Delaware Sea-Level Rise Inundation Mapping Methodology

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Delaware Sea-Level Rise Inundation Mapping Methodology

In early 2014, topographic LiDAR was collected for the entire state of Delaware through a collaboration between the USGS, Delaware Geological Survey (DGS), Department of Natural Resources and Environmental Control (DNREC), and Delaware Department of Transportation (DelDOT), funded through the Hurricane Sandy Supplemental Fund. The state-wide LiDAR data has a RMSEz of 6.3 cm in open terrain. From these data, a seamless, statewide 1-meter, hydro-flattened, bare earth digital elevation model (DEM) was produced.

This topographic DEM was used to develop new bathtub-model sea-level rise (SLR) coastal inundation maps for the state of Delaware. Inundation maps correspond to updated sea-level rise planning scenarios and include surfaces from Mean Higher-High Water (MHHW) to 7 feet above MHHW, in 1-foot increments. These maps will help advise long-range planning of infrastructure, facilities, land management, land use, and capital spending.

This documents details the steps taken to produce the bathtub-model SLR coastal inundation maps for the state of Delaware from the 2014 LiDAR data. A brief outline of the analysis steps is shown below, with greater detail described in the subsequent test. Analyses were conducted using ArcGIS 10.3 software.

Outline of Sea-Level Rise Inundation Mapping Methodology

1) Watersheds potentially affected by SLR were identified and MHHW was determined for each using NOAA VDatum tool. Elevations associated with each of the SLR scenarios were calculated for each watershed.
2) Watershed DEMs were created from the statewide LiDAR-based 1-m DEM. Watershed DEMs were reclassified based on the SLR scenario elevations for that particular watershed.
3) County-wide reclassified raster data was converted to polygons for each of the target elevations.
4) Polygon were simplified and smoothed to create more manageable layers.
5) Hydrologically disconnected areas were removed from each layer.
6) County layers were combined to create statewide bare earth SLR inundation maps.
7) Elevated roadways and bridges not represented in the bare earth DEM were identified, manually assessed for inundation for each SLR scenario, and removed from the bare earth inundation maps at the appropriate levels.

1. Watershed Identification

Each watershed in the state of Delaware with the potential to be affected by SLR was identified. Analysis was carried out on the resulting 65 watersheds (Figure 1).

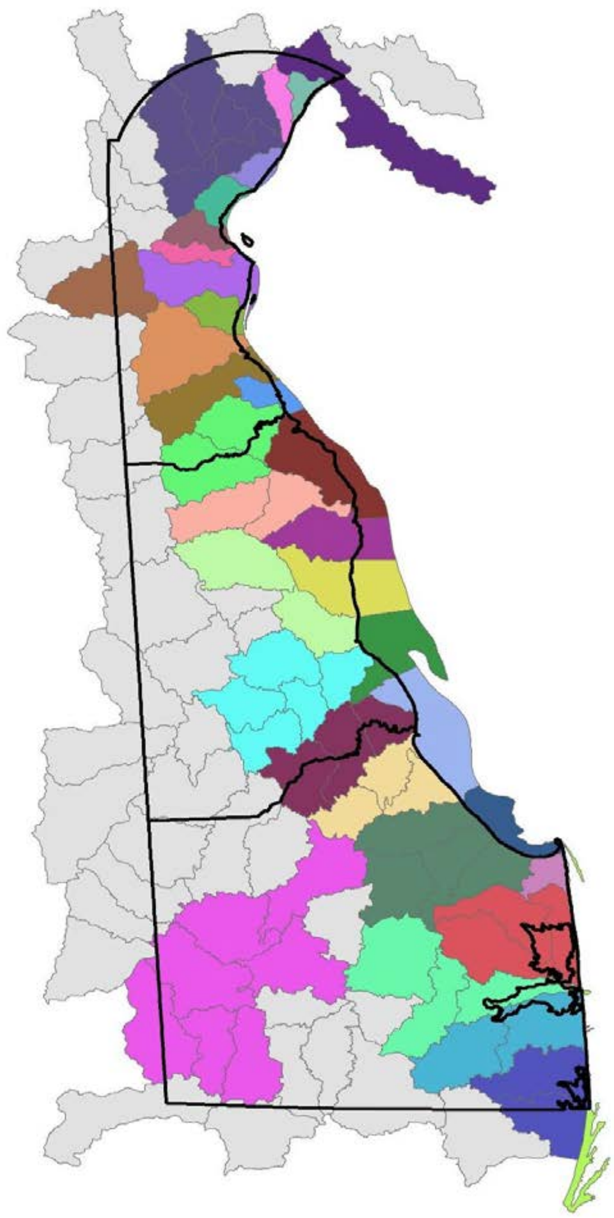

Figure 1: Watersheds expected to be affected by SLR.
Watersheds with the same MHHW are shown in the same color.

2. MHHW for Each Watershed

NOAA's VDatum tool was used to determine MHHW at the mouth of each coastal watershed (http://vdatum.noaa.gov/, see examples shown in Figure 2).

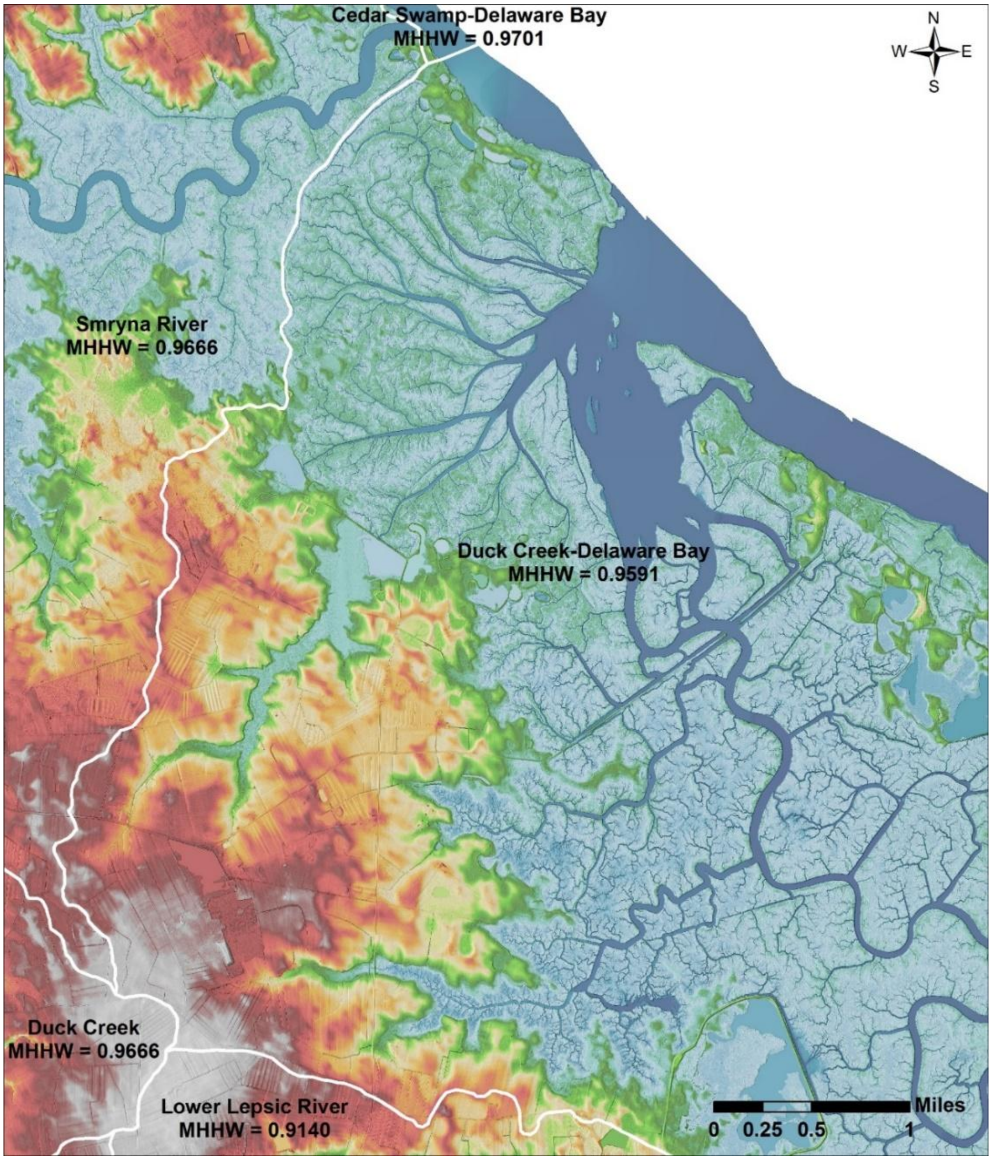

Figure 2: MHHW for several watersheds in Delaware expected to be affected by SLR

Watersheds were then grouped by MHHW, resulting in 35 watersheds for analysis (see Figure 1). The elevations to be considered for each of the SLR scenarios were calculated and are shown in Table 1.

Table 1: Elevations (in meters) of each SLR planning Scenario to be considered

SLR Scenarios	MHHW	1ft	2ft	3ft	4ft	5ft	6ft	7ft
m	**0**	**0.3048**	**0.6096**	**0.9144**	**1.2192**	**1.524**	**1.8288**	**2.1336**
Aswm	0.0995	0.4043	0.7091	1.0139	1.3187	1.6235	1.9283	2.2331
RhBay	0.1579	0.4627	0.7675	1.0723	1.3771	1.6819	1.9867	2.2915
IndianR	0.2466	0.5514	0.8562	1.1610	1.4658	1.7706	2.0754	2.3802
IndianN	0.2710	0.5758	0.8806	1.1854	1.4902	1.7950	2.0998	2.4046
NantR	0.3578	0.6626	0.9674	1.2722	1.5770	1.8818	2.1866	2.4914
WGRC	0.3963	0.7011	1.0059	1.3107	1.6155	1.9203	2.2251	2.5299
AtlanticS	0.5300	0.8348	1.1396	1.4444	1.7492	2.0540	2.3588	2.6636
Atlantic	0.5700	0.8748	1.1796	1.4844	1.7892	2.0940	2.3988	2.7036
BrkHrb	0.6116	0.9164	1.2212	1.5260	1.8308	2.1356	2.4404	2.7452
CDWest	0.6258	0.9306	1.2354	1.5402	1.8450	2.1498	2.4546	2.7594
Brdkl	0.6274	0.9322	1.2370	1.5418	1.8466	2.1514	2.4562	2.7610
Cedar	0.7444	1.0492	1.3540	1.6588	1.9636	2.2684	2.5732	2.8780
Misp	0.7458	1.0506	1.3554	1.6602	1.9650	2.2698	2.5746	2.8794
GrecosC	0.7802	1.0850	1.3898	1.6946	1.9994	2.3042	2.6090	2.9138
BrkGut	0.8402	1.1450	1.4498	1.7546	2.0594	2.3642	2.6690	2.9738
Mrdkl	0.8424	1.1472	1.4520	1.7568	2.0616	2.3664	2.6712	2.9760
StJones	0.8474	1.1522	1.4570	1.7618	2.0666	2.3714	2.6762	2.9810
LittleR	0.8812	1.1860	1.4908	1.7956	2.1004	2.4052	2.7100	3.0148
SimonsR	0.9072	1.2120	1.5168	1.8216	2.1264	2.4312	2.7360	3.0408
Lepsic	0.9140	1.2188	1.5236	1.8284	2.1332	2.4380	2.7428	3.0476
DrgnCr	0.9190	1.2238	1.5286	1.8334	2.1382	2.4430	2.7478	3.0526
RdLnCr	0.9226	1.2274	1.5322	1.8370	2.1418	2.4466	2.7514	3.0562
CDEast	0.9241	1.2289	1.5337	1.8385	2.1433	2.4481	2.7529	3.0577
Army	0.9323	1.2371	1.5419	1.8467	2.1515	2.4563	2.7611	3.0659
BrdDk	0.9430	1.2478	1.5526	1.8574	2.1622	2.4670	2.7718	3.0766
DuckCr	0.9591	1.2639	1.5687	1.8735	2.1783	2.4831	2.7879	3.0927
OldmansCr	0.9640	1.2688	1.5736	1.8784	2.1832	2.4880	2.7928	3.0976
SmrynaR	0.9666	1.2714	1.5762	1.8810	2.1858	2.4906	2.7954	3.1002
AugustCr	0.9670	1.2718	1.5766	1.8814	2.1862	2.4910	2.7958	3.1006
Christina	0.9693	1.2741	1.5789	1.8837	2.1885	2.4933	2.7981	3.1029
CedarSwmp	0.9701	1.2749	1.5797	1.8845	2.1893	2.4941	2.7989	3.1037
DrawyerCr	0.9784	1.2832	1.5880	1.8928	2.1976	2.5024	2.8072	3.1120
BlkBrdCr	0.9787	1.2835	1.5883	1.8931	2.1979	2.5027	2.8075	3.1123
StoneyCr	0.9878	1.2926	1.5974	1.9022	2.2070	2.5118	2.8166	3.1214
MatsonRn	0.9901	1.2949	1.5997	1.9045	2.2093	2.5141	2.8189	3.1237

3. Watershed Based DEM Analysis

The hydro-flattened DEM was clipped to each watershed boundary (see example shown in Figure 3) using the *Image Analysis* window in ArcGIS.

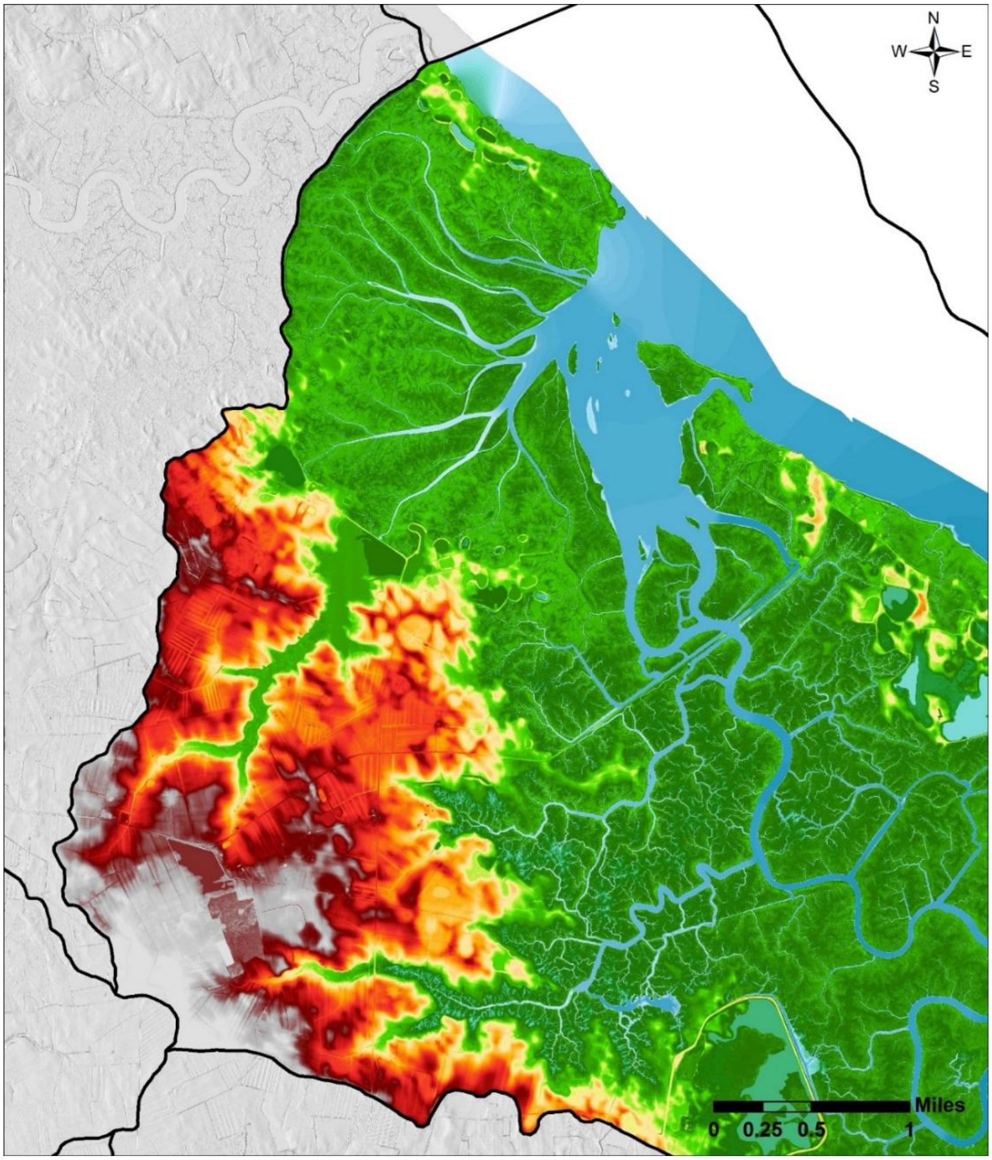

Figure 3: DEM for a portion of Duck Creek-Delaware Bay watershed

For each watershed DEM, the symbology was classified with 9 divisions (representing MHHW, 1ft, 2ft, 3ft, 4ft, 5ft, 6ft, 7ft, and above). Figures 4 and 5 shows the manual symbology classification of the for Duck Creek-Delaware Bay watershed.

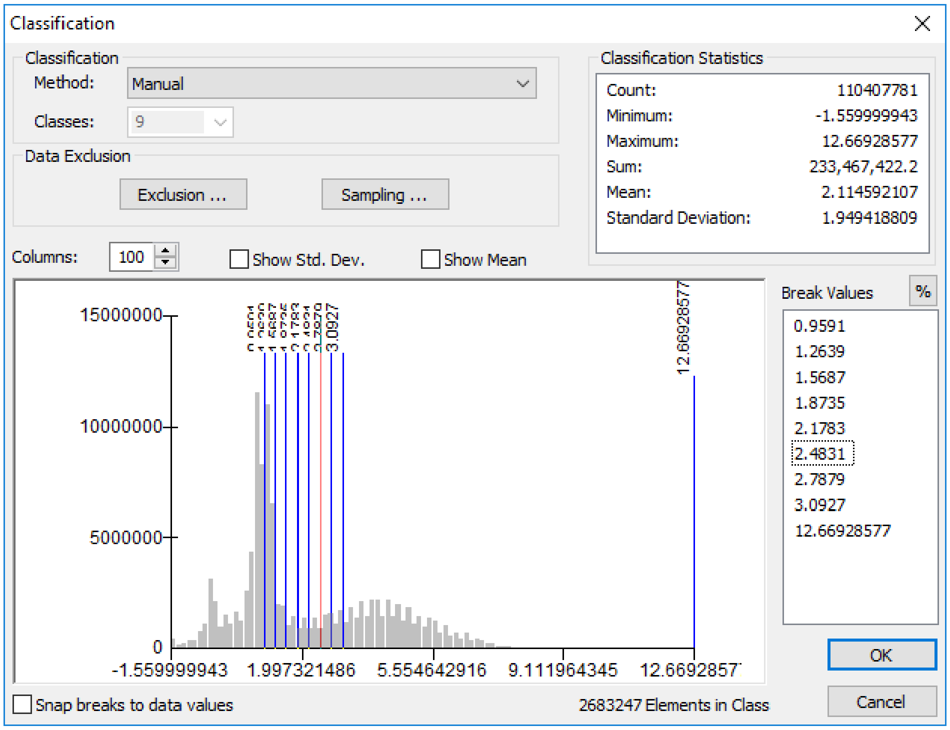

Figure 4: Manual classification of the symbology for Duck Creek-Delaware Bay watershed with a MHHW of 0.9591 m

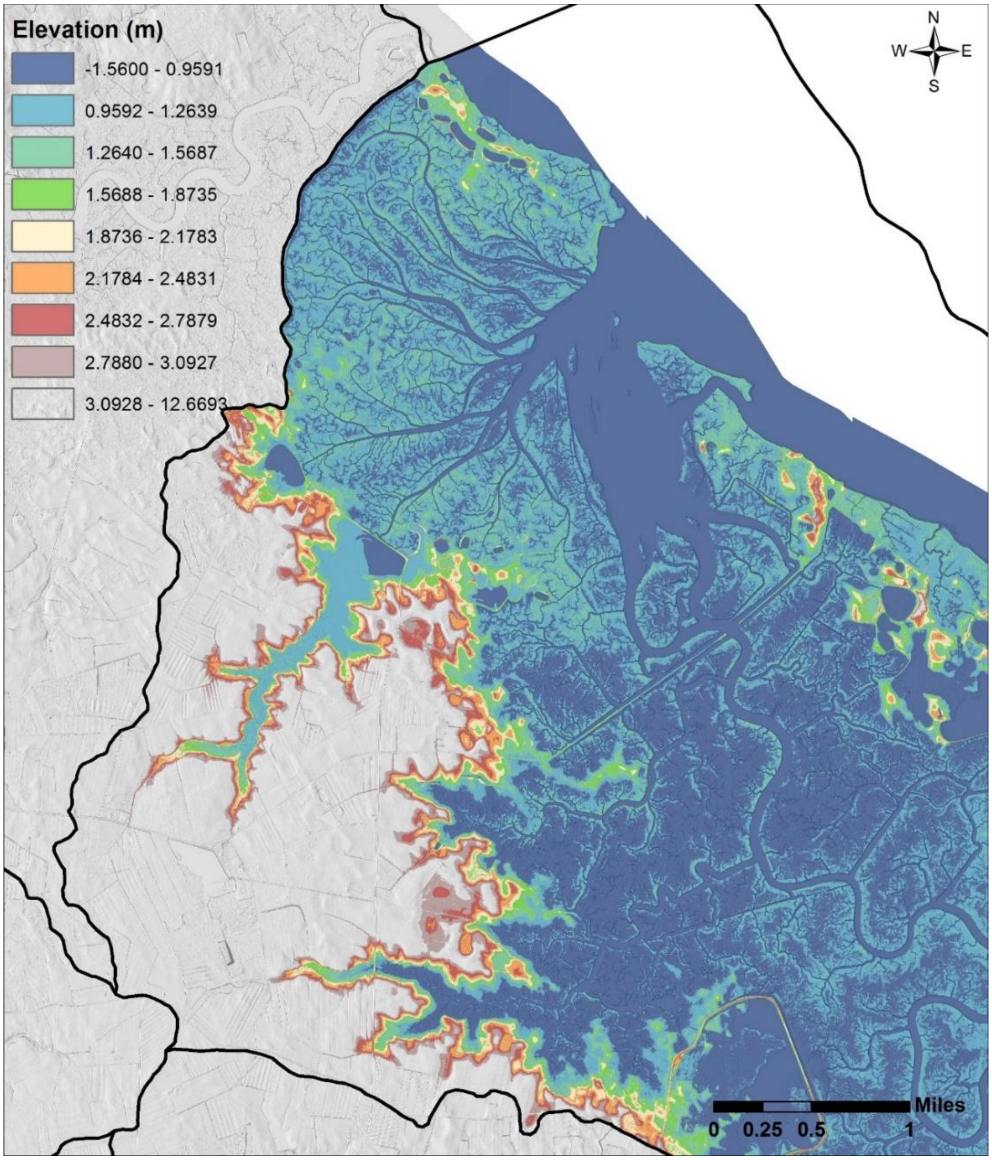

Figure 5: Duck Creek-Delaware Bay watershed with symbology classification corresponding to the eight SLR planning scenarios

The individual watershed DEMs were reclassified using the *Reclassify* function. The reclassification started at a value of 0 went to 7, with elevations above this being set to "NoData" (see Figure 6).

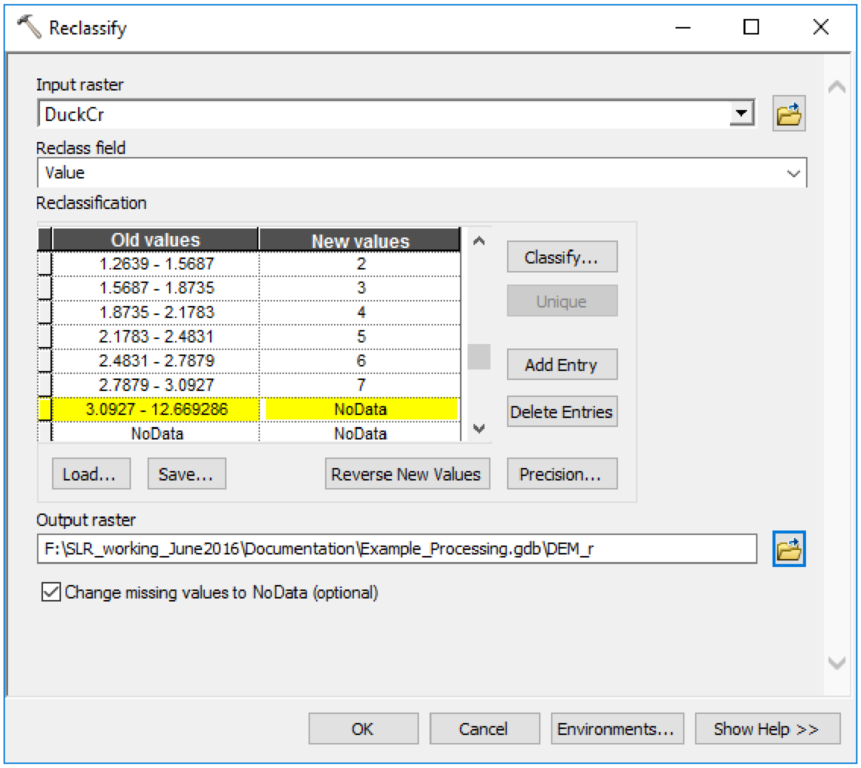

Figure 6: Reclassification of the DEM for Duck Creek-Delaware Bay watershed for the eight SLR scenarios

After each watershed was processed in this way to create a reclassified DEM with values of 0-7, the watershed DEMs were merge back to a statewide reclassified DEM (see Figure 7).

The statewide reclassified DEM was subset to create grid files for each of the three counties in Delaware since processing the entire state at once was not possible due to computing limitations. The county boundaries were buffered by 50 meters to create overlap between counties during subsequent bathtub-model SLR analysis.

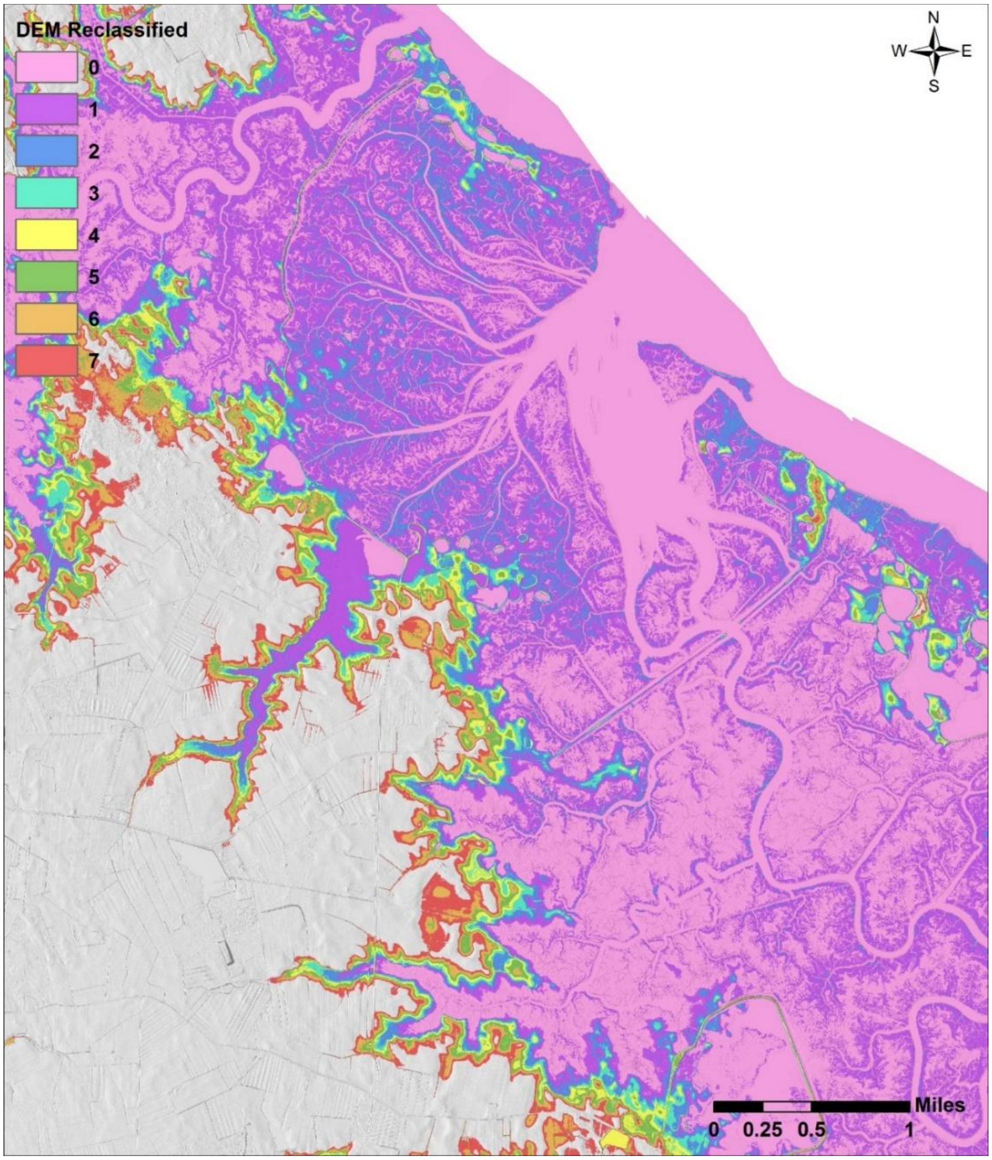

Figure 7: Individual watershed reclassified DEMs were merged to create a reclassified DEM for the entire state, shown here in the region of Duck Creek-Delaware Bay

4. Conversion to Polygon

A field called "unit" was added to the attribute table of the reclassified DEM (Figure 8), and this field was used during the conversion from raster to polygon. Within the attribute table, the desired scenario level and lower levels were selected. For example, for the 2ft SLR scenario, the Values of 0, 1, and 2 were selected (see Figure 8). The *Raster to Polygon* function was then used to convert from the raster format to polygons including all areas at elevations below the specified SLR level (see Figures 8-12 for 2ft SLR scenario sample). The "simplify polygons" option was not selected during this process.

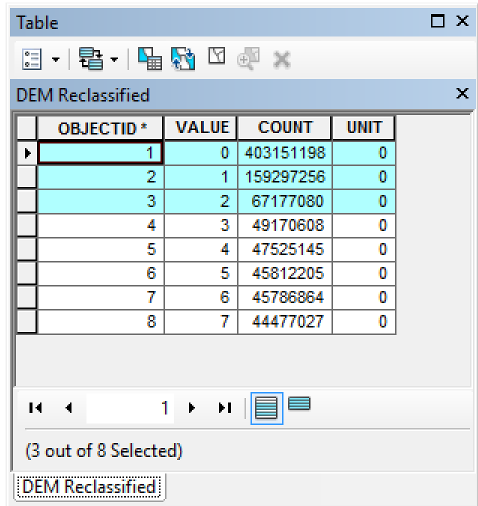

Figure 8: Attribute table for the reclassified DEM showing the selection of Values 0, 1, and 2 in preparation for conversion from raster to polygon for the 2ft SLR scenario

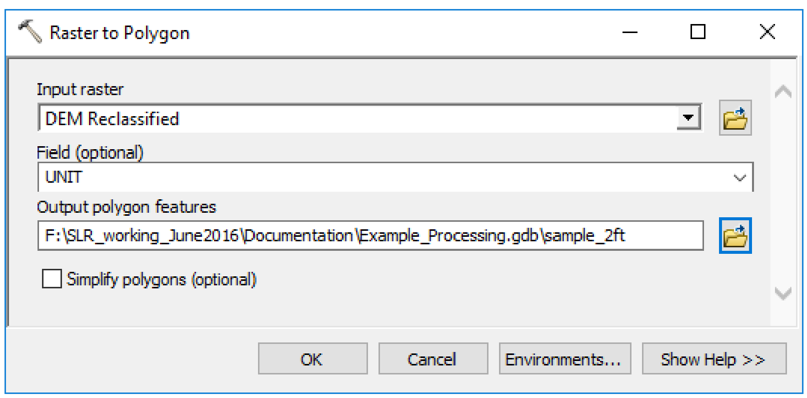

Figure 9: ArcGIS dialogue box for raster to polygon conversion

Figure 10: Results of raster to polygon conversion for the 2ft SLR scenario. Inset region is shown in Figure 11.

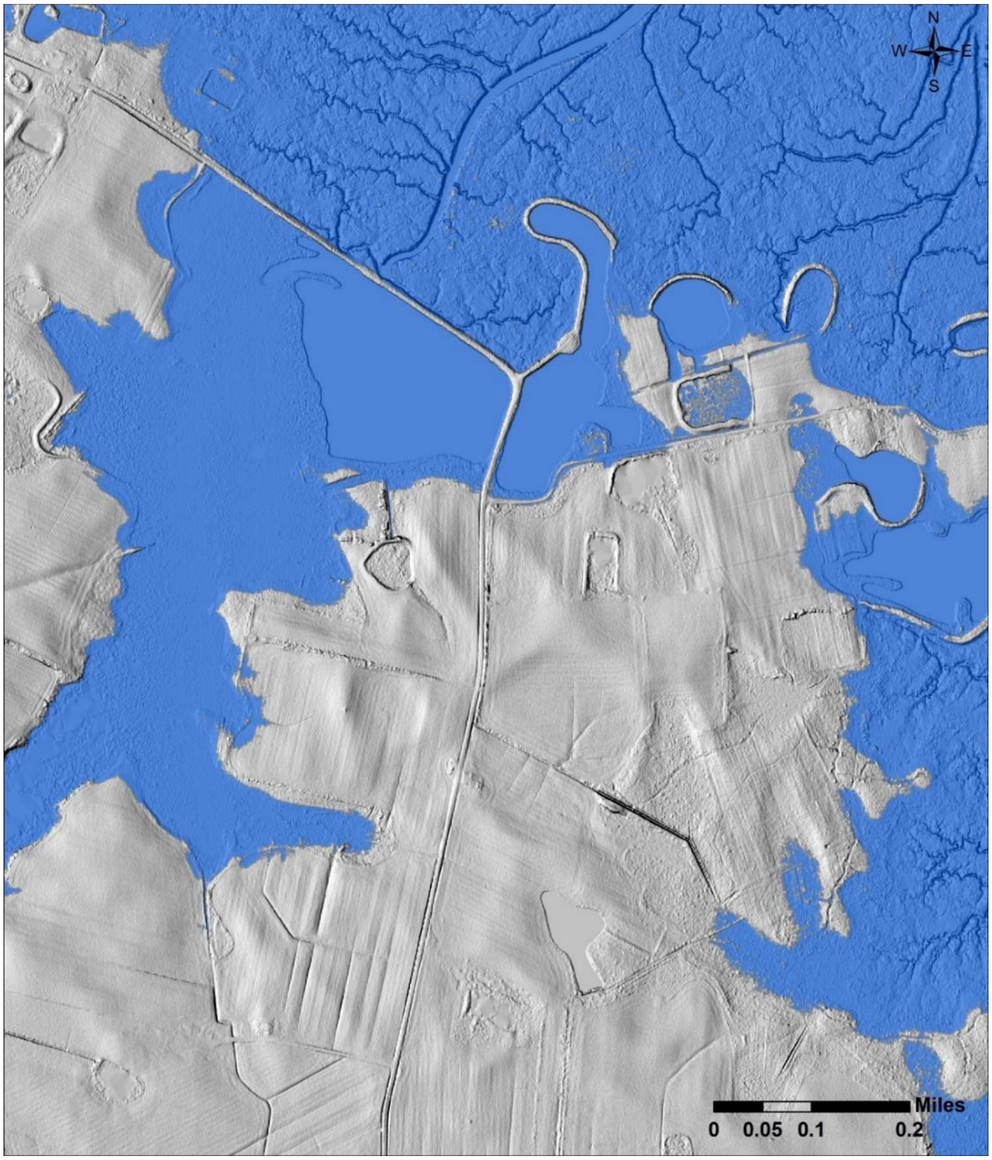

Figure 11: Results of raster to polygon conversion for the 2ft SLR scenario for a portion of Duck Creek-Delaware Bay watershed

The results of the *Raster to Polygon* conversion include numerous small polygons and detailed polygon boundaries that exactly match the 1-m reclassified raster (see Figure 12). In the following steps, these small scale features will be smoothed and generalized to create statewide SLR layers of manageable file size and with greater usability than the direct conversion from raster to polygon.

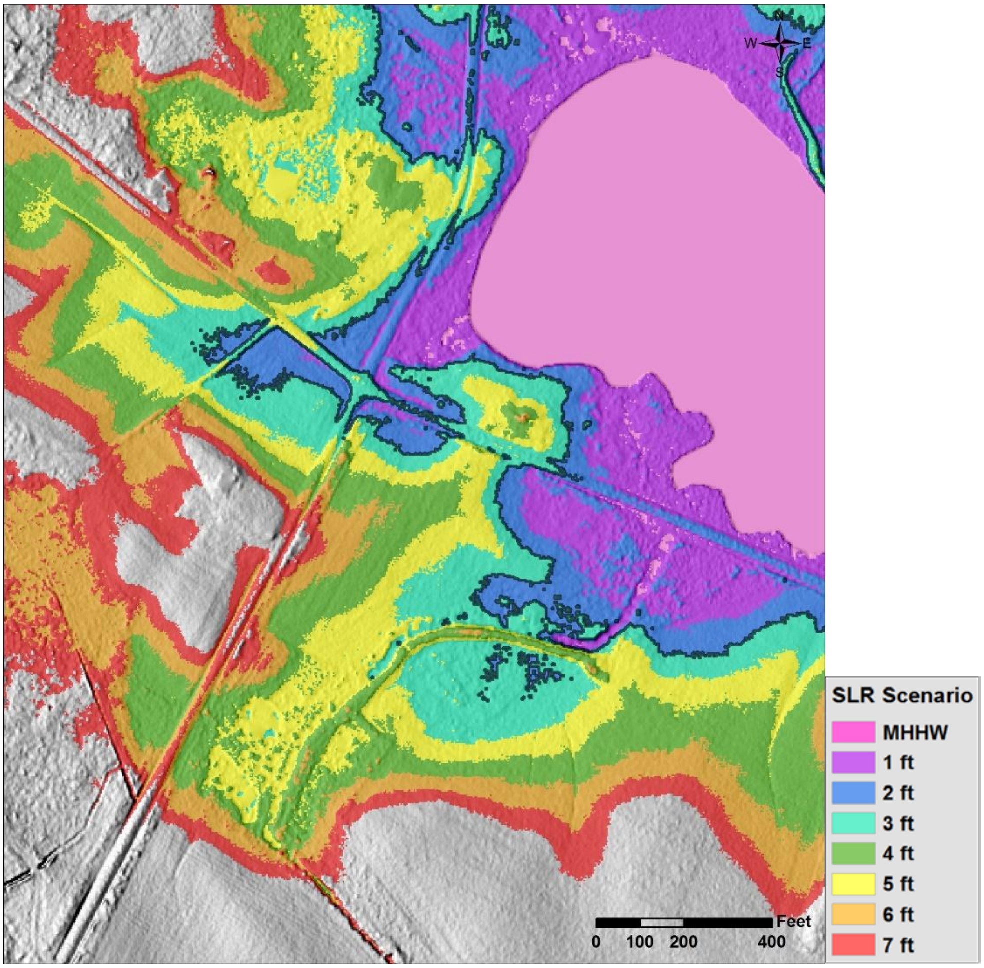

Figure 12: Reclassified raster showing the eight SLR planning scenario elevation classes and black line showing polygon boundary resulting from Raster to Polygon conversion for the 2ft SLR scenario. Note the large number of small polygons and the exact match to the reclassified raster shown.

5. Polygon Simplification

The following steps were taken to process the raw polygons for each SLR scenario for each county.

- *Dissolve* (Figure 13)
  - Create multipart features = true
  - Unsplit lines = false

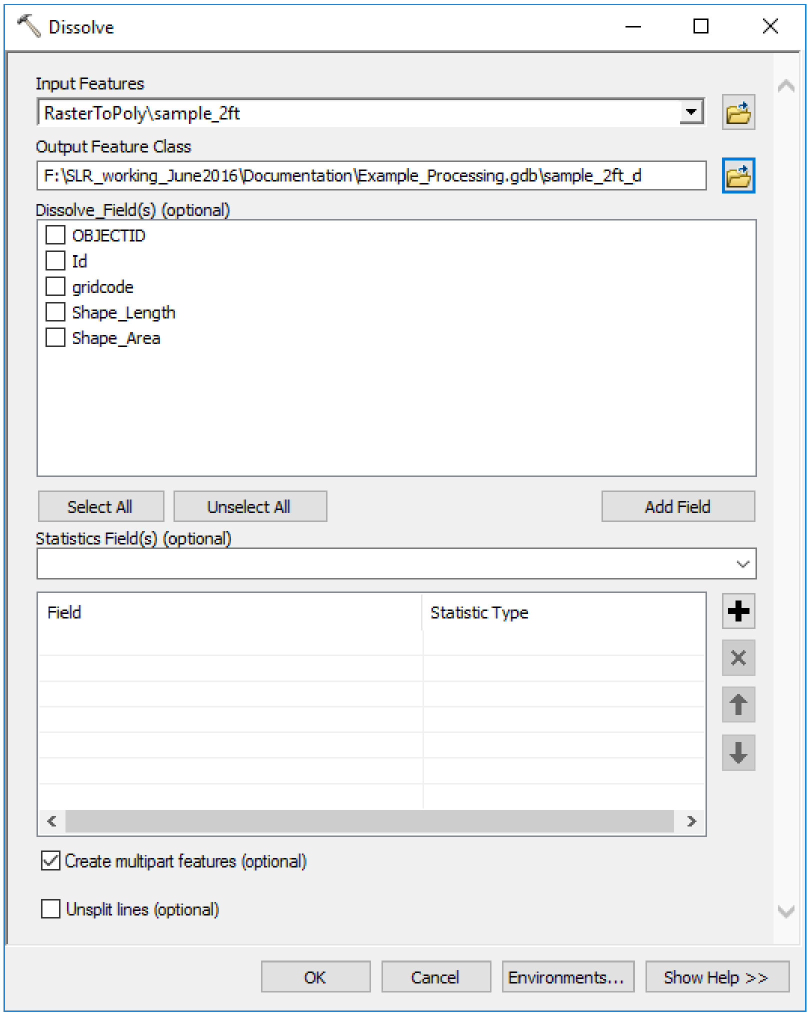

Figure 13: Dialogue box for *Dissolve* function

- *Simplify Polygon* (Figure 14)
  - Simplify Algorithm = Bend_Simplify
  - Reference Baseline = 10 Meter
  - Minimum Area = 500 Square Meters
  - Handling Topological Errors = No_Check
  - Keep collapsed points = false

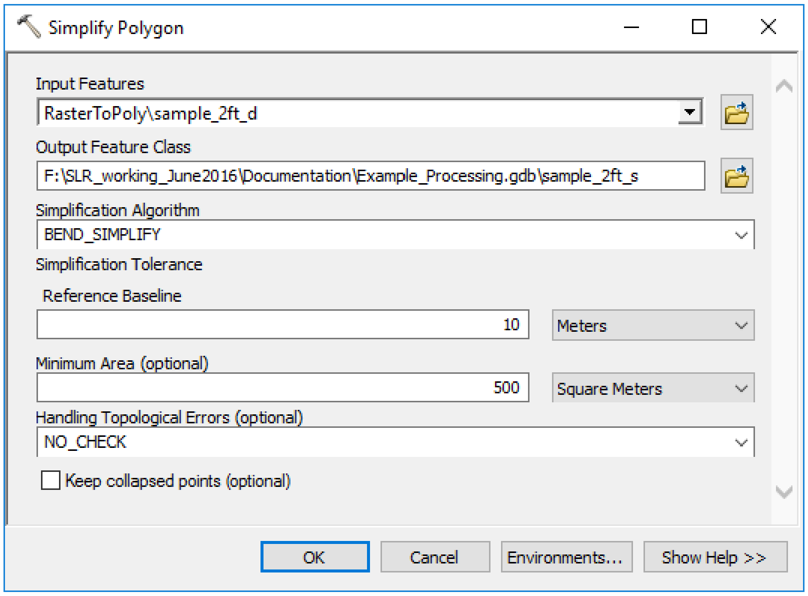

Figure 14: Dialogue box for *Simplfy Polygon* function

- *Multipart to Singlepart*

- *Smooth Polygon* (Figure 15)
  - Smoothing Algorithm = PAEK
  - Smoothing Tolerance = 5 Meters
  - Preserve endpoint for rings = false
  - Handling Topological Errors = No_Check

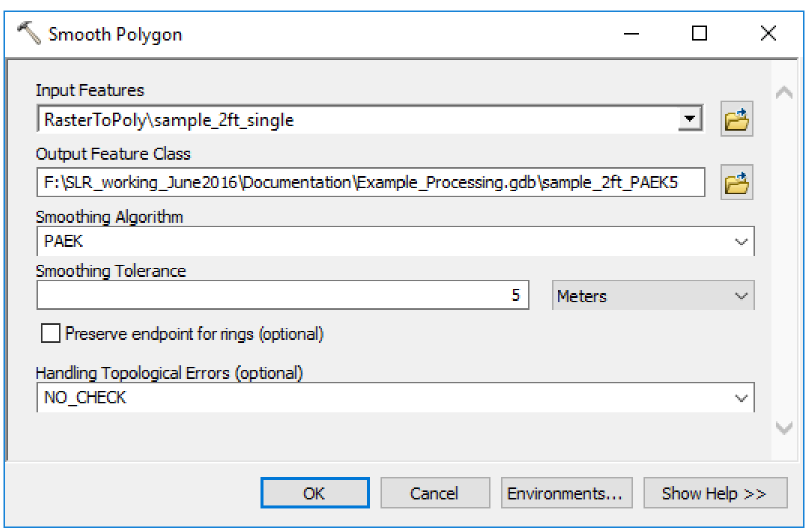

Figure 15: Dialogue box for *Smooth Polygon* function

- *Generalize* to reduce the point density
  - Tolerance = 0.01 Meters

- *Clip* to the next highest level (6ft layer clipped by 7ft layer, etc.)
    - to remove any overlap that could have been created from the smoothing and generalization

- *Generalize* to reduce the point density and file size
    - Tolerance = 0.2 Meters

These processes result in simpler and smoother polygons, as the example in Figure 16 shows. The resulting SLR layers were extended on the eastern side to meet the Delaware state boundary.

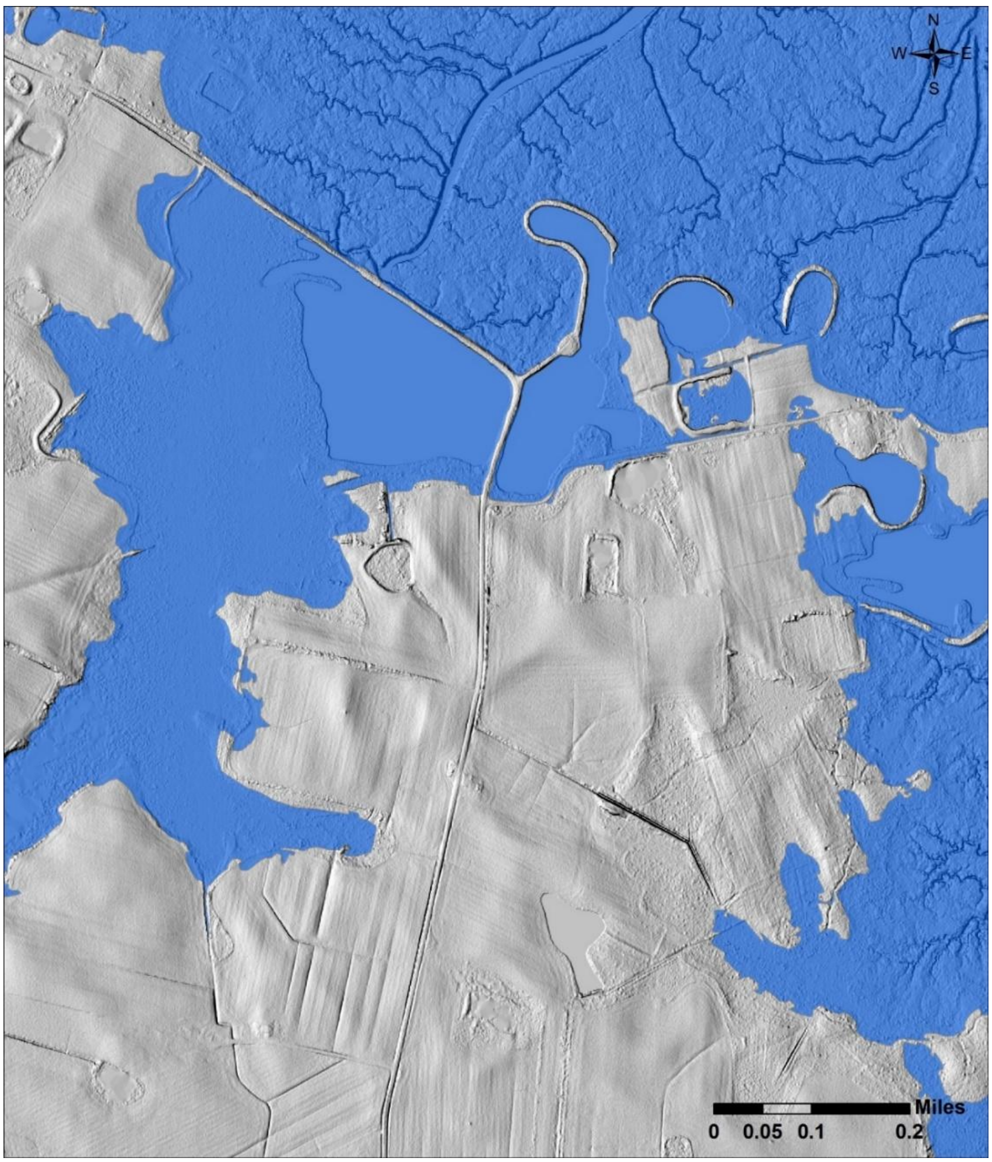

Figure 16: Polygons resulting from further processing of the 2ft SLR scenario for a portion of Duck Creek-Delaware Bay watershed. Compare to Figure 11.

6. Removal of Disconnected Areas

Not all areas with areas with elevations below a particular SLR scenario are expected to be inundated. Some regions are hydrologically disconnected, and even though their elevations are lower than the elevation of a particular scenario, they are not included in the inundation model. Initially all non-connected polygons were assigned to be removed. These disconnected polygons were then manually reviewed for the entire coverage area and those polygons where a direct connection could be identified were added back into the final layers. For example, those areas that were only disconnected because a bridge/overpass were included, as were those areas connected by culvert or some type of water conduit. Areas protected by dykes, dams, or other water control structures were also removed (see Figures 17-19).

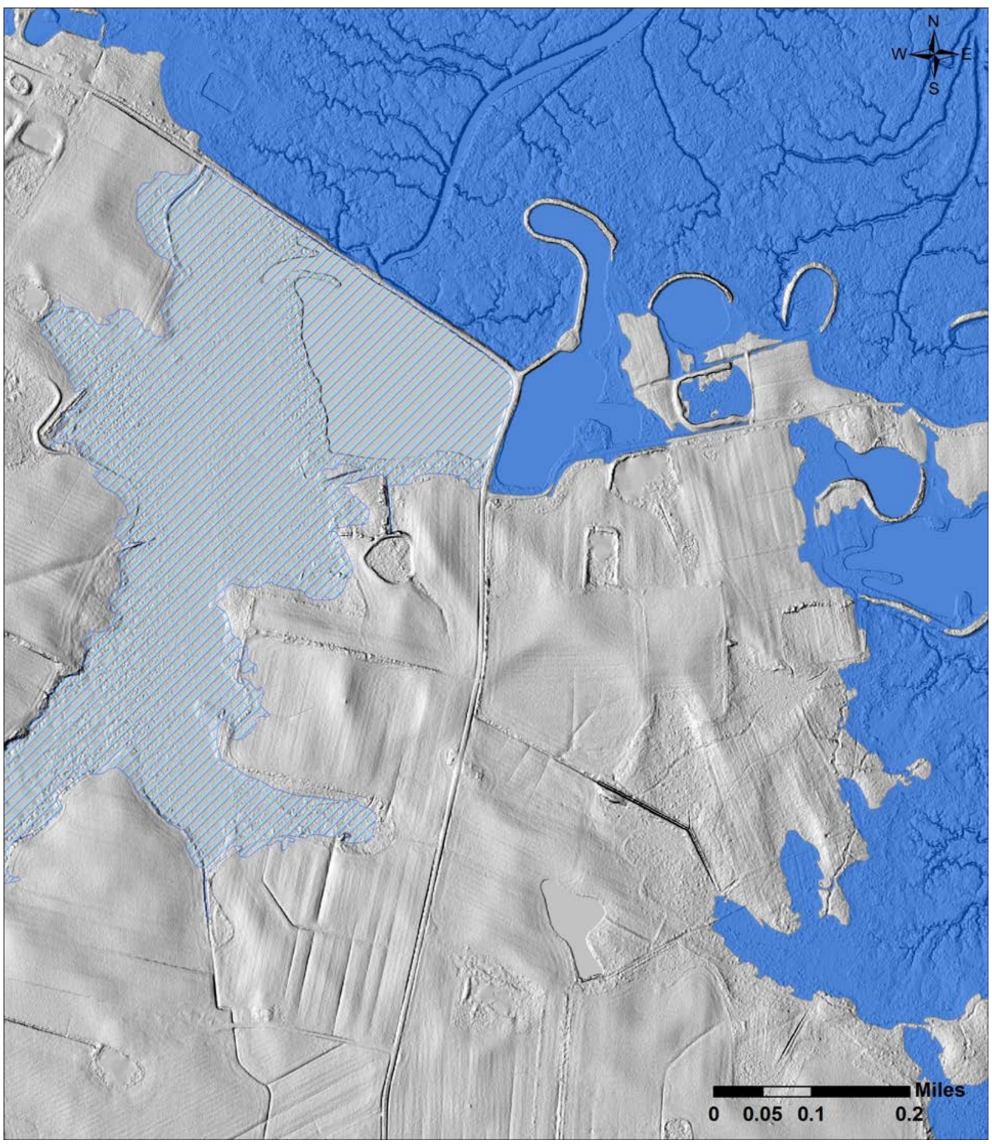

Figure 17: 2ft SLR scenario for a portion of Duck Creek-Delaware Bay watershed showing hydrologically disconnected polygons (striped) to be removed from the final inundation model

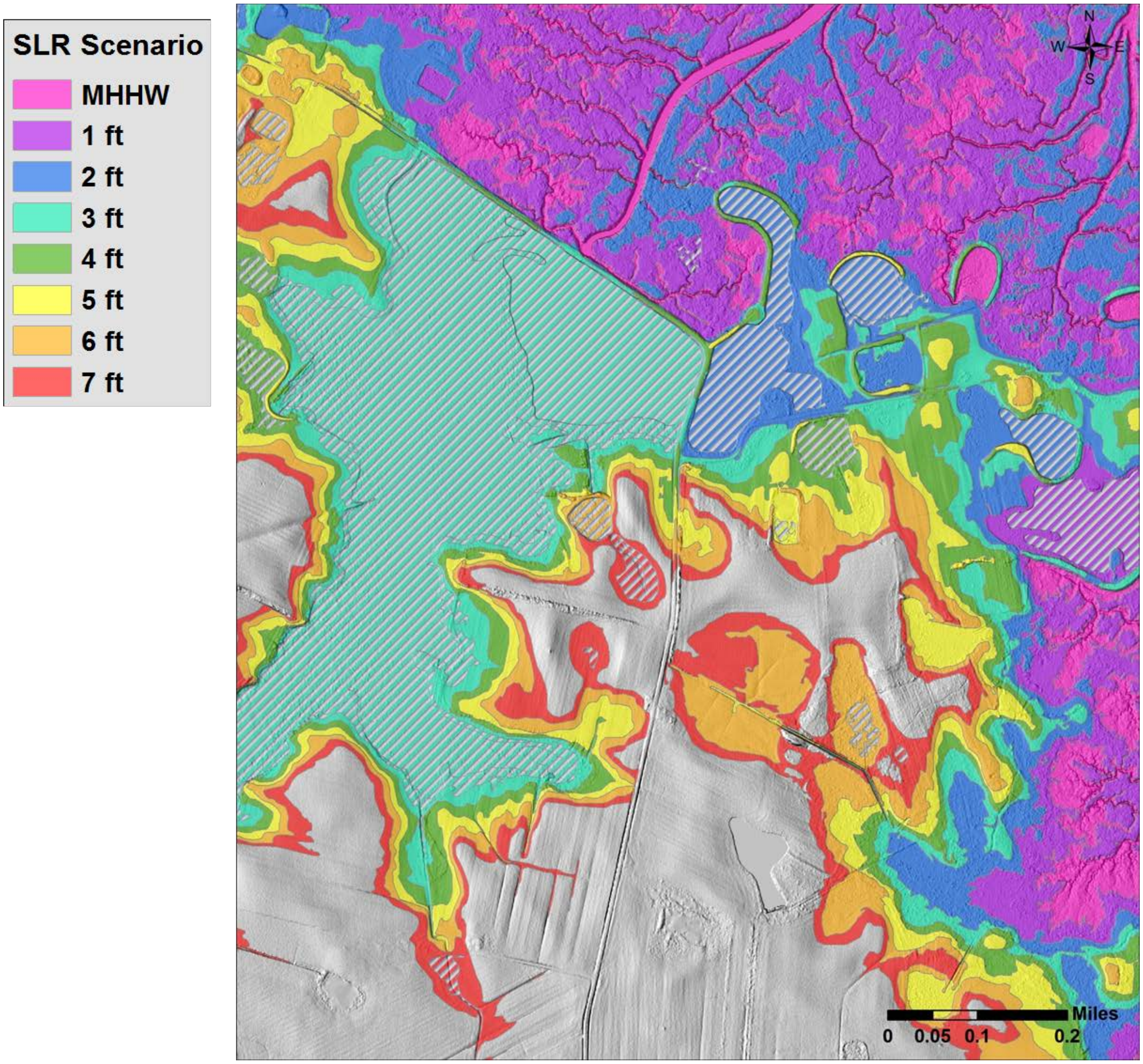

Figure 18: All eight SLR scenarios for a portion of Duck Creek-Delaware Bay watershed showing hydrologically disconnected polygons (striped) to be removed from the final inundation model

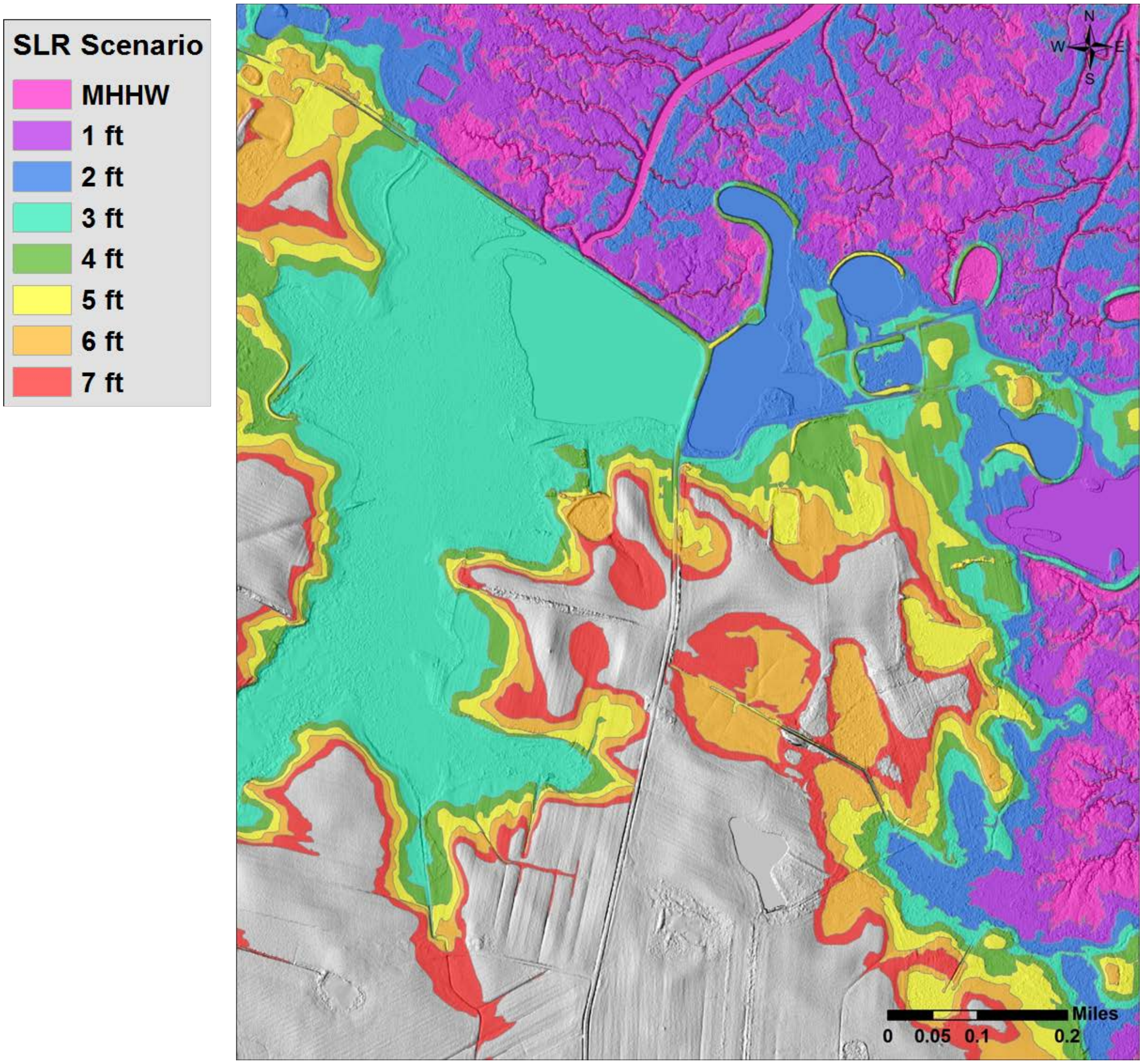

Figure 19: Bare earth SLR inundation models for a portion of Duck Creek-Delaware Bay watershed with hydrologically disconnected polygons removed

7. Statewide Bare Earth SLR Layers

The county SLR layers were combined into statewide layers using the *Merge* function. The *Dissolve* function was then used to combine overlapping polygons along the borders. The layers were once again clipped to the layer above (e.g., 6ft layer clipped by 7ft layer to remove any overlap that could have been created from the merging of the county files. Each of the eight resulting SLR layers was also checked for small polygons (less than several hundred square meters area) that were disconnected or artifacts. The result of these analyses are the statewide bare earth SLR layers.

8. Elevated Roadways

When the bare earth DEM was created by the LiDAR vendor, elevated roadways and bridges were often removed (see Figure 20), along with buildings, trees, and other non-surface features. In order to assess the impact of SLR on elevated roadways and bridges, these features were manually identified and added to the SLR layers.

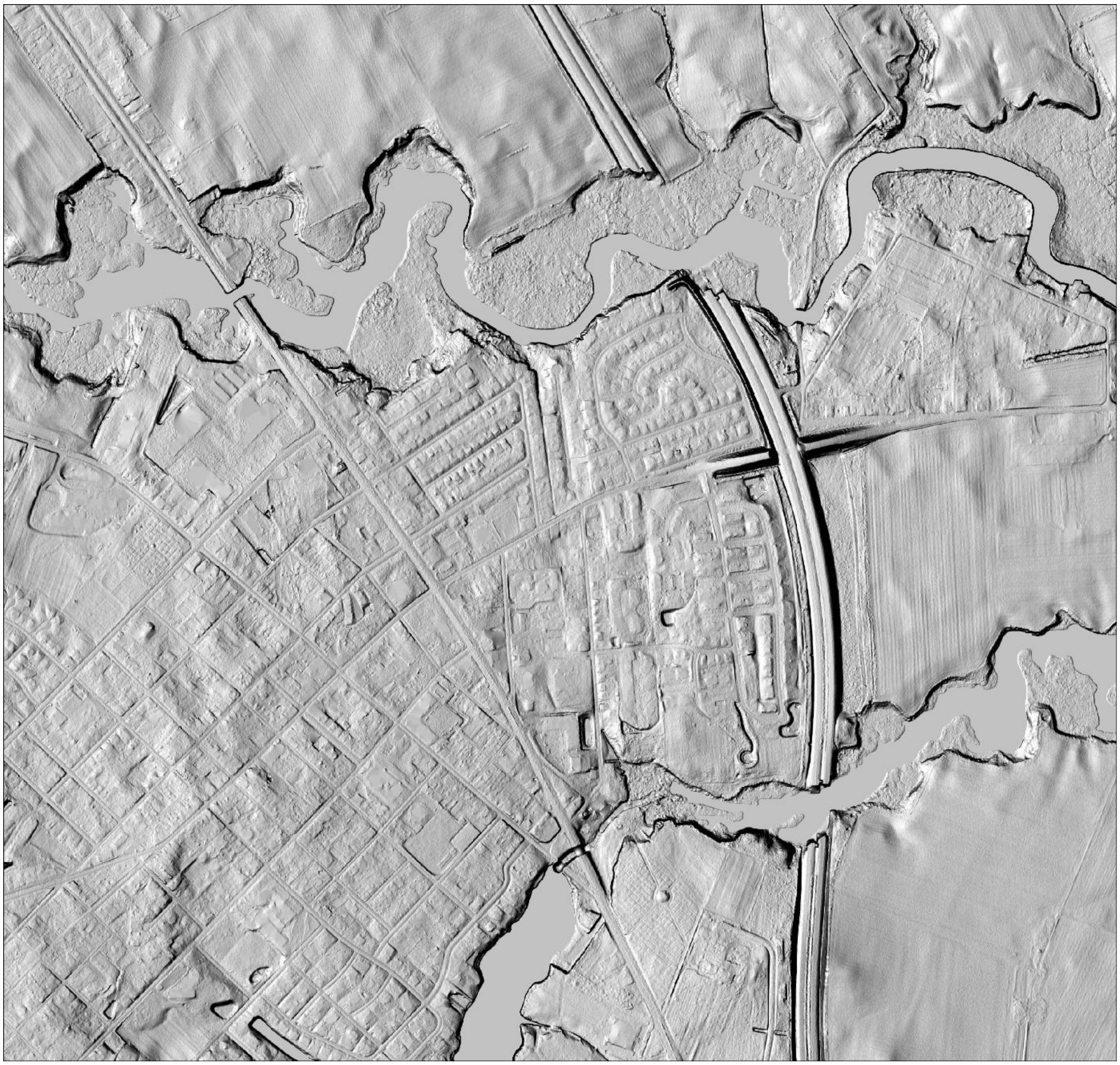

Figure 20: Bare earth hillshade model showing bridges removed from the bare earth DEM

The bare earth DEM, LiDAR point cloud, 2012 Delaware imagery, DelDOT bridges data, and previous SLR maps were used to identify the locations of elevated roadways and bridges in the areas covered by the SLR planning scenarios.

The new 7ft SLR bare earth layer was used to identify which roadways would never be inundated in the new SLR scenarios and which would be inundated in some of the SLR scenarios (Figure 21).

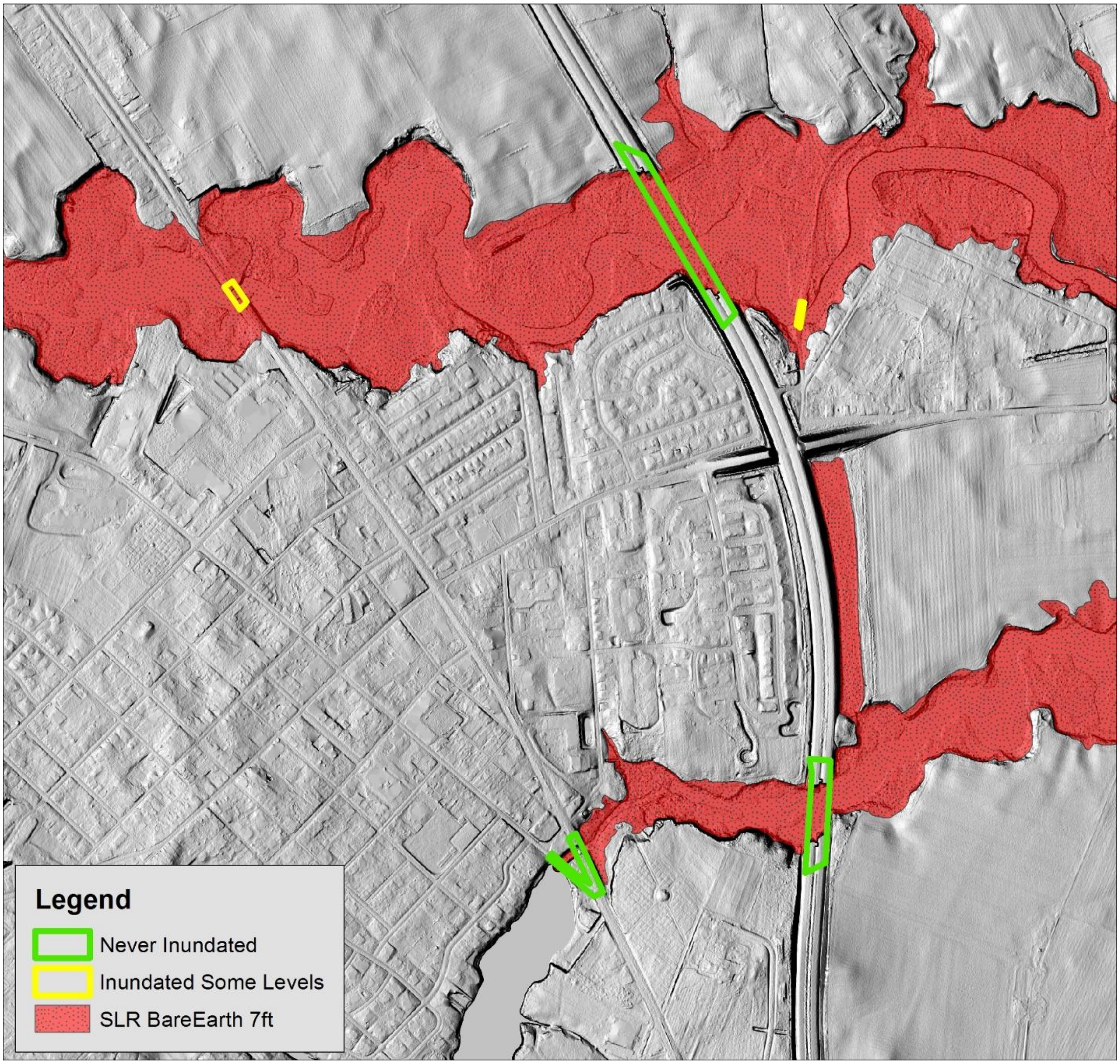

Figure 21: Bare earth hillshade model and 7ft SLR layer showing elevated roadways and bridges which would not be inundated at any of the SLR scenarios and those which would be inundated for some scenarios

The 162 roadways and bridges identified as never being inundated were removed from each of the eight SLR layers using the *Erase* function (see Figure 22).

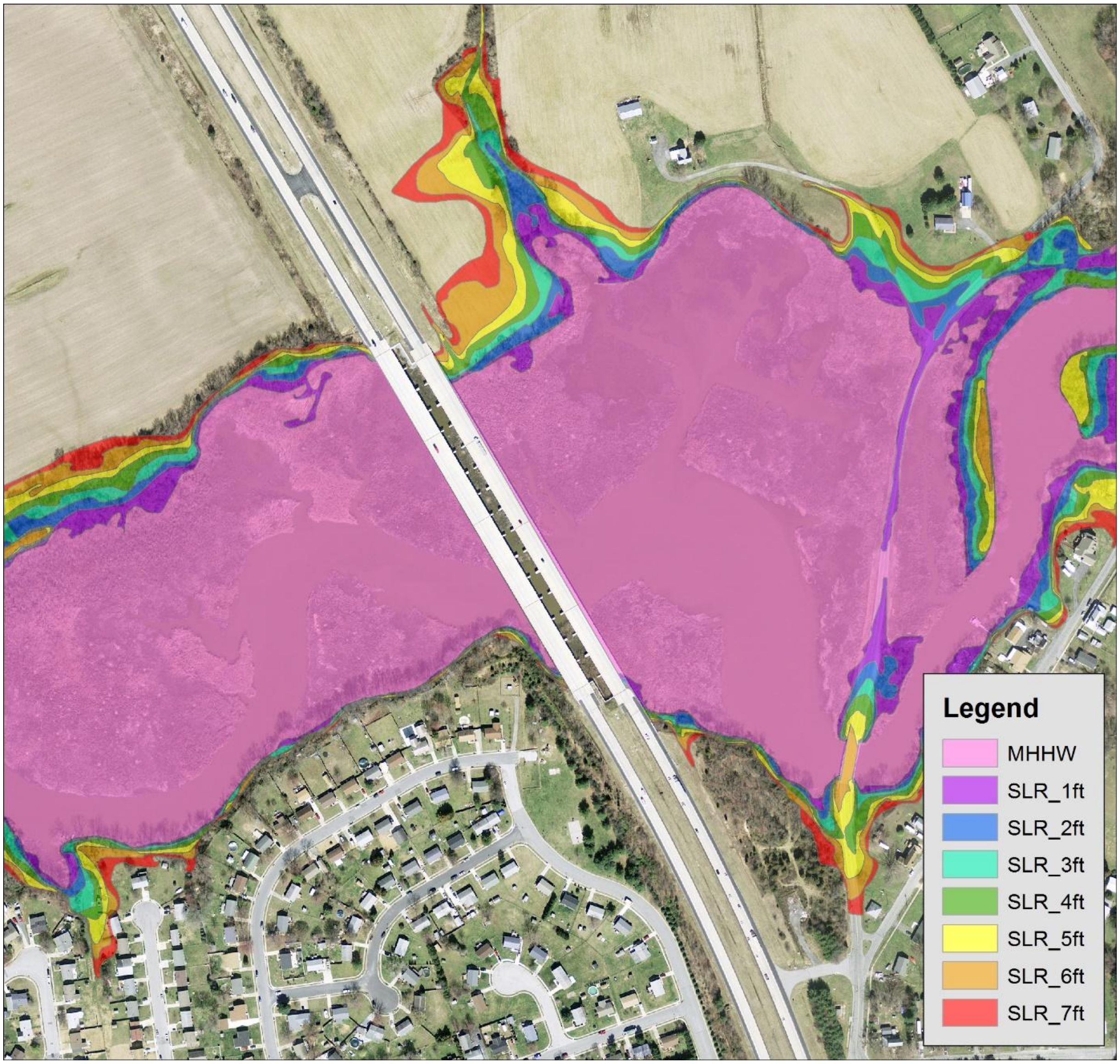

Figure 22: SLR map showing bridges removed from the final layers

The 92 elevated roadways and bridges which were identified as being inundated for some of the SLR planning scenarios were each manually examined (see Figure 23). The LiDAR point cloud was used to create a 1-m digital surface model (DSM) using the minimum bin method (the value of minimum point within the grid cell was chosen). This created a grid based model of the road surface which was then used with the corresponding watershed MHHW level to determine the extent of inundation at for each of the SLR scenarios (Figure 24). This resulted in layers for each SLR scenario that included the area to be erased for each of these bridges. These layers were used to adjust the bare earth SLR layers using the *Erase* function (Figure 25).

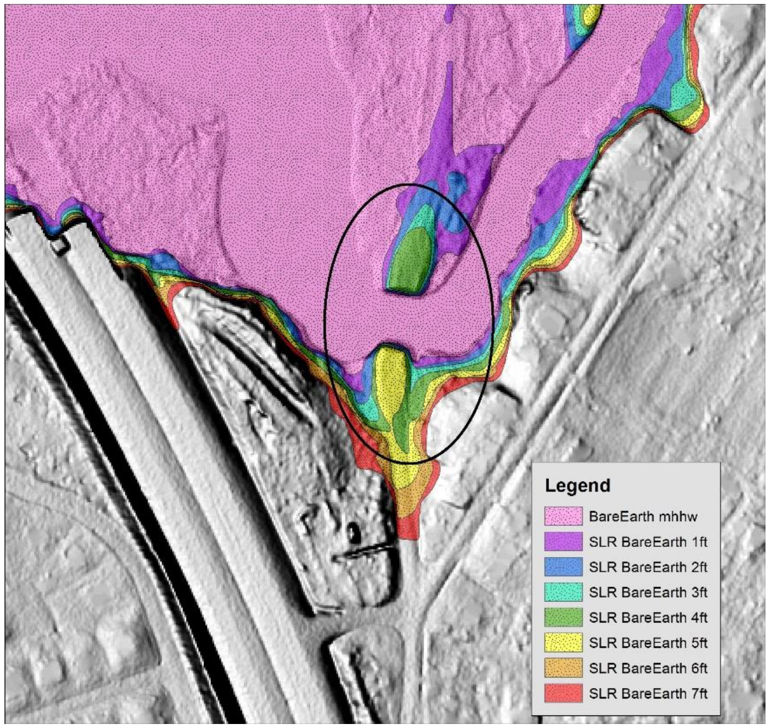

Figure 23: Bare earth SLR layers showing how a bridge not included in the bare earth DEM would be inundated for some SLR scenarios

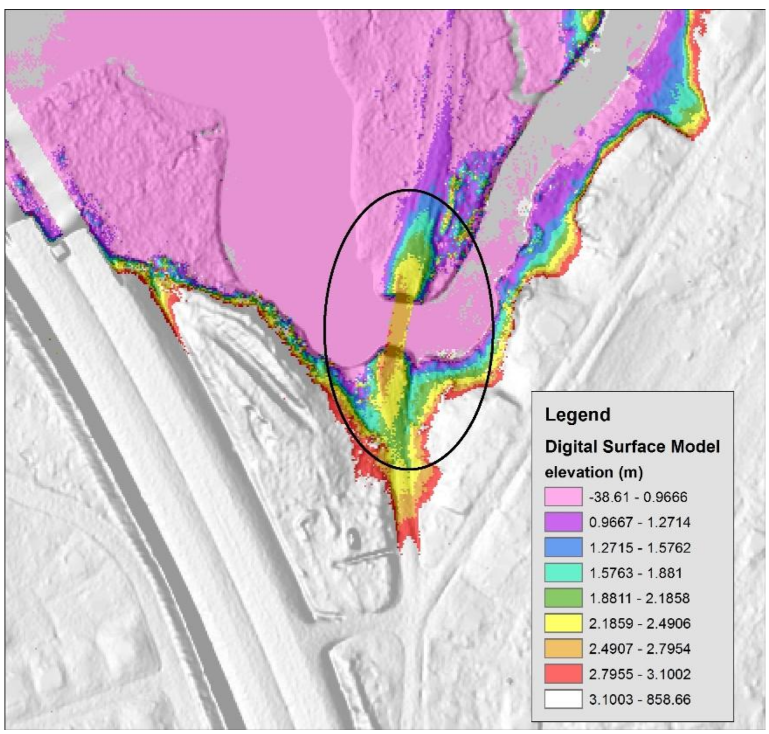

Figure 24: DSM showing the land surface with the bridge included. The DSM has been classified to match the SLR scenarios, allowing identification of which areas will be inundated for each scenario.

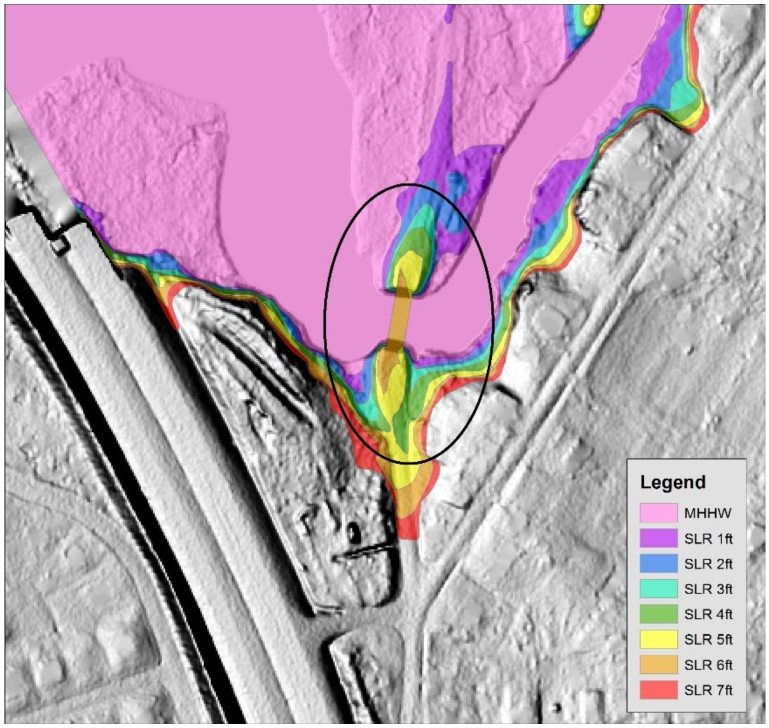

Figure 25: Final SLR layers adjusted based on the actual bridge surface elevations

After all bridges and elevated roadways were accounted for in the SLR layers, the *Multipart to Single Part* function was again applied to each layer to separate polygons divided by the bridge clipping. The layers were clipped to the layer above, and small fragment polygons were examined and those not representing necessary information were removed. The resulting eight statewide layers constitute the bathtub-model SLR coastal inundation mapping for the state of Delaware.

9. Final Products

The final products of these analyses are a geodatabase containing eight layers representing the bare earth bathtub-model Sea-Level Rise coastal inundation mapping (see Section 7) and eight layers showing the SLR coastal inundation mapping with elevated roadways and bridges accounted for. These layers include surfaces from Mean Higher-High Water (MHHW) to 7 feet above MHHW, in 1-foot increments.