (Mean High Water)
- 100-year Riverine Flood with Coastal Flooding from Category 1 Hurricane
- 500-year Riverine Flood with Coastal Flooding from Category 1 Hurricane
- 100-year Riverine Flood with Coastal Flooding from Category 3 Hurricane
- 500-year Riverine Flood with Coastal Flooding from Category 3 Hurricane

Future Conditions (w/0.5 m sea level rise)
- 100-year Riverine Flood with Coastal Flooding from Category 1 Hurricane
- 500-year Riverine Flood with Coastal Flooding from Category 1 Hurricane
- 100-year Riverine Flood with Coastal Flooding from Category 3 Hurricane
- 500-year Riverine Flood with Coastal Flooding from Category 3 Hurricane

6. Along all DelDOT roads, hurricanes and severe storms may inundate 437 miles (6% of roads) in the 100-year floodplain, 533 miles (8%) in the 500-year floodplain, 212 miles (3%) during a Category 1 storm and 794 miles (11%) during a Category 3 storm (Table 10.2). Along major Federal/state highways, flooding would inundate 119 miles (7%) in the 100-year floodplain, 143 miles (8%) in the 500-year floodplain, 71 miles (4%) during a Category 1 coastal storm and 229 miles (13%) during a Category 3 storm.

Table 10.2. Road miles inundated by flooding in Delaware

Storm Category	Total Roads Inundated (mi)	Major Roads Inundated (mi)
100-yr Storm	437 (6%)	119 (7%)
500-yr Storm	533 (8%)	143 (8%)
Cat 1 Storm	212 (3%)	71 (4%)
Cat 2 Storm	450 (6%)	138 (8%)
Cat 3 Storm	794 (11%)	229 (13%)
Road Miles	**7,000 (100%)**	**1,700 (100%**

Historic Storm Analysis

7. Hurricane Irene (August 28, 2011) and Sandy (October 29, 2012) were two of the most severe Category 1 storms to ever pass near Delaware causing significant flooding. Two of the more severe storms to cross over Delaware were Tropical Storm Bertha in 1996 with 58 mph winds and Tropical Storm Floyd on September 16, 1999 with winds up to 64 mph and 24-hour rainfall of 10.58 inches at Greenwood, Delaware at state record and destroyed 33 homes in New Castle County. According to the EPA storm surge inundation map, there is a 10- to 30-year probability that a hurricane will impact Sussex County, Delaware and a 30- to 100-year probability that a hurricane will impact New Castle County and Kent County, Delaware.

8. Originally forecast to hit near Lewes, Delaware in October 2012, the eye of Superstorm Sandy hit Atlantic City, New Jersey coast just 60 miles north of the Delaware beaches (and then passed through Wilmington) and caused the highest flood tide on record damaging the Route 1 bridge over the Indian

River inlet. The peak stage over time ranged from 6.51 feet at Indian River Bay at 9:00 hours on October 29, 2012 to 7.20 feet at 12:00 hours on October 30 at Delaware River at New Castle. The peak stages ranged from 4.82 feet at Little Assawoman Bay to 9.37 feet at Ship John Shoal, Delaware. The inundation analysis indicates that if the storm crossed Delaware to the south as originally forecast, flood peaks during Sandy would have increased from 6.1 feet to 15.8 feet at Delaware City and from 6.1 feet to 13.8 feet at Lewes, Delaware. The flood inundation area would have spread inland from Indian River and Rehoboth Bay, miles west along the Delaware Bay to Route 1in Sussex County and through Route 9 in Kent and New Castle counties.

Recommendations

1. Review and revise the DelDOT road design and bridge design manuals to consider strengthening the hydraulic design criteria for bridges and culverts to pass the 100-year frequency flood (instead of the current 50-year flood specification)

2. Conduct a systematic review of the DelDOT system to enlarge and/or replace bridges and culverts to adequately pass the 100-year flood and raise bridge deck elevations above the 100-year flood elevation with at least 2 feet of freeboard.

3. Conduct a strategic review of the DelDOT highway system to determine the road segments at high risk to flood inundation and program capital funding to raise or flood proof these vulnerable roadway sections.

References

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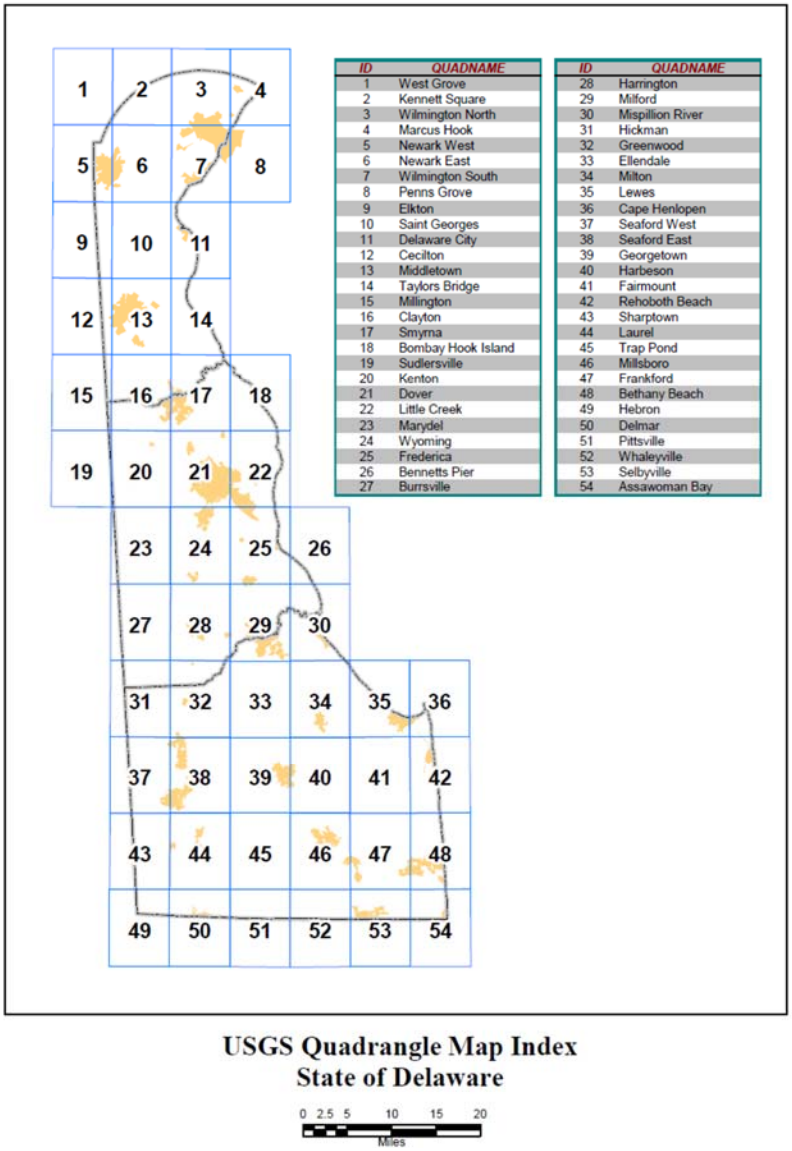
Ries, K. G. and J. A. Dillow, 2006. Magnitude and Frequency of Floods on Nontidal Streams in Delaware. USGS. Scientific Investigations Report 2006-5146.

United States Census, 2017. United States Census and American Fact Finder. United States Army Corps of Engineers, 2017. USACE SimSuite Software Package.

Appendix A

The following figures show samples of the map series for the State of Delaware produced for this study, depicting flooding and inundation mapped following to the USGS 1:24,000 scale topographic quadrangle framework. Map Series A presents flooding and inundation based on FEMA flood zones and SLOSH model inundation for Category 1-3 storms, based off current Mean Higher High Water (MHHW), and Map Series B presents the same layers based off a future 0.5 meter sea level rise scenario. Both series present bridge flooding (overtopping) based on the hydraulic study.

Figure A.1 shows the quadrangle index for the State of Delaware. Figures A.2 and A.3 present sample maps from the map series. Respectively, these depict the Newark East quadrangle with flooding and inundation based on current MHHW, and the Millsboro quadrangle, based on a sea level rise scenario of 0.5 meters. These map series are being delivered to DelDOT as a separate document.



ID	QUADNAME	ID	QUADNAME
1	West Grove	28	Harrington
2	Kennett Square	29	Milford
3	Wilmington North	30	Mispillion River
4	Marcus Hook	31	Hickman
5	Newark West	32	Greenwood
6	Newark East	33	Ellendale
7	Wilmington South	34	Milton
8	Penns Grove	35	Lewes
9	Elkton	36	Cape Henlopen
10	Saint Georges	37	Seaford West
11	Delaware City	38	Seaford East
12	Cecilton	39	Georgetown
13	Middletown	40	Harbeson
14	Taylors Bridge	41	Fairmount
15	Millington	42	Rehoboth Beach
16	Clayton	43	Sharptown
17	Smyrna	44	Laurel
18	Bombay Hook Island	45	Trap Pond
19	Sudlersville	46	Millsboro
20	Kenton	47	Frankford
21	Dover	48	Bethany Beach
22	Little Creek	49	Hebron
23	Marydel	50	Delmar
24	Wyoming	51	Pittsville
25	Frederica	52	Whaleyville
26	Bennetts Pier	53	Selbyville
27	Burrsville	54	Assawoman Bay

Figure A.1. USGS Quadrangle Map Index State of Delaware

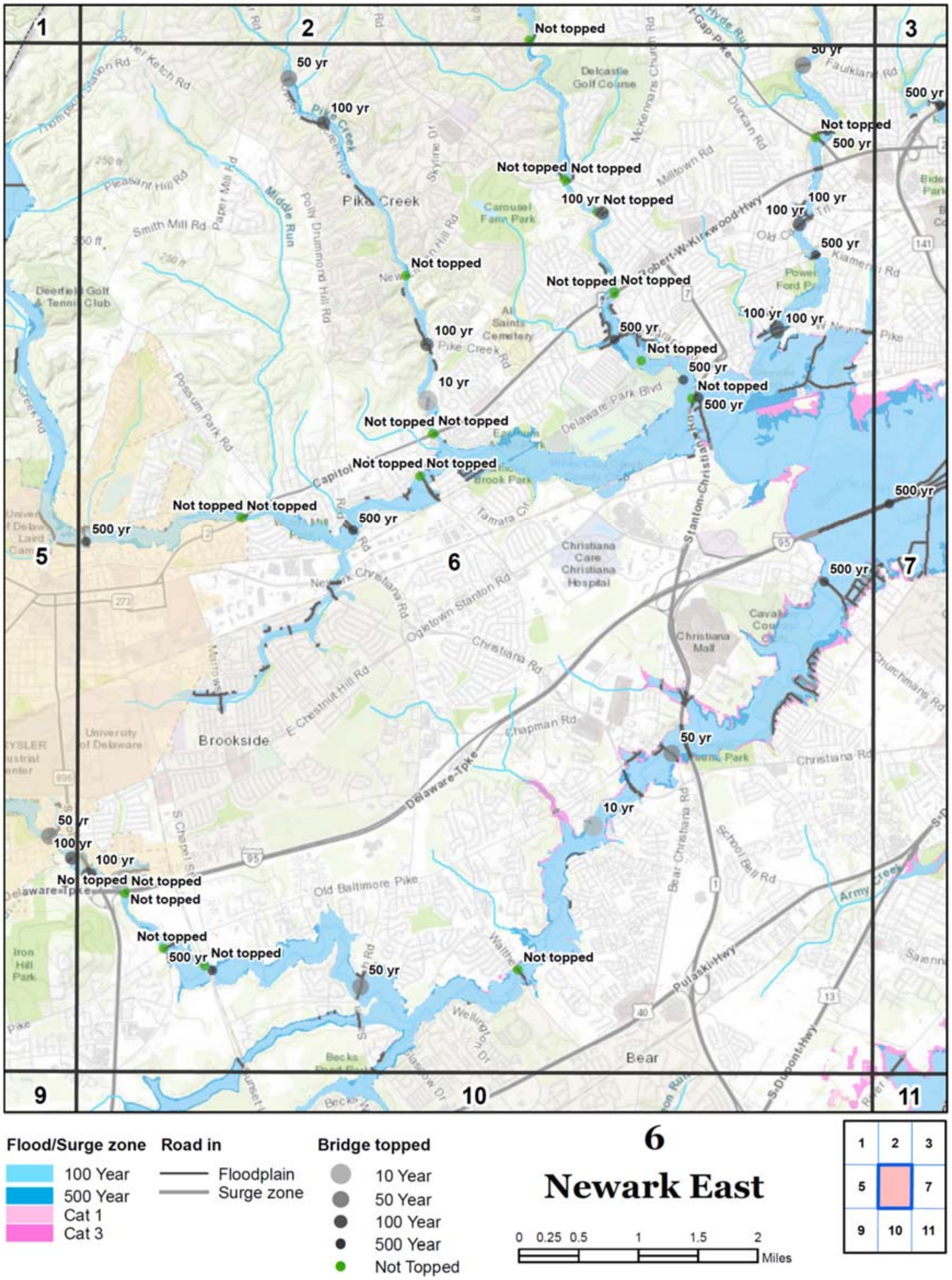


Figure A.2. Floodplain and bridge inundation map from MHHW – Newark East Quadrangle

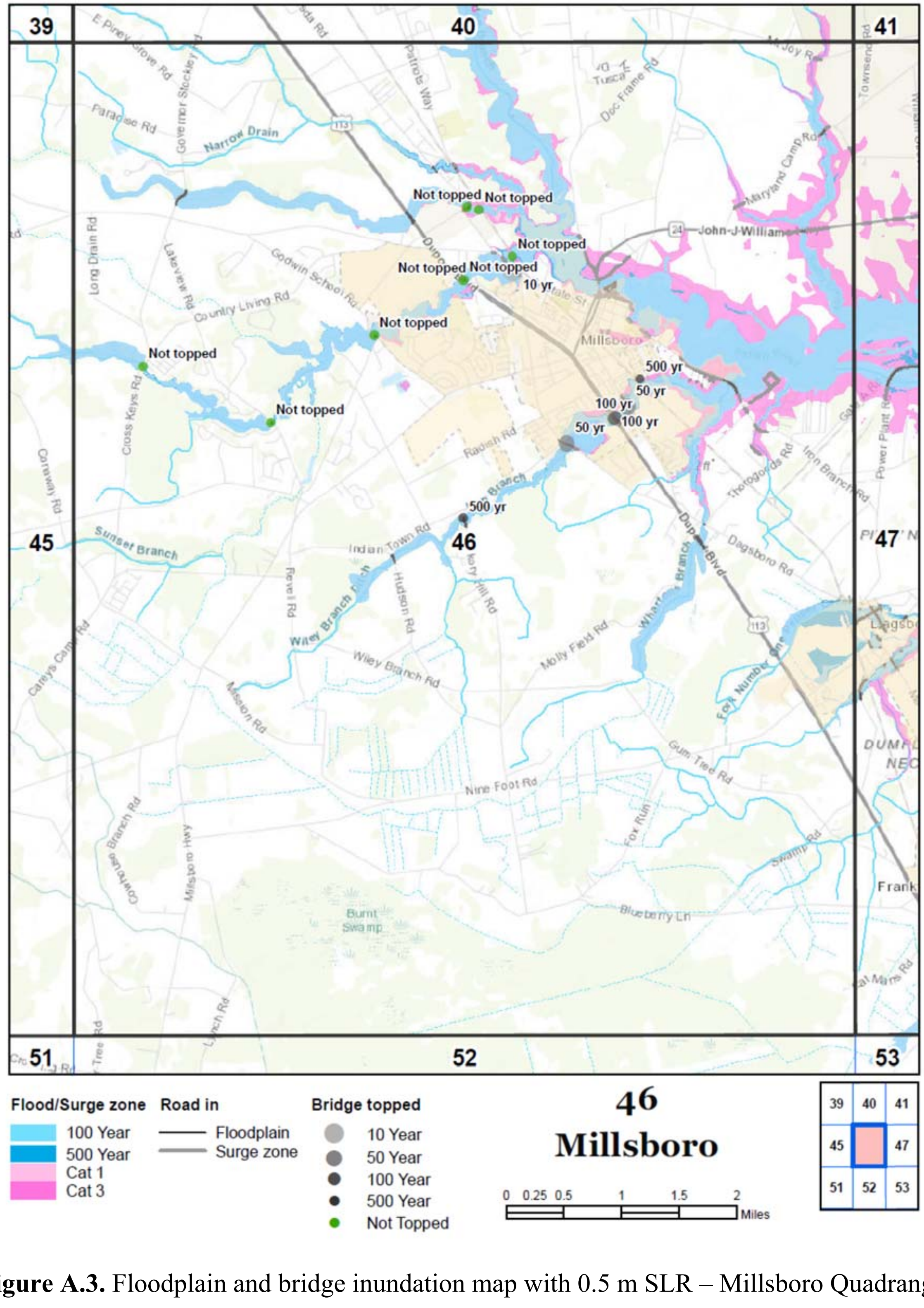


Figure A.3. Floodplain and bridge inundation map with 0.5 m SLR – Millsboro Quadrangle