ATTACHMENT A – BOUNDARY CONDITION & EVENT ANALYSIS

Lower Eastwick
Infrastructure and Flood Evaluation
Hydrology and Hydraulic Modeling

Attachment A
Boundary Condition & Event Analysis

March 2021

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A.1.0 Introduction

The purpose of Attachment A is to describe the model boundaries and provide justification for selecting the flooding events and associated data that were utilized to construct and calibrate the model. These data provide the external forcing mechanism that combine with internal physical geometry (e.g., river cross sections, surface terrain, levees, weirs, etc.) and hydraulic parameters (e.g., Manning's roughness coefficients, cross section/grid cell spacing, etc.) to compute results at the areas of interest in accordance with the study objective. Model boundaries are mainly located at the horizontal limits of the model, but vertically are defined by the land surface elevations and infiltration to groundwater. The effects of internal, but distributed, boundary effects due to rainfall and sewers are also considered and discussed herein. Groundwater elevations fluctuate, but occur at several feet below the land surface throughout the majority of the study area and are conservatively assumed to have little impact upon flood model results.

Flooding in Eastwick can occur due to terrestrial flooding (i.e., runoff resulting from rainfall), tidal surge emanating from the ocean (i.e., rising water from gravitational forces combined with atmospheric pressure and high wind), or a combination of the two.

After completing extensive research the range of extreme events selected for evaluation as part of this study include the following:

- Tropical Storm Isaias (approximate 10-year [10 percent annual chance] terrestrial event affecting Eastwick, August 2020)
- 100-year (1 percent annual chance) terrestrial event
- Hurricane Sandy (the highest tidal surge recorded at Philadelphia, October 2012)
- Great Appalachian Storm of 1950 adjusted to 2020 (the highest tidal surge recorded at Philadelphia when adjusted for sea level rise)
- 100-year (1 percent annual chance) terrestrial event estimated at 2100
- Great Appalachian Storm of 1950 adjusted to 2100
- 100-year (1 percent annual chance) terrestrial event coincident with 10-year (10% annual chance) tidal event
- 10-year (10 percent annual chance) terrestrial event coincident with Great Appalachian Storm of 1950 adjusted to 2020

The remainder of this attachment provides an analysis of these events to justify their selection and to document the methods by which boundary condition data were generated for each event. Table A-1 below provides a summary of these data and indication of the sections where they are discussed.

Table A-1: Boundary Condition Data Summary

Upstream flows: Darby Creek, Cobbs Creek and Schuylkill River
Type/method: Gaging Station Flow Data
See Section A2
River/stream flow downstream of gages:
Type/method: Estimation based upon proportion of drainage area
See Section A2
Upstream tide elevation data: Bridesburg and Philadelphia:
Type/method: Gaging station stage data
See Section A3
Downstream tide elevation data: Delaware City, New Castle and Marcus Hook
Type/method: Gaging station stage data
See Section A3
Runoff generated within Eastwick:
Type/method: Synthetic hydrograph estimation
See Section A4
Storm sewer flows:
Type/method: Constant removal rates approximated at selected locations
See Attachment B, Section B5

A.2.0 Terrestrial Flooding Analysis

Terrestrial flooding results from the accumulation of runoff that occurs when rainfall is unable to infiltrate or be stored on the land surface. Runoff collects and advances in the downgradient direction as overland flow until it reaches sewers, ditches or other conveyance systems. Ultimately, conveyed runoff discharges to streams and rivers where it is discharged downstream to their receiving water bodies.

Runoff upstream of Eastwick flows to Cobbs Creek, Darby Creek or the Schuylkill River. Runoff generated within Eastwick itself flows to storm sewers where it is ultimately discharged to Mingo Creek and pumped into the Schuylkill River via the Mingo Creek pumping station. This section addresses flow in Cobbs Creek, Darby Creek and the Schuylkill River and runoff within Eastwick is addressed in Section A.4.0.

A.2.1 Upstream Streamflow Gaging Stations

Figure A-1 shows upstream gaging stations near Eastwick and the watersheds associated with the Darby Creek and Cobbs Creek gages. Discharge data are available at 5-minute increments for Cobbs Creek from October 18, 2005 to the present, and stage data are available from October 1, 2007 to the present (USGS 2020b).

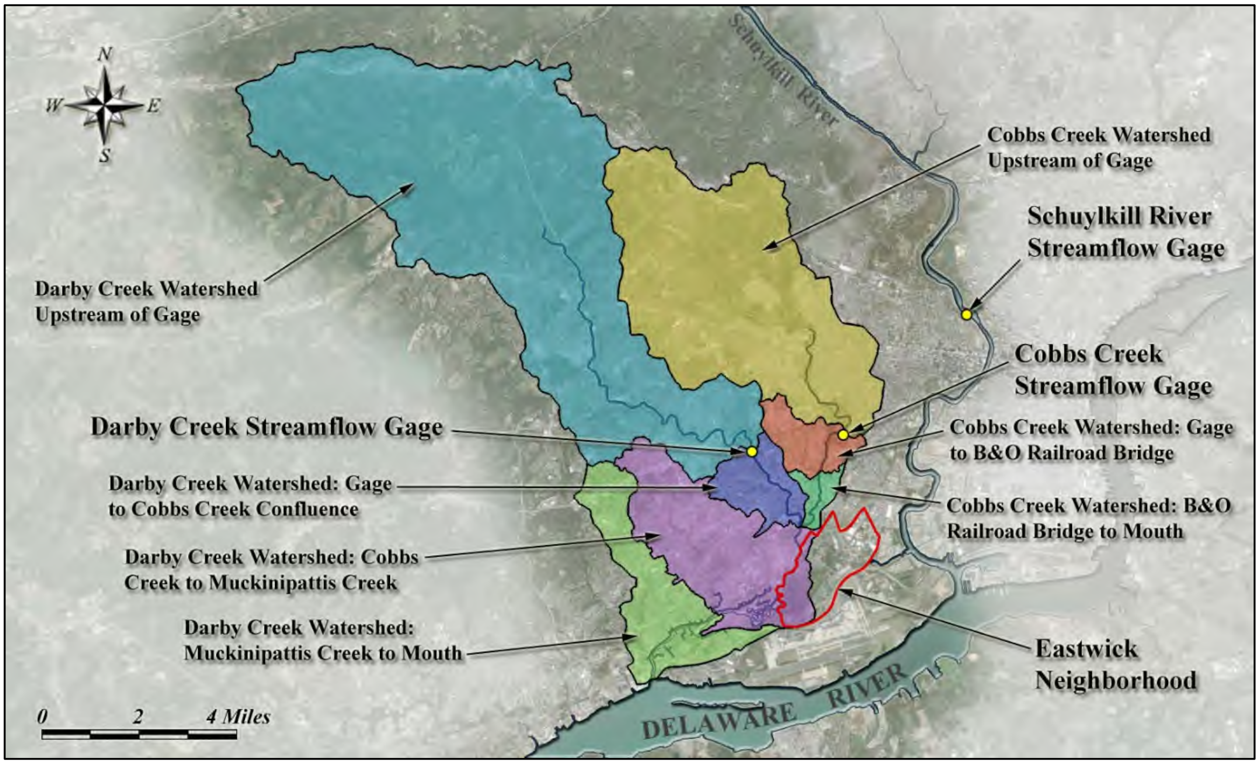

Figure A-1: Watersheds and Upstream Streamflow Gages near Eastwick

Discharge and stage data are available at 5-minute increments for Darby Creek from November 19, 2018 to the present (USGS 2020a). Mean daily discharge data are available from January 2, 1964 through September 29, 1990 and from November 19, 2018 to the present (ibid).

Discharge data are available at 30-minute increments for the Schuylkill River from January 1, 1986 to the present, and stage data are available from October 1, 2007 to the present (USGS 2020c). Mean daily discharge data are available from October 31, 1931 to the present (ibid).

A.2.2 Estimation of Flow Downstream of Gages

A streamflow gage provides the potential for directly estimating total discharge from the watershed upstream of its location. Flow discharging to the waterbody downstream of the gage must be estimated in another manner.

A simplified approach was taken to the estimation of inflow to Darby Creek and Cobbs Creek downstream of their gages by scaling estimated gage flows by the proportion of the downstream watershed area to the area of the watershed draining to the gage. Watersheds contributing to the gages and downstream inflow are shown in Figure A-1 and their areas are given in Table A-2. As an example of the simplified approach used, consider that Cobbs Creek watershed has an area of 19.68 square miles flowing to the gage. In order to estimate inflow for the watershed named "Cobbs Creek: B&O Railroad Bridge to Mouth", the ratio of its area (0.69 square miles) to that of the gage area (0.69/19.68) is computed as 0.035 or 3.5 percent. Inflows to Cobbs Creek from this segment would be estimated as the gage flow multiplied by 3.5 percent.

Table A-2: Areas of Darby Creek and Cobbs Creek Subwatersheds

Watershed Designation	Area (Square Miles)
Darby Creek: Upstream of Gage	37.51
Darby Creek: Gage to Cobbs Creek Confluence	2.31
Darby Creek: Cobbs Creek to Muckinipattis Creek	8.52
Darby Creek: Muckinipattis Creek to Mouth	5.64
Cobbs Creek: Upstream of Gage	19.68
Cobbs Creek: Gage to B&O Railroad Bridge	1.88
Cobbs Creek: B&O Railroad Bridge to Mouth	0.69

This estimation technique does not consider the distribution of local rainfall or the effect of local lag[1]. However, given the relatively small size of the Darby Creek and Cobbs Creek watersheds, rainfall distribution in the downstream watersheds is expected to significantly reflect that of the gage data. Given that the downstream watershed areas are considerably smaller than the watershed areas at the gages, downstream lag is expected to be less than the observed lag at the gages. Ignoring differences in lag produces slightly higher downstream flows by more closely adding peak flows in the Darby and Cobbs Creeks. Therefore, this approach is potentially more conservative in terms of estimating extreme events. Also, the watershed areas contributing inflow between the gages and the confluence of Darby Creek and Cobbs Creek are less than ten percent of the watershed area flowing to the gages, estimation error associated with this method is not likely to affect the calibration of river stage at the Darby Creek 84th Street Gage (see Attachment B). Darby Creek inflows downstream of the Cobbs Creek mouth discharge to that portion of the creek where tidal flow is dominant and terrestrial inflow is expected to have an almost unmeasurable effect.

Given the above considerations and the fact that other estimation methods, such as synthetic hydrographs, also have associated high estimation error, we considered this simplified approach to the estimation of intermediate inflow suitable and appropriate.

The Schuylkill River streamflow gage is located just above the Fairmont Dam which is the upstream model boundary (see Attachment B). Therefore, the gage provides boundary condition flows to the model at that location. Schuylkill River terrestrial inflows downstream of the gage is assumed to be minor compared to tidal flows and has therefore been ignored.

Delaware River flow is implicit in the river stage data used at the model boundaries. Terrestrial inflows to the Delaware River between the upstream and downstream model boundaries is assumed to be minor in comparison to tidal flow and has therefore been ignored.

A.2.3 Tropical Storm Isaias

Tropical Storm Isaias reached Eastwick on August 4, 2020 and caused considerable flooding within the community. Tropical Storm Isaias was selected for model calibration purposes because

[1] Lag is the delay between the time runoff from a rainfall event over a watershed begins until runoff reaches its maximum peak.

it was a significant terrestrial runoff event that was recorded by proximal gages, and due to immediate post-storm efforts by USACE and coordination by the City of Philadelphia (urged by community stakeholders) a fairly good high watermark data set was collected and available for calibration (see Attachment B, Section B6.2). Additional modeling benefits resulting from this storm are that it was approximately the 10-year (10 percent chance) terrestrial storm event (as will be demonstrated below), and also that recent land form modifications had been completed in the Cobbs Creek riverbank overflow area and adjacent to the landfill.

Tropical Storm Isaias data, available at 5-minute increments, was downloaded from the USGS website (see Section A.2.1) and used as upstream model boundary condition data for calibration. Inflows downstream of the gages were estimated as described in Section A.2.2. During model calibration, as further described in Attachment B, it was found that the flow data obtained from the USGS gaging stations at Cobbs Creek and Darby Creek were lower than expected. Accordingly, further evaluation of the gage flows was conducted and, as a result, estimated gage flows were revised as described below in Section A2.3.1.

A.2.3.1 Re-rating of Darby Creek and Cobbs Creek Gage Flows

The Philadelphia District of the United States Army Corps of Engineers (USACE) reported that peak flows at the Cobbs Creek gage for Hurricanes Irene and Hurricane Lee were measured (USACE 2014; USACE 2016). USACE stated the following regarding the Cobbs Creek gage:

> "However a review of the stream measurement file indicates that the measurement method was indirect. This means it was an estimate based on either extrapolation or calculation. In addition, the peak flows reported for Irene and Lee are suspect because the gage data at high flows may be impacted by the bridge downstream of the gage. When flows are high and the water level at the bridge reaches the low steel above the opening, the relationship used for calculation and extrapolation at the gage is affected. The last truly measured gage flow (908cfs) occurred at an elevation lower than the low steel of the bridge so the impact of the bridge on the gage calculations is not known." (USACE, 2016).

According to the data provided on the USGS website (USGS 2020a), the gage flows indicated by USACE for Hurricane Irene and Lee remain unchanged at the time of this report.

USACE indicated that a hydraulic model would be required to provide more accurate flow calculations at the gage. Presently, only data from the hydraulic model used in the 1977 Flood Insurance Study (FIS) (FEMA, 2017) is available. USACE indicated that they ran their hydraulic model with flows estimated from both the USGS rating curve[2] and a rating curve constructed from the 1977 FIS and obtained "a much better match" (USCE 2016) to project high water marks using flows estimated from the FIS rating curve.

On the basis of these findings, the 1977 FIS study rating curve was used to convert measured Cobbs Creek stage values to flows for this study. Because the modeling conducted for this study is for unsteady flow, it is necessary to develop a rating curve for the full range of flows,

[2] A rating curve is a graph of water surface elevation versus flow (discharge) at a fixed location.

not just the estimated peak flows used in the USACE studies. Accordingly, a composite rating curve was developed using the field-measured low flow data of the USGS gage and the computed high flow data of the 1977 FIS study. Figure A-2 shows the rating curve used to compute USGS flows (as reported on their website), the rating curve derived[3] from the 1977 FIS study, and the rating curve of this study. Like the USACE study (as further discussed in Attachment B), this study was only able to achieve a good calibration with the revised composite rating curve.

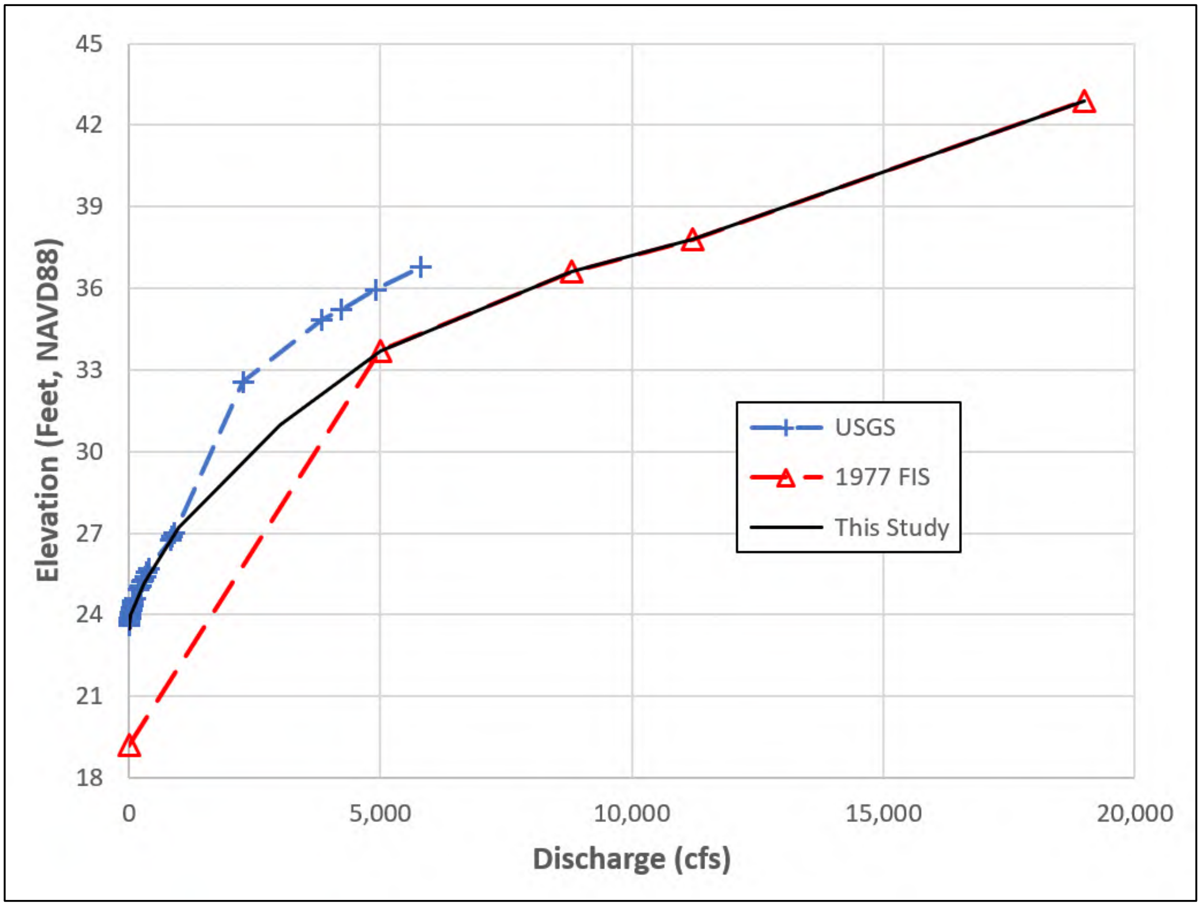

Figure A-2: Cobbs Creek Rating Curves

The USACE studies did not consider flows from the Darby Creek gage, presumably because 5-minute interval data was not available at the time of their studies. The data accuracy issues raised by USACE for the Cobbs Creek gage also apply to the Darby Creek gage. Specifically, a bridge opening immediately downstream of the bridge[4] affects high flows. Accordingly, a composite rating curve was developed for the Darby Creek gage location also using the USGS data for low flows and 1977 FIS study data for high flows. The portion of "This Study" curve

[3] Volume 2 of the FIS study has profiles for Cobbs Creek that indicate computed elevations at the gage (approximately 150 feet upstream of the Cemetery Access Road) for the 10%, 2%, 1% and 0.2% annual chance floods. Flows computed at this location are given in Volume 1 of the FIS study as 5,000 cfs, 8,800 cfs, 11,200 cfs, and 19,000 cfs, respectively.

[4] The gage is mounted on the upstream side of the bridge.

between the USGS curve and the 1977 FIS curve was visually fit by AKRF. As the figure shows, the fit portion only affects flows between approximately 2,000 cfs and 5,000 cfs. Higher flows (see Figure A-4), that principally affect overflow into Eastwick, are in the 5,000 cfs to 12,000 cfs range and fall on the 1977 FIS curve. Therefore, the AKRF-fitted portion of the curve is not expected to significantly affect the results of the model.

Examination of the Darby Creek gage flow measurement data (USGS 2020b) indicates that the current gage rating curve is based upon data from September 1, 2000 to the present and having a peak flow measurement of 1,180 cfs with a discharge measurement quality code of poor[5]. The peak flow estimated at the gage during Tropical Storm Isaias in August 2020 was 6,070 cfs.

Figure A-3 shows the Darby Creek rating curve used to compute USGS flows (as reported on their website), the rating curve derived from the 1977 FIS study, and the rating curve of this study. Extrapolated USGS rating curve values were constructed from values of stage and flow reported by USGS for Tropical Storm Isaias.

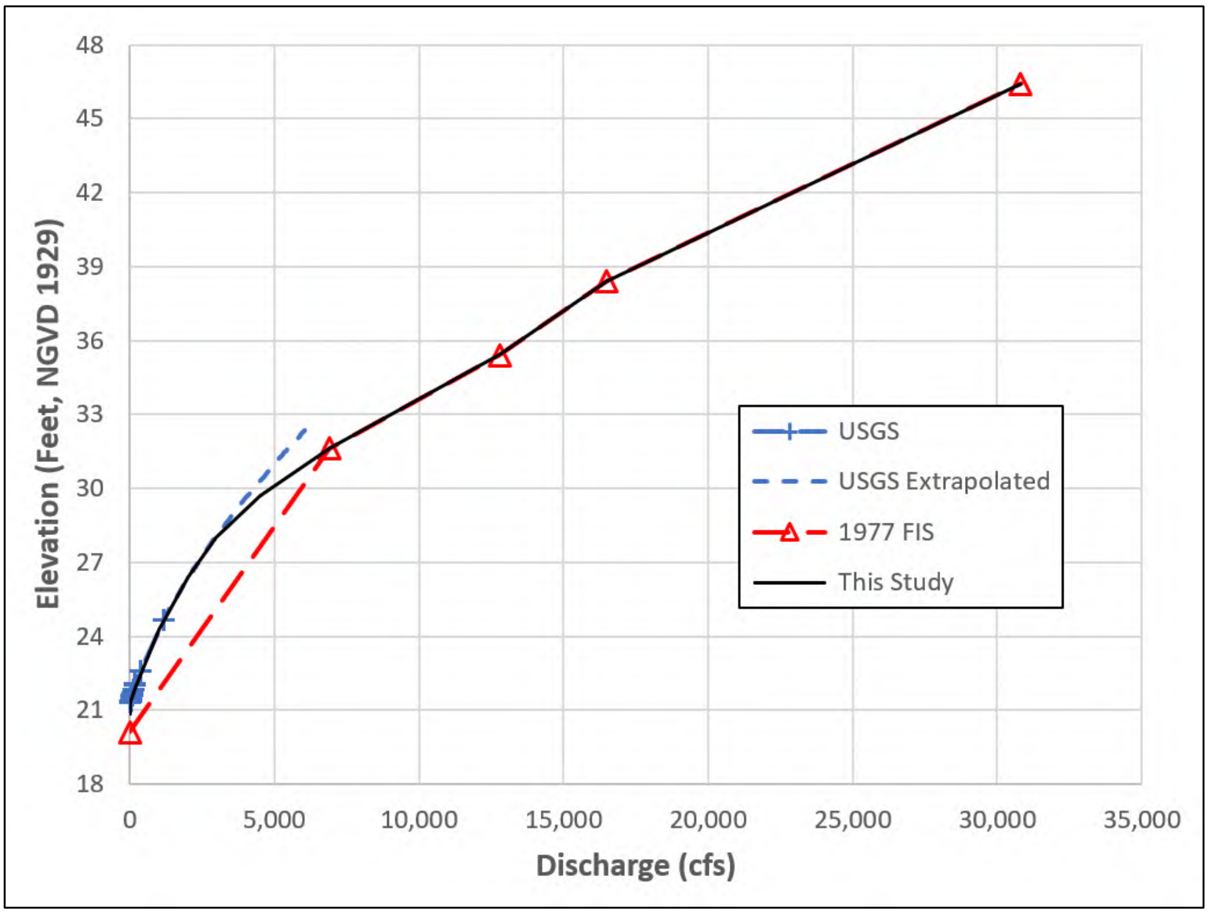

Figure A-3: Darby Creek Rating Curves

[5] The USGS web page (https://help.waterdata.usgs.gov/codes-and-parameters/discharge-measurement-quality-code) defines poor as "The data are >8% (percent) of the actual flow." Our interpretation of the USGS definition is that poor data may <u>deviate</u> by more than 8 percent from the actual flow.

The portion of "This Study" curve between the USGS curve and the 1977 FIS curve was visually fit by AKRF to match the USGS Extrapolated curve and the 1977 FIS curve. A slight curve has been added between the USGS Extrapolated and 1977 FIS curves. Given its length, and the shape of the adjoining curves, this fit curve is not expected to significantly affect the results of the model.

Figure A-4 shows the initial USGS-reported and the revised (re-rated) flows during Tropical Storm Isaias at the Cobbs Creek and Darby Creek gages. It should be noted that there are missing USGS flow values for Darby Creek at the time of peak flooding. Stage values were reported during this period, but flow values were not estimated in the available data set.

During Tropical Storm Isaias, even though Darby Creek has a greater drainage area, the estimated peak flow at the Cobbs Creek gage was nearly 12,000 cfs as compared with an estimated peak of about 8,000 cfs at the Darby Creek gage. However, the total volume of flow (the area under the hydrograph curve) in Darby Creek was larger than that of Cobbs Creek. The difference is likely due to slightly different rainfall distributions in the two watersheds and possibly other factors such as land use, watershed shape, etc.

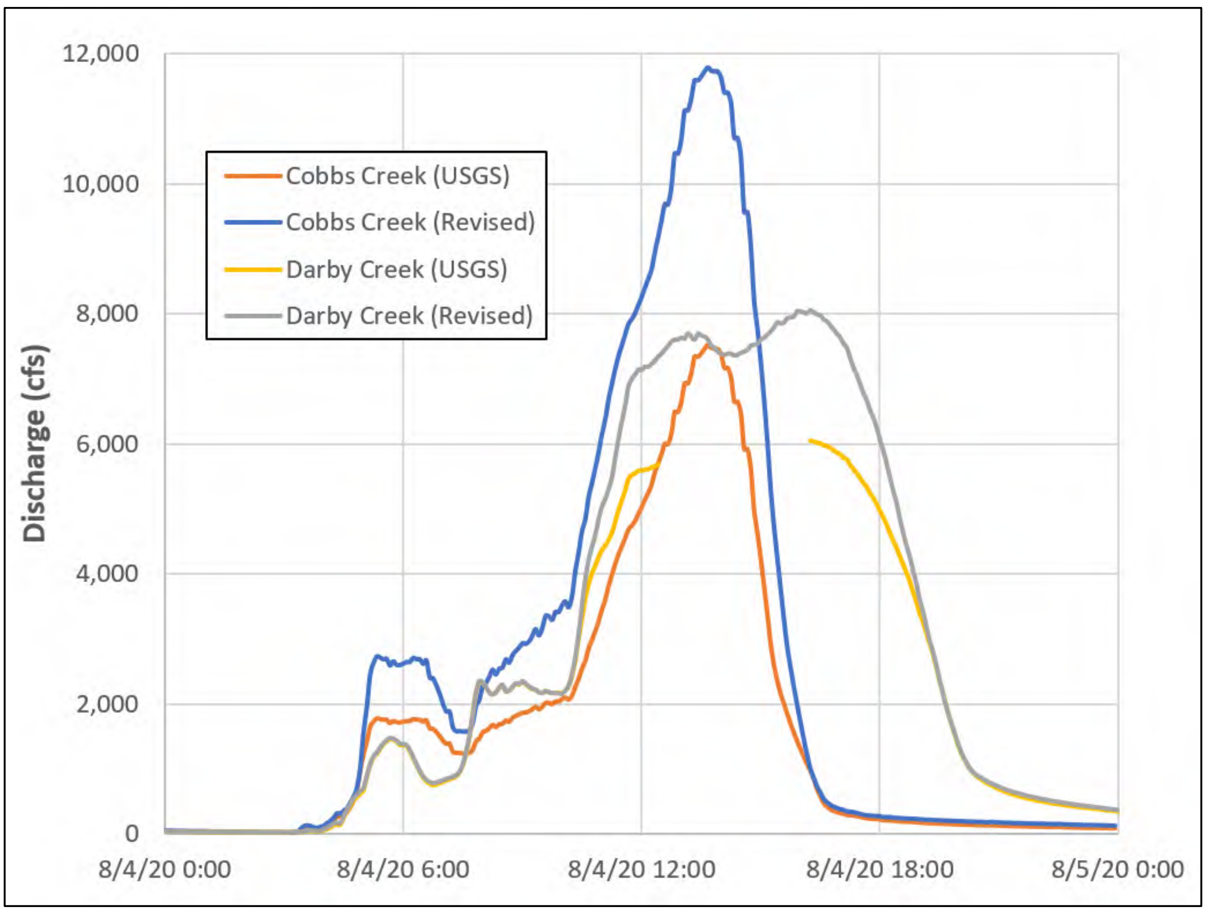

Figure A-4: Tropical Storm Isaias Flow at Cobbs Creek and Darby Creek Gages

It is difficult to estimate the recurrence interval of Tropical Storm Isaias at Eastwick without a long-term gage record at Eastwick or performing a detailed analysis similar to the "Darby and Cobbs Watersheds Hydrologic Study" (hereafter referred to as "USACE study") (USACE 2016). However, some general conclusions can be inferred based upon the results of the USACE study.

At the Darby Creek gage, the USACE study estimates the 5-year flow at 6,898 cfs and the 10-year flow at 9,079 cfs. Given that the peak estimated flow at the Darby Creek gage was 8,060 cfs (Figure A-4), this would indicate that the recurrence interval was between 5- and 10-years.

The USACE study does not provide estimates at the Cobbs Creek gage, but instead provides estimates at Woodland Avenue, which is between the gage and Eastwick. Because Woodland Avenue is downstream of the gage, it is expected that flow estimates would likely be a little higher than at the gage for each recurrence interval. At Woodland Avenue, the USACE study estimates the 20-year flow at 8,272 cfs, the 50-year flow at 10,840 cfs and the 100-year flow at 13,055 cfs. The peak flow estimated at the Cobbs Creek gage was 11,780 cfs. Keeping in mind that the USACE study flow estimates would likely be lower at the upstream gage location, we can estimate that the recurrence interval was approximately 50-years at the Cobbs Creek gage.

Given that the Darby Creek watershed and flow volume is greater than Cobbs Creek, and given their respective estimated recurrence intervals of 5- to 10-years and 50-years, the combined recurrence interval can be estimated as greater than 10-years and probably between the 10- and 20-year terrestrial storm event.

A.2.3.2 Schuylkill River Flow

Schuylkill River flow from USGS streamflow gage (see Figure A-1) is plotted in Figure A-5 together with Schuylkill River hydrographs from other flood events discussed in the following sections. Comparing the plots of Figure A-4 and Figure A-5, it can be observed that Darby Creek and Cobbs Creek peak between noon and 6:00 pm whereas the peak flow on the Schuylkill River arrived close to midnight. This is undoubtedly because of the much larger size of the Schuylkill River watershed and it corresponding greater lag.

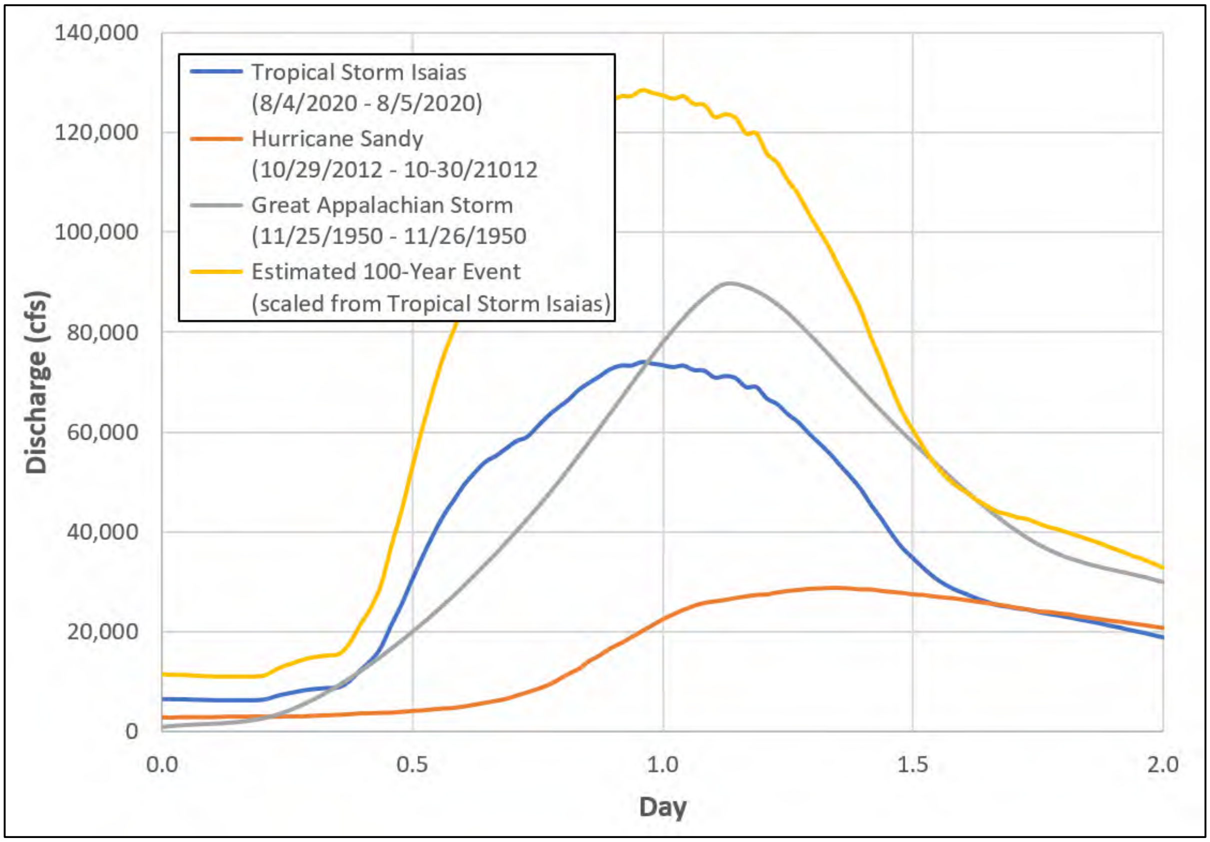

Figure A-5: Schuylkill River Flow for Selected Storm Events

There are 90 years of peak streamflow data available for the Schuylkill River gage. These data were analyzed using the USACE HEC-SSP Statistical Software Package (USACE 2019) and performing a Bulletin 17B flow frequency analysis. The data and results of this analysis are displayed in Figure A-6. Although Tropical Storm Isaias data was not used in the analysis which only considers years with complete data, its peak flow value recorded at the Schuylkill River gage of 74,000 cfs is plotted on Figure A-6. The figure indicates that the Tropical Storm Isaias peak flow recurrence interval was between 5-years and 10-years (probability of exceedance equal to 10%-20% in a given year).

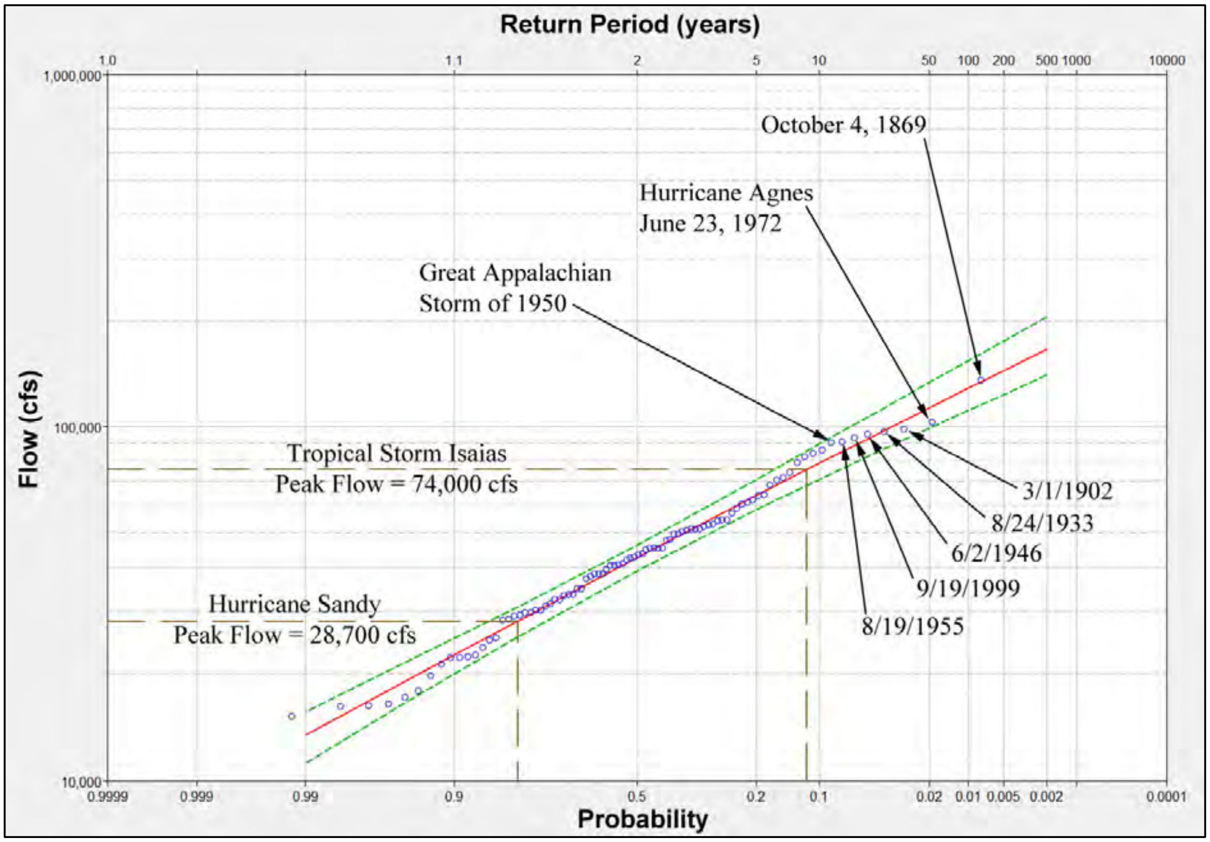

Figure A-6: Schuylkill River: Annual Peak Flow Extreme Event Analysis
(Source: USACE 2019; modified by AKRF)

It is noteworthy that the largest flood event recorded at the Schuylkill River gage occurred on October 4, 1869, more than 150 years ago. Furthermore, seven of the eight greatest flood events recorded at this gage occurred more than 50 years ago (See Figure A-6). These facts provide important relative to recurrence interval and planning for flood resiliency.

We also acknowledge that anthropogenic factors (e.g., urbanization/industrialization/sprawl that reduce lag in the lower watershed or construction of large dams that increase river storage in the upper watershed) have likely altered peak flow observations during the period of record. While further review of such factors along with regional hydrologic trends may prove useful and thus are relatable to the objective of this study, detailed analysis of anthropogenic controls/effects are beyond the scope of this study at this time.

A.2.4 Hurricane Sandy

Flow estimates are available for Hurricane Sandy at the Cobbs Creek gage, but no flow estimates are available at the Darby Creek gage (see Section A.2.1). Cobbs Creek gage stage values were re-estimated in accordance with the techniques documented in Section A.2.3.1 and flows were estimated for downstream watersheds as documented in Section A.2.2. Flows for Darby Creek watershed and its downstream watersheds were estimated by multiplying the Cobbs Creek gage flow estimates by the proportion of their areas divided by the Cobbs Creek gage watershed area. Schuylkill River flow during Hurricane Sandy is plotted on Figure A-5 and the analysis displayed on Figure A-6 indicates that its peak flow of 28,700 cfs corresponds to a recurrence interval of between 1-year and 2-years (probability of exceedance equal to 50%-90% in a given year).

A.2.5 Great Appalachian Storm of 1950

No streamflow gage data was available for the Great Appalachian Storm of 1950 (also referred to as the Thanksgiving Day Storm of 1950) for either Darby Creek or Cobbs Creek. Instead, as further documented in Section A.4.5, rainfall estimates are available which allow a simplified comparison of the terrestrial event with more recent flood events. The total rainfall during the 1950 event was 3.46 inches which is 83% of the total rainfall during Tropical Storm Isaias (see Section A.4.3). A simplified approach was taken to estimate 1950 event flows as 83% of Tropical Storm Isaias flows. This approach ignores the greater percentage of infiltration that would occur with less rainfall and the effect of land use change. Ignoring these factors is conservative because doing so has the effect of over-estimating terrestrial flow values.

As noted in Section A2.1, mean daily discharge data are available at the Schuylkill River gage during the 1950 storm event. In addition, the Great Appalachian Storm of 1950 recorded the peak flow for the year and its value is recorded as 89,800 cfs in the gage peak annual flow record. As shown on Figure A-6, this storm corresponded to between a 10-year and 50-year recurrence interval flood in terms of peak flow recurrence on the Schuylkill River. The hydrograph shown on Figure A-5 was constructed by matching the peak flow and approximating instantaneous flow values such that the average flow for each day shown on the plot and the surrounding 2 days matched the average daily flow reported for the gage.

A.2.6 100-Year Terrestrial Flood

The 100-year terrestrial flood was approximated by scaling Tropical Storm Isaias gage flows to match 100-year flows estimated in the USACE study (USACE 2014). Darby Creek gage flows were scaled by a factor of 2.26 which is the ratio of the estimated USACE study 100-year flow (18,199 cfs) divided by the peak Darby Creek estimated gage flow (8,060 cfs – see Section A2.3.1). Cobbs Creek gage flows were scaled by a factor of 1.11, which is the ratio of the estimated USACE study 100-year flow at Woodland Avenue (13,055 cfs) divided by the peak Cobbs Creek estimated gage flow (11,780 cfs – see Section A2.3.1). Downstream watershed flows were estimated as documented in Section A.2.2.

The peak 100-year flow computed by annual peak flow extreme event analysis for the Schuylkill River shown in Figure A-6 is 129,000 cfs. The 100-year flood hydrograph shown in Figure A-5 was approximated by scaling Tropical Storm Isaias flows by the ratio of 1.74 which is equal to the peak 100-year flow divided by peak Tropical Storm Isaias flow (129,000/74,000).

A.3.0 Tidal Surge Analysis

With the exception of negligible tidal effect from the Chesapeake Bay through the Chesapeake and Delaware Canal, all tidal surge reaching the mouth of Darby Creek and the Schuylkill River is propagated from the Atlantic Ocean, through the Delaware Bay and Delaware River. Figure A–7 shows Eastwick relative to the river, bay and ocean, and also shows several key tide gages maintained by the National Oceanic and Atmospheric Administration (NOAA) on the Delaware River.

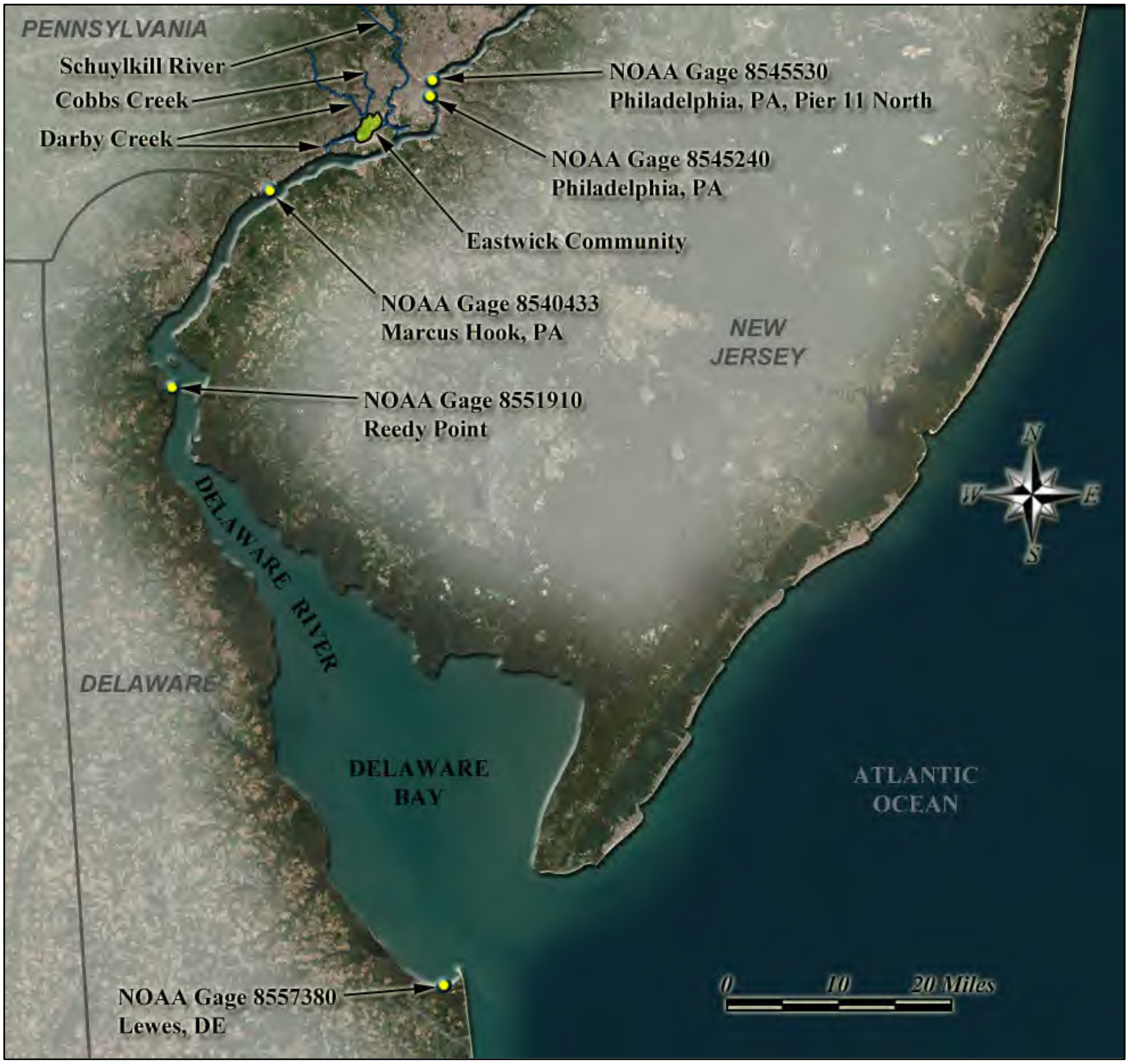

Figure A-7: Selected Delaware River and Bay Tide Gages

The following subsections document key tidal surge events expected to occur at Eastwick and their approximate recurrence intervals.

A.3.1 Historical Extreme Tidal Events

Storm surge events reaching Philadelphia are plotted by NOAA, and here reproduced as Figure A-8, based upon the combined tidal gage data recorded at Pier 11 North and Philadelphia (see Figure A-7). It should be noted that the extreme event analysis of Figure A-8 has been performed by NOAA. The 1 year per 100 (red line) is the 1-percent chance tidal flood event which is equal to the 100-year event in terms of recurrence intervals. The yellow line is the 10-year event, the green line is the 2-year event, and the blue line is the 1-year event. Storms associated with some of the greater tidal surge events have been noted on Figure A-8. The Great Appalachian Storm of 1950, the unnamed event of November 28, 1993 (approximate 10-year tidal surge event), and Hurricane Sandy are discussed in greater detail in the following sections.

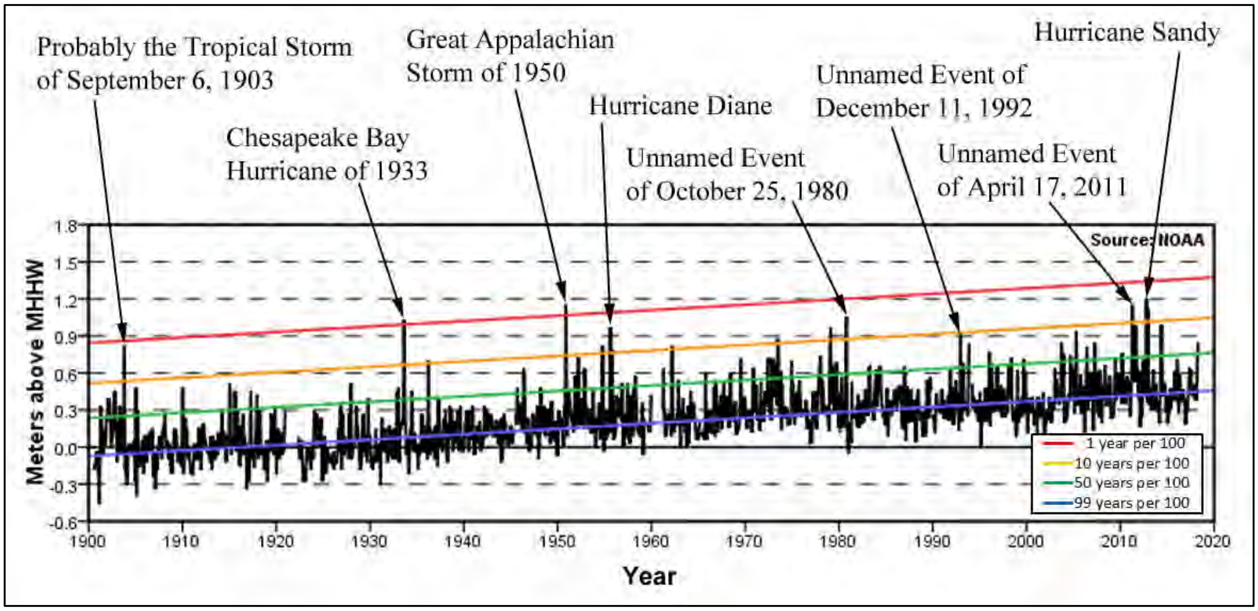

Figure A-8: Extreme Water Levels at Philadelphia
(Source: NOAA 2020a, modified by AKRF)

The three worst storm surge events relative to mean higher high water (MHHW) at the time of the storm[6], all occurred 69-117 years ago. The event that occurred in the first decade of 1900 was probably the so-called "Vagabond Hurricane," a tropical storm that hit the New Jersey coast on September 6, 1903 (ACP 2019, CBS 2011). The next unusual tidal surge event was a result of the "Chesapeake Bay Hurricane" (NWS 2012) of August 23-24, 1933. According to NOAA (Figure A-8), this storm produced the second highest recorded exceedance of tidal surge above MHHW at Philadelphia.

The highest recorded exceedance of tidal surge above mean higher high water at Philadelphia was the "Great Appalachian Storm of 1950" (NWS 2020) that occurred on November 25. The highest recorded tide elevation at Philadelphia was 1.199 meters above MHHW, caused by Hurricane Sandy.

A.3.2 Historical Events Adjusted for Sea Level Rise

As indicated on Figure A-8, sea level at Philadelphia has been rising over the gage period of record. This means that if storms like the Great Appalachian Storm of 1950 were to occur today or at some

[6] Mean higher high water is the average of the higher of the two high tides that occur each day. As evident on Figure A-8, MHHW has been increasing over the tidal period of record at Philadelphia.

point in the future, their surge would be added to a higher mean sea level, resulting in correspondingly increased tidal surge elevations.

Historical sea level rise at Philadelphia has been measured at gages 8545530 (Pier 11 North) and 8545240 (Philadelphia). The historic rate of increase has been fairly linear at about one foot per century (see Figure A-9). The sea level rise rate of Figure A-9 provides the basis for the adjustments of Section A3.5 and one of the future sea level rise projections of Section A3.6.

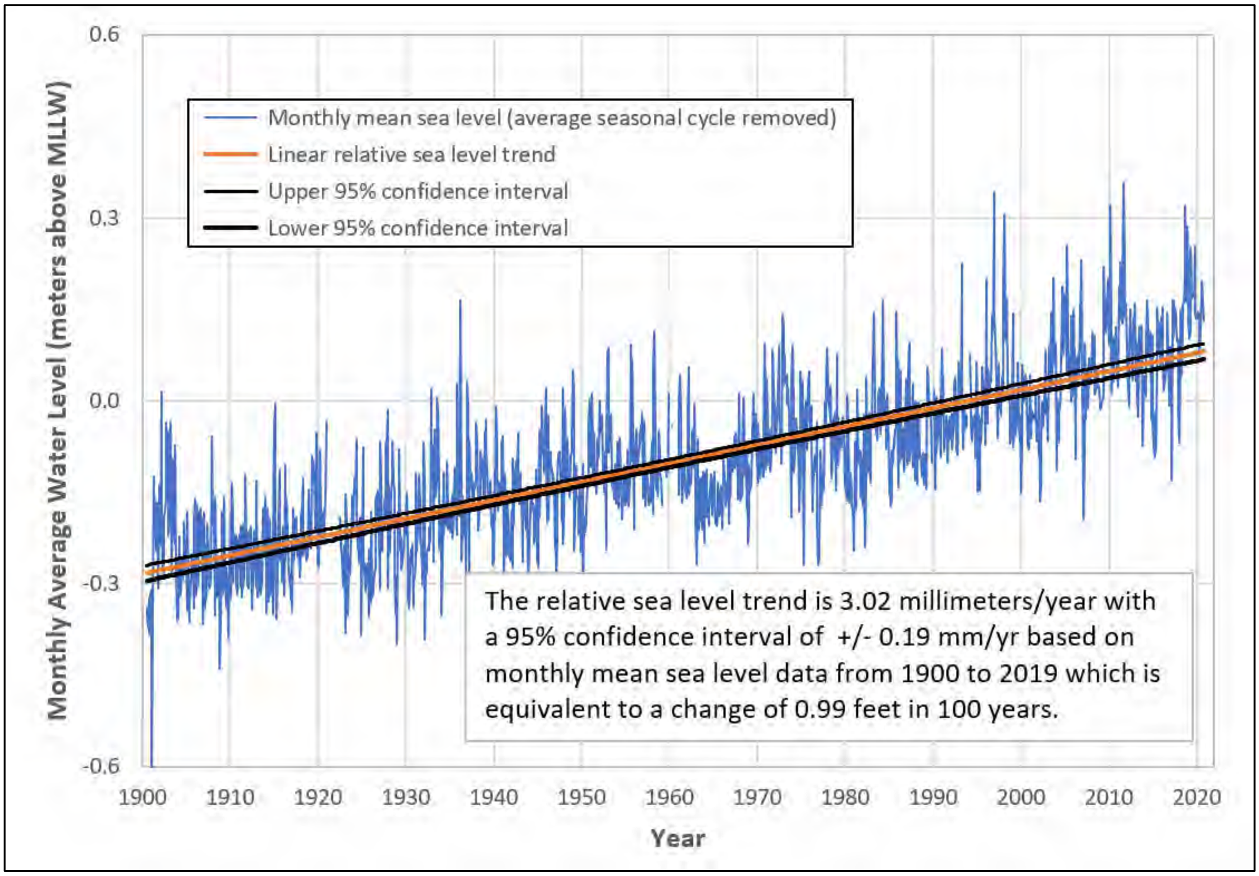

Figure A-9: Sea Level Rise at Philadelphia
(Source: NOAA 2020a, modified by AKRF)

A.3.3 Tropical Storm Isaias

A large number of river stage gages were available to record tide elevations in the vicinity of Eastwick during Tropical Storm Isaias. Of these, ten were used to provide model boundary condition or calibration data. These gages are shown in Figure A-10 and their information is given in Table A-3 below.

Table A-3: Tide Gage Information

Gage ID	Operator	Station ID
Bridesburg	NOAA	8546252
Philadelphia	NOAA	8545240
Schuylkill River	USGS	01474501
Fort Mifflin	USGS	01474703
Darby Creek	USGS	01475553
Marcus Hook	NOAA	8540433
Delaware Memorial Bridge	USGS	01482100
New Castle	USGS	01482170
Delaware City	NOAA	8551762
Reedy Point	NOAA	8551910

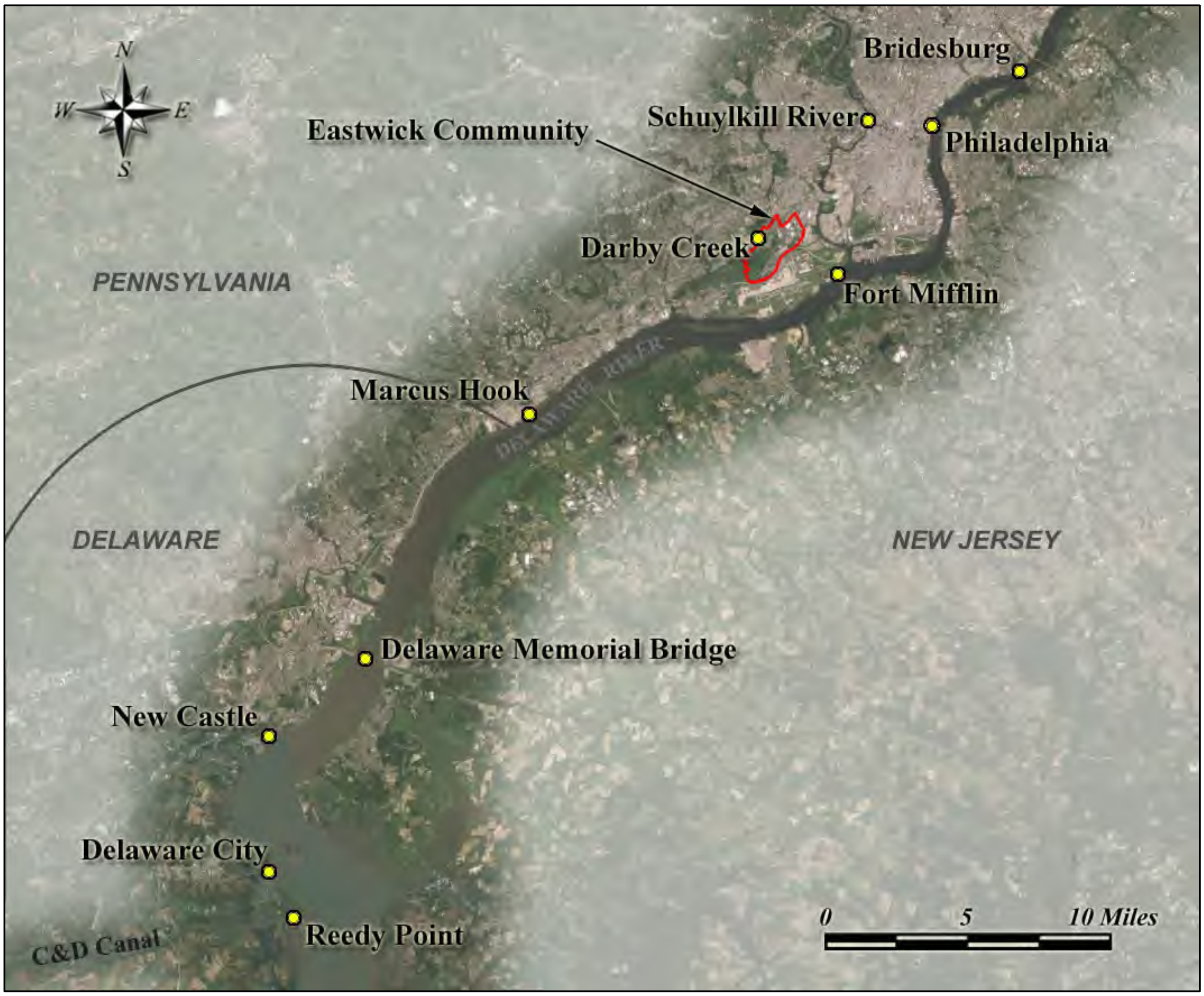

Figure A-10: Tide Gages with Available Data During Tropical Storm Isaias

Gages data is reported in feet relative to the North American Vertical Datum of 1988 (NAVD88) for the Philadelphia, Schuylkill River, Darby Creek, Marcus Hook, Delaware Memorial Bridge, New Castle, and Reedy Point gages. Gage data at Bridesburg and Delaware City are reported in feet relative to local mean sea level and were converted to NAVD88 datum using NOAA's online vertical datum transformation tool, VDatum (NOAA 2020c). Data at Fort Mifflin is available in feet relative to an arbitrary datum and was adjusted vertically to provide a reasonable match to modeled data (these data were only used to compare tide curve amplitude and shape).

Plots of tide elevation versus time are given in Figure A-11. Reedy Point is the downstream Delaware River tide gage, Marcus Hook is centrally located on the Delaware River, and Philadelphia is the key upstream tide gage used in this analysis. As Figure A-11 shows, the time between tides (high tide to high tide at a location) is just over 12 hours (12 hours and 25 minutes). Given that tides propagate inland from the sea, high tide (as well as low tide) occurs a few hours later at Philadelphia as compared to Reedy Point. The average tidal amplitude (high tide minus low tide) during Tropical Storm Isaias was about 6-7 feet at these stations.

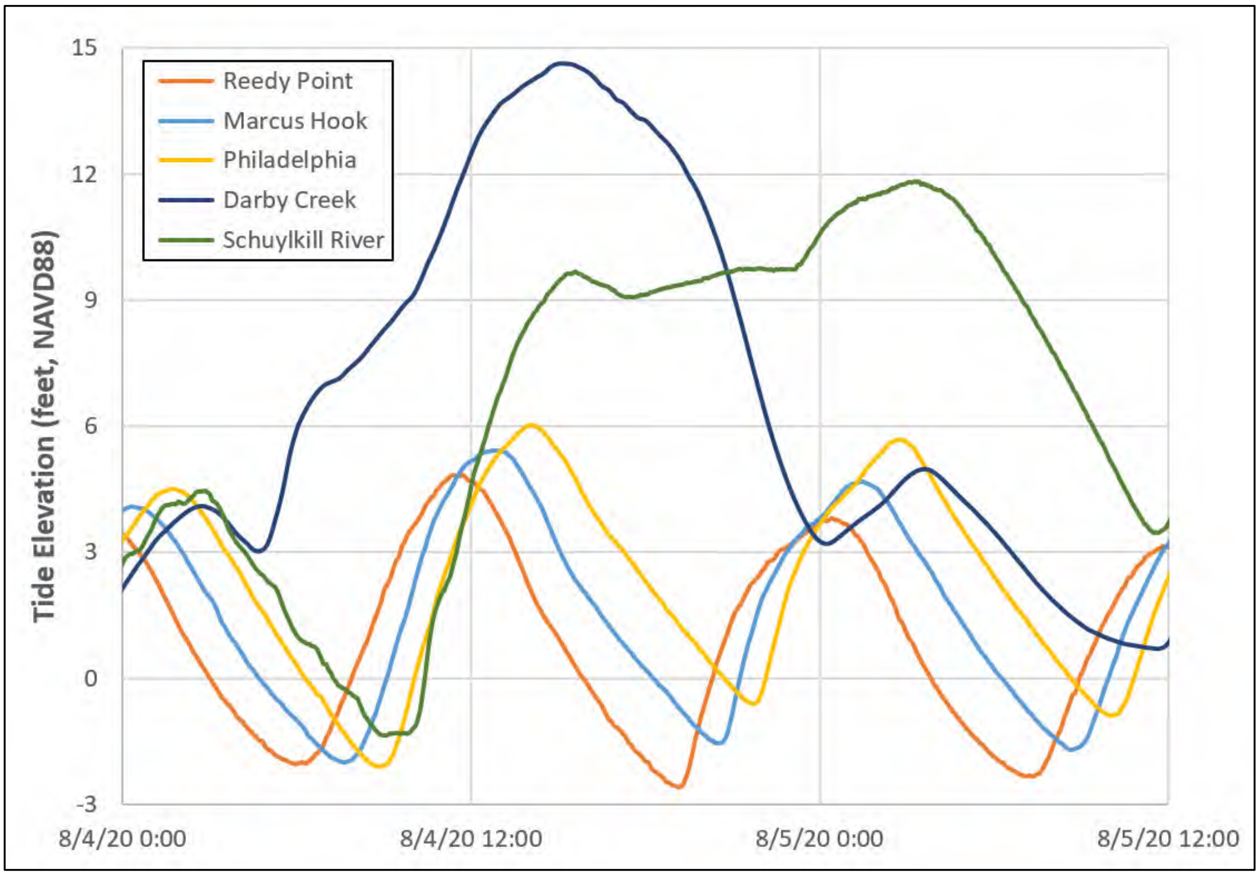

Figure A-11: Stage at Selected Tide Gages During Tropical Storm Isaias

Darby Creek and Schuylkill River tides are also plotted on Figure A-11. In the early hours of August 4, 2020, Darby Creek tide is similar to Marcus Hook tide with the exception that it lags by a few hours. This correlation is evident again for higher Darby Creek tide levels in the earlier hours of August 5, 2020. In between these times, Darby Creek stage rises dramatically to nearly elevation 15 feet, NAVD88. This increase reflects the large amount of streamflow caused by runoff from Tropical Storm Isaias rainfall. A similar pattern can be observed for the Schuylkill River gage, with the exception that its peak stage occurs about 12 hours later due to the greater lag in the Schuylkill River watershed as compared to that in the Darby Creek and Cobbs Creek watersheds (see Section A2.3.2 for further discussion on this).

A.3.4 Hurricane Sandy

Hurricane Sandy tide elevation data is plotted on Figure A-12 for Reedy Point, Marcus Hook and Philadelphia. USGS tide stations at Darby Creek and the Schuylkill River did not come online until later and no data was available during the period. Hurricane Sandy produced the highest tide elevation recorded to date at the Philadelphia gage at 7.52 feet, NAVD88 (1.2 meters above MHHW – also see Figure A-8).

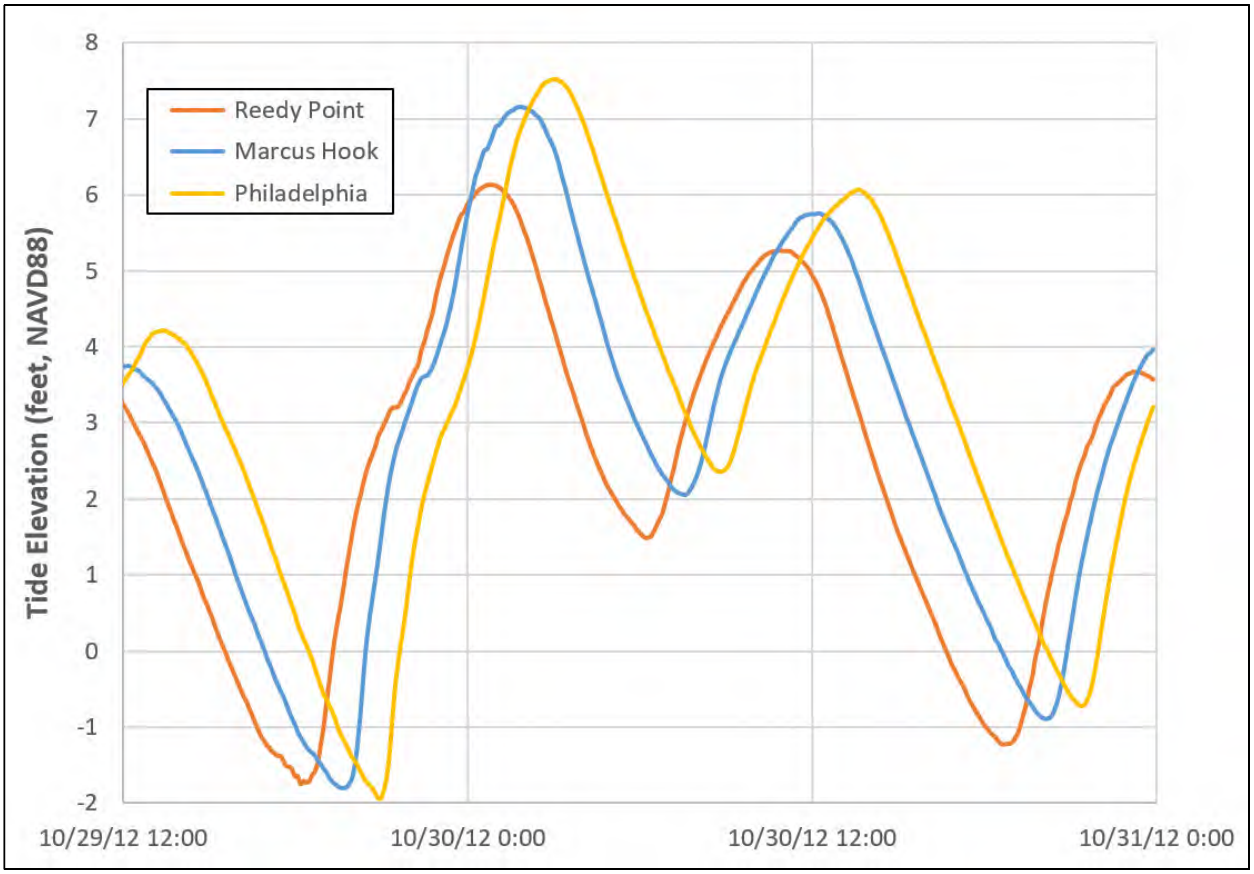

Figure A-12: Stage at Selected Tide Gages During Hurricane Sandy

A.3.5 Great Appalachian Storm of 1950 Adjusted to 2020

Tide stage data are not available for the Great Appalachian Storm of 1950 at Philadelphia, Marcus Hook, Reedy Point or any other station within the region shown in Figure A-10 with the exception of hourly stage data at Pier 11 North (see Figure A-7 for location). Accordingly, the Pier 11 North data was used and tide data was estimated at Marcus Hook as described in this section.

As documented in Section A.3.2, sea level has risen at a rate of approximately 3.02 mm/year over the 70 years that have elapsed since the Great Appalachian Storm of 1950 occurred. This results in an increase in sea level of approximately 0.21 meters or 0.69 feet. Figure A-13 shows the tidal stage graph for the Great Appalachian Storm of 1950 and the values adjusted for sea level rise (SLR) by 0.69 feet to indicate the tidal surge that would occur should the same event occur today (all other factors, such as conveyance, being equal).

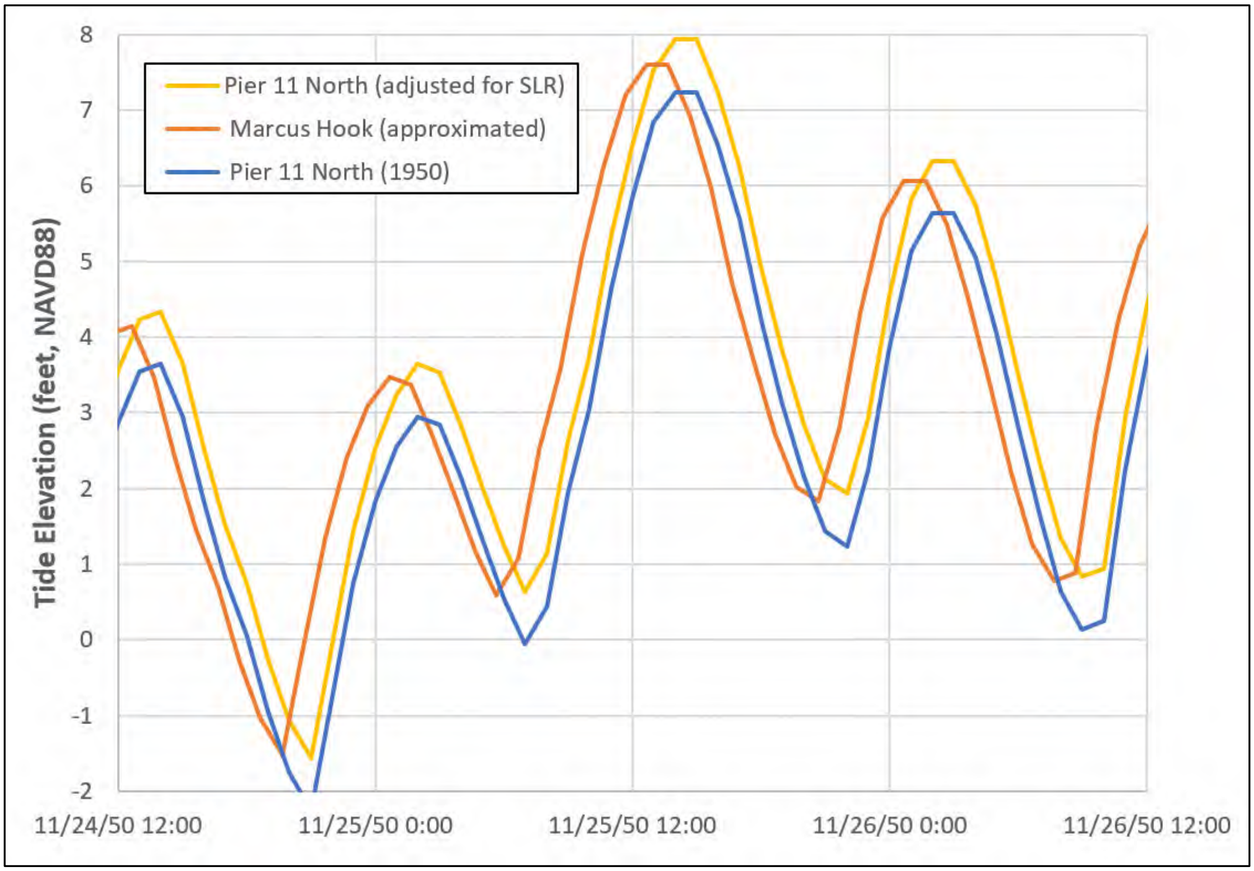

Figure A-13: Stage at Selected Tide Gages During the Great Appalachian Storm of 1950

Tidal data is required at Marcus Hook since it is a boundary condition for the predictive flood model for the 1950 storm conditions. See Attachment B – Existing Conditions for additional discussion and analysis.

Marcus Hook tide data was estimated by transforming Pier 11 North data. The transforms were determined from Hurricane Sandy tide data using the Philadelphia station as a surrogate for Pier 11 North. Hurricane Sandy was used because, of all the major storms evaluated, that storm resulted in the least drop in peak tide elevation with respect to Philadelphia. Using Hurricane Sandy to estimate Marcus Hook is therefore conservative in terms of the Eastwick flood evaluation because it results in higher flood levels. Drop in flood levels between tide stations is further discussed in Section A5.0.

The transform procedure is as follows:

1. Plot Hurricane Sandy tide data at Marcus Hook and Philadelphia (see Figure A-12).
2. Apply transforms for lag, scale and vertical translation to the Philadelphia data until a reasonable match is achieved at Marcus Hook.
3. Apply the transforms to the 1950 Pier 11 North data to approximate 1950 Marcus Hook tide.

This procedure resulted in final values of 80 minutes for lag, a scale of 96% and a vertical shift of -0.05 feet. The final Hurricane Sandy calibration is shown in Figure A-14.

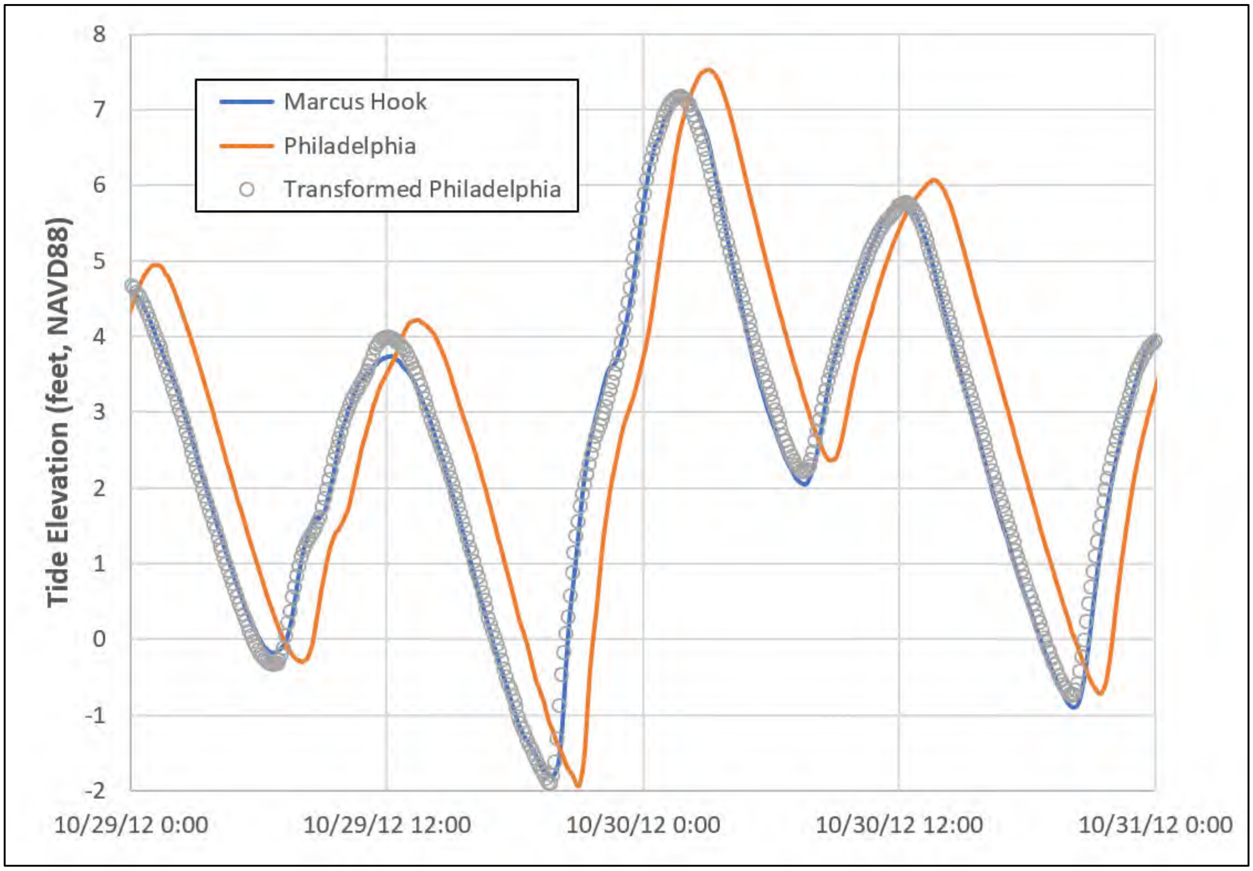

Figure A-14: Approximation of Marcus Hook Gage Data using Philadelphia Gage Data

A.3.6 Approximate 10-Year Surge Event

The 10-year tidal surge event is approximated as the unnamed event of December 11, 1992 based on its peak tide elevation of 6.63 feet, NAVD88 at Philadelphia (see Figure A-8). Like the Great Appalachian Storm of 1950, the storm was adjusted for SLR by adding the rate of 3.02 mm/year over the 28 years that have elapsed since November 28, 1993. This results in an increase of approximately 0.085 meters or 0.28 feet for an adjusted peak tide elevation of 6.91 feet, NAVD88. Data at Marcus Hook was approximated using the transform method described in Section A.3.5.

A.4.0 Internal Runoff

Within Eastwick, rainfall was converted to runoff using the Natural Resources Conservation Service (NRCS) methods described in National Engineering Handbook (NEH) Part 630 (USDA 2020a).

A.4.1 Drainage Areas and Application Points

Because the model assumes that storm sewer flow is minor compared to extreme event flood flows, the effect of individual storm sewer inlets was ignored. Instead, the model takes the approach of applying drainage over a larger area, with its limits defined by surface topography (not storm sewer networks), and allowing it to drain topographic low points in the two-dimensional HEC-RAS model. The gross effect of storm sewers is simulated in the model by removing flow from the topographic low points (this is described in detail in Attachment B).

Figure A-15 shows twelve areas that drain to local topographic low points in Eastwick.

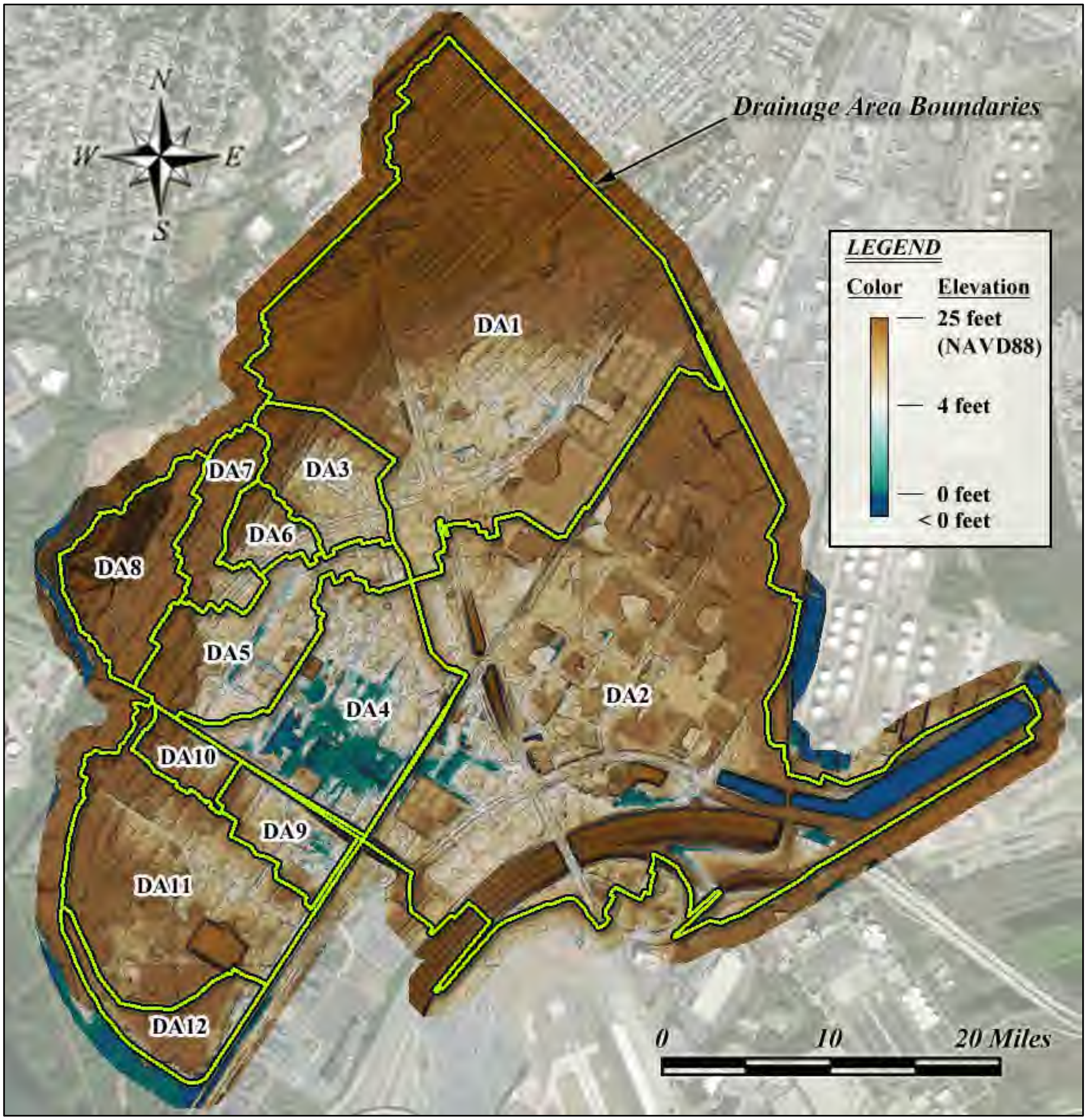

Figure A-15: Eastwick Internal Drainage Areas

A.4.2 Land Use, Curve Numbers, and Concentration Times

In accordance with the NRCS methods, runoff soil loss parameters were determined from land use and soil properties. Soils are mapped by NRCS (USDA 2020b) as Made Land (Clearview Landfill) or Urban Land. Made land has a hydrologic soil group (HSG) classification B (moderate infiltration rate) and Urban Land does not have an assigned HSG classification. HSG classification C (slow infiltration rate) was assumed for Urban Land soils because the soils within Eastwick were reportedly a mixture of marsh material and hydraulic fill (dredge disposal) (IS 2019).

Curve numbers were determined upon land use, as defined by the City of Philadelphia's mapping of impervious surfaces (OpenDataPhilly 2020) and by assignment of percent wooded, open space and bare soil for non-impervious surfaces. This assignment was made based upon current orthophotography (ESRI 2020). Composite curve numbers were computed for each drainage area in GIS based upon polygons of soil HSG classification, land use, and their unique corresponding NRCS CN values. Land use, in terms of NRCS CN values, is shown in Figure A-16 and the composite values are given in Table A-4.

Time of concentration (the time required for runoff to travel from the hydraulically most distant point in the drainage area to the outlet) was computed for each drainage area in accordance with the methods described in NEH Part 630, Chapter 15. Flow concentration pathways were delineated on the project topography (see Figure A-15) and flow types, surface conditions, and surface grades were estimated from project topography and orthophotographs.

Table A-4: Internal Runoff Hydrologic Parameters

Drainage Area ID	Area (Acres)	CN	Tc (hrs)
DA1	409.5	94	1.0
DA2	550.6	93	1.0
DA3	43.9	84	0.6
DA4	107.2	87	0.6
DA5	70.1	93	0.6
DA6	17.5	84	0.4
DA7	30.3	90	0.6
DA8	56.2	86	0.4
DA9	29.9	87	0.4
DA10	16.9	93	0.3
DA11	136.0	93	0.8
DA12	33.2	93	0.6

Figure A-16: Eastwick Internal Drainage Land Use

A.4.3 Rainfall Distribution and Runoff

Because Eastwick is heavily urbanized, the timing between rainfall and peak runoff is relatively short with times of concentration an hour or less (Table A-4). A much more important factor affecting the timing of runoff is the actual occurrence and timing of rainfall. The following subsections describe the actual distribution of rainfall for each storm and its corresponding runoff, as determined using NRCS methods.

Hourly rainfall data was obtained for Philadelphia International Airport (NOAA 2020a) and used to develop cumulative distribution curves for unit hydrograph computation. Cumulative percent rainfall and resulting NRCS hydrographs are plotted for each major terrestrial storm event of this analysis in Figure A-17. Table A-5 gives the total rainfall for each storm event.

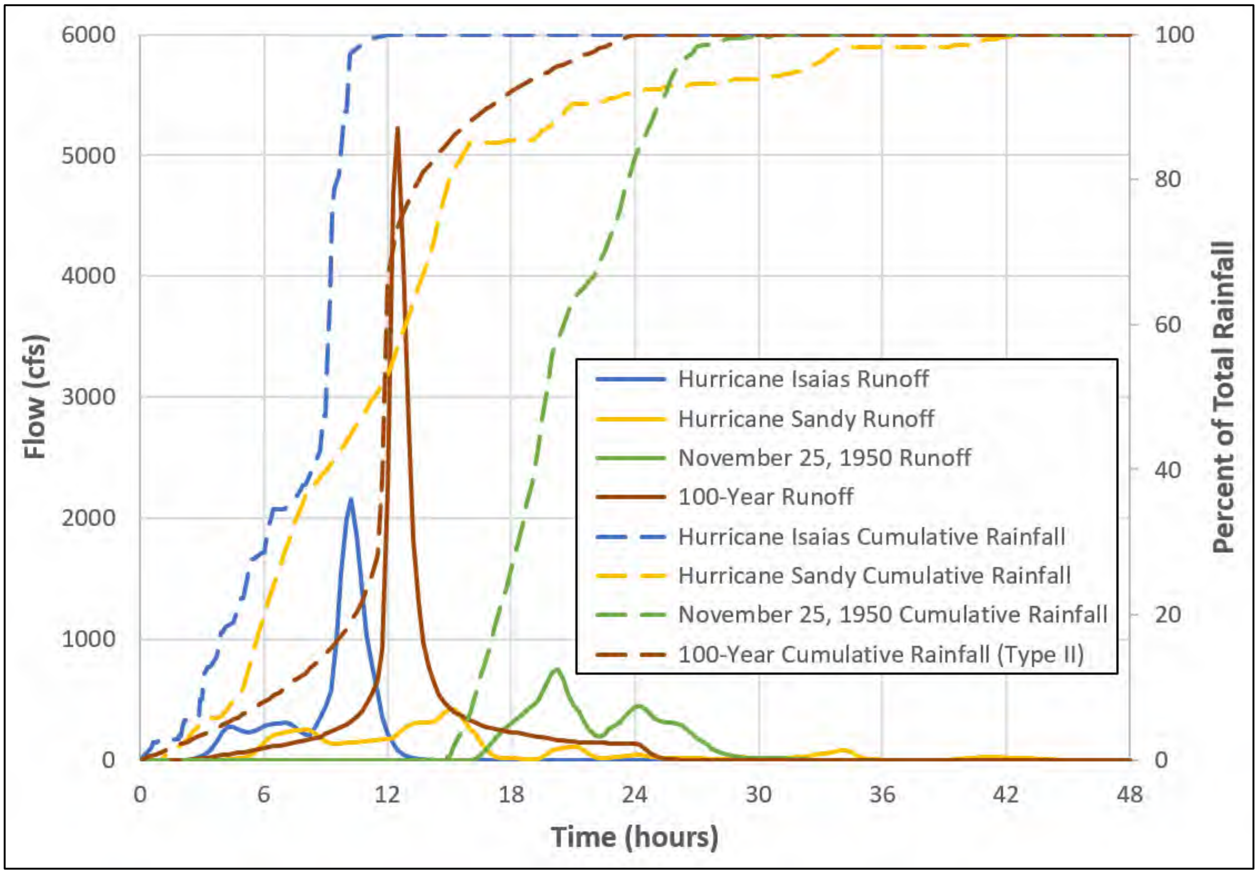

Figure A-17: Internal Runoff and Rainfall Distributions

Table A-5: Total Rainfall at Philadelphia International Airport for Selected Events

Event Name	Rainfall (inches)
Great Appalachian Storm of 1950	3.46
Tropical Storm Isaias	4.16
Hurricane Sandy	2.94
100-year	7.70

The distribution for the 100-year event was assumed to be the NRCS Type II rainfall distribution. The precipitation total for the 100-year event was obtained from NOAA's online Precipitation Frequency Data Server application (NOAA 2020d) at the Philadelphia International Airport (Latitude: 39.8737°; Longitude: -75.2315°) for a 24-hour duration.

A.5.0 Joint Occurrence of Events

This section considers the likelihood of tidal surge and terrestrial runoff flood events occurring simultaneously. Rather than a formal statistical analysis of joint probability, a more pragmatic approach is followed by which historical extreme events of both types (tidal surge and terrestrial runoff) are considered and a semi-quantitative analysis is performed.

A.5.1 Characterization of Delaware River Peak Tidal Elevations and Flow

Peak tidal elevations at Philadelphia are a function of tidal surge emanating upriver from the Atlantic Ocean, atmospheric forces of wind and pressure, and runoff from the Delaware River watershed. The plot of exceedances of tidal surge above MHHW at Philadelphia given as Figure A-8 shows graphically all extreme tidal events recorded at Philadelphia. Tidal exceedances are defined in terms of elevation above MHHW at the time of the storm (see footnote 5 in Section A3.1).

Table A-6 lists the height of peak tide above MHHW as obtained from the station data for the 16 greatest events of Figure A-8 with Tropical Storm Isaias also included for reference. Recurrence interval was estimated from the plot of Figure A-8 and it is important to note that it is estimated relative to mean sea level at the time of the event. For example, in Table A-6, the peak tide elevation for Hurricane Sandy is 1.198 meters above MHHW which is less than the peak tide elevation of 1.115 meters above MHHW for the Great Appalachian Storm of 1950. This is because sea level has risen approximately 0.19 meters since 1950 and therefore the 1950 event would have had a peak elevation of 1.31 meters above MHHW had it occurred on October 30, 2012, the date of Hurricane Sandy. Sea level rise is further discussed in Section A6.

Table A-6: Ranked Highest Tidal Exceedances at Philadelphia

Rank	Date	Meters above MHHW	Rec. Int. (years)	Storm Name
1	11/25/1950	1.115	152	Great Appalachian Storm (nor'easter)
2	8/24/1933	0.987	97	Chesapeake Bay Hurricane
3	9/6/1903	0.825	76	Probably the “Vagabond Hurricane”
4	8/13/1955	0.963	36	Hurricane Diane
5	10/30/2012	1.198	31	Hurricane Sandy
6	10/25/1980	1.051	30	Unknown
7	4/16/2011	1.149	23	Unnamed nor'easter
8	12/21/2012	1.117	18	Winter Storm Draco
9	2/26/1979	0.951	16	Unknown
10	10/15/1954	0.810	13	Hurricane Hazel
11	3/21/1936	0.704	11	Unknown
12	10/17/1955	0.780	10	Unknown
13	12/11/1992	0.920	9	December 1992 Nor'easter
14	6/30/1973	0.816	8	Unknown
15	8/27/2011	0.985	8	Hurricane Irene
16	3/8/1962	0.749	7	Ash Wednesday Storm of 1962 (nor'easter)
-	8/4/2020	0.743	2	Tropical Storm Isaias

Because Marcus Hook is a downstream boundary, for which no gaging station data existed in 1950, it is necessary to estimate the peak tide elevation for the Great Appalachian Storm of 1950. The peak tide elevation is a result of the combined effect several factors including tidal surge, atmospheric forces, and runoff. Rather than attempting to evaluate these forces, historic events were evaluated to conservatively estimate the 1950 Marcus Hook peak tide elevation.

Figure A-18 shows profiles for peak tides of several of the events from Table A-6 for which data was also available at Marcus Hook, Reedy Point, and Lewes (see Figure A-7). As the figure shows, the least drop in maximum tide elevation between Philadelphia and Marcus Hook occurred during Hurricane Sandy, indicating that, of the events evaluated, the combined effect of tidal surge, atmospheric and runoff during Hurricane Sandy resulted in the worst case at Marcus Hook with respect to Philadelphia. Accordingly, this event was used for the transform procedure documented in Section A3.5.

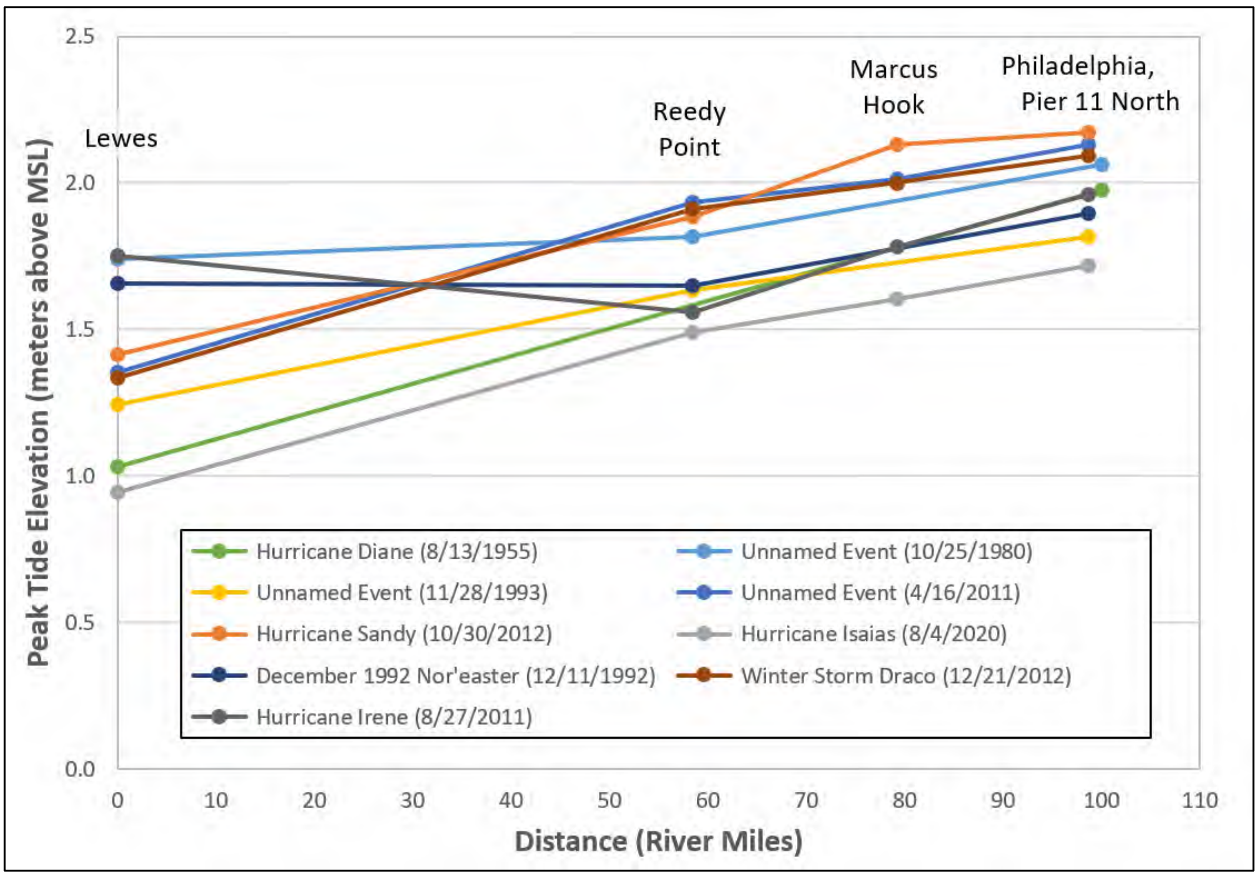

Figure A-18: Delaware River Peak Tide Profiles for Selected Floods

A.5.2 Correlation of Schuylkill River Flow and Delaware River Tide

The joint occurrence of high Delaware River tide elevations and Schuylkill River flows could result in floodwaters emanating from the Schuylkill River and flooding the Eastwick community from the east. The period of tidal stage record at the USGS gage named "Schuylkill River near

30th Street Station" is too short to allow proper extreme event analysis of tidal flooding in the Schuylkill River (4 years of data, USGS 2020d). Instead, the approach taken here is to evaluate the joint occurrence of Schuylkill River extreme flow events and Delaware River extreme tidal events.

Figure A-6 shows the HEC-SSP analysis of Schuylkill River noting largest events. The joint occurrence of extreme tidal events in the Delaware River with extreme flow events in the Schuylkill River can be evaluated by comparing Table A-6 and Figure A-6. The most extreme tidal event on Table A-6 is the Great Appalachian Storm of 1950 which had an estimated tidal surge recurrence interval of 152 years. The Schuylkill River peak flow (89,800 cfs as reported in the station's annual peak data and shown on Figure A-6) recurrence interval for this event, as estimated from Figure A-6, is 17 years. The actual flow that occurred at the time of peak tide during this event is unknown.

The second ranked event of Table A-6, the Chesapeake Bay Hurricane of 1933 is estimated as nearly a 100-year event for tidal surge and slightly more than a 20-year event for peak Schuylkill River peak flow (96,200 cfs as reported in the station's annual peak data and shown on Figure A-6). Again, the actual flow that occurred at the time of peak tide during this event is unknown.

Nothing is known about Schuylkill River flow during the Vagabond Hurricane of 1903, but all the remaining events in Table A-6 had a Schuylkill River peak flow recurrence interval of less than 10-years with the exception of Hurricane Irene which is estimated at 13-years (83,900 cfs as reported in the station's annual peak data).

After January 26, 1986, 30-minute data is available for the USGS Schuylkill River station (USGS 2020d), allowing flow that occurred at peak tide to be directly compared. Comparison of these events (Table A-6, ranks 5, 7, 8, 13, 15, and Tropical Storm Isaias) reveals that the actual flow recorded at the time of peak tide elevation had an estimated recurrence interval of 1-year or less with the exception of Tropical Storm Isaias which was estimated at slightly over 2-years. Furthermore, peak flow occurred an average of 7 hours (range of 1.3 to 13.8 hours) after the time of peak tide. This would indicate that the joint occurrence of peak tide and peak flow discussed above for the Great Appalachian Storm of 1950 and the Chesapeake Bay Hurricane of 1933, would likely have a flow recurrence interval at time of peak tide that is less than (and probably much less than) that of the peak flow reported above. As reported above for Hurricane Irene, the peak flow recurrence interval at the time of peak tide is estimated at 13-years, but the actual flow reported at the time of peak tide is estimated at less than 1-year (17,000 cfs).

In summary, there does not appear to be a strong correlation between extreme tidal peak events in the Delaware River at Philadelphia and peak flow events in the Schuylkill River. The historic worst-case event is the Great Appalachian Storm of 1950, which is one of the events explicitly modeled in this study. Other storms appear to occur at maximum joint occurrences around 10-years or less for either peak tide in the Delaware River or peak flow in the Schuylkill River.

A.5.3 Correlation of Cobbs Creek Flow and Delaware River Stage

The correlation between runoff in Cobbs Creek and Delaware River stage was evaluated using the 15-years of data that exist from October 18, 2005 to the present for the USGS Cobbs Creek at Mt. Moriah gage (USGS 2020a). The analysis could not be performed for the USGS Darby Creek Near Darby gage because only 4 years of data are available. However, Darby Creek is sufficiently similar to Cobbs Creek in terms of flood flows that the Cobbs Creek analysis conclusions presented here can be expected to also apply to Darby Creek.

An extreme event analysis was performed on the Cobbs Creek data to estimate recurrence intervals for peak flows using HEC-SSP Bulletin 17B flow frequency analysis. Daily maximum peak flow recurrence intervals for Cobbs Creek extreme events were plotted against maximum Delaware River tide recurrence intervals (estimated at Philadelphia from Figure A-8). This plot is presented below as Figure A-19.

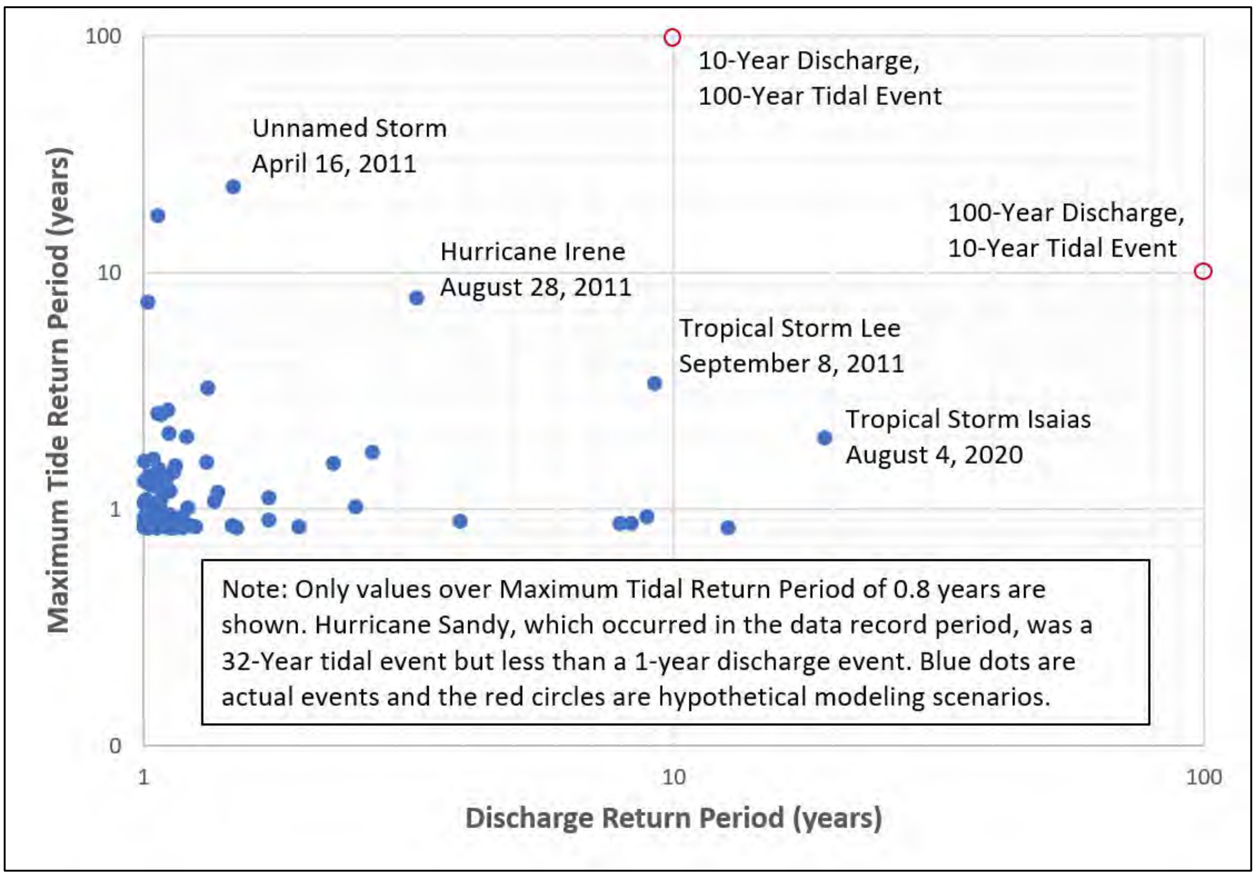

Figure A-19: Return Period Correlation of Cobbs Creek Flow and Philadelphia Stage

As indicated in Figure A-19, there were a number of significant extreme events for both peak tide in the Delaware River at Philadelphia and peak flow in Cobbs Creek over the 15-year analysis period. An unnamed storm on April 16, 2011 had an estimated peak tide recurrence interval at Philadelphia of about 23-years and Tropical Storm Isaias had a peak flow recurrence interval at Cobbs Creek of nearly 20-years. Significant events in between these events included Hurricane

Irene and Tropical Storm Lee. Based upon the analysis of these data, it appears that extreme events of tide at Philadelphia and flow at Cobbs Creek may be somewhat negatively correlated. This may be due to the fact that most, if not all, large storms move from the ocean inland and produce rainfall at a later time than the tidal peak. The lag between peak rainfall and peak runoff at the gage would further tend to offset the runoff peak to a later time than the tidal peak.

A.5.4 Summary of Joint Event Occurrence at Eastwick

On the basis of the analysis and discussion of the above sections, it was concluded that the joint occurrence of the following events is sufficient to bracket the joint occurrence of tidal and runoff events at Eastwick:

- 10-year tidal surge event combined with the 100-year runoff event, and
- 100-year tidal surge event combined with the 10-year runoff event.

These joint events are show with red circles on Figure A-19. This evaluation conservatively considers the Great Appalachian storm of 1950 to meet the first Criterion. The second criterion is evaluated using the unnamed event of December 11, 1992 from Figure A-8 in combination with 100-year runoff events described in Sections A2 and A4.

A.6.0 Sea Level Rise and Climate Change Conditions

Sea level has been rising in the Atlantic Ocean, resulting in a corresponding rise in the Delaware River estuary. In addition, rainfall patterns have been changing with increased rainfall amounts predicted by climate models. Both of these factors will increase future flooding in Eastwick. This section provides a basis for quantifying the increases to boundary conditions so that increased flooding within the Eastwick community can be assessed.

A.6.1 Projected Sea Level Rise

Figure A-20 shows the historical period of monthly mean sea maximum tide levels at Philadelphia that was presented in Figure A-7, but projections for sea level rise (SLR) are added to the year 2100. The projections are from the Sea Level Trends, Regional Scenarios of the NOAA Philadelphia gage web page (NOAA 2020b). The regional scenarios presented in Figure A-20 are based upon six representative global mean sea level rise scenarios as documented in NOAA Technical Report NOS CO-OPS 083 (NOAA 2017).

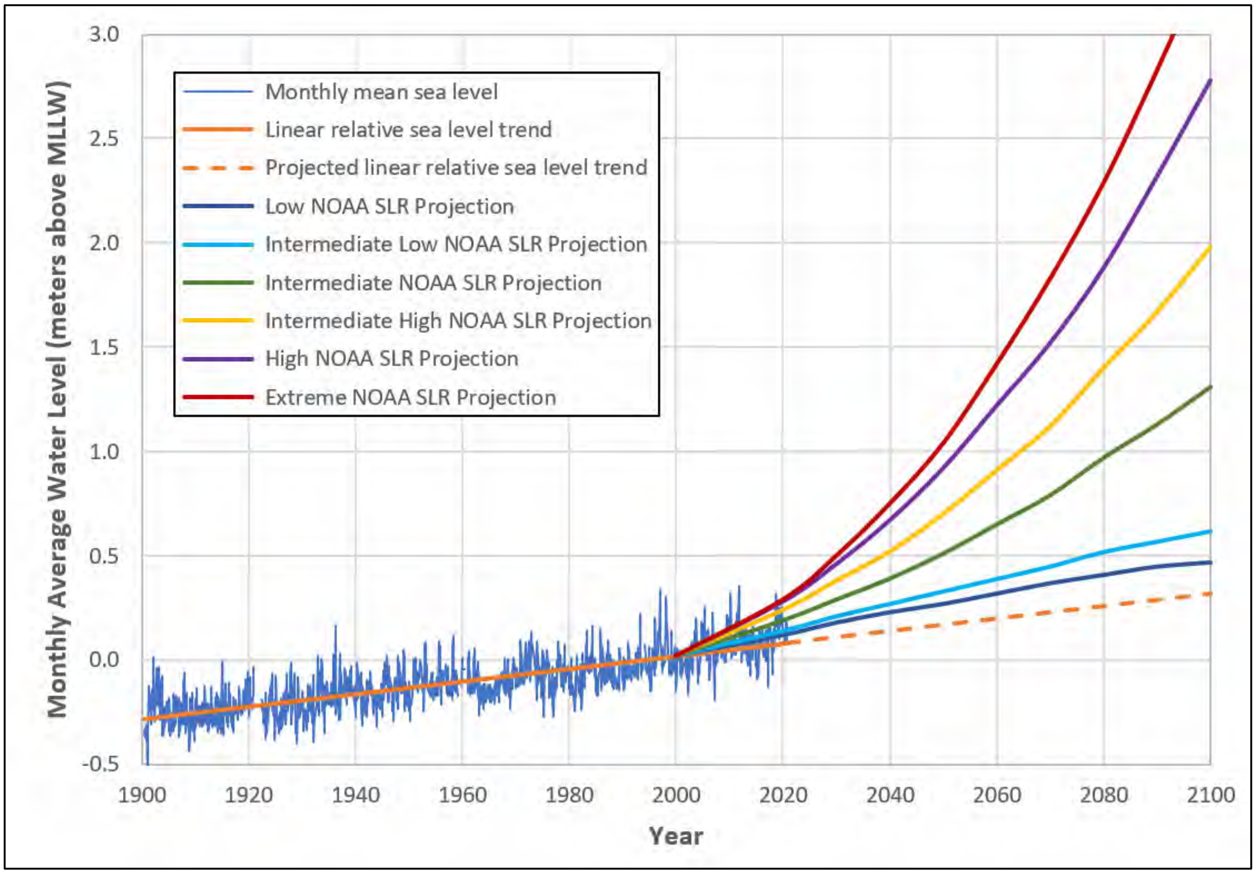

Figure A-20: Historical Sea Level Trend and SLR Scenarios at Philadelphia
(Source: NOAA 2020b)

As Figure A-20 shows, the rise in sea levels over the past 120 years has been fairly linear with no clear recent indication of an increase in the rate of change. This trend, projected out to 2020 on Figure A-20 indicates that there would be a 0.24 meter (0.79 foot) increase in sea level by the end of the century. NOAA SLR projections are all higher.

For this study, the Intermediate NOAA SLR projection of 1.28 meters increase above 2020 mean sea level was chosen for further analysis.

A.6.2 Future Terrestrial Flood and Runoff Event Estimation

Future terrestrial runoff was estimated based upon the results presented in a recent paper in which global climate model precipitation output was statistically downscaled for Philadelphia (Maimone 2019). The paper presents the results of an extreme storm event analysis based on 1900–2016 observed precipitation data at Philadelphia International Airport (current) and adjusted precipitation time series for 2080–2100 (future). Comparison of these two time series results for the 100-year return period indicates that the future 24-hour 100-year rainfall is expected to increase from approximately 193 mm to 212 mm, an increase of approximately 10%.

In accordance with these results, the 24-hour 100-year rainfall amount of 7.70 inches presented in Section 4.3 is increased by 10% percent to 8.47 inches for internal Eastwick runoff analysis. In addition, the 100-year terrestrial flood hydrographs discussed in Section A2.6 were increased by 10% to represent future flooding conditions.

A.7.0 Summary of Existing Condition Events

Tropical Storm Isaias – This event was used for model calibration and also to approximate the 10-year terrestrial event. Upstream flow data was provided by the USGS Schuylkill River, Darby Creek and Cobbs Creek gaging station. Inflows to Cobbs Creek and Darby Creek downstream of the gages was estimated by scaling of the gage data proportional to the drainage areas of the inflows divided by the drainage area of the gage. Runoff generated by precipitation falling within Eastwick was computed using NRCS techniques with the hourly rainfall distribution recorded at Philadelphia International Airport. Upstream tidal data is provided by the NOAA Philadelphia gage and downstream tidal data is provided by the NOAA Marcus Hook gage. Other tidal gaging station are used for calibration data.

100-year terrestrial event – Terrestrial runoff for this event was approximated by scaling Tropical Storm Isaias gage flows at Darby Creek and Cobbs Creek to match 100-year flows estimated in the USACE study. Tropical Storm Isaias gage flows for the USGS Schuylkill River gage were scaled to match the 100-year flow value at that location. Inflows to Cobbs Creek and Darby Creek downstream of the gages was estimated by scaling of the upstream data proportional to the drainage areas of the inflows divided by the drainage area at the gages. Runoff generated by precipitation falling within Eastwick was computed using NRCS techniques with a NRCS 24-hour, Type II rainfall distribution and 7.70 inches of total rainfall. Tropical Storm Isaias upstream tide data at Philadelphia and downstream tide data at Marcus Hook were used for the 100-year terrestrial event.

Hurricane Sandy – This event produced the highest tidal surge recorded at Philadelphia. Upstream runoff was provided by the USGS Cobbs Creek and Schuylkill River gaging stations. Upstream runoff in Darby Creek was estimated by proportionally scaling Cobbs Creek flows according to drainage areas. Inflows to Cobbs Creek and Darby Creek downstream of the gages was estimated by scaling of the gage data proportional to the drainage areas of the inflows divided by the drainage area of the gage. Runoff generated by precipitation falling within Eastwick was computed using NRCS techniques with the hourly rainfall distribution recorded at Philadelphia International Airport. Upstream tidal data is provided by the NOAA Philadelphia gage and downstream tidal data is provided by the NOAA Marcus Hook gage.

Great Appalachian Storm of 1950 adjusted to 2020 – This event produced the highest tidal surge recorded at Philadelphia when adjusted for sea level rise. Since no gage data was available for Darby Creek and Cobbs Creek, upstream flows were estimated by scaling Tropical Storm Isaias flows by the proportion of total rainfall at Philadelphia recorded in the 1950 event divided by Tropical Storm Isaias rainfall. Inflows to Cobbs Creek and Darby Creek downstream of the gages was estimated by scaling of the gage data proportional to the drainage areas of the inflows divided by the drainage area of the gage. Runoff generated by precipitation falling within Eastwick was computed using NRCS techniques with the hourly rainfall distribution recorded at Philadelphia International Airport. Schuylkill River flows were estimated from the recorded peak flow and average daily flow data. Upstream tidal data is provided by the NOAA Philadelphia Pier 11 North gage hourly data. These data were transformed to approximate downstream tidal conditions at Marcus Hook. Both upstream and downstream tide data were adjusted by adding 0.69 feet to account for sea level rise that has occurred since 1950.

<u>100-year terrestrial event estimated at 2100</u> – This is the same as the 100-year terrestrial event except that upstream flows and inflows downstream of gages were increased by 10%. Rainfall used to generate internal runoff was also increased by 10%, resulting in a total 24-hour rainfall amount of 8.47 inches.

<u>Great Appalachian Storm of 1950 adjusted to 2100</u> – This is the same as the Great Appalachian Storm of 1950 adjusted to 2020 with the exception that tidal boundary conditions are increased by historic rates to 2000 and by an additional 1.28 meters to estimate year 2100 conditions.

<u>100-year terrestrial event coincident with 10-year tidal event</u> – The 100-year terrestrial event is the same as discussed above with the exception that the 10-year tidal surge event is approximated as the unnamed event of December 11, 1992. Tide data for that event were used for upstream boundary conditions at Philadelphia and downstream boundary conditions at Marcus Hook. These tidal boundary conditions were adjusted by adding 0.28 feet to account for sea level rise that has occurred since December 11, 1992.

<u>10-year terrestrial event coincident with Great Appalachian Storm of 1950 adjusted to 2020</u> – This event is a combination of Tropical Storm Isaias terrestrial flows and internal runoff, plus tidal conditions described for the Great Appalachian Storm of 1950 adjusted to 2020.

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ATTACHMENT B – EXISTING CONDITIONS FLOOD MODEL

Lower Eastwick
Infrastructure and Flood Evaluation
Hydrology and Hydraulic Modeling

Attachment B
Existing Conditions Flood Model

March 2021

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B.1.0 Introduction

This attachment documents the details of a hydrodynamic model constructed for the purpose of evaluating flooding in the vicinity of parcels owned by Philadelphia Redevelopment Authority (PRA) and the Philadelphia School District. Details of model boundary conditions are described in Attachment A of this report.

The model described here considers land surface conditions as they presently exist within the Eastwick community and the model domain. This means that it is assumed that hard structural solutions are not immediately available to mitigate flooding in the Eastwick community and that flooding will not only continue to pass through the community as it has historically, but that it will also increase in frequency, duration and depth over time. The model does consider the effect that land surface modifications would have on PRA properties and adjacent properties (but this attachment only addresses existing conditions). The model does consider the effects of runoff generated from precipitation falling within Eastwick and it also considers removal of flows from Eastwick by storm sewers. However, these two factors are only considered at a scale suitable for evaluating their effects during extreme flood events and the model cannot be used to predict local runoff conditions or storm sewer performance.

B.2.0 Model Domain and Boundary Conditions

This section begins with a description of how floodwaters enter the Eastwick community and how they are removed. Next, the surrounding flow systems, or pathways by which floodwaters are conveyed to the community, are described. Based upon a conceptual understanding of this system, a description is given of the flow model used in this study that represents the key features of the flow system with sufficient accuracy to evaluate flooding within the Eastwick community.

B.2.1 Description of Flow System

There are three primary sources of flooding in the Eastwick community: runoff from excess precipitation falling within Eastwick, overflow from Cobbs and Darby Creek caused by terrestrial runoff, and tidal flooding. Flooding from these sources often combines in some manner, resulting in worse flooding conditions within the community. Presently, floodwaters are removed from the community by storm sewers and recharge. These flooding factors are illustrated in Figure B-1 below. There are other potential flooding mechanisms, such as terrestrial runoff in the Schuylkill River and Delaware River; however, these were found to be relatively minor in comparison to those shown in Figure B-1.

There are two primary flow domains which must be considered in evaluating how floodwaters reach and move through Eastwick. These domains can be thought of in terms of near field and far field. The near field domain includes the terrain and flow systems (e.g., storm sewers and roadways) of the Eastwick community itself and the systems affecting the movement of floodwaters at the perimeter of the Eastwick community (e.g., levees[1], channels, Mingo Creek pump station).

[1] This refers to diked landforms. It is our understanding that there are no FEMA-certified levees in Eastwick.

The far field domain is comprised of the flow systems by which flood waters are delivered to Eastwick. This is composed of the Delaware River, Schuylkill River, Darby Creek and Cobbs Creek. Each of these water bodies is theoretically capable of conveying floodwaters to Eastwick emanating from both tidal surge and runoff caused by rainfall.

The flow mechanisms by which floodwaters move in the near field and far field domains are very different and modeled accordingly. One-dimensional flow processes adequately evaluate far field flow in the rivers and creeks, but two-dimensional flow processes dominate within the near field. Because of this difference, the near field and far field model domains are discussed separately, beginning with the far field domain in the following two sections.

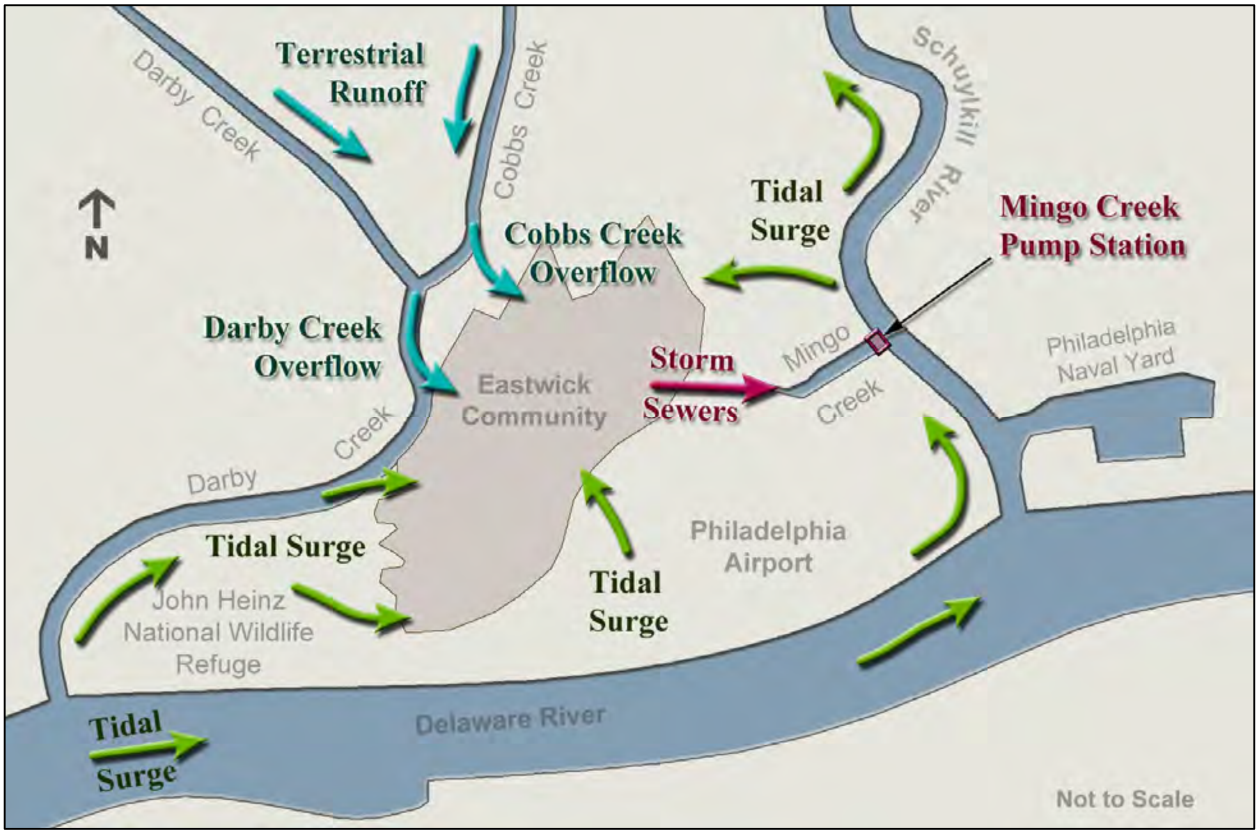

Figure B-1: Concept Sketch of Eastwick Flooding Sources

B.2.2 Far Field Model Domain and Boundary Conditions

The Delaware River is an estuarine waterbody to its upstream "head of tide"[2] which is located just downstream of the USGS streamflow gage at Trenton, NJ (see Figure B-2). Above the head of tide, flooding is mainly caused by extreme flows resulting from runoff caused by precipitation falling in the Upper Delaware River watershed, which covers an area of approximately 7,973 square miles. Downstream of this point, tidal and meteorological forces (mainly wind) also affect flooding.

[2] Head of tide is defined as the farthest point upstream where a river is affected by tidal fluctuations.

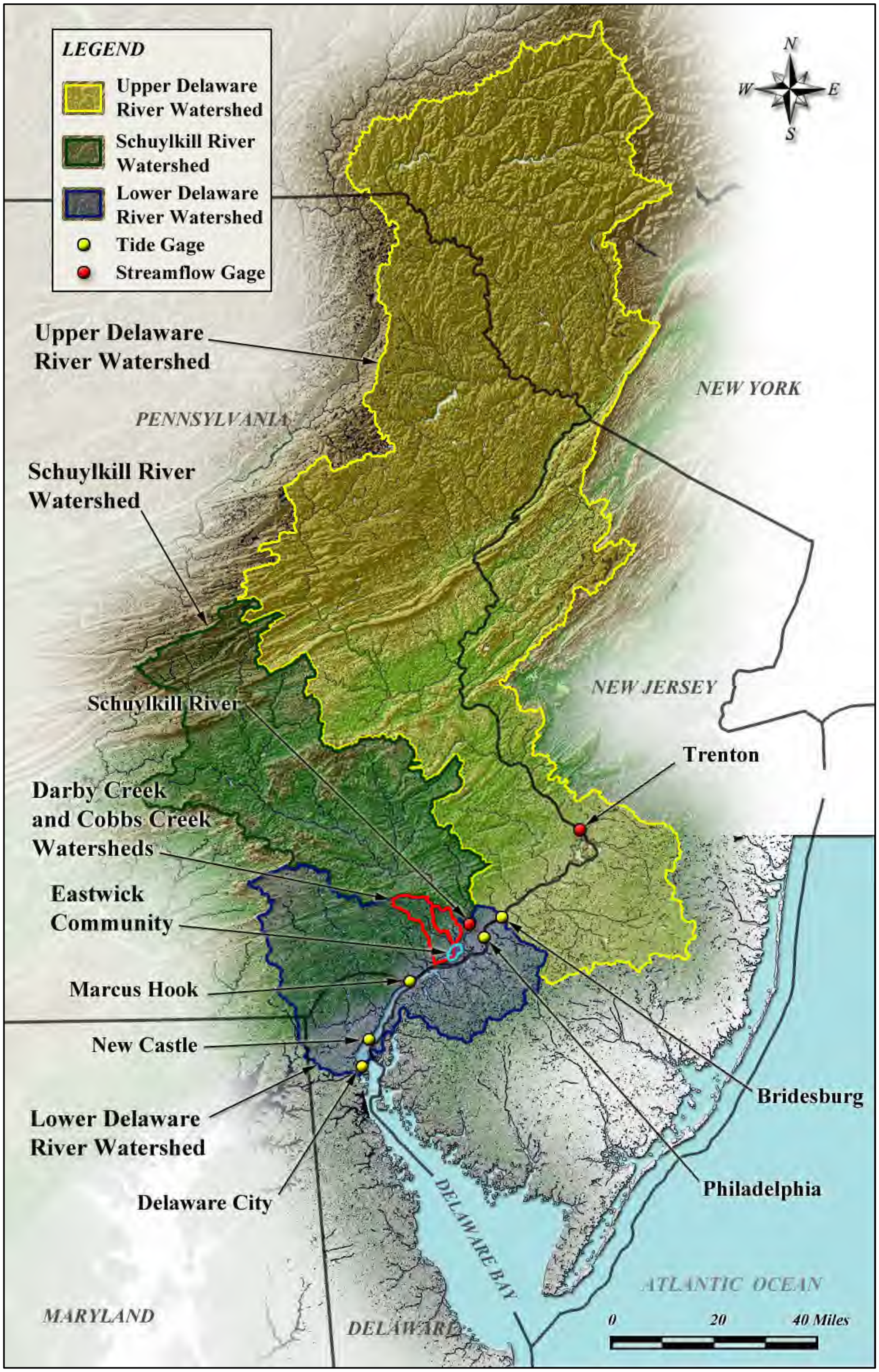

Figure B-2: Major Far Field Watersheds and Gages

The combined effect of these forces (flow, tide, wind, etc.) are fully described for the one-dimensional flow process by the relationship between time and stage provided at a tide gage.

Accordingly, the tide gages at Philadelphia and Bridesburg (see Figures B-2 and B-3) are used as the upstream model boundary. Gages at Delaware City, New Castle and Marcus Hook are used for downstream model boundaries. These boundaries, and their use in the various far field models of this study, are further discussed in Section B6.1.

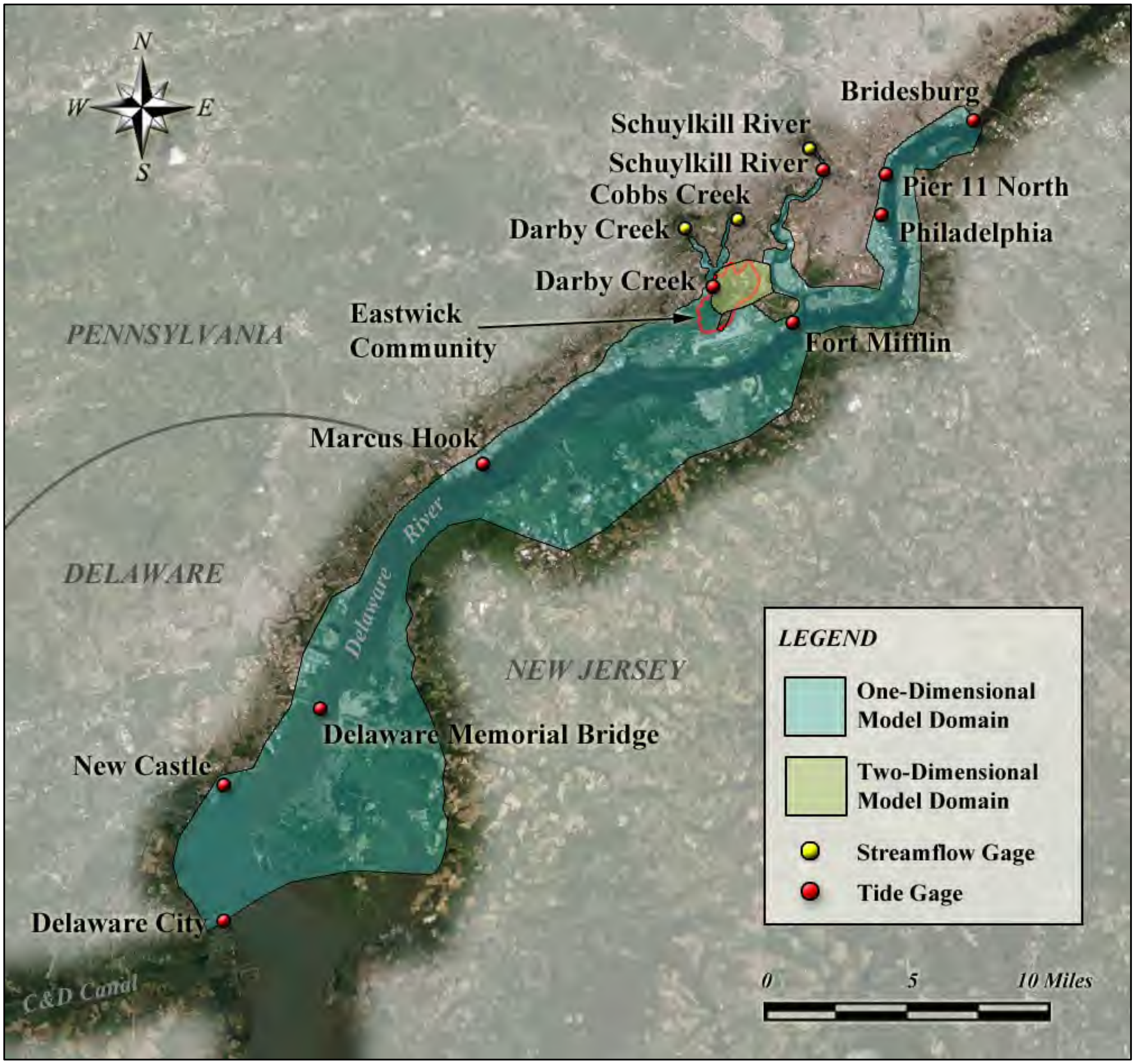

Figure B-3: Model Domains

Flow from the Schuylkill River watershed, which covers an area of approximately 1,893 square miles, is recorded by the USGS Schuylkill River streamflow gage (see figures B-2 and B-3). This gage describes flow at the far field model upstream boundary condition for the Schuylkill River.

Figure B-2 shows the Darby Creek and Cobbs Creek watersheds. A portion of these creeks are used for the far field model domain and are further discussed below. Other tributaries in the Lower Delaware River watershed include Brandywine Creek, Christina River, Chester Creek, and numerous other smaller rivers, streams and creeks. As the modeling described in the next section will indicate, estuarine flows in the Delaware River model domain are dominated by tidal flow emanating from the Delaware Bay. Lower Delaware River watershed inflows are much smaller than combined Upper Delaware River, Schuylkill River and tidal flows and do not have a significant effect upon model results. Lateral inflows to the model from these sources was therefore ignored.

Figure B-3 shows the far field and near field model domains which are labeled (and hereafter also referred to) as the one-dimensional (1D) and two-dimensional (2D) model domains respectively. Upstream boundary condition flow in Cobbs Creek is defined by the Cobbs Creek streamflow gage data and upstream boundary condition flow in Darby Creek is defined by the Darby Creek streamflow gage or simulated from other data. Lateral inflow to Cobbs Creek and Darby Creek is also estimated from gage data. This is discussed further in Section B3 and Attachment A.

B.2.3 Near Field Model Domain and Boundary Conditions

The 2D model domain, shown in Figure B-4, is connected to the far field model domain through boundaries along Cobbs Creek, Darby Creek, the Schuylkill River and overflow from the Delaware River through Philadelphia International Airport. All flow, except for runoff from direct precipitation and simulated storm sewer flow, enters Eastwick through these boundaries.

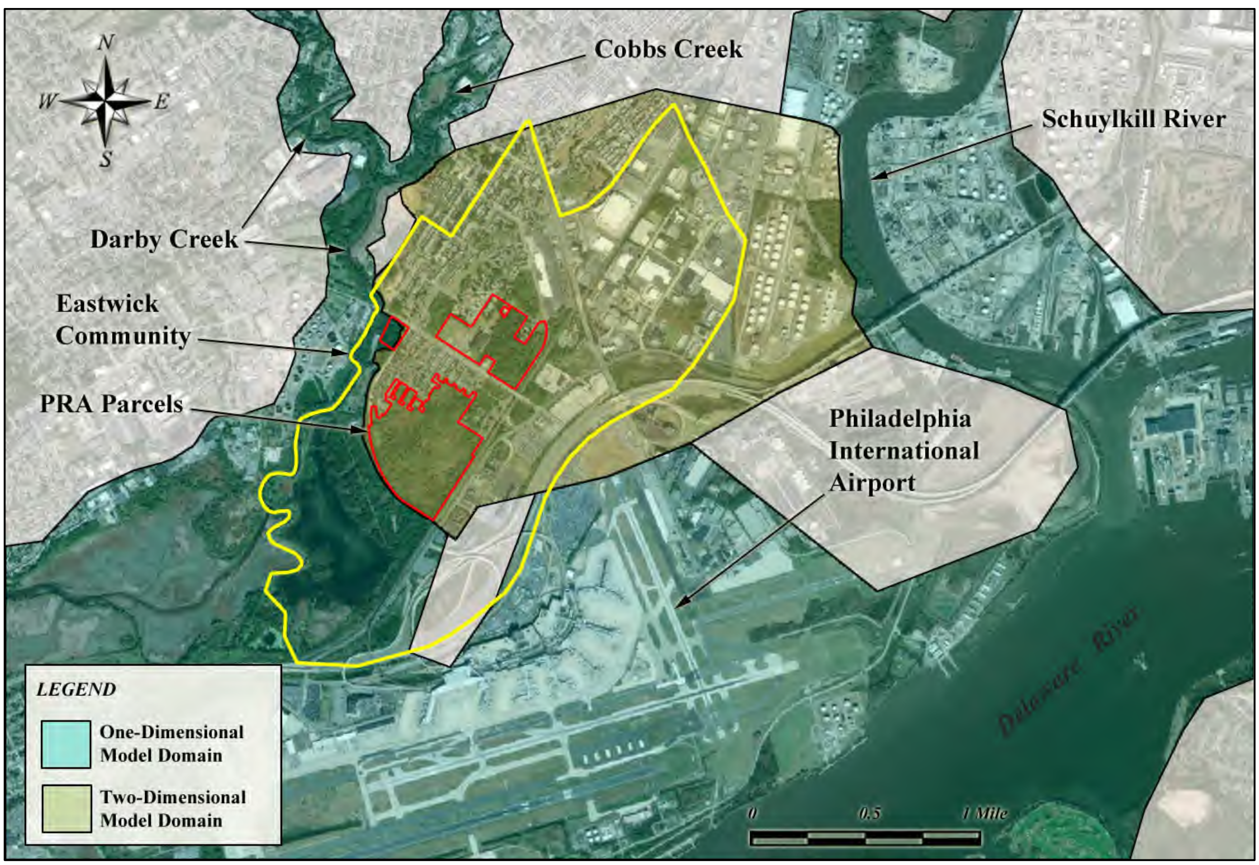

Figure B-4: Model Domains Near Eastwick

B.3.0 HEC-RAS Model and Geometry

The computer model used for the 1D hydrodynamic analysis was the U. S. Army Corps of Engineers, Hydrologic Engineering Center's River Analysis System (HEC-RAS) program (USACE 2019). HEC-RAS's capabilities include computation of unsteady flow simulations using geometry described by reach lengths and bathymetric cross sections, and boundary conditions described by measured stage and flow data. Calibration parameters include channel and floodplain roughness, and expansion and contraction coefficients.

B.3.1 One-Dimensional Model Geometry

Bathymetry data is available from various sources for the Modeled Reach of the Delaware River including National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information's ("NCEI") combined topographic and bathymetric digital elevation model (DEM) data (NCEI 2018) and NOAA Nautical Charts (NOAA 2018). A comparison of the data from these sources indicated that the NCEI data were more detailed in channel areas and the Nautical Charts were more accurate and detailed elsewhere. Accordingly, data were combined from these two sources using the Nautical Chart data as the base information and supplementing it with the NCEI data. The NCEI DEM is shown for the Modeled Reach in Figure B-5.

Also shown on Figure B-5 is the location of the 1D model centerline which was situated along the estimated thalweg of the main channel. Cross sections (see Figure B-5) were placed in accordance with 1D modeling theory to describe representative geometry throughout the modeled domain. In order to model sea level rise conditions, cross sections were extended horizontally until the 5-meter (16.4 feet) contour was reached. This contour is shown in Figure B-5.

The Delaware River portion of the model includes three reaches:

1) Lower Delaware River from the downstream model boundary (this varies – see Section B-1) to the Darby Creek confluence;
2) Middle Delaware River from the Darby Creek confluence to the Schuylkill River confluence; and
3) Upper Delaware River from the Schuylkill River confluence to the upstream model boundary (this varies – see Section B-1).

Tide gages shown in Figure B-5 provide boundary condition and calibration data as further discussed in Section B.1 and Attachment A.

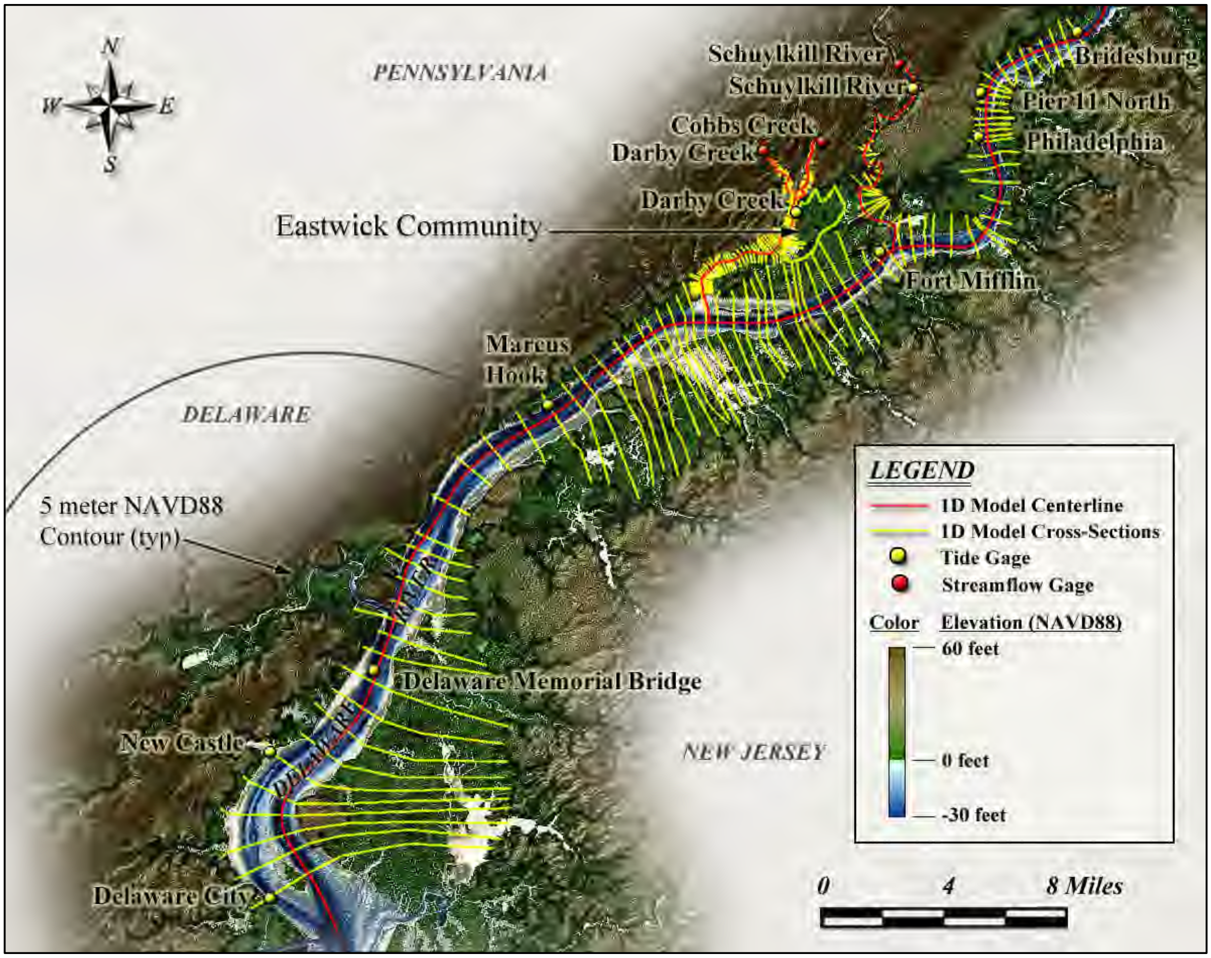

Figure B-5: 1D Model Geometry – Full 1D Domain
(DEM Source: NCEI 2018)

Schuylkill River is modeled as a single reach from its mouth at the Delaware River to the head of tide at Philadelphia Water's Department Fairmount Dam, immediately downstream of USGS's Schuylkill River streamflow gage. There is a tide gage just downstream of the dam at 30th Street Station in Philadelphia that provides calibration data (see Figure B-5).

Schuylkill River bathymetry was obtained from the combined source of the NOAA NECI DEM and NOAA Nautical Charts, with adjustments to invert elevations based on the FEMA FIS profile (FEMA 2019).

The USACE 2014 model (USACE 2014; Moore 2020a) geometry was used for Darby Creek and Cobbs Creek. Model geometry was modified, as appropriate and particularly in Tinicum Marsh downstream of the Darby Creek tide gage, using 2018 LiDAR elevation data (PASDA 2020), bathymetric data (Moore 2020b), and aerial photography (Nearmap 2020). Model geometry was extended from the upstream limit of the USACE 2014 model to the Darby Creek and Cobbs Creek USGS stream gages, which provide upstream boundary condition flows. See Figure B-6 for Darby Creek and Cobbs Creek model sections and gage locations.

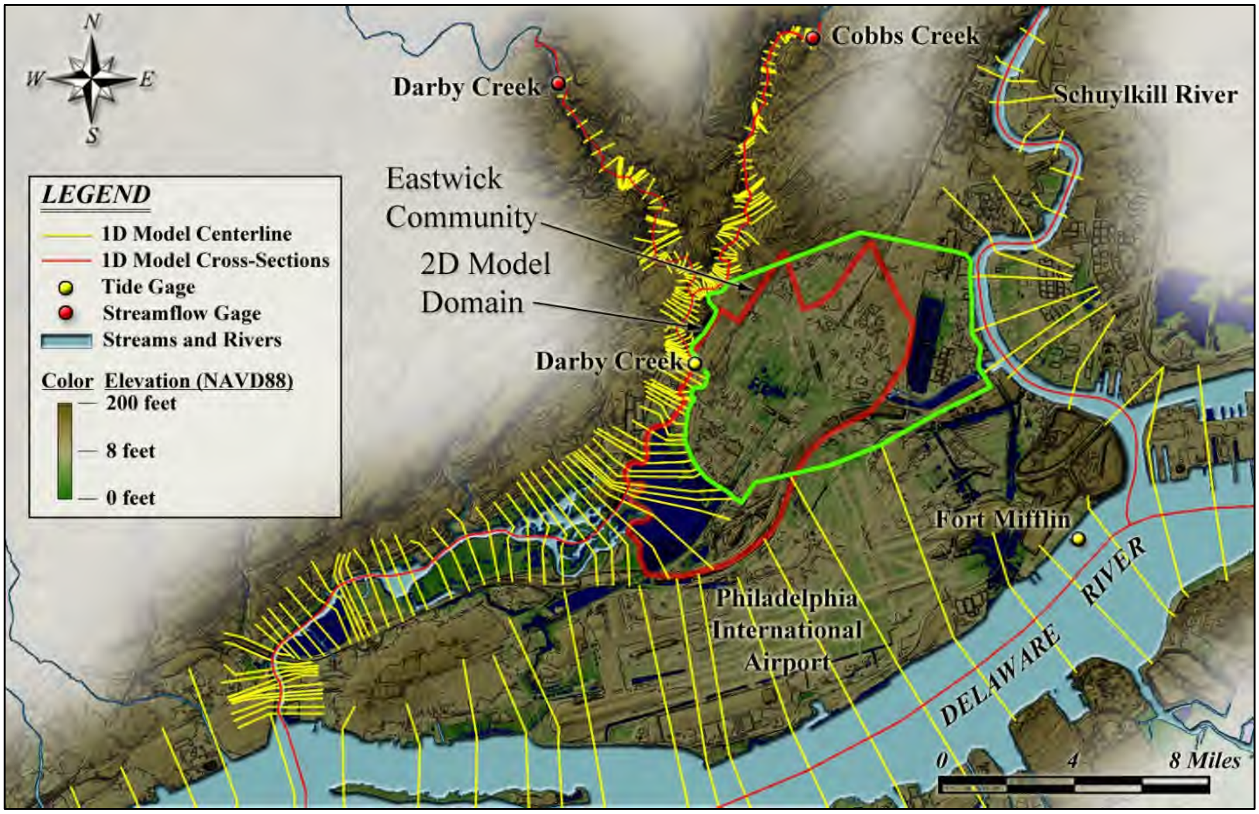

Figure B-6: 1D Model Geometry – Near Eastwick

B.3.2 Two-Dimensional Model Geometry

The HEC-RAS two-dimensional (2D) connects to the 1D model by levee flow between the ends of the 1D cross sections intersecting the 2D model boundary (see Figure B-7). These levee connections occur along Darby Creek and Cobbs Creek, at the airport on the south, and along the Schuylkill River on the east. Figure B-7 also shows the Darby Creek tide gage (used for calibration of creek flows) and an outline of the PRA properties under consideration for this evaluation.

Surface terrain used in the 2D model is shown in Figure B-8. The terrain used for the project in the 2D model area is a one-foot horizontal resolution digital elevation model (DEM), which was derived by AKRF from 2018 Light Detection and Ranging (LiDAR) data (PASDA 2020). The vertical datum for the DEM is the National Vertical Geodetic Datum of 1988 (NAVD88).

On the west side, most of the 2D model domain boundary is located on Darby Creek and Cobbs Creek banks and levees. The boundary in this area is separated from the 1D model cross sections due to high ground at Clearview Landfill, which is located just south and east of the Darby Creek and Cobbs Creek confluence (see Figure B-7). On the north side, the boundary is situated within Eastwick on land with elevations higher than those on which the flooding of this evaluation occurs. Local street flooding due to runoff generated by precipitation falling within Eastwick may occur outside the model boundary in this area and those flows are incorporated into the model as external boundary condition flows (see Attachment A).

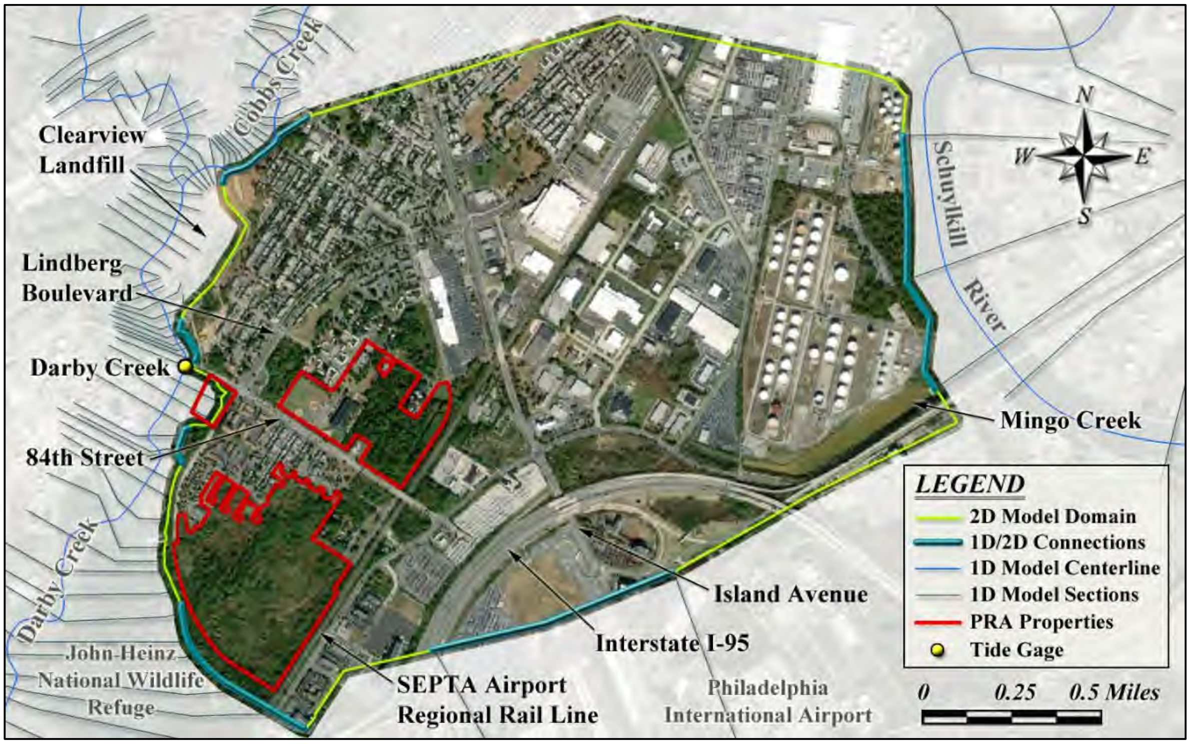

Figure B-7: 2D Model Boundary and Connections to 1D Model

On the east, the 2D model domain boundary is located on the Schuylkill River bank and flow to and from the river is described by a levee and occurs mostly in the area of the tank farm on the northeast. On the south, the boundary is situated on higher ground flooding, with the exception of the central portion that is located south of Interstate I-95. In this central portion, floodwaters from the Delaware River may inundate the Philadelphia International Airport and pass under Interstate I-95 at Island Avenue. The I-95 and Island Avenue interchange roadway ramps act as levees in this area and were incorporated into the 2D model to properly describe flow.

Within the 2D model domain, the land is depressed in the vicinity of the northeast PRA property (Site 3) which is termed the "Pepper Bowl" in the Philadelphia Redevelopment Authority Lower Eastwick Public Land Strategy because the area contains some of the lowest elevations in all of Eastwick, including areas that are at or below sea level (IS 2019). As described in Section B2.1, flow from Cobbs Creek overflows its bank just above Clearview Landfill and floods southeast through the community, passing over Lindberg Boulevard until it reaches the low area of the "Pepper Bowl." Floodwaters that accumulate within this low area are retained until they are drained by storm sewers or infiltration to groundwater.

A levee[3], having top elevations at approximately elevation 8 feet, NAVD88 or more, is situated within Eastwick and provides protection to a part of the community from tidal storm surge emanating from Darby Creek and John Heinz National Wildlife Refuge. The 2D model boundary is situated on this levee from just south of 84th street down to the south until it reaches the SEPTA Airport Regional Rail Line. At this point, the levee curves to the northeast along the westerly side of the rail line and continues almost to Island Avenue. The levee in this area of the rail line presents

[3] It is our understanding that this levee is not FEMA-certified.

a barrier to flow from flooding in the "Pepper Bowl" to low areas east in the direction of Mingo Creek.

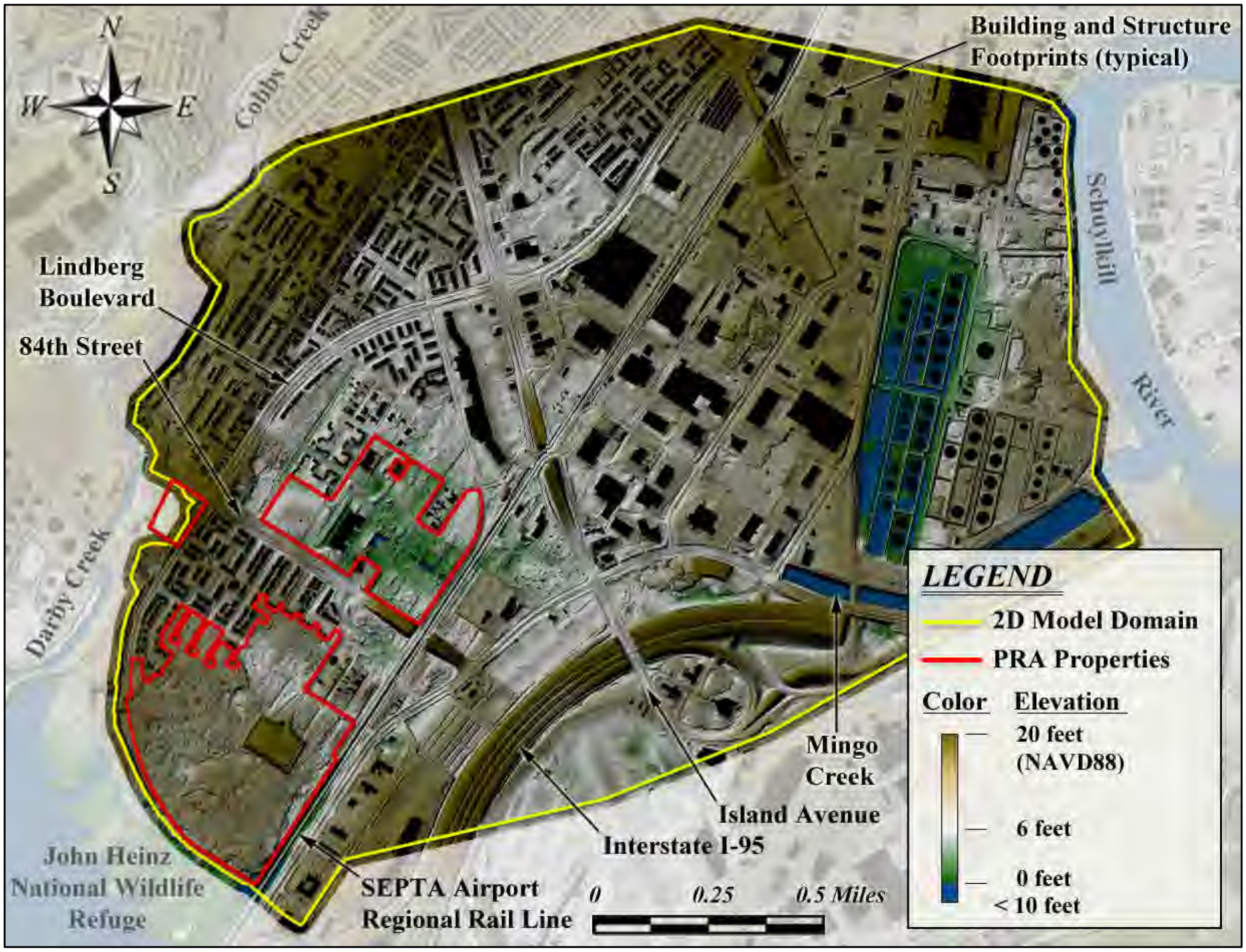

Figure B-8: 2D Model – Existing Topography

A HEC-RAS 2D model mesh for existing conditions analysis (see Figure B-9) was developed with default rectangular cell spacing of 50 feet by 50 feet. Refinement areas were defined by breaklines aligned along roadway centerlines and curb lines in areas where significant flow occurs. This was determined by iterative process where initial model runs informed the placement of breaklines until cell refinement resulted in cells with flow properly represented. A total of 86 break lines were defined having near spacing (immediately adjacent cells) of 15 feet and far spacing of 49 feet. The final model existing conditions mesh, shown as Figure B-9, contains 42,629 cells.

Figure B-9 also shows locations of the lateral structures that connect the 1D model cross sections to the 2D model.

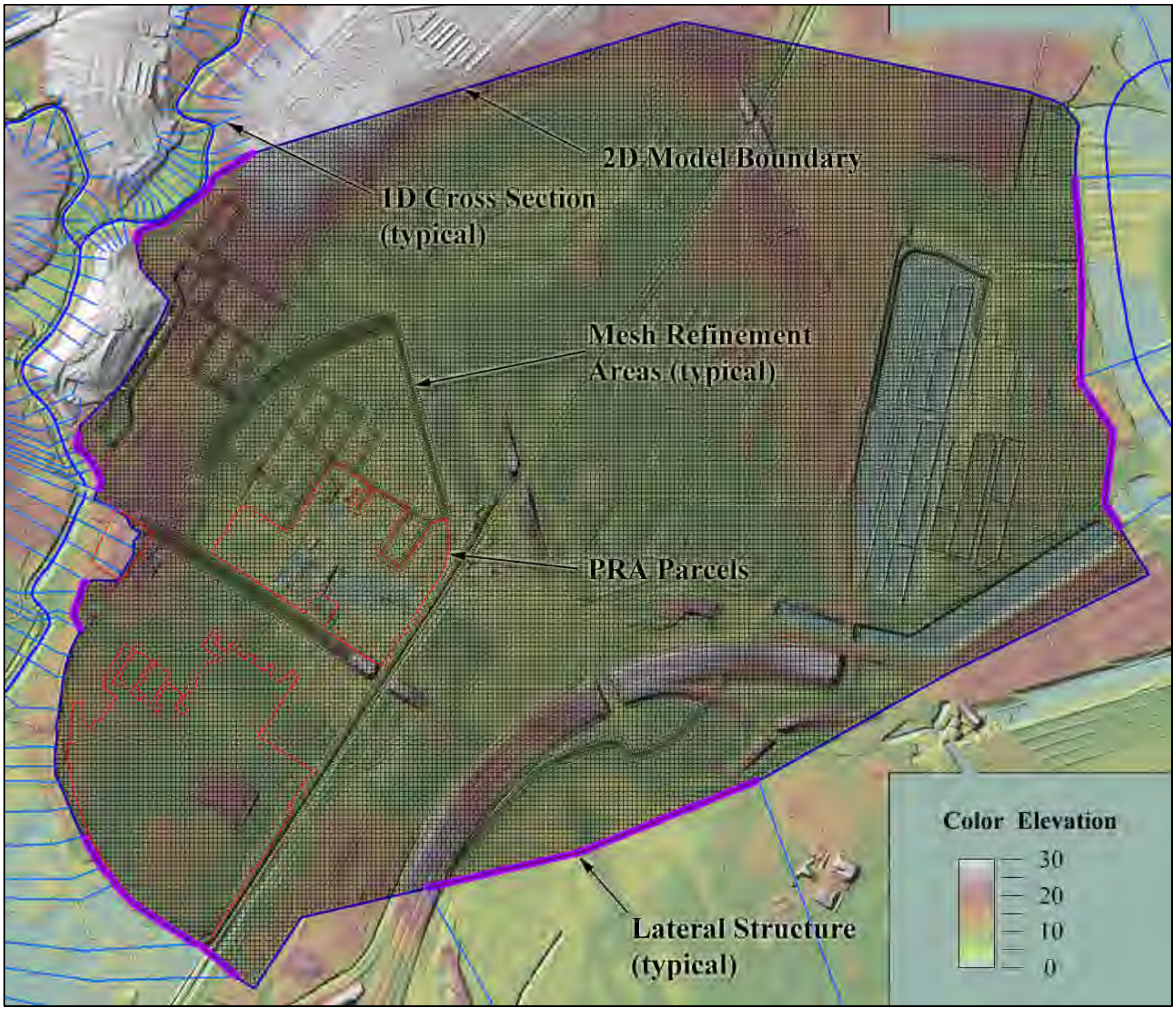

Figure B-9: 2D Model – Existing Conditions Model Mesh

B.4.0 Existing Land Use and Model Parameters

B.4.1 Land Use and Roughness Coefficients

Surface roughness, as defined by Manning's N coefficients, is typically the principal calibration parameter for HEC-RAS models. However, initial values are selected based upon previously-published N values corresponding to land use or river-bottom conditions. In 1D model areas, these values, and all subsequent calibration values, were selected to be within the ranges given in Table 3-1 of the HEC-RAS Hydraulic Reference Manual (USACE 2016).

There are large areas of the Eastwick 2D model domain for which no calibration data are available and flow predictions in these areas must rely upon best estimates based upon land use and published N values. Initial (and final, where no further calibration was performed) values of Manning's N for major land use categories for the 2D model are given in Table B-1 below. The source for all values except for ponded areas and buildings chapter 15 of the United States Department of Agriculture National Engineering Handbook, Hydrology (USDA 2010). Ponded areas were approximated with reference to other values as being mostly smooth but with some edge vegetation and irregularities. Buildings are set at a high value to allow for water to be stored in, but not move through the structures. Areas with mixed use of wooded, vegetated and grass were estimated as a weighted average according to the proportion of each use. Surface roughness for the 2D model is shown in Figure B-10 below.

Table B-1: Eastwick 2D Model Major Land Use Category Roughness Coefficients

Description	Manning's N Coefficient
Paved and Concrete	0.011
Wooded Areas	0.40
Vegetated (shrub) Areas	0.15
Grass Areas	0.15
Bare Soil Areas	0.011
Ponded Areas	0.04
Buildings	100

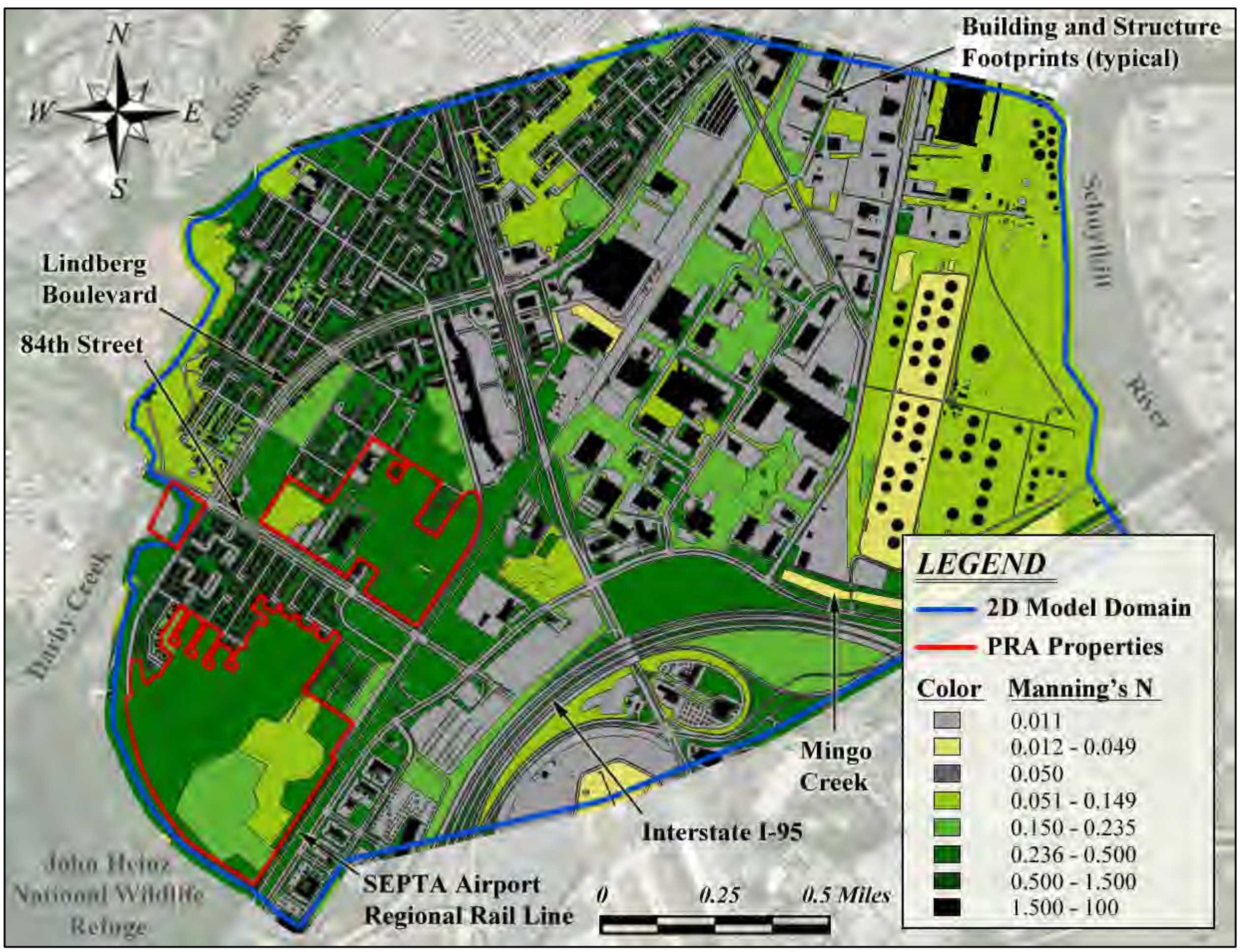

Figure B-10: 2D Model – Surface Roughness

The Manning's N for Wooded Areas in Table B-1 is higher than those typically given for overbank areas in the HEC-RAS Hydraulic Reference Manual. This value was used due to the sheet-flow characteristic of shallow water flowing over the terrain. As water depth increases, Manning's N would be expected to decrease to fall within the range listed in the HEC-RAS Hydraulic Reference Manual. The higher Manning's N value was used within the 2D model flow area for the following reasons:

1. Most wooded areas within the model domain are expected to have flow conditions consistent with sheet flow.
2. The area in the immediate vicinity of the former Pepper School, or the "Pepper Bowl" and the southwestern portion of the 2D model experience lower flow velocity at higher flood depths. As a result, the Manning's N has lesser effect.
3. The higher Manning's N values within the 2D model areas are conservatively appropriate considering the objective of the study and future area planning relative to maximum flood depths.

B.4.2 Other Model Parameters

Expansion and contraction coefficients for the 1D model were set according to typical values of 0.3 and 0.1, respectively in river reaches and 0.5 and 0.3, respectively at bridges. Bridge overflows were modeled as broad crested weirs with weir coefficients of 2.6. Ineffective flow areas were identified and modeled in accordance with HEC-RAS guidance. The junction of the Schuylkill River and the Delaware River and the junction of Darby Creek and the Delaware River were both modeled by forcing equal water surface elevations. The higher-energy environment of the Darby Creek and Cobbs Creek junction was modeled using the energy balance method.

B.5.0 Storm Sewer and Mingo Creek Pump Station Flow

Stormwater from the Eastwick area drains by storm sewer to Mingo Creek and is pumped to the Schuylkill River (PWD 2020). The Mingo Creek pump station houses six, 500-horsepower pumps, each capable of pumping 124 cubic feet per second (a 24-hour, 5-year storm event). (IS 2019). As indicated by the reported 5-year storm event capacity and subsequently demonstrated in the modeling results of this evaluation, these pumping rates are relatively small with respect to extreme event flows that occur within Eastwick. However, they do provide drainage after flood events and have some limited effect during flood events.

Storm sewer model flow rates were apportioned on the basis of comparing the overall sewershed (PWD 2020) with modeled areas. Storm sewer withdrawals were modeled as internal boundary conditions by assigning negative flow values. HEC-RAS applies negative flow by withdrawing up to that rate, if available from the cells connected to the internal boundary. Two withdrawals were modeled with 200 cfs withdrawn from "Pepper Bowl" and 100 cfs withdrawn from the low area southwest of the intersection of 84th Street and the SEPTA Airport Regional Rail Line.

To check the assumption of the model that individual storm sewer flow is minor and total storm sewer flow is relatively low as compared to extreme event runoff and Cobbs Creek overflow, the flood volume budget within Eastwick was evaluated for Tropical Storm Isaias. This was done by comparing the total inflow volume to the total storm sewer discharge volume and the results are presented in Table B-2.

Table B-2: Volumetric Budget Check for Tropical Storm Isaias

Inflows	At Peak Storage (cubic feet)	At End of Storm (cubic feet)
Flow Over Cobbs Creek Bank	21,403,260	21,403,260
Darby Creek Overflow Between 84th Street and Landfill	1,404	1,404
Darby Creek Overflow at John Heinz NWR Entrance	138,244	138,244
Darby Creek - Southern Levee Overflow	12,007,847	12,007,847
Internal Hydrograph Runoff	17,843,864	17,843,864
Outflows		
Flow in Northern Storm Sewers	3,960,000	7,200,000
Flow in Southern Storm Sewers	2,880,500	4,500,500
Total Inflow Volume	51,394,621	51,394,621
Total Storm Sewer Volume	6,840,500	11,700,500
Storm Sewer Fraction of Flow	13.3%	22.8%

The volumetric budget check of Table B-2 presents results at two times: at the time of peak storage (8/4/2020 19:30, as measured in the middle of the "Pepper Bowl"), and at the end of the model event (8/4/2020 24:00). The time of peak storage is significant because it is only budgetary flows up to that time that contribute to the peak storage condition. More significantly, analysis of the results indicates that all of the inflow (bank overflows and internal hydrograph runoff) occurs by the time of peak storage. Storm sewer flow continues and draws down floodwaters after peak storage occurs.

The fraction of storm sewer flow computed for Tropical Storm Isaias at the time of peak storage is 13.3%. Given that Tropical Storm Isaias was approximately a 10-year (10% annual chance occurrence), this fraction would be lower for more extreme events and the assumption that it is a small component of model flows appears to be justified.

B.6.0 Model Calibration

The flow model has been calibrated in areas for which data is available. These areas include the Delaware River and Schuylkill rivers, Darby Creek up to its confluence with Cobbs Creek, Cobbs Creek up to the overflow, and the 2D model in portions of Eastwick where Tropical Storm Isaias high watermark data is available. Upper reaches of Darby and Cobbs creek were modeled solely for purposes of more properly representing the timing of flows arriving from upstream gages, and therefore more detailed calibration is not considered to be important (nor is it possible because of lack of data). Much of the Eastwick 2D model is uncalibrated, however this is not considered to be important because flow velocities in these areas are relatively low and flooding is more a matter of volumetric filling rather than timing of flows. Typical parameters were used in all uncalibrated areas.

Because the Delaware River is large in comparison to Darby and Cobbs creeks, its flow is not measurably affected by the flow from the creeks. As a result, the Delaware River and Schuylkill River portions of the 1D model were first calibrated independently of Darby Creek, Cobbs Creek and the 2D model. Delaware and Schuylkill River tide gages (shown in Figure B-3) were used for these calibrations.

Under low flow conditions, where there is no overflow from Cobbs Creek into the Eastwick community, the 1D model of Darby and Cobbs creeks downstream of the overflow can also be calibrated independently of the 2D model. Accordingly, these reaches were calibrated using the Darby Creek tide gage (see Figure B-7).

B.6.1 One-dimensional Model Calibration

The 1D model was calibrated using tide stage and flow data from NOAA and USGS gages that was collected during Tropical Storm Isaias. Boundary condition data are discussed in detail in Attachment A. Initial boundaries for the Delaware River 1D model were set downstream at Delaware City (NOAA 2020d) and upstream at Bridesburg (NOAA 2020c). The Schuylkill River boundary is set at Fairmount Dam and is described by flow (see Attachment A). The 1D model was calibrated to data from NOAA and USGS gages located within the domain including the following (from downstream to upstream): New Castle (USGS 2020e); Delaware Memorial Bridge (USGS 2020f); Marcus Hook (NOAA 2020a); Darby Creek (USGS 2020g); Fort Mifflin (USGS 2020h); Schuylkill River (USGS 2020d); and Philadelphia (NOAA 2020b).

Calibration was achieved by adjusting a single value for bottom roughness, Manning's N, until a reasonable match was achieved between the simulated and observed tide data. Variation in model results resulting from various modeled Manning's N values was found to be greatest at Marcus Hook, which is the tide station located closest to the middle of the model domain. Final calibration results for Marcus Hook are shown in Figure B-11.

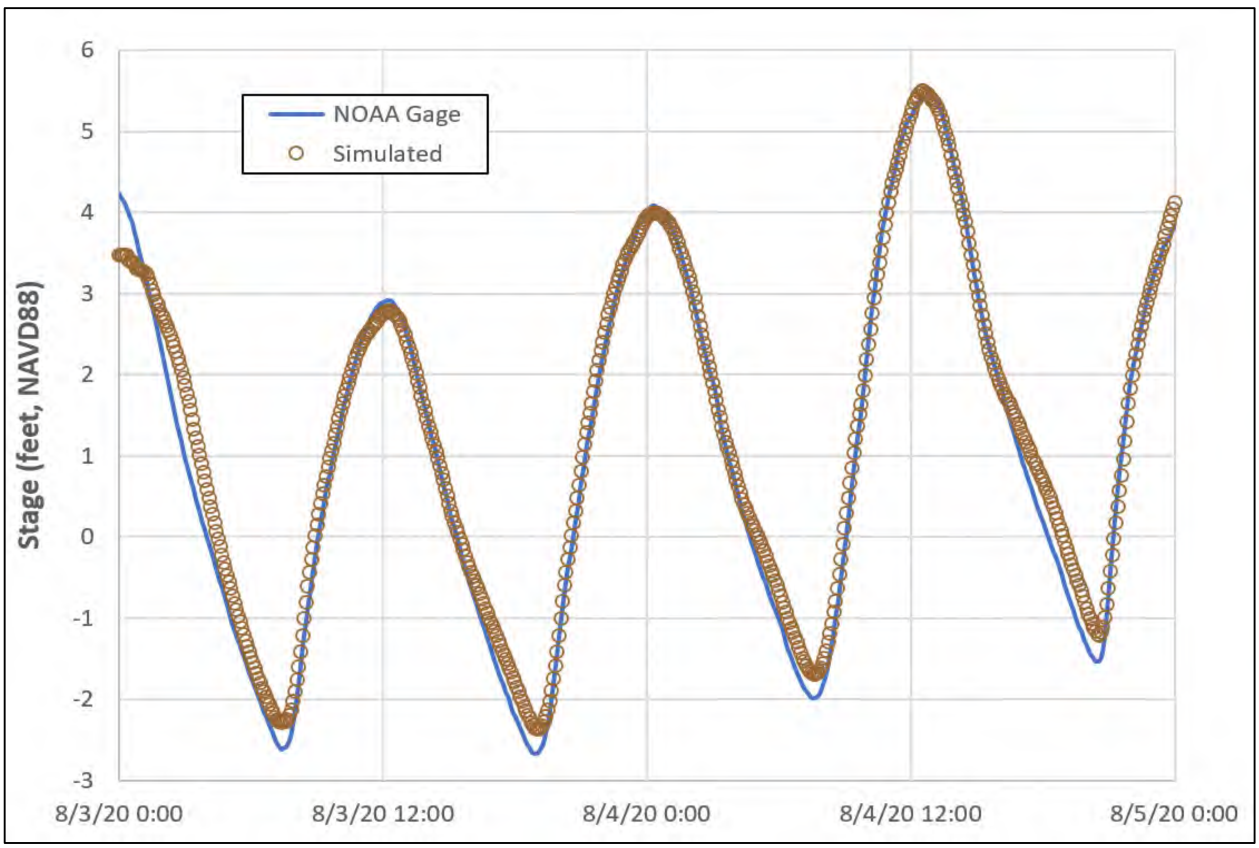

Figure B-11: Plot of Final Calibration Results at Marcus Hook

It should be noted that good calibration results were not obtained using the Delaware City gage as the downstream boundary. This is possibly due to two-dimensional flow effects in the gage location because of its proximity to the C&D canal. Final calibration runs were completed using New Castle gage as the downstream boundary.

The HEC-RAS Hydraulic Reference Manual (USACE 2016) states that Manning's N values can range between 0.016 and 0.030 for straight and uniform dredged channels. The best match between modeled and observed conditions was achieved using a Manning's N value of 0.015 which is slightly lower than the low end of the suggested range, and closer to values reported for smooth paved surfaces. This low value may reflect the smooth sediment surface of the estuary or some other factor such as under-estimation of cross-sectional area and tributary storage (which, with the exception of Darby Creek and the Schuylkill River, was ignored). However, the basic function of the Delaware River 1D model is to provide an estimation of tidal surge elevations at the mouth of Darby Creek and the Schuylkill River. In addition, as described below, after calibration, the final model boundary conditions were moved inwards to the Marcus Hook and Philadelphia gages. This further increases the estimation accuracy at the river mouths and therefore the calibration accuracy shown in Figure B-11 is considered to be suitable for the purposes of this evaluation.

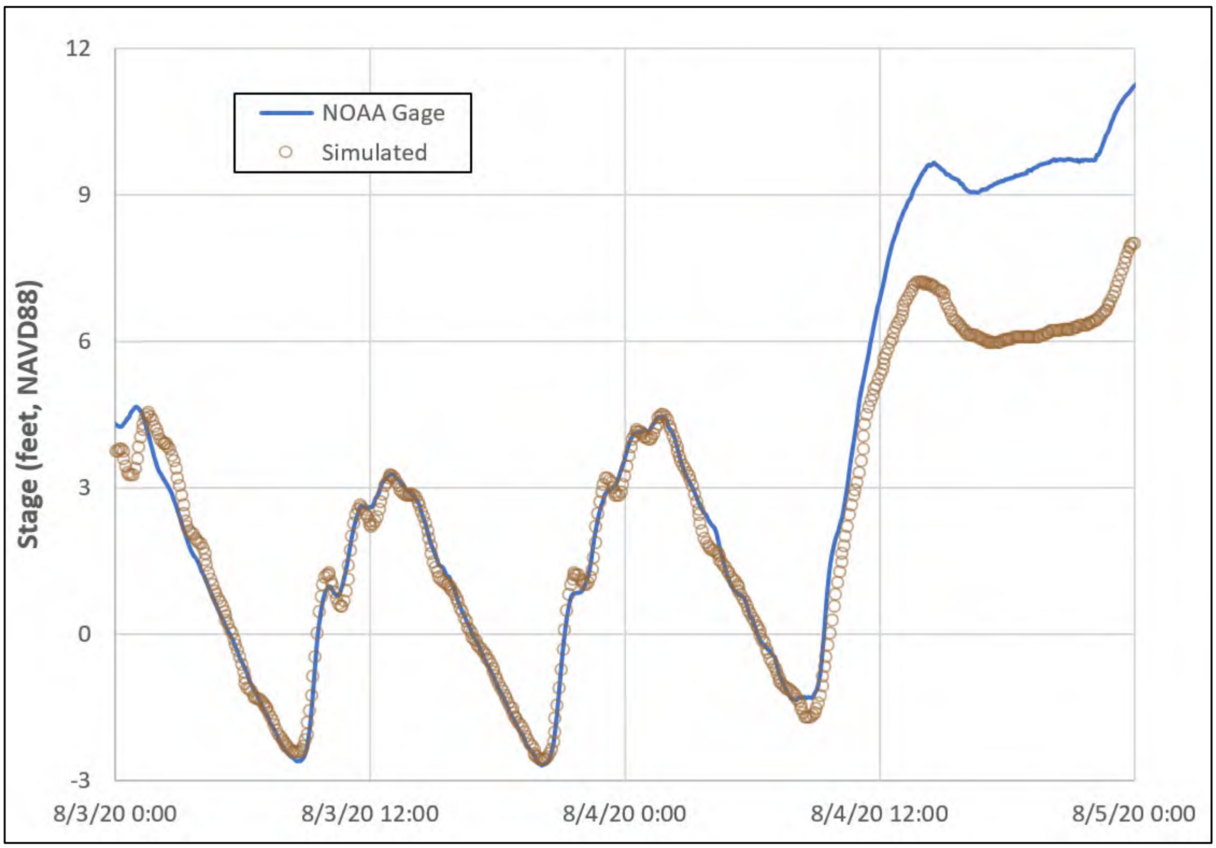

Figure B-12: Plot of Final Calibration Results at the Schuylkill River

The Schuylkill River was calibrated to the tide gage data on the river (see Figure B-3) and the calibration plot is shown as Figure B-12 above. As shown on the plot, a good calibration was achieved on tidal data, but not to high river flow conditions. A review of the FEMA flood profiles (FEMA 2019) indicates that flooding caused by upstream river flow is greatly affected by bridges upstream of Mingo Creek, whereas tidal flow dominates in the area of Mingo Creek. Upstream bridges were not included in the model and therefore the model does not properly represent high down-river flow in the area of the gage. However, these bridges are upstream of the Mingo Creek overflow area and the lack of high-flow calibration upstream does not affect the model accuracy at Mingo Creek.

The calibrated Manning's N coefficient for the Schuylkill River channel is 0.02. This resulted in not just a match of the timing and amplitude of the tidal waves, but also the secondary waves shorter-period waves (period of approximately 90 minutes) visible on Figure B-12. It is believed that these shorter period waves are momentum waves reflecting off Fairmount Dam. Overbank Manning's N values were set at 0.05 which is consistent with the range of 0.03 to 0.06 used by FEMA in the flood insurance study (FEMA 2019).

B.6.2 Two-dimensional Model Calibration

As stated in section B6.1, the Delaware River portion of the 1D model was shortened to include just the reach between the Marcus Hook and Philadelphia tide gages. Tide data at Marcus Hook and Philadelphia, which had been used for calibration, was then used as boundary condition data. The 1D model, which includes the Schuylkill River, Darby Creek and Cobbs Creek reaches for all runs, was then combined with the 2D model for calibration.

Two data sets are available for 2D model calibration of Tropical Storm Isaias flows: the Darby Creek gage (USGS 2020g) and high watermark data collected by USACE (Dohm 2020). High watermark data were provided in the form of water depths, so they had to be transformed to high watermark elevations. This was accomplished by carefully reviewing the reported ground location to determine the nearby vertical object (fence post, tree, pole, etc.) on which the watermark was likely observed. The ground elevation, as determined from the project DEM (see Section B3.1), at the point of measurement was estimated and added to the watermark depth to obtain an estimate of high watermark elevation at each reported high watermark location. It is possible that these transformed high watermark data elevations could have error of +/- a foot. Metadata associated with the watermarks was requested from USACE to help evaluate and minimize any potential error; however, USACE was unable to provide this information at the time of the request.

Initial calibration runs resulted in poor matches of both of these data sets with simulated peak water surface elevations two or more feet lower than the peak recorded at the Darby Creek gage. In addition, computed elevations in the Cobbs Creek overflow area were significantly lower than the watermark elevation data in that area. Further to the southeast along the overflow, computed elevations from the initial calibration runs were higher than the watermark elevation data and the model predicted well over a foot of flooding on 84th Street in the vicinity of the Pepper School. Review of aerial news footage taken during the event (ABC 2020) indicates that flooding of this area on 84th street was minimal at best during Tropical Storm Isaias. Taken together, these results indicated that the model was over-predicting flow through Eastwick and under-predicting peak flood flows in Cobbs Creek.

Further evaluation of flow conditions in the Eastwick overflow area showed that flow impedance had not properly been accounted for where floodwaters had moved through the residential neighborhoods. Two primary factors were identified as the cause of significant impedance. First, is the extensive fencing and walls that exist throughout the community. Most of the dwelling units have fenced-in back yards and many also have fences in side and front yard areas as well. Eastwick park has fencing around tennis and basketball courts as well as other fenced areas and walls. Construction fencing was placed along most of the boundary between the landfill and the residences, and silt fencing upgradient further added to flow impedance in many areas. Review of the aerial news footage indicated that a significant amount of debris may have accumulated in the fences further increasing flow impedance. Areas with fences are shown in Figure B-13 and a Manning's N roughness value of 1.0 was assigned in these areas rather than the mixed vegetation values shown in Figure B-10.

Figure B-13: Manning's N Adjustments in Overflow Area

The second impedance factor identified was the large number of vehicles observed in the aerial news footage that were parked both on and off the roadways. An attempt was made to compensate for this by adjusting the off-street parking from the Manning's N value of 0.011 to a value of 0.05. Only off-street values were modified and roadway Manning's N values were maintained at 0.011.

The final calibration plot for stage at the Darby Creek gage is shown as Figure B-14 with the Philadelphia gage data also shown for reference purposes. A somewhat poor calibration was achieved for tidal stage data on August 3, 2020; however, a reasonably good match of the peak flood was achieved. Given the limited flow and calibration data, and the assumptions made for tributary inflows downstream of the upstream flow boundaries (see Attachment A), it is our assessment that this calibration is reasonable.

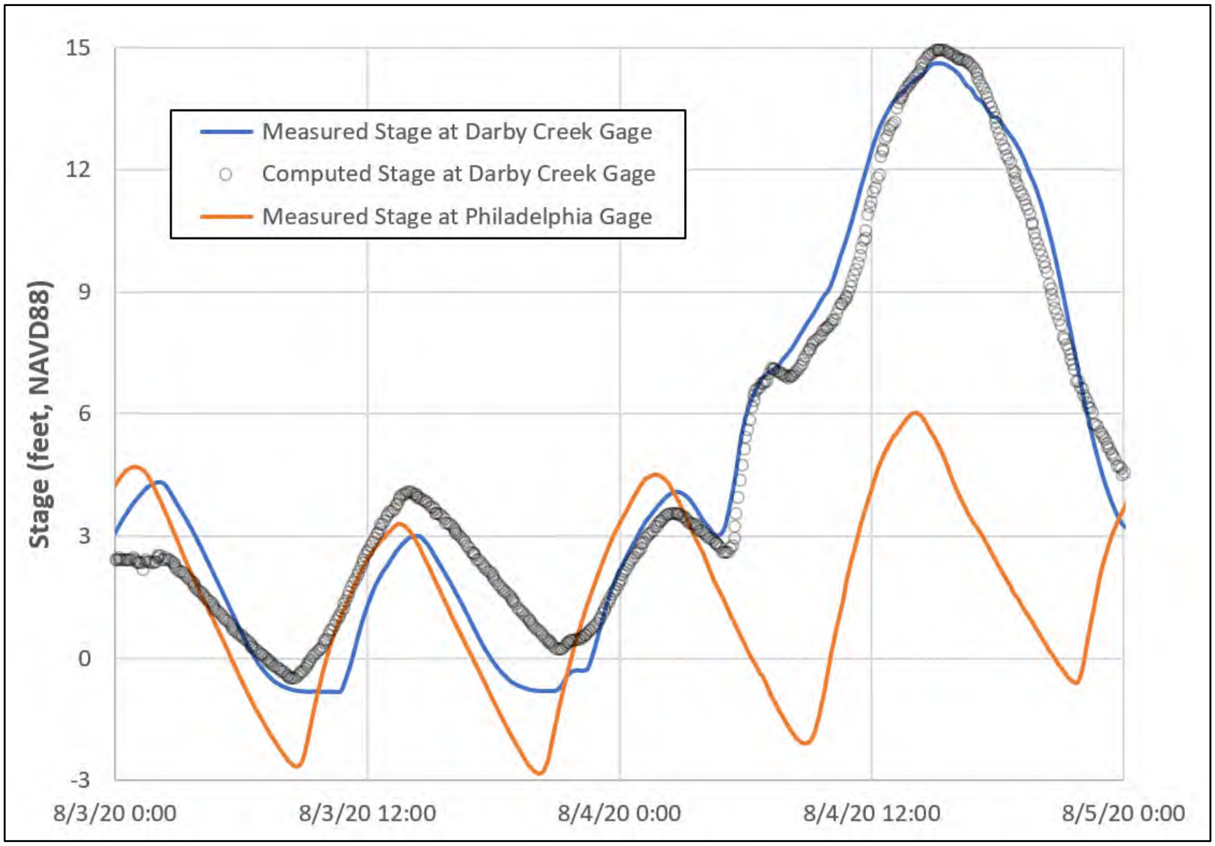

Figure B-14: Plot of Final Calibration Results at Darby Creek Gage

Final calibration values and their corresponding high watermark elevations within Eastwick are shown in Figure B-15. Figure B-16 gives a paired watermark and simulated elevation data plot of the values shown in Figure B-15. As Figure B-16 shows, the R2 value for the regression fit is high (0.89) and, more importantly, the regression line closely matches the exact match line. The Root Mean Square Error[4] (RMSE) is 0.77 feet, which would include watermark estimation error (as discussed earlier in this section, there could be errors of +/- a foot in the watermark data set provided by USACE) as well as model error.

[4] RMSE is a standard way to measure the error of a model in predicting quantitative data and is defined as the square root of the average of the squared differences between observed and predicted values.

Based on the data shown for these calibrations, it is our assessment that the model is suitable for the purposes of evaluating reuse alternatives for the vacant publicly owned parcels in Eastwick.

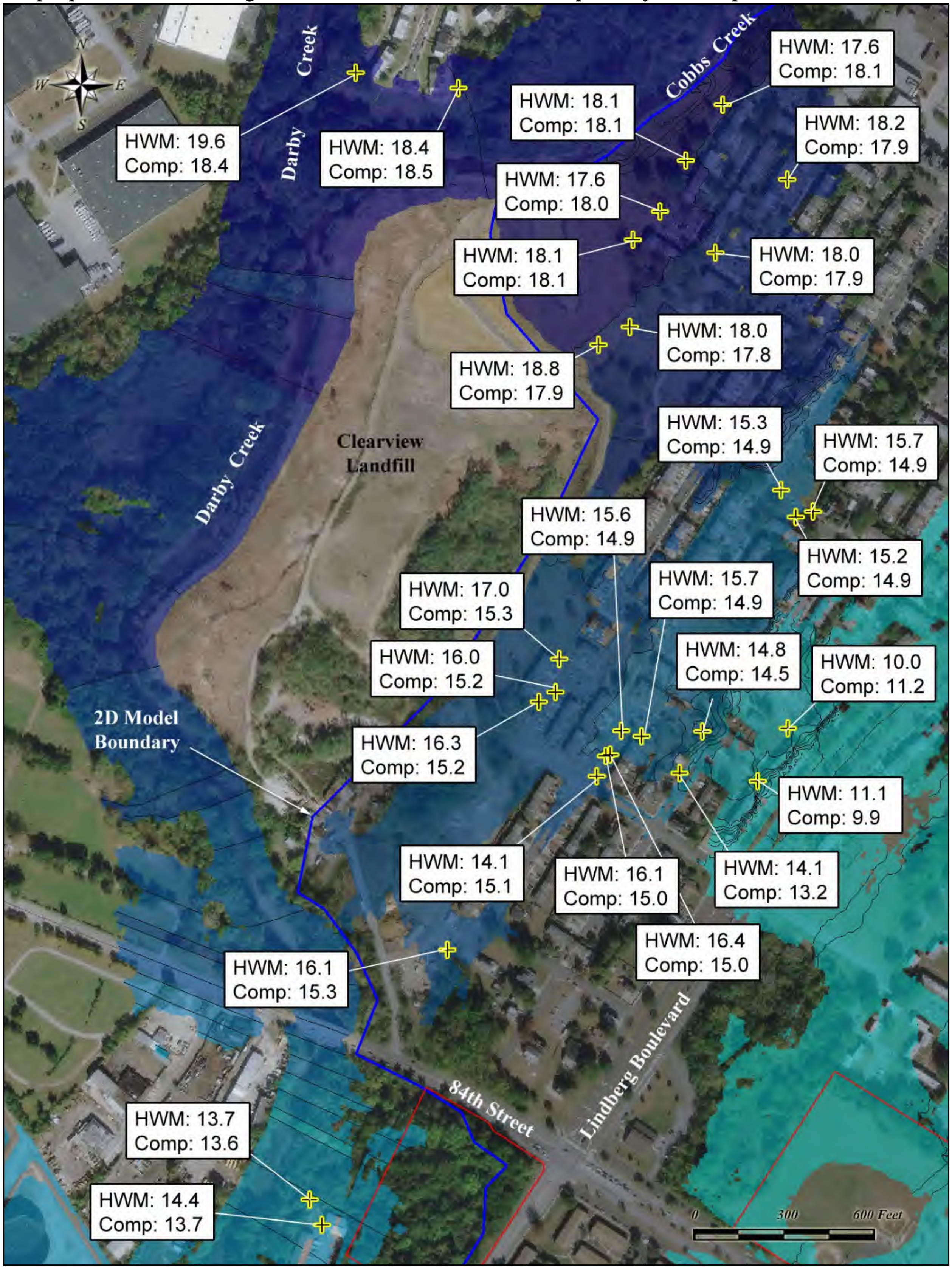

Figure B-15: Final 2D Model Calibration to Watermark Data

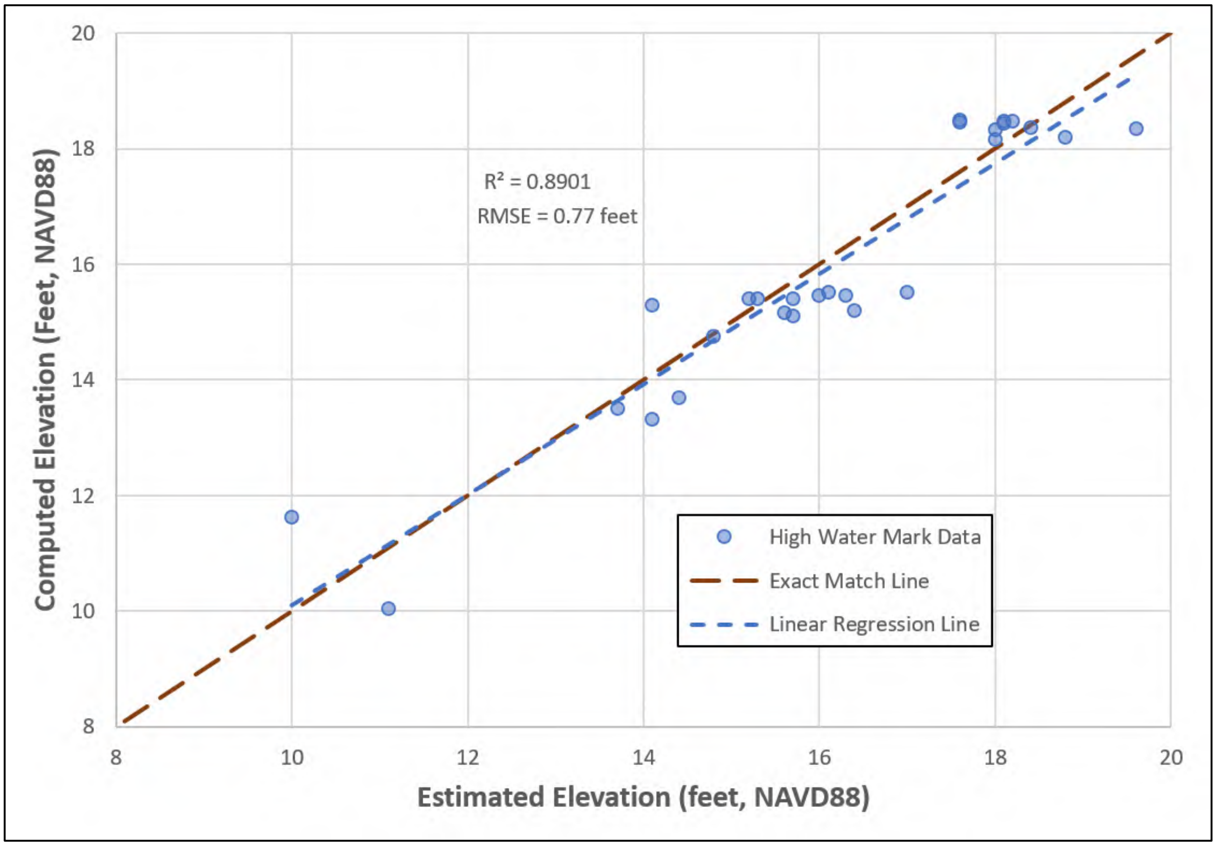

Figure B-16: Paired Watermark Data Calibration Plot

B.7.0 Results of Model Simulations

Final model results of computed maximum water surface elevations and depths are shown for each of the boundary condition scenarios identified for analysis in Attachment A. Those scenarios include the following:

- Tropical Storm Isaias (August 4, 2020)
- The 100-year terrestrial event
- Hurricane Sandy (October 30, 2012)
- The Great Appalachian Storm of 1950 Adjusted to 2020
- The 100-year Terrestrial Event Estimated at 2100
- The Great Appalachian Storm of 1950 Adjusted to 2100
- The 100-year Terrestrial Event Coincident with 10-year tidal event
- The 10-year Terrestrial Event coincident with Great Appalachian Storm of 1950 adjusted to 2020

These results are further discussed in the report.

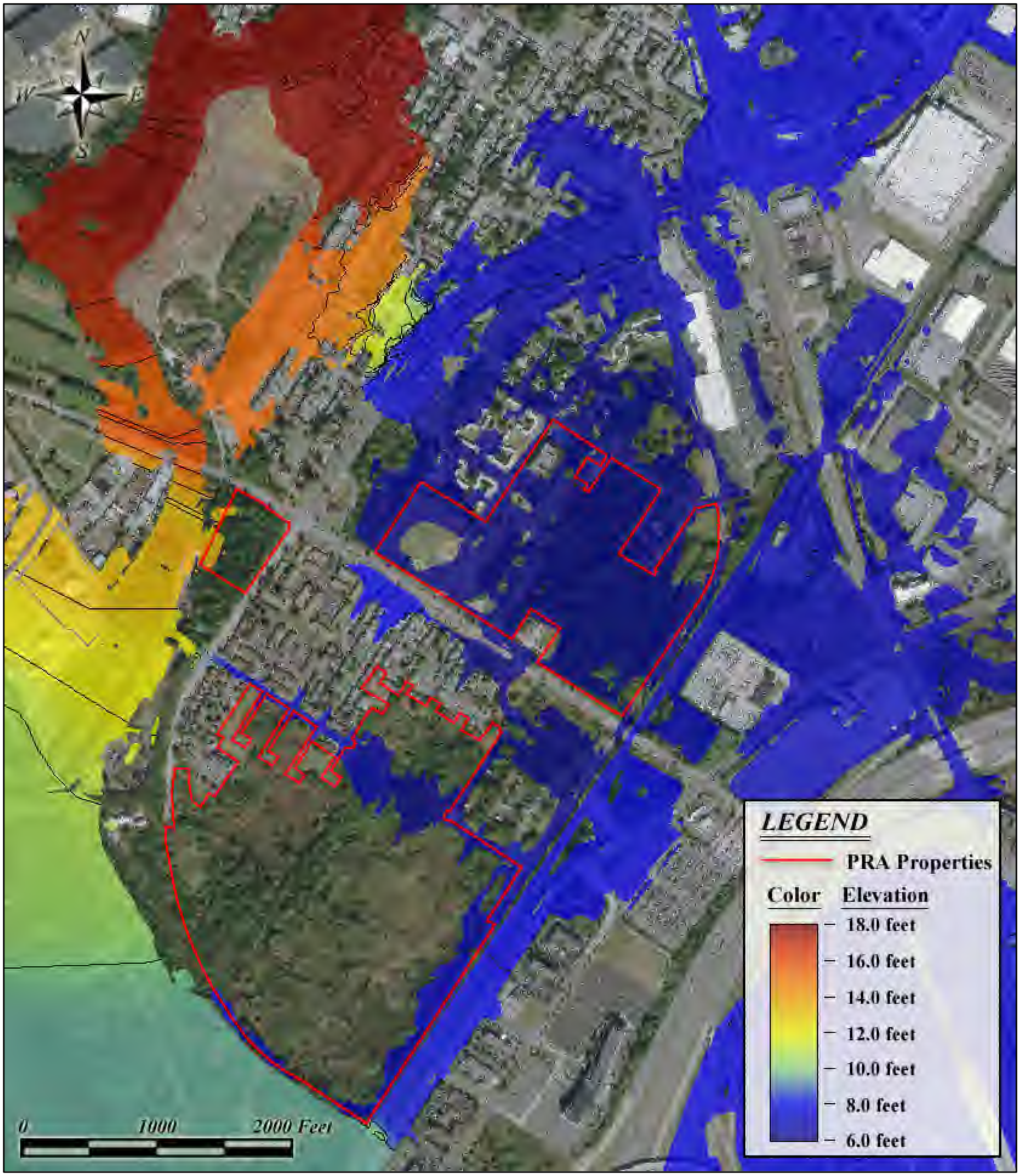

Figure B-17: Tropical Storm Isaias – Computed Maximum Water Surface Elevations

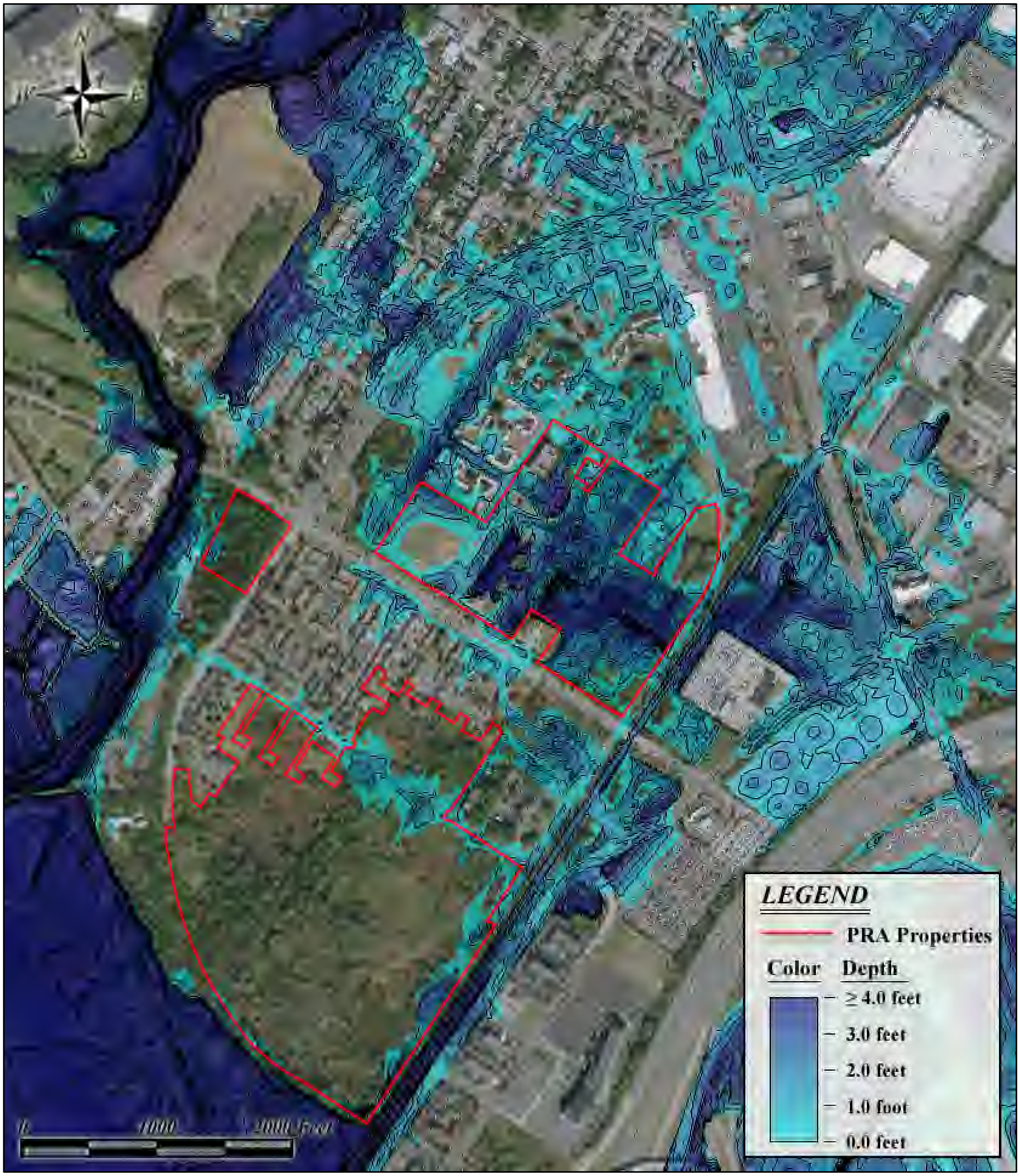

Figure B-18: Tropical Storm Isaias – Computed Maximum Water Depths

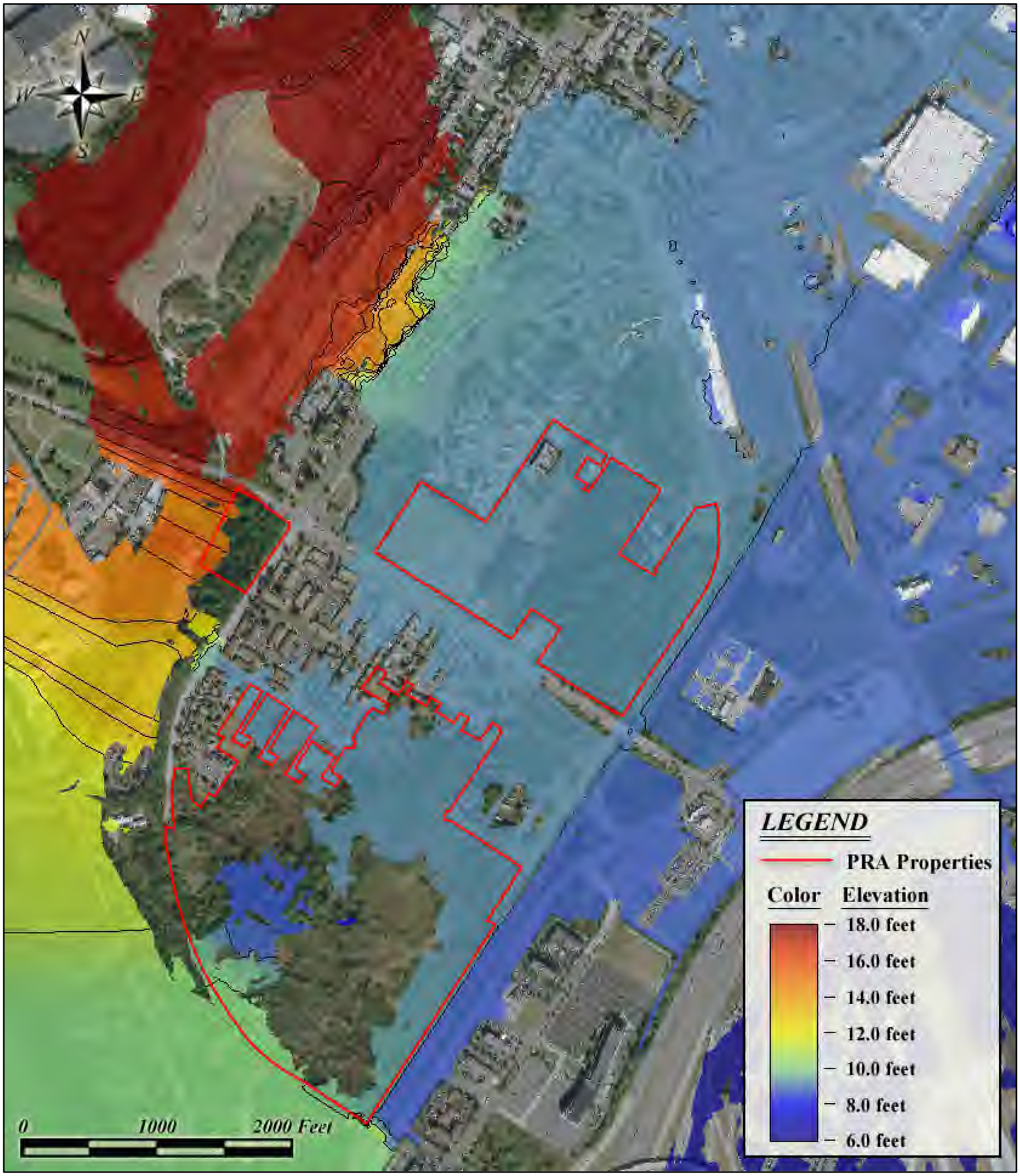

Figure B-19: 100-year terrestrial event – Computed Maximum Water Surface Elevations

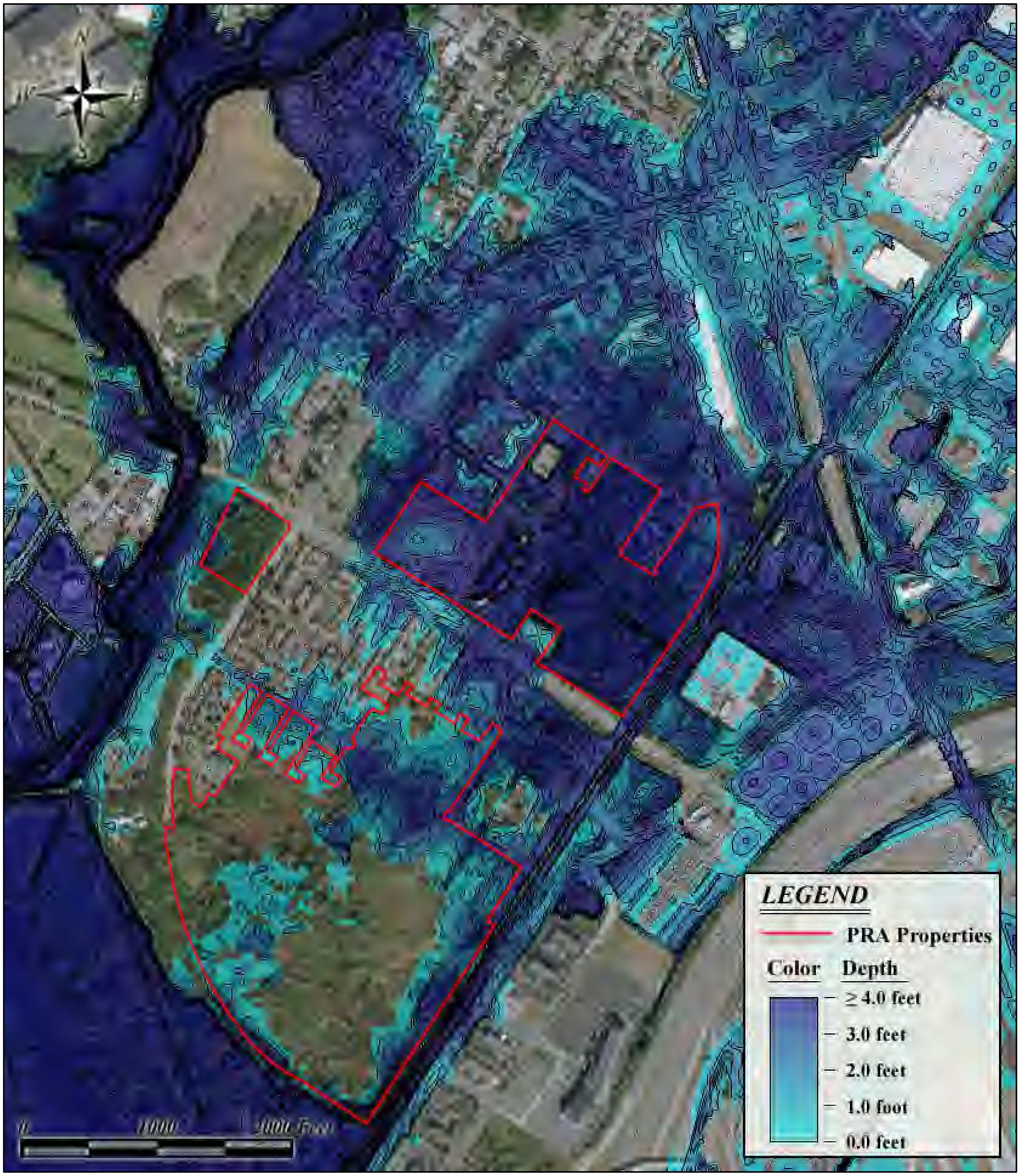

Figure B-20: 100-year terrestrial event – Computed Maximum Water Depths

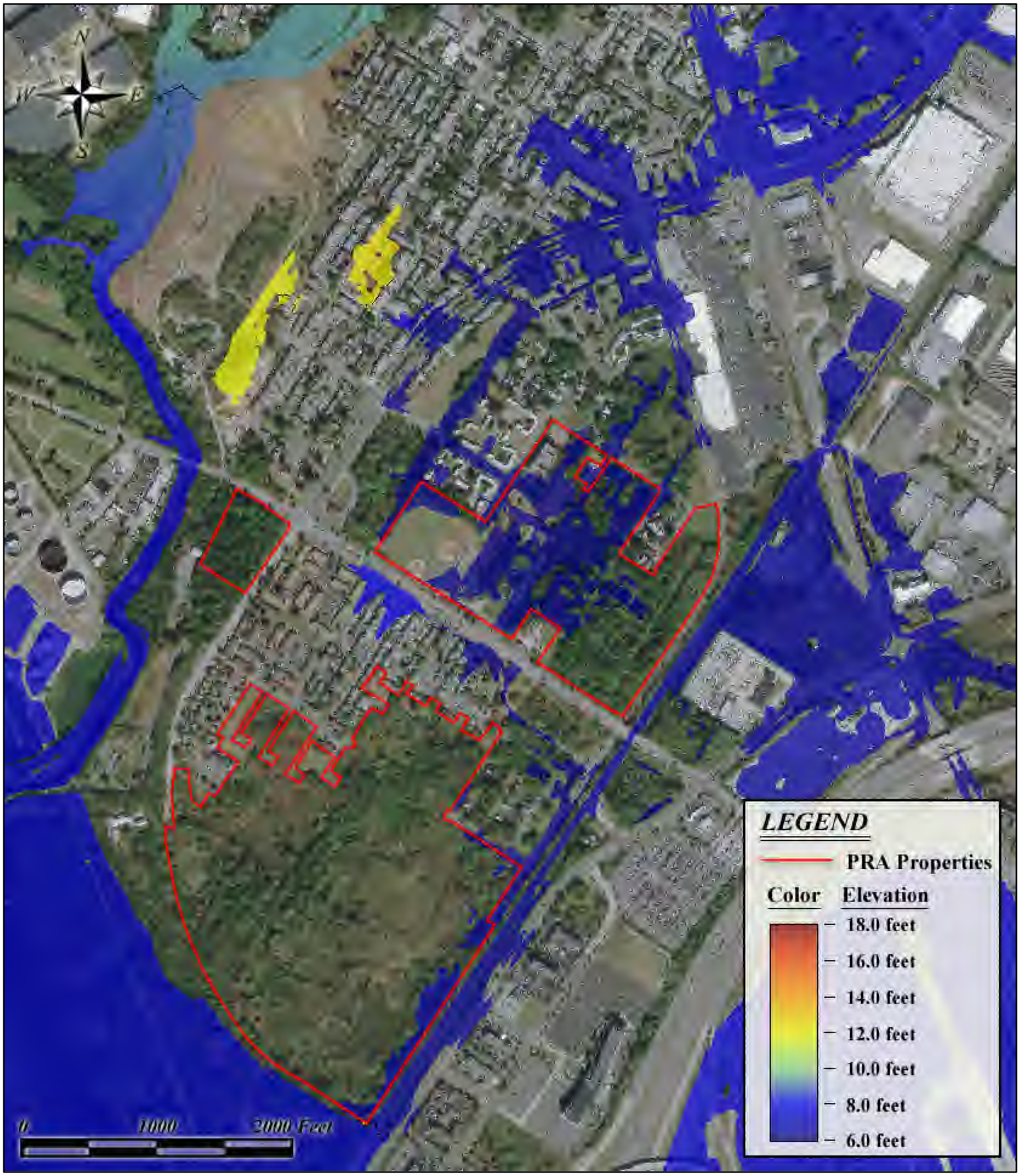

Figure B-21: Hurricane Sandy – Computed Maximum Water Surface Elevations

Note, all of the water shown internal to Eastwick on this figure is caused by runoff resulting from precipitation falling within Eastwick. Please refer to Section B1 for further discussion of this issue.

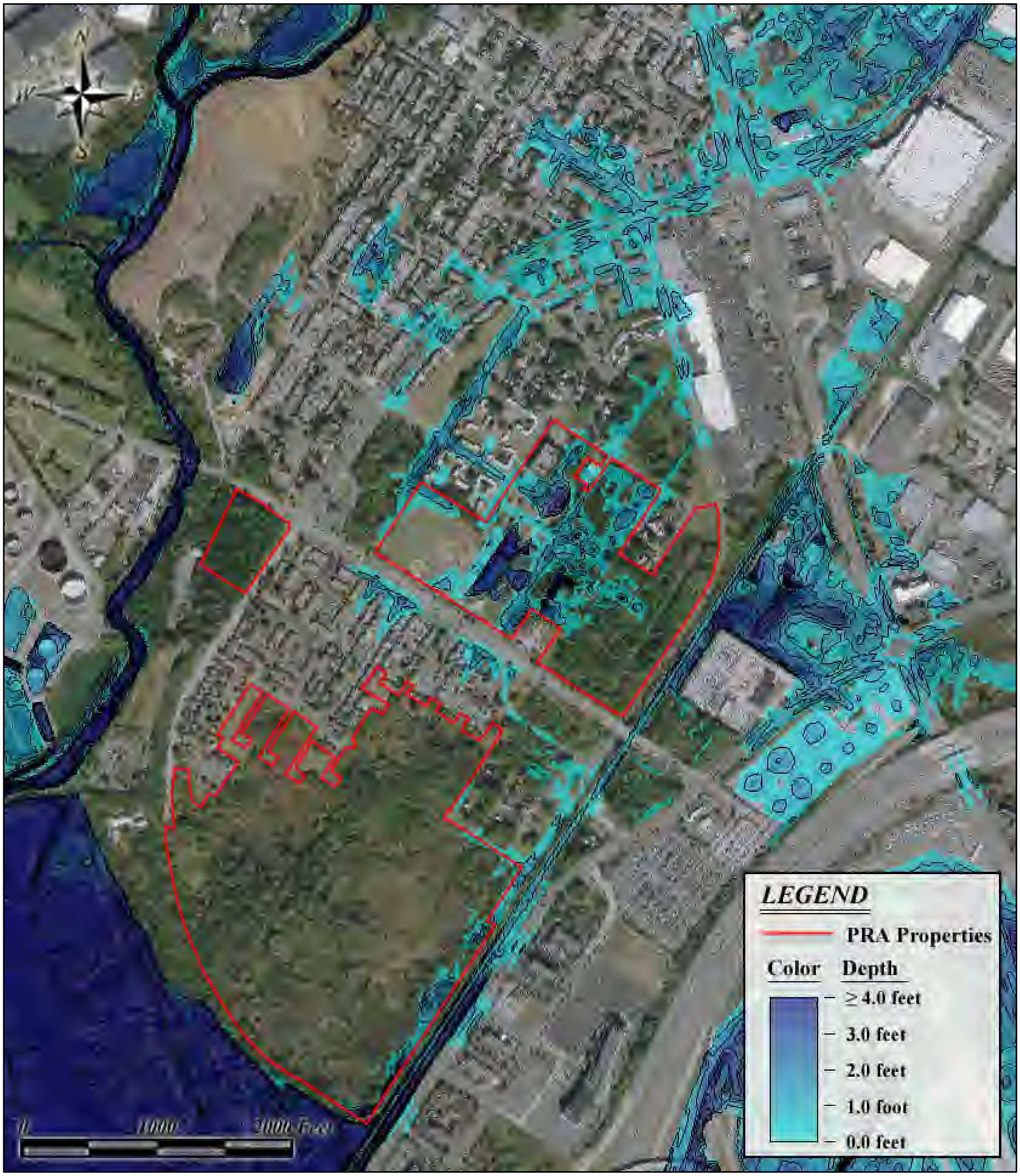

Figure B-22: Hurricane Sandy – Computed Maximum Water Depths

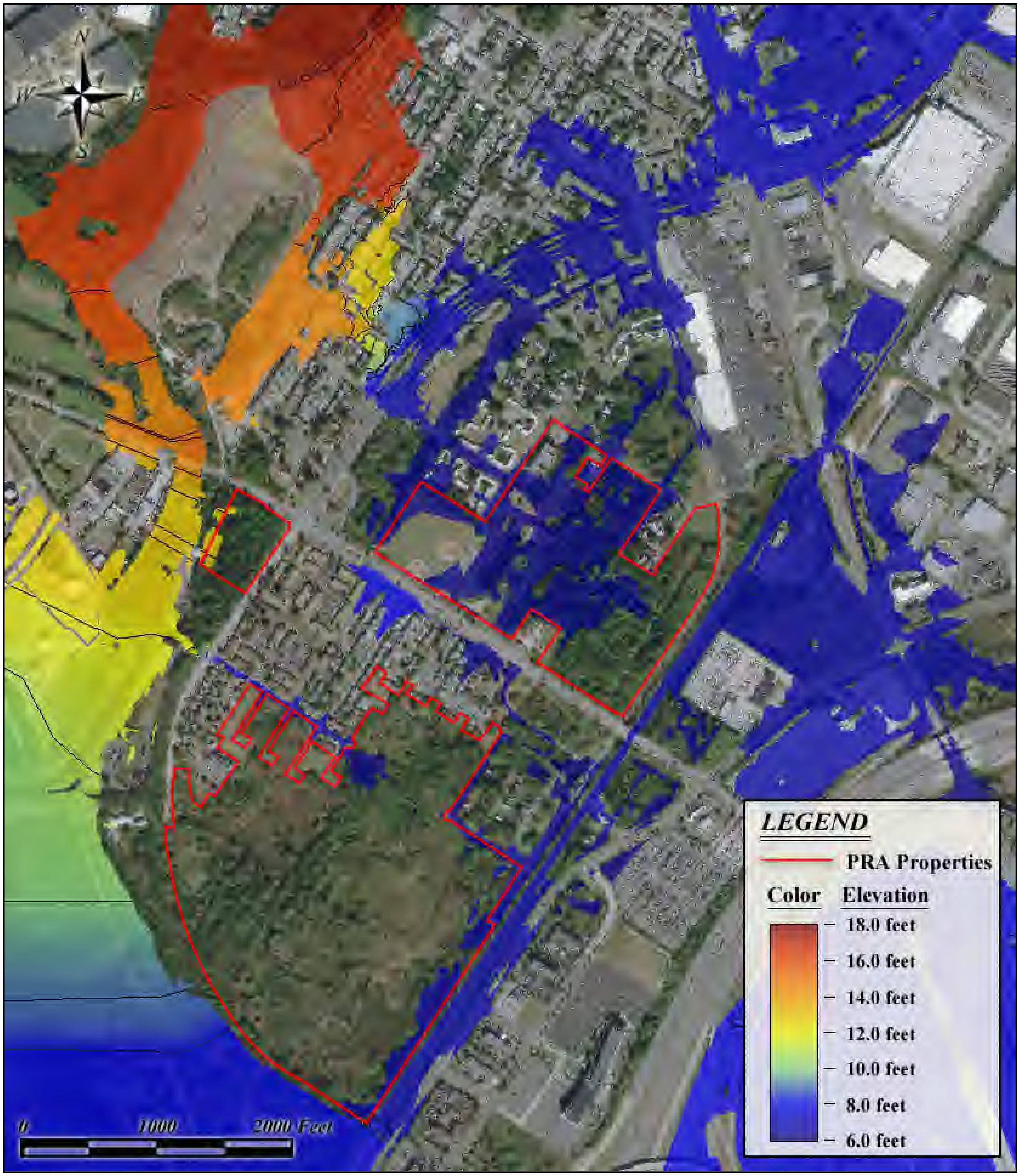

Figure B-23: Great Appalachian Storm of 1950 Adjusted to 2020 – Computed Maximum Water Surface Elevations

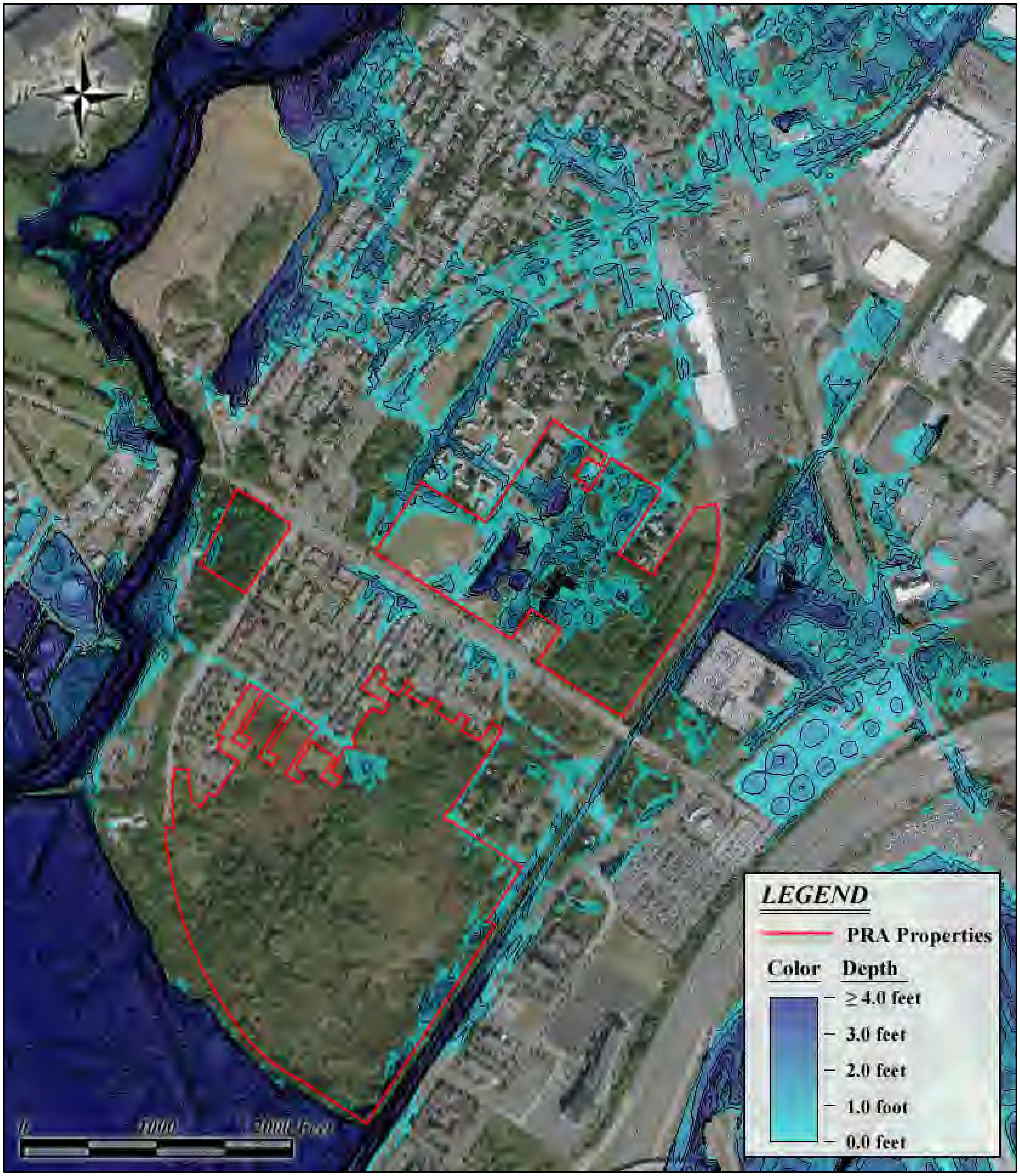

Figure B-24: Great Appalachian Storm of 1950 Adjusted to 2020 – Computed Maximum Water Depths

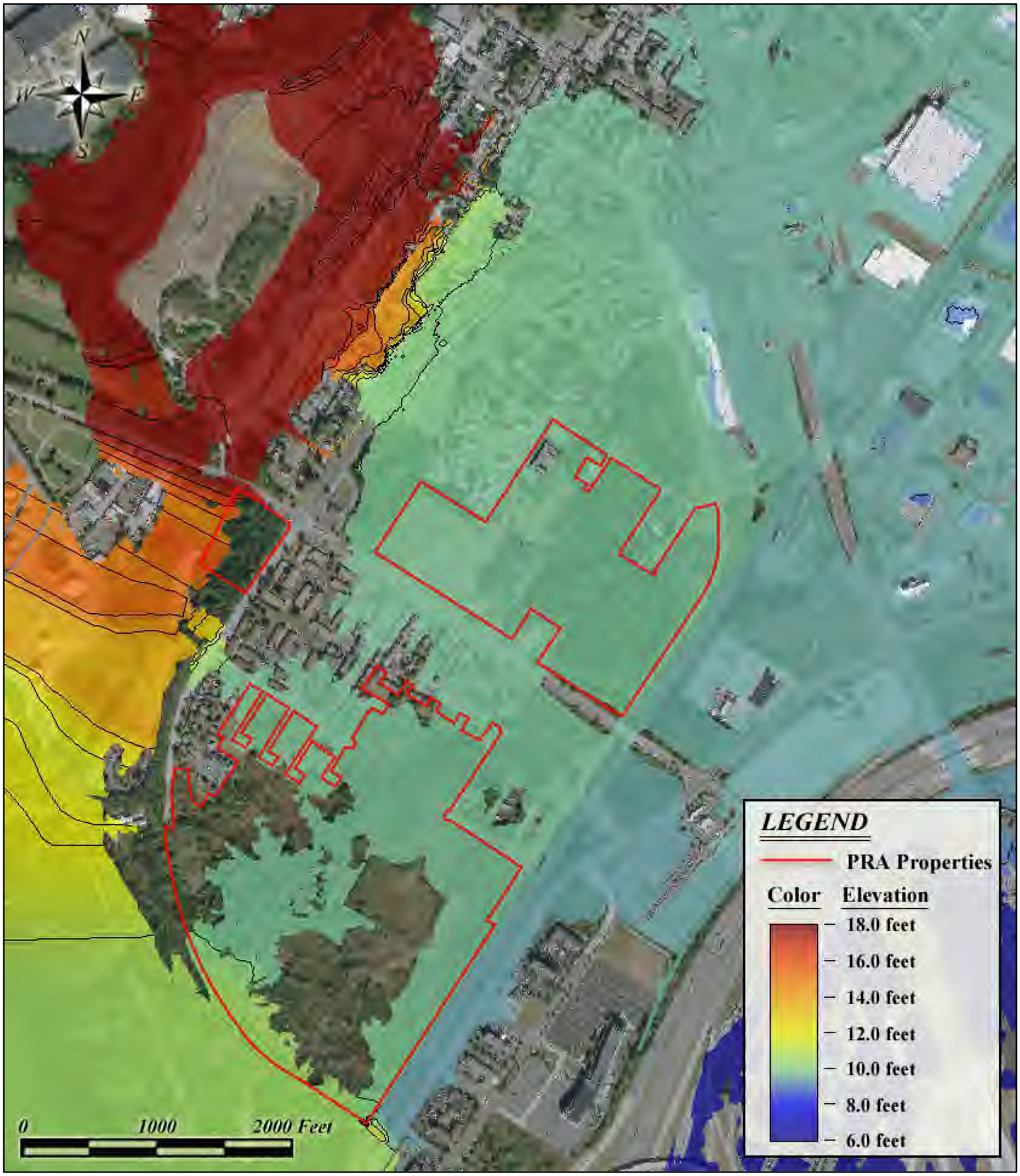

Figure B-25: 100-year Terrestrial Event Estimated at 2100 – Computed Maximum Water Surface Elevations

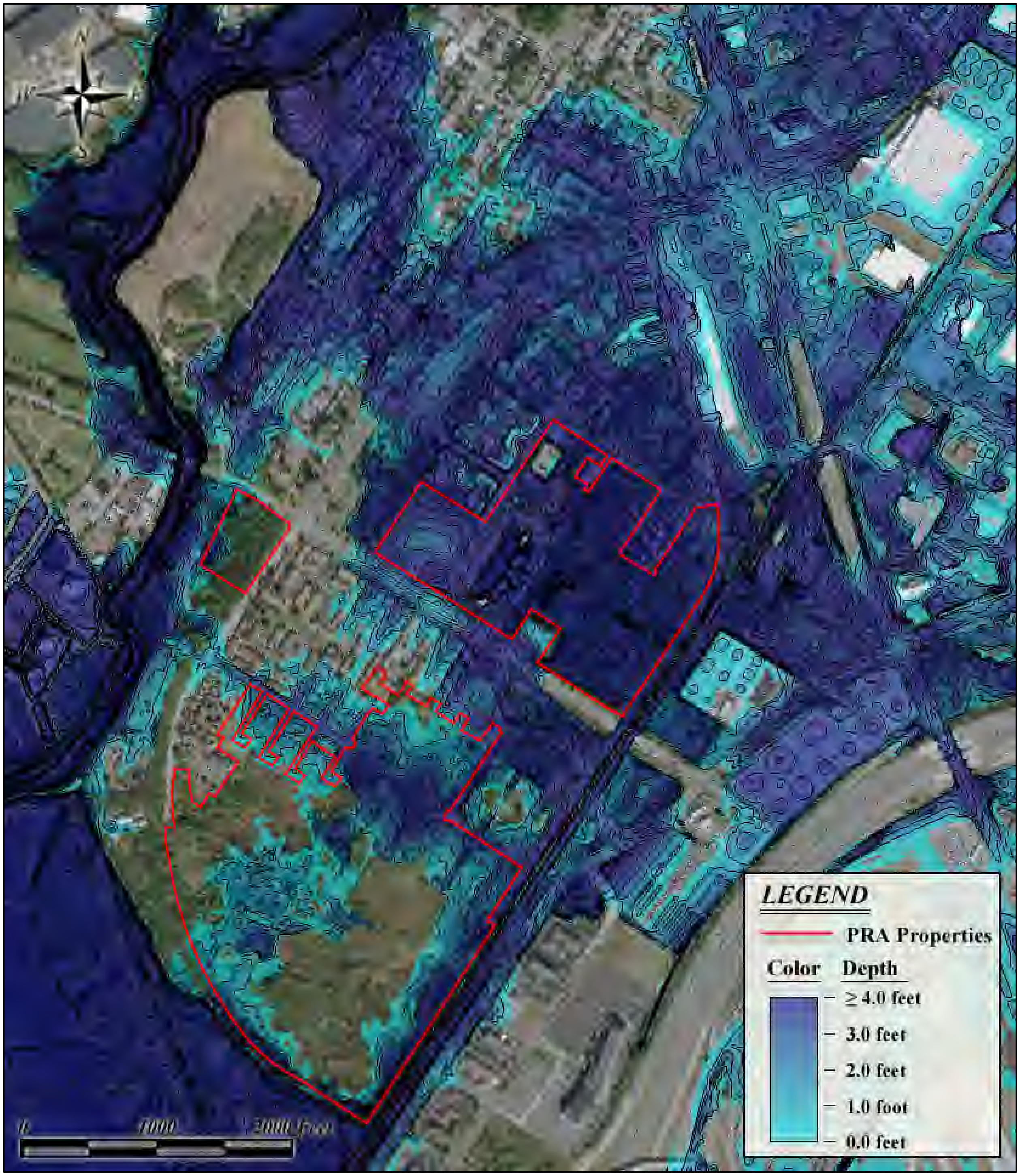

Figure B-26: 100-year Terrestrial Event Estimated at 2100 – Computed Maximum Water Depths

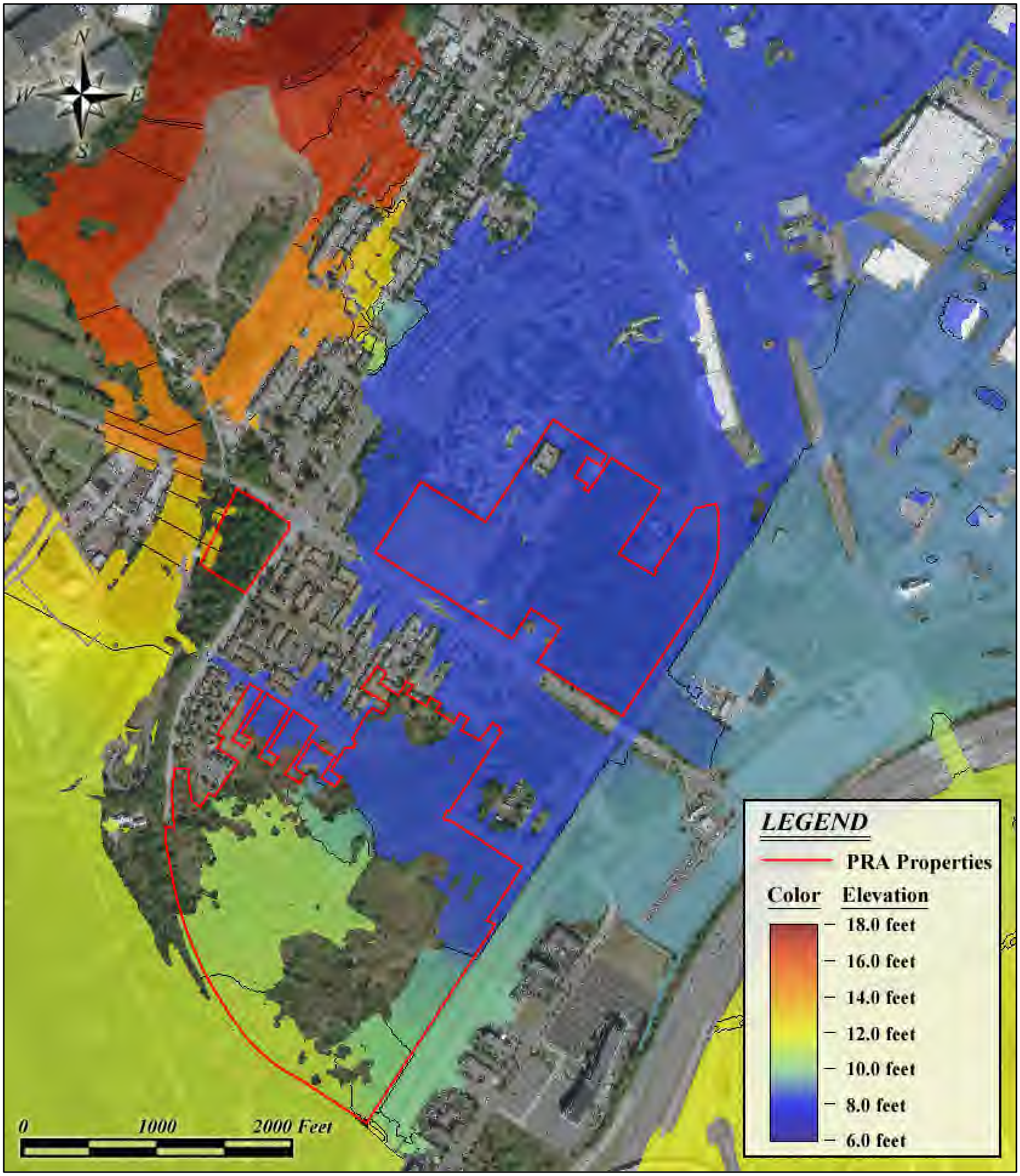

Figure B-27: Great Appalachian Storm of 1950 Adjusted to 2100 – Computed Maximum Water Surface Elevations

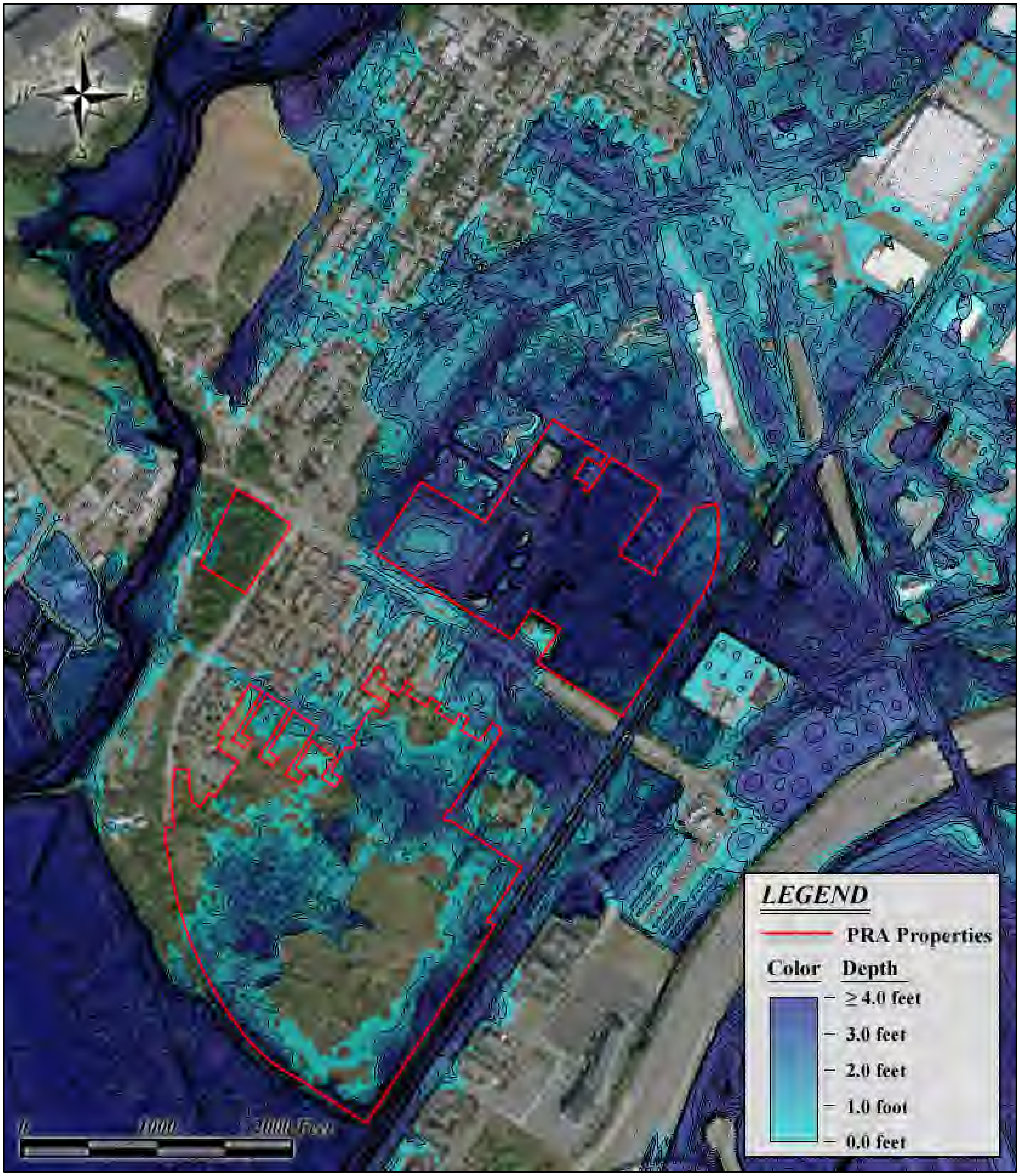

Figure B-28: Great Appalachian Storm of 1950 Adjusted to 2100 – Computed Maximum Water Depths

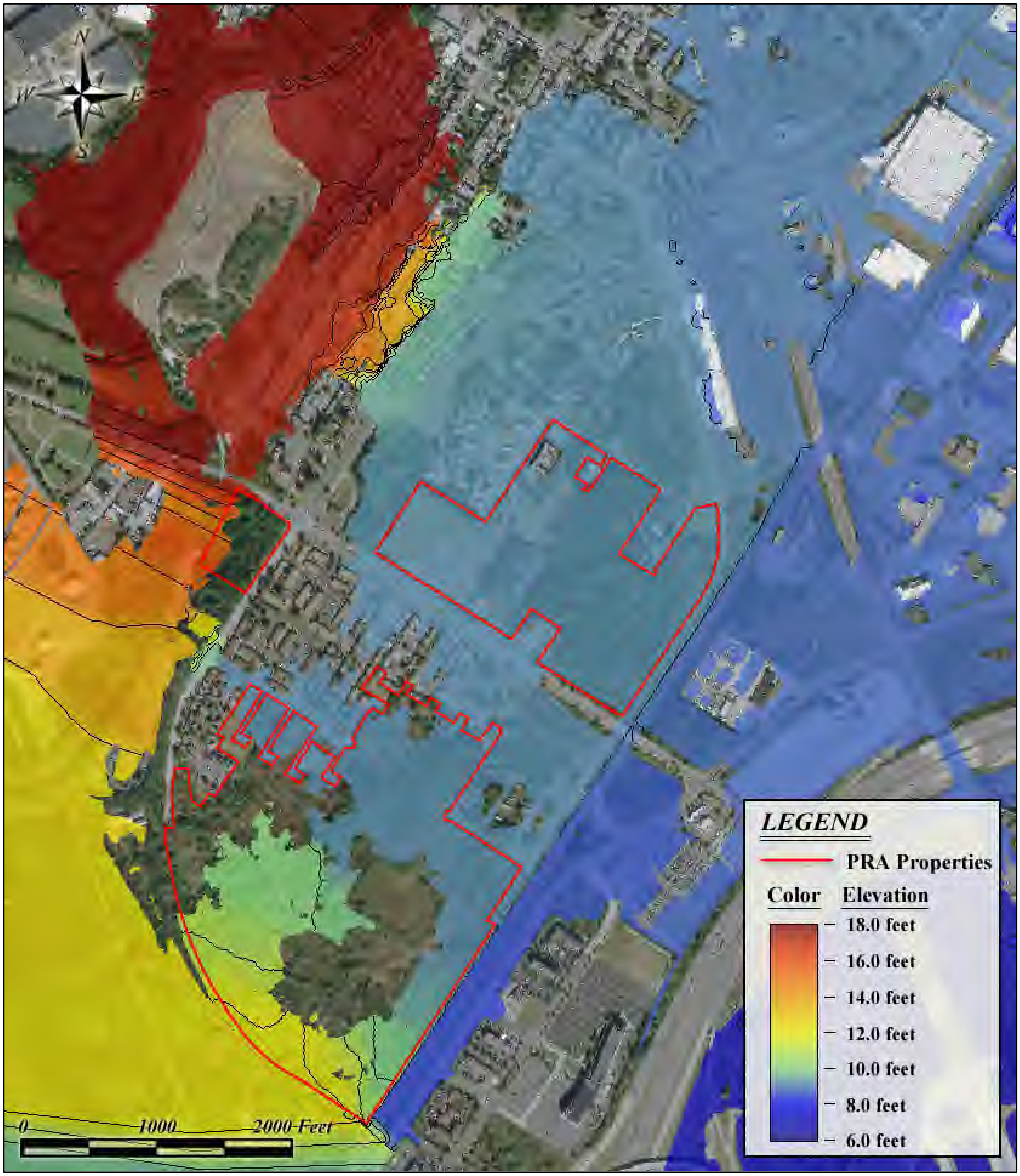

Figure B-29: 100-year Terrestrial Event Coincident with 10-year Tidal Event – Computed Maximum Water Surface Elevations

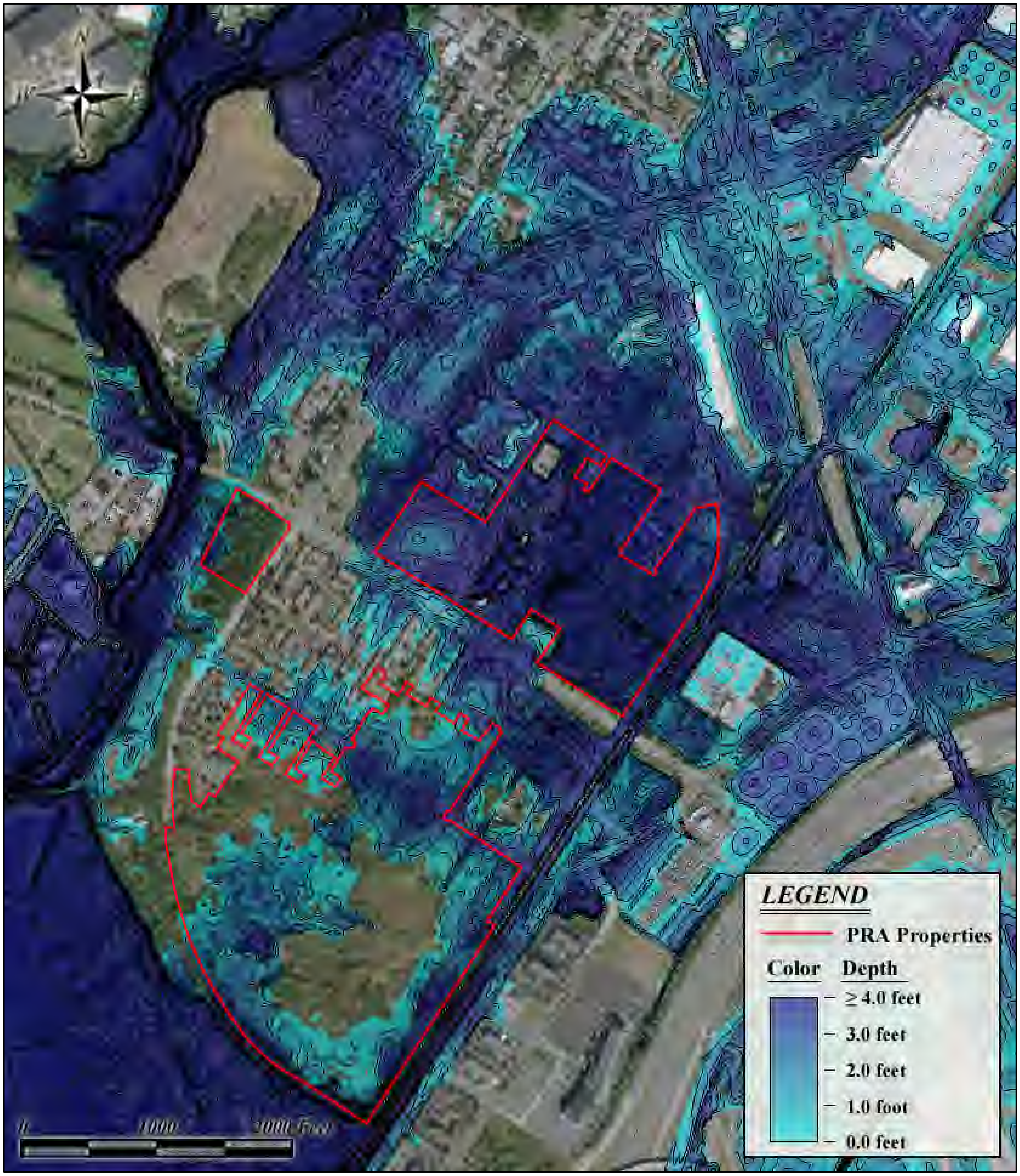

Figure B-30: 100-year Terrestrial Event Coincident with 10-year Tidal Event – Computed Maximum Water Depths

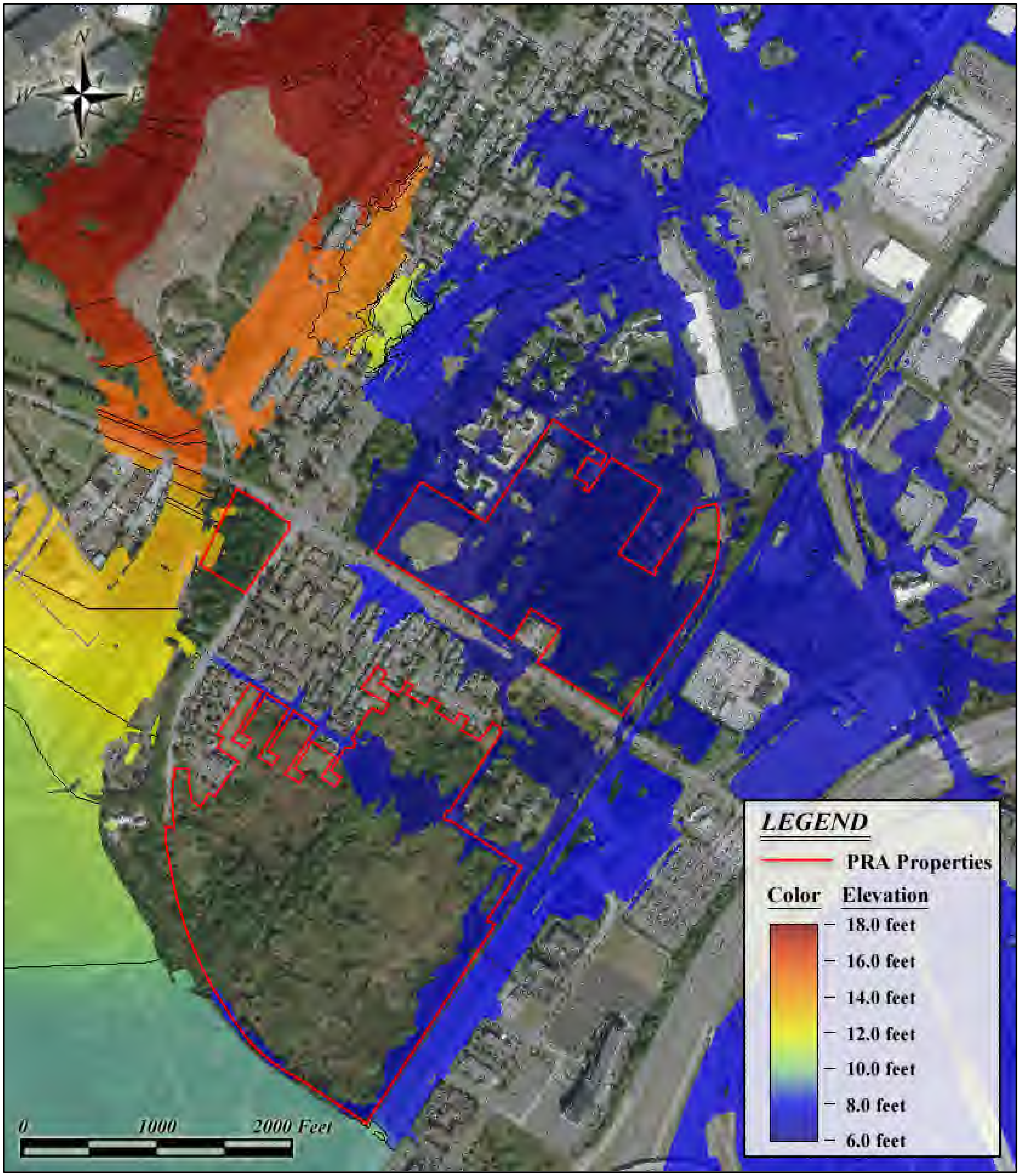

Figure B-31: 10-year Terrestrial Event coincident with Adjusted Great Appalachian Storm of 1950 – Computed Maximum Water Surface Elevations

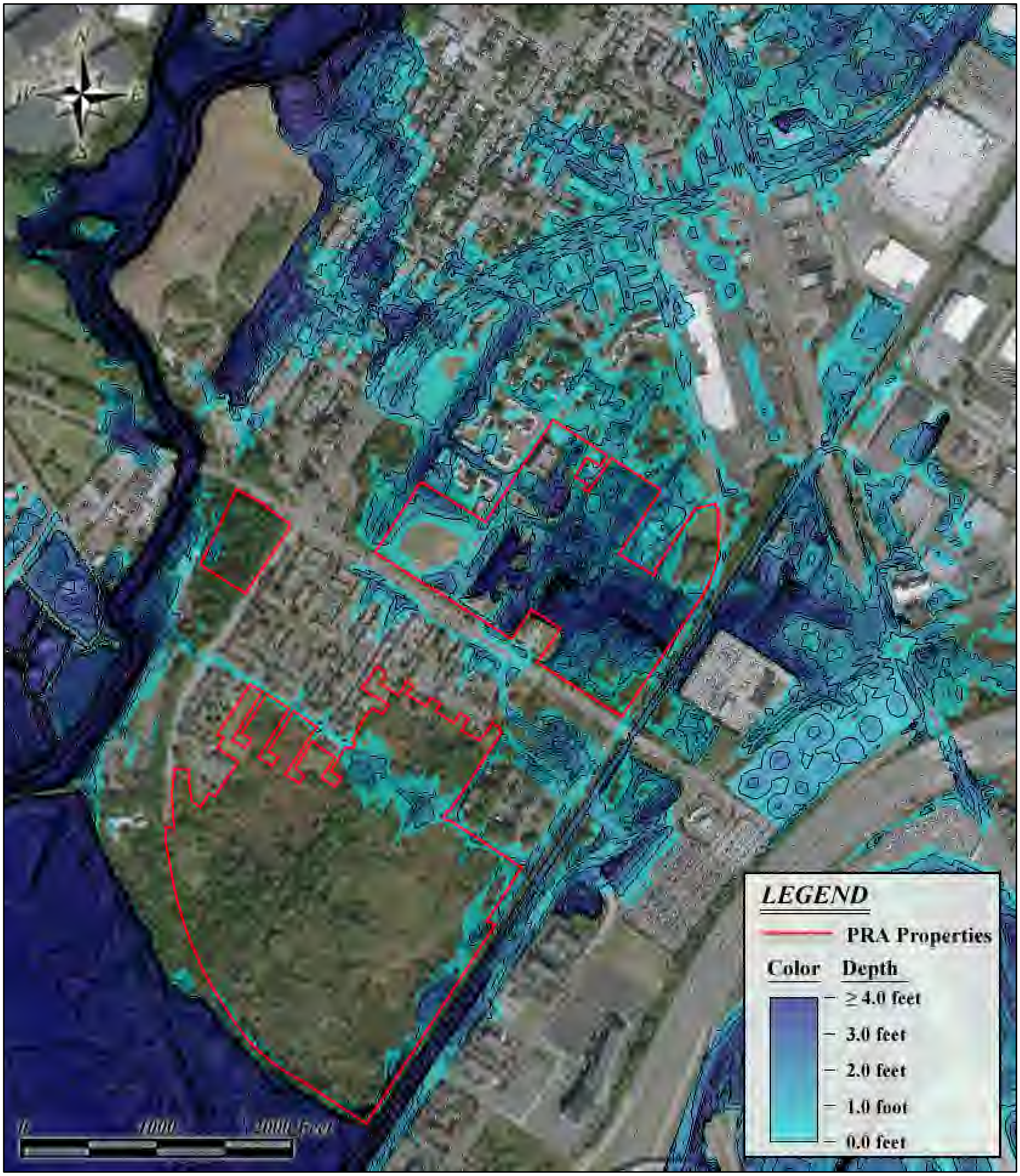

Figure B-32: 10-year Terrestrial Event coincident with Adjusted Great Appalachian Storm of 1950 – Computed Maximum Water Depths

B.8.0 Model Limitations

One of the more important limitations of this model is that it has not been validated by independent data sets at this time. The model has been calibrated and therefore it is our assessment that it can be utilized for its intended purpose. Future monitoring and data collection in Eastwick would allow for model validation of tidal surge and/or larger terrestrial runoff events.

This model has been constructed to evaluate the potential for beneficial reuse of available public lands as outlined in the 2019 Lower Eastwick Public Land Strategy (LEPLS) and approved by Eastwick Community Stakeholders with the support of city, state, and federal agencies. While it is our hope as scientists and engineers that this model may also be useful to other related studies in the area, it should not be used or considered for alternative purposes or objectives other than that for which it was intended. As with any similar flood model, this tool should not be used indiscriminately without first confirming all assumptions and inputs that would establish conditions or guide appropriate adjustments for alternative objectives.

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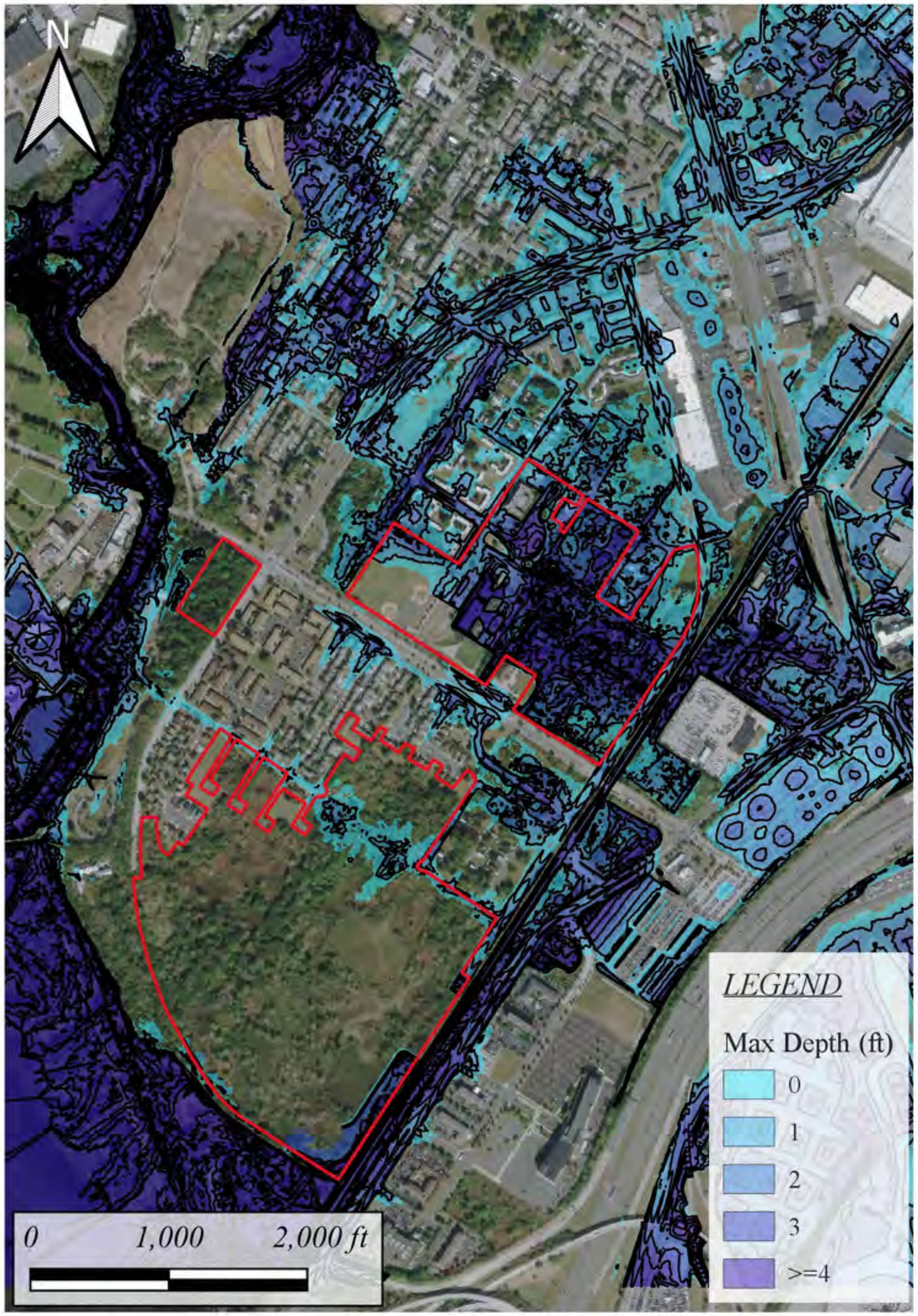
ATTACHMENT C – LEPLS REUSE CONCEPTS FLOOD MODEL RESULTS

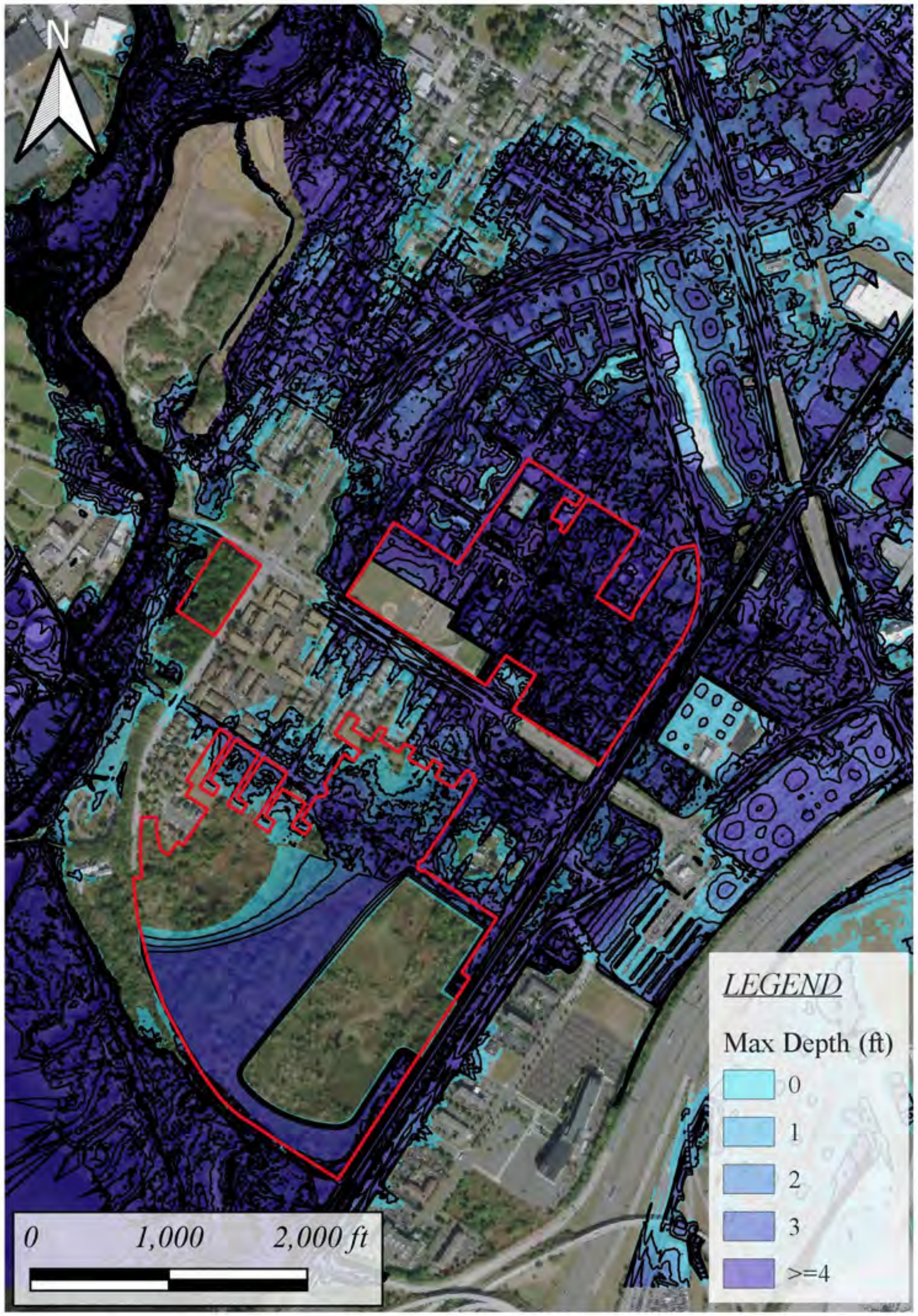
Attachment C-1. Hurricane Isaias LEPLS Reuse Concepts Model Results



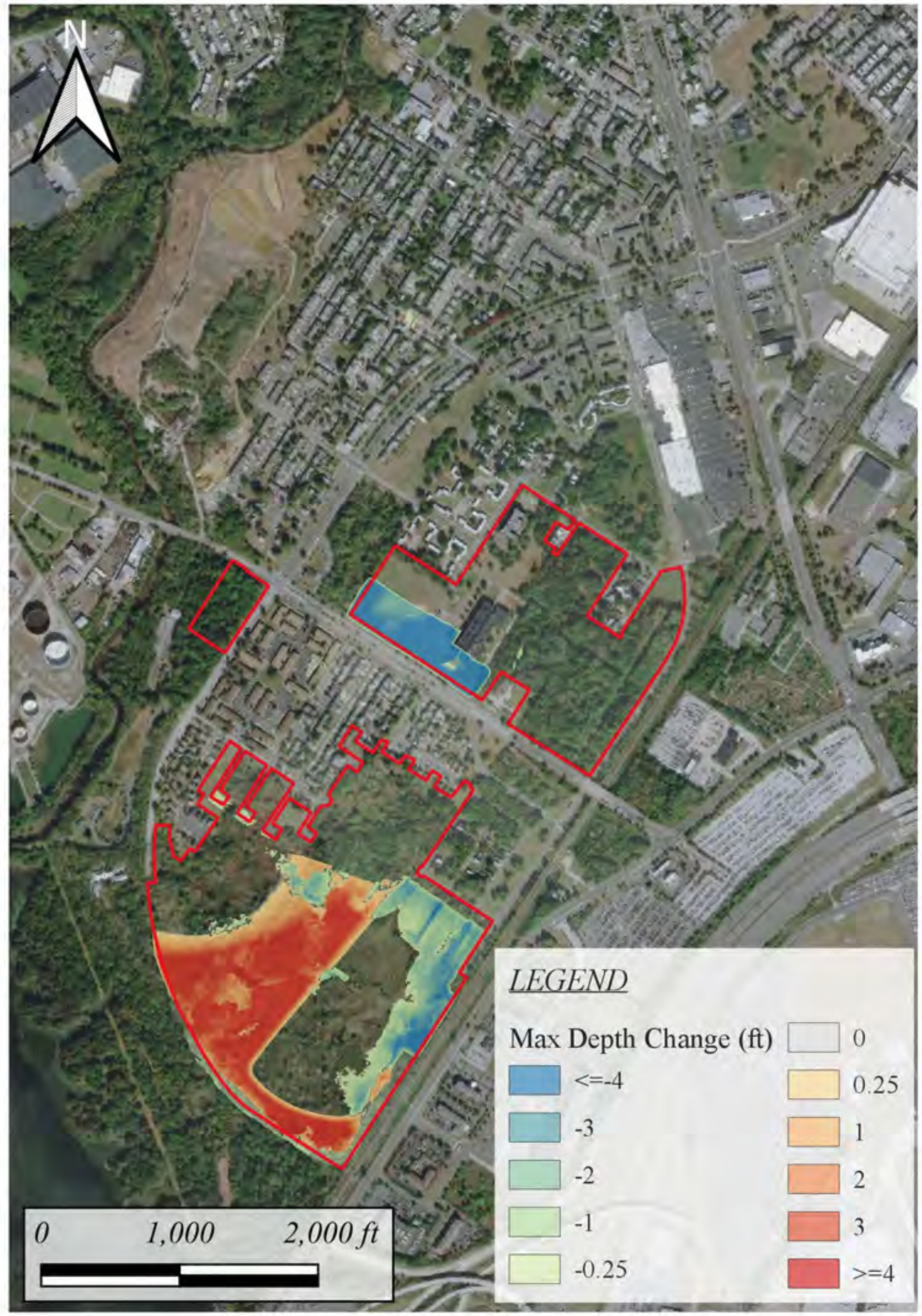
LEPLS Reuse Concepts - Maximum Depth (ft)

LEPLS Reuse Concepts - Change in Maximum Depth from Existing Conditions (ft)

Attachment C-2. 100-Year Terrestrial LEPLS Reuse Concepts Model Results

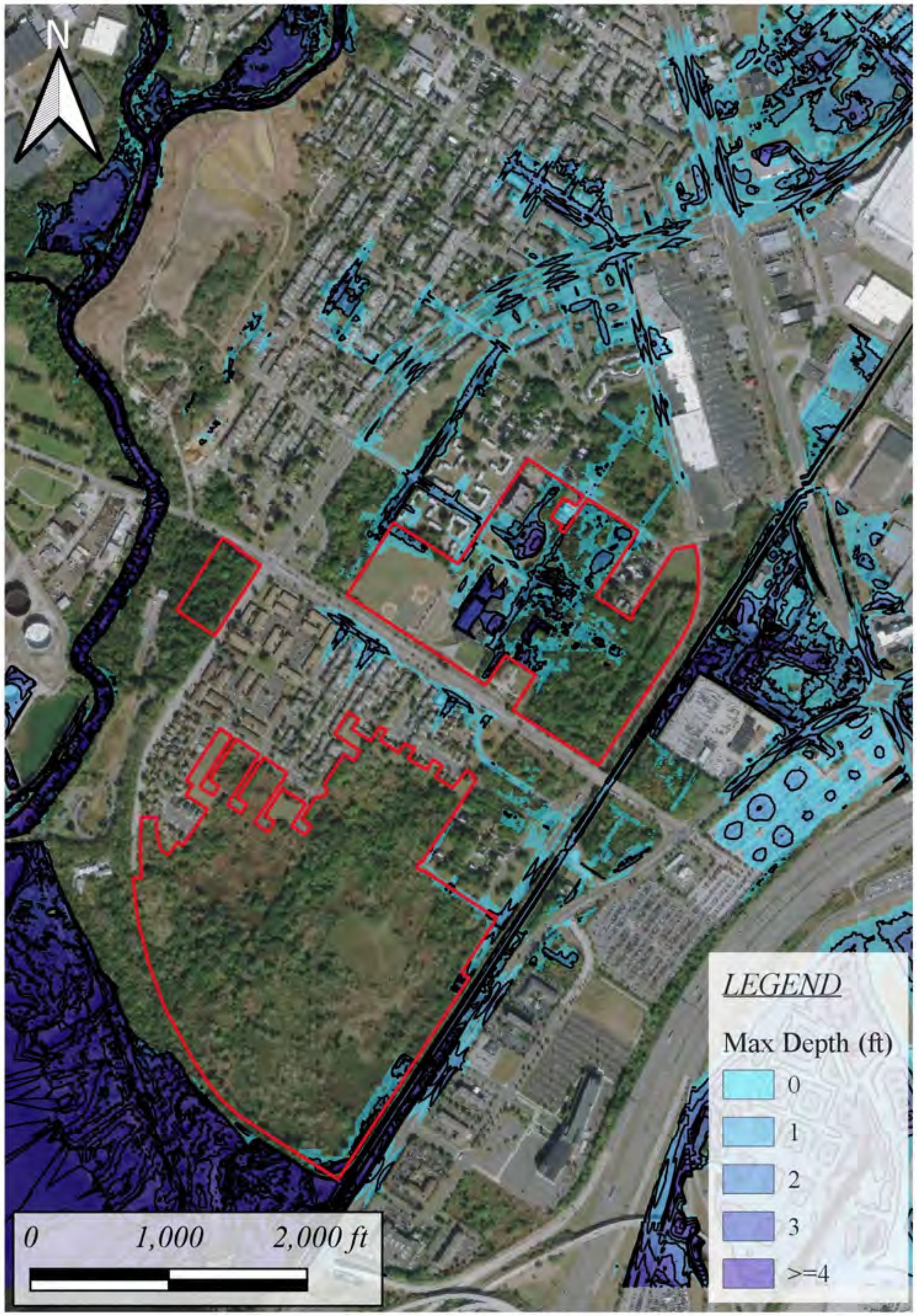


LEPLS Reuse Concepts - Maximum Depth (ft)



LEPLS Reuse Concepts - Change in Maximum Depth from Existing Conditions (ft)

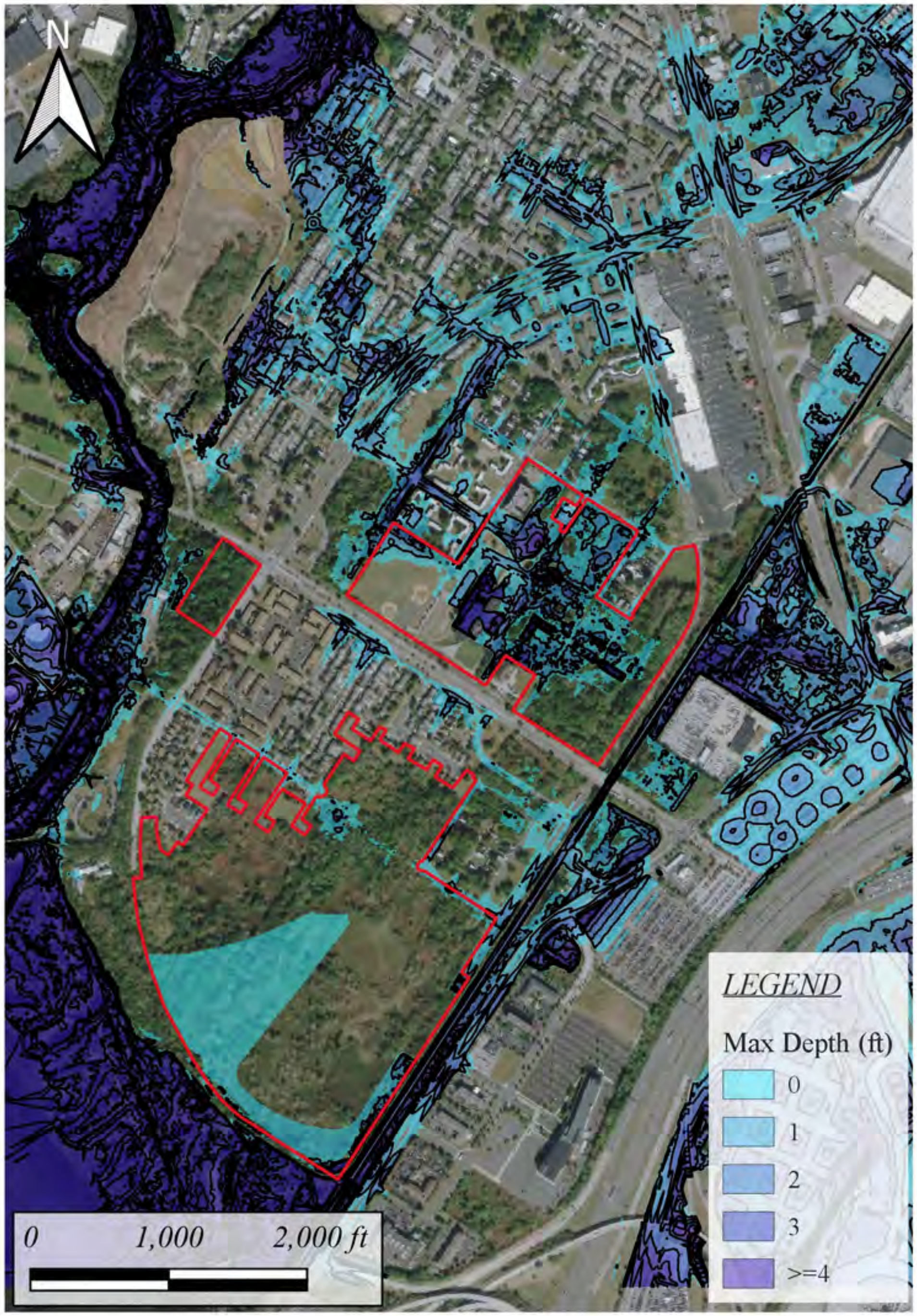
Attachment C-3. Hurricane Sandy LEPLS Reuse Concepts Model Results



LEPLS Reuse Concepts - Maximum Depth (ft)

LEPLS Reuse Concepts - Change in Maximum Depth from Existing Conditions (ft)

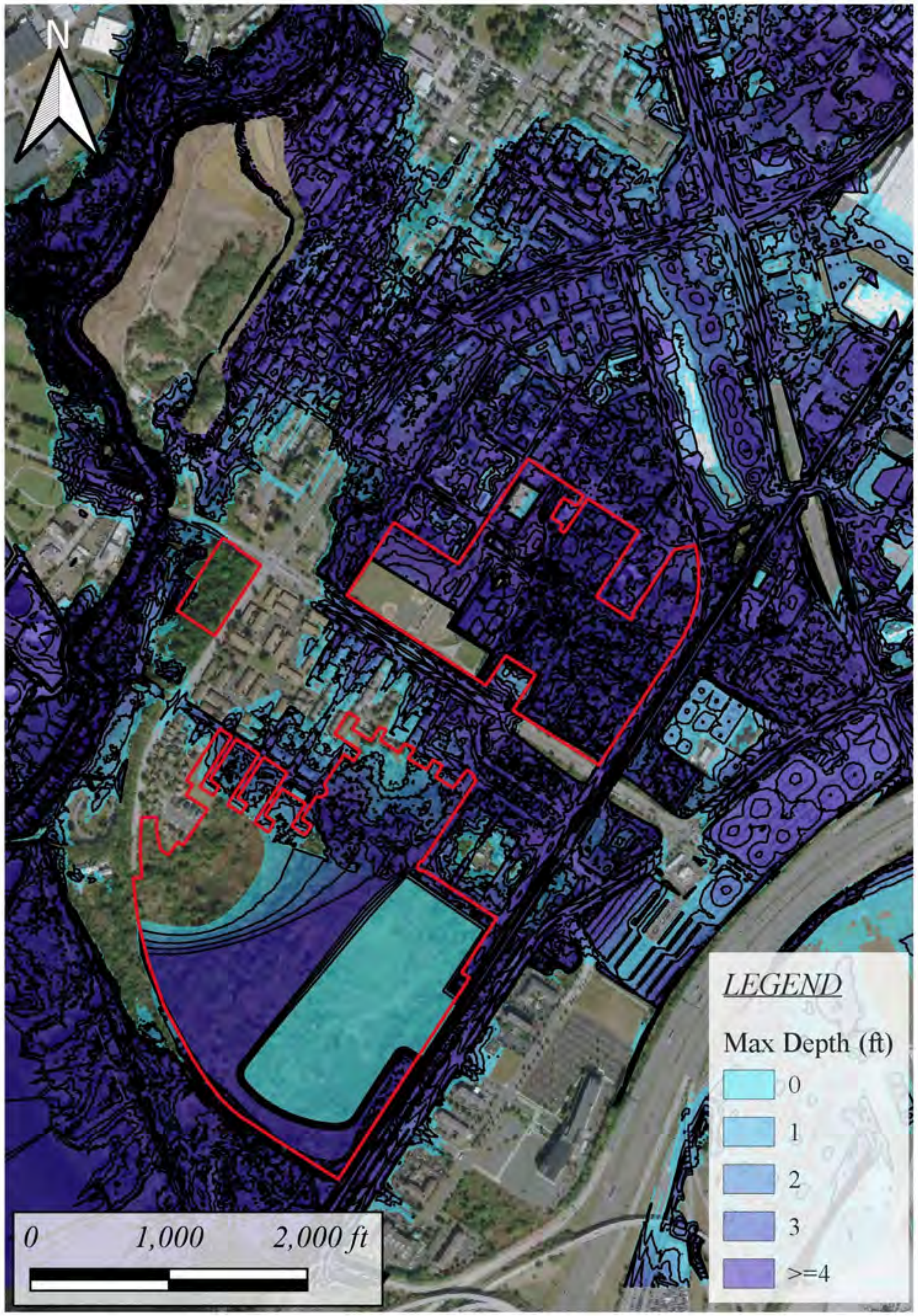
Attachment C-4. 1950 Great Appalachian Storm Adjusted to 2020 LEPLS Reuse Concepts Model Results



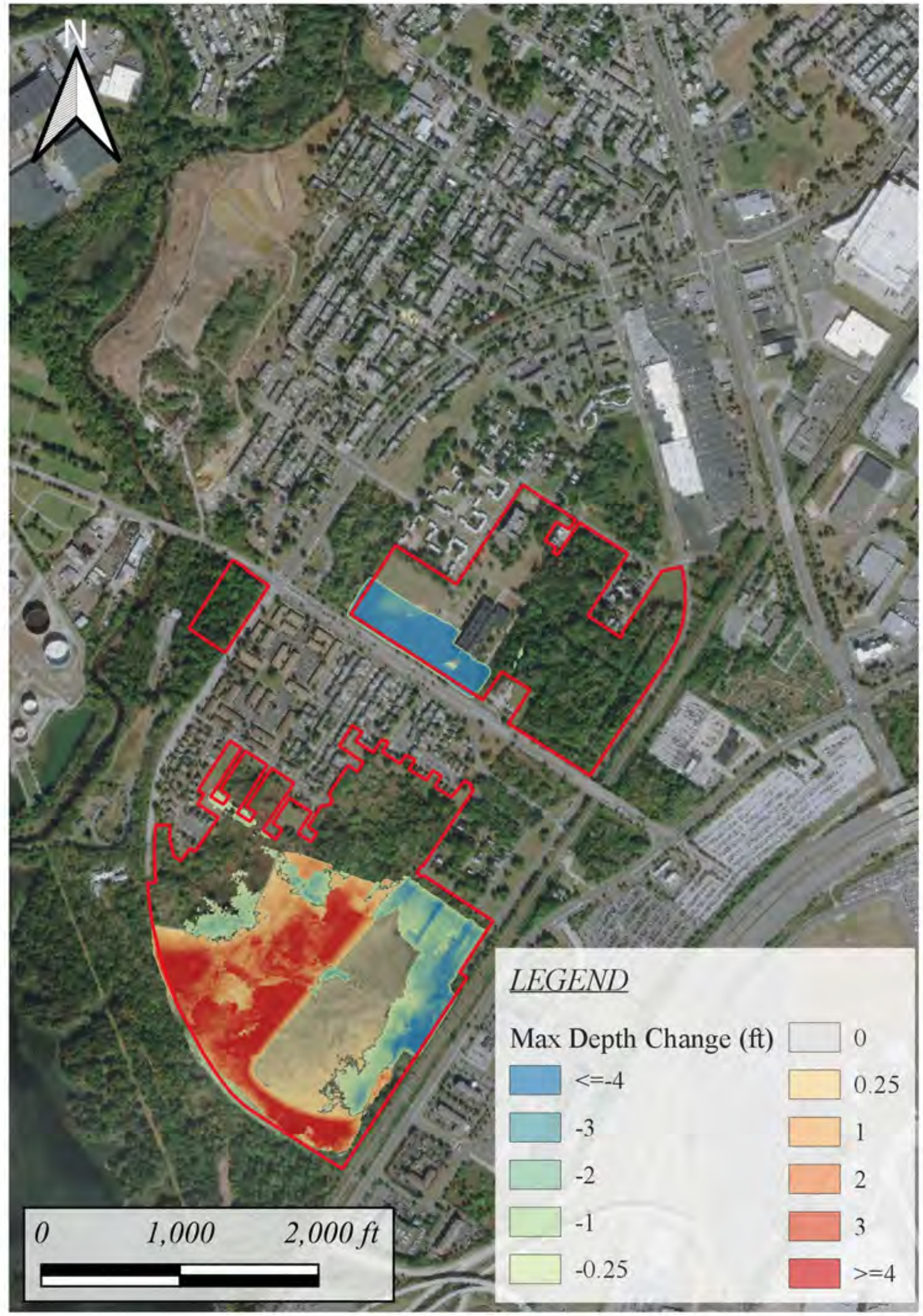
LEPLS Reuse Concepts - Maximum Depth (ft)

LEPLS Reuse Concepts - Change in Maximum Depth from Existing Conditions (ft)

Attachment C-5. 100-Year Terrestrial at 2100 LEPLS Reuse Concepts Model Results

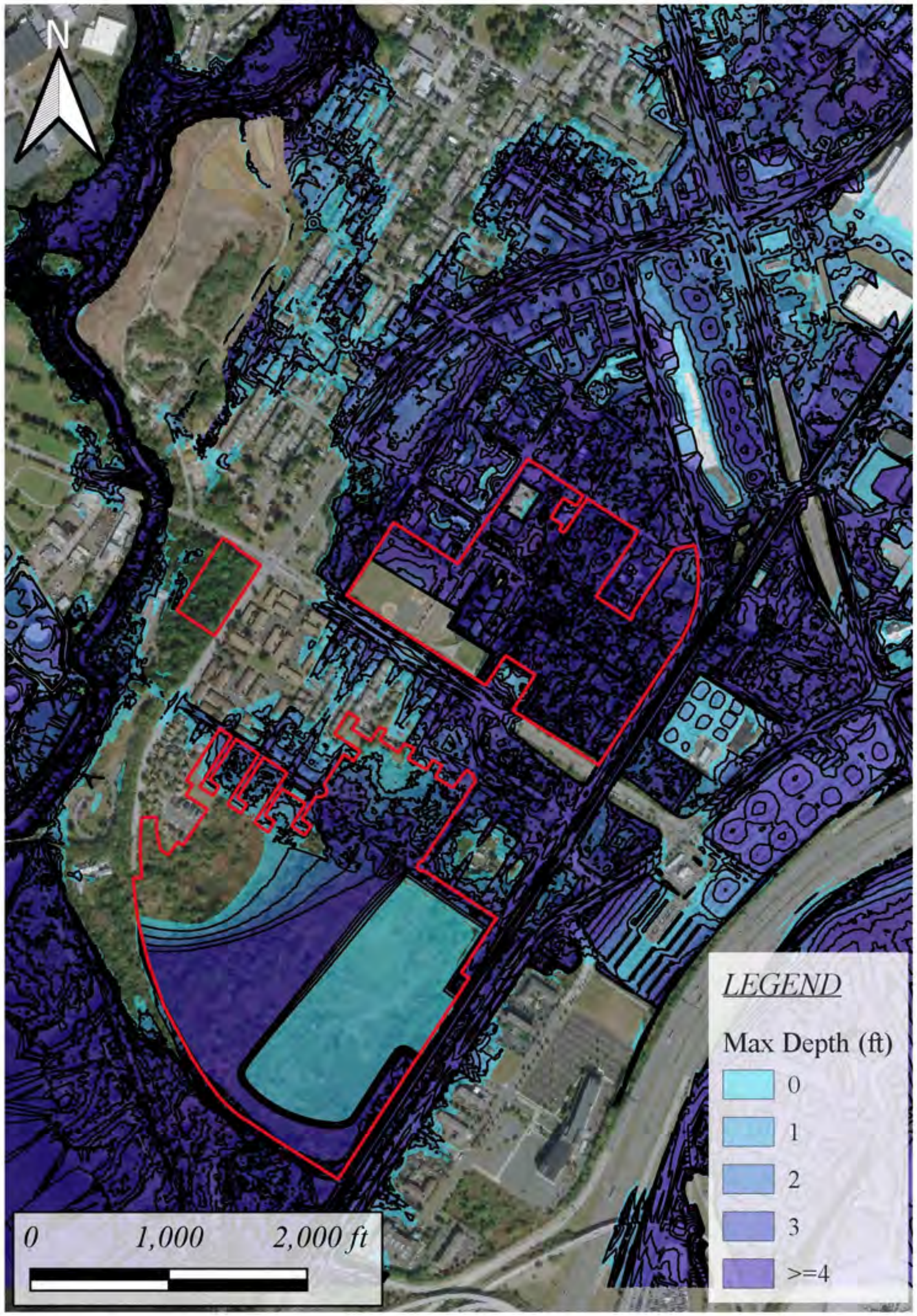


LEPLS Reuse Concepts - Maximum Depth (ft)

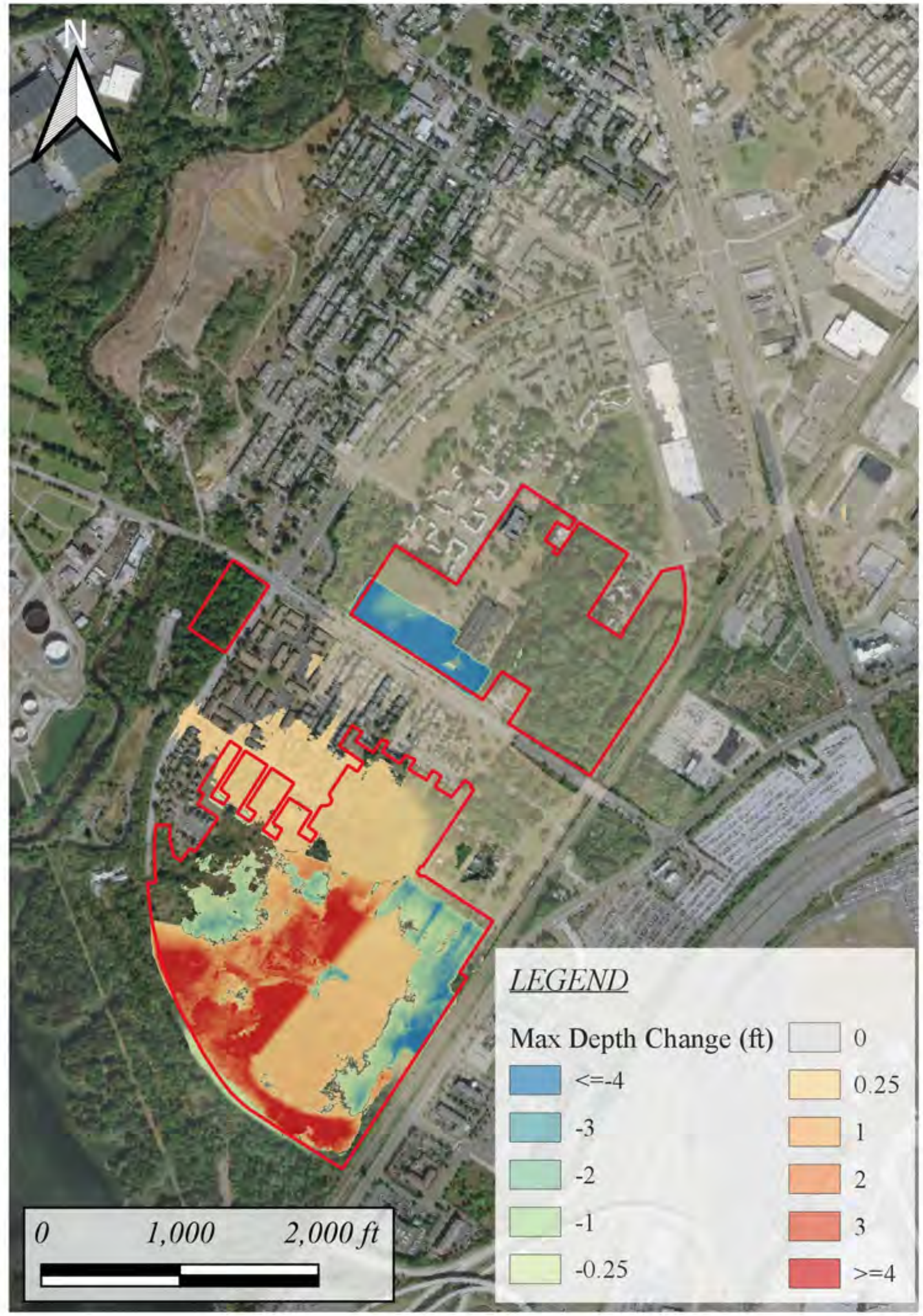


LEPLS Reuse Concepts - Change in Maximum Depth from Existing Conditions (ft)

Attachment C-6. 1950 Great Appalachian Storm Adjusted to 2100 LEPLS Reuse Concepts Model Results

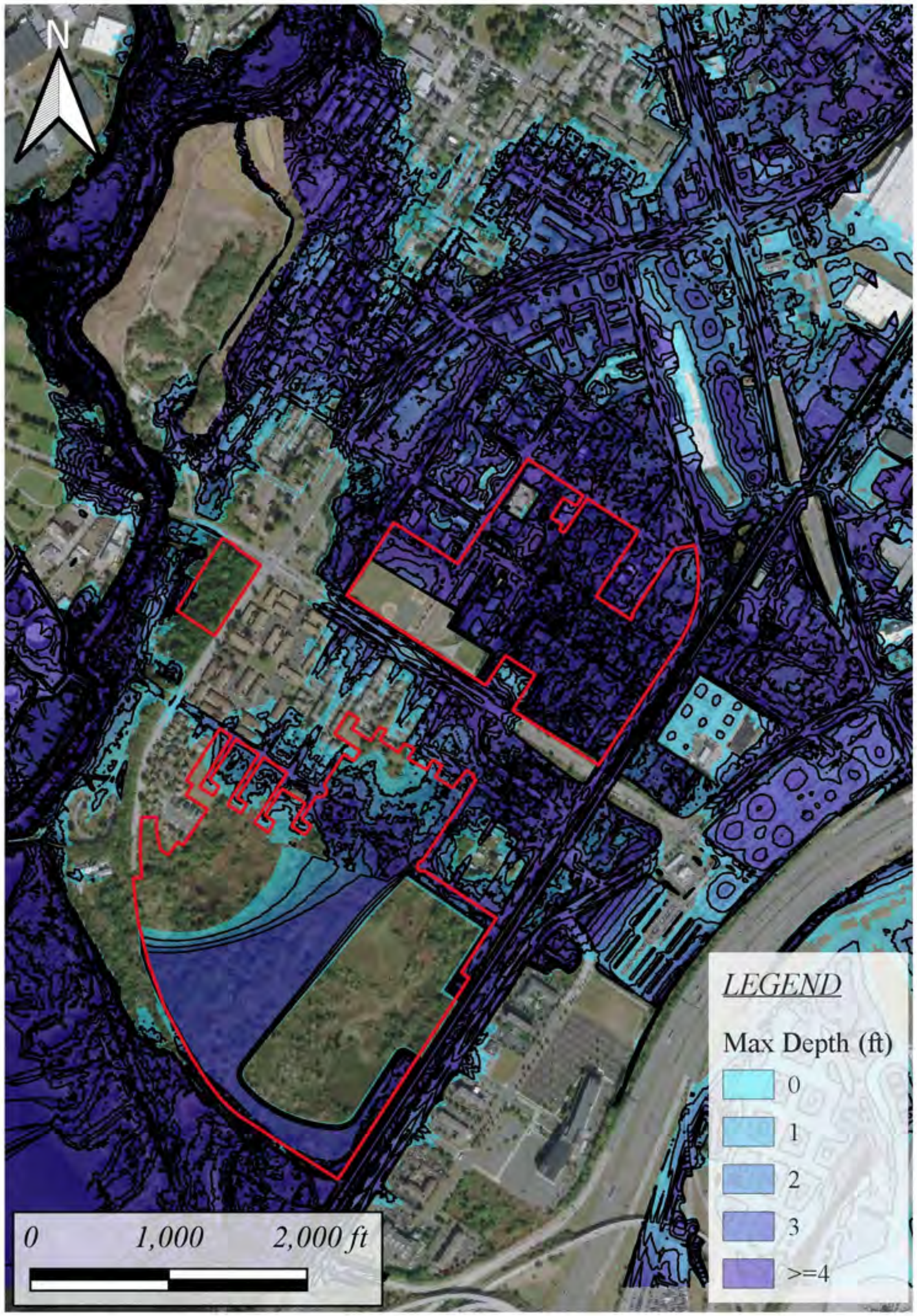


LEPLS Reuse Concepts - Maximum Depth (ft)

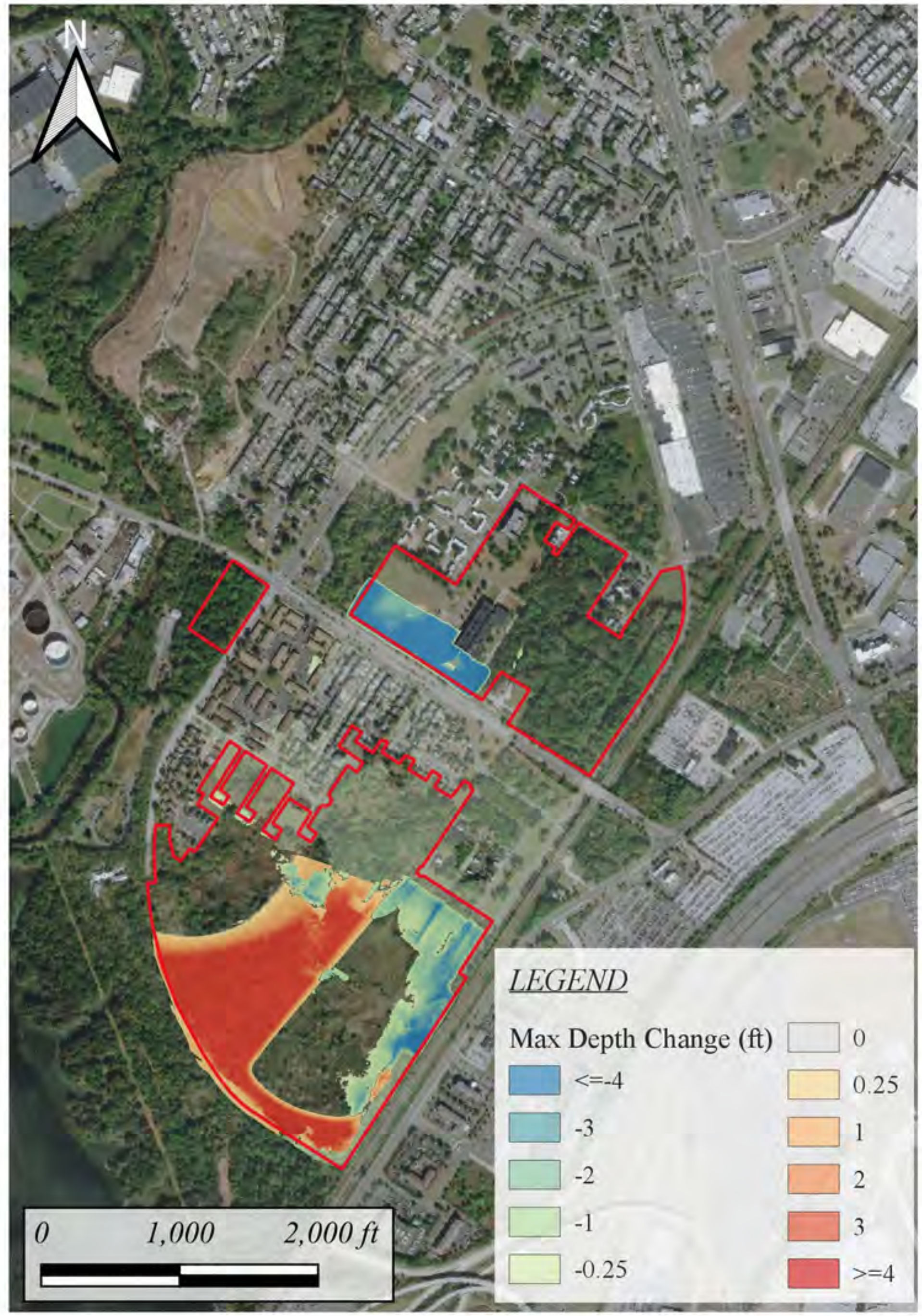


LEPLS Reuse Concepts - Change in Maximum Depth from Existing Conditions (ft)

Attachment C-7. The 100-year Terrestrial Event & 10-year Tidal Event LEPLS Reuse Concepts Model Results

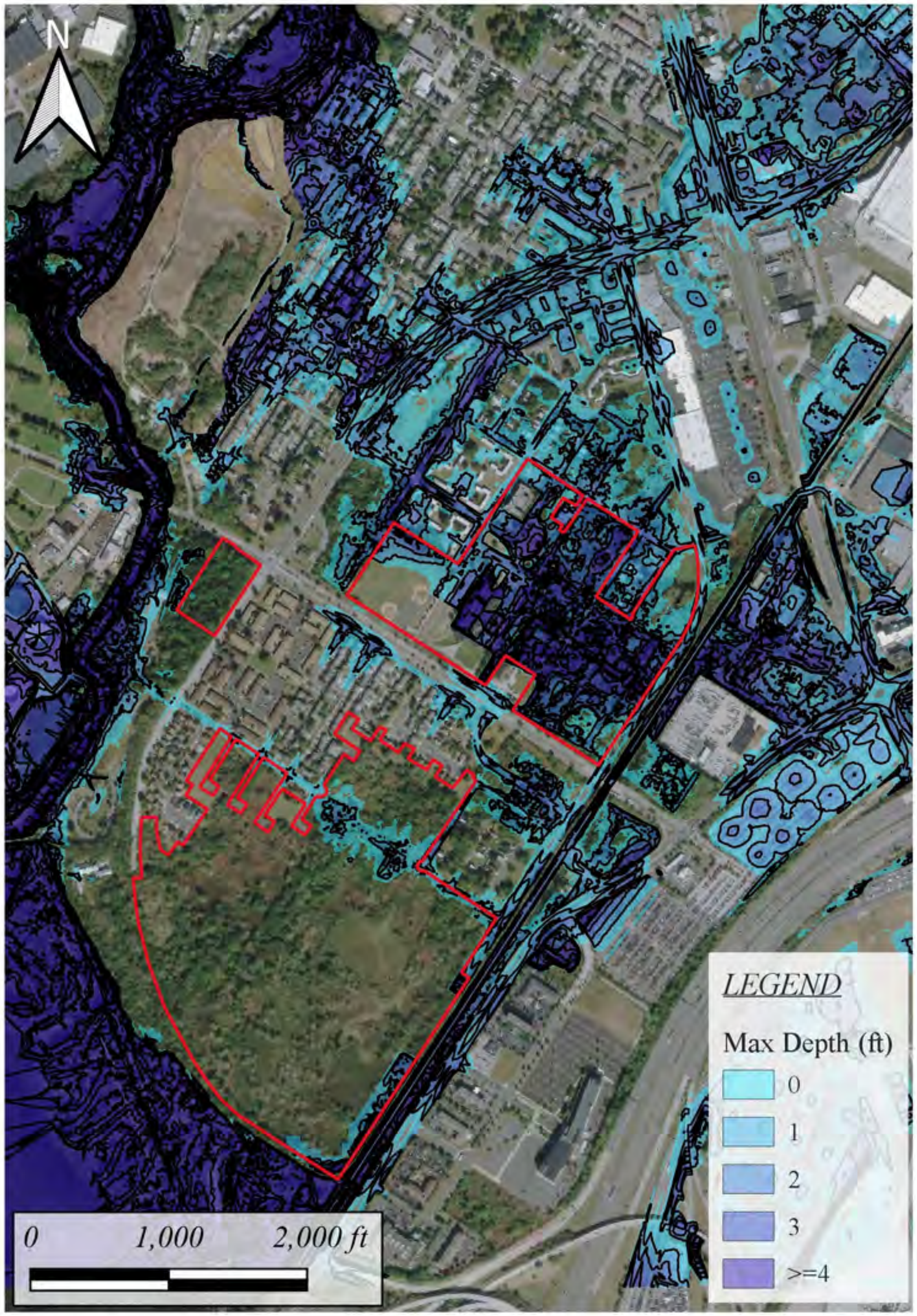


LEPLS Reuse Concepts - Maximum Depth (ft)



LEPLS Reuse Concepts - Change in Maximum Depth from Existing Conditions (ft)

Attachment C-8. The 10-year Terrestrial Event & Great Appalachian Storm of 1950 Adjusted to 2020 LEPLS Reuse Concepts Model Results

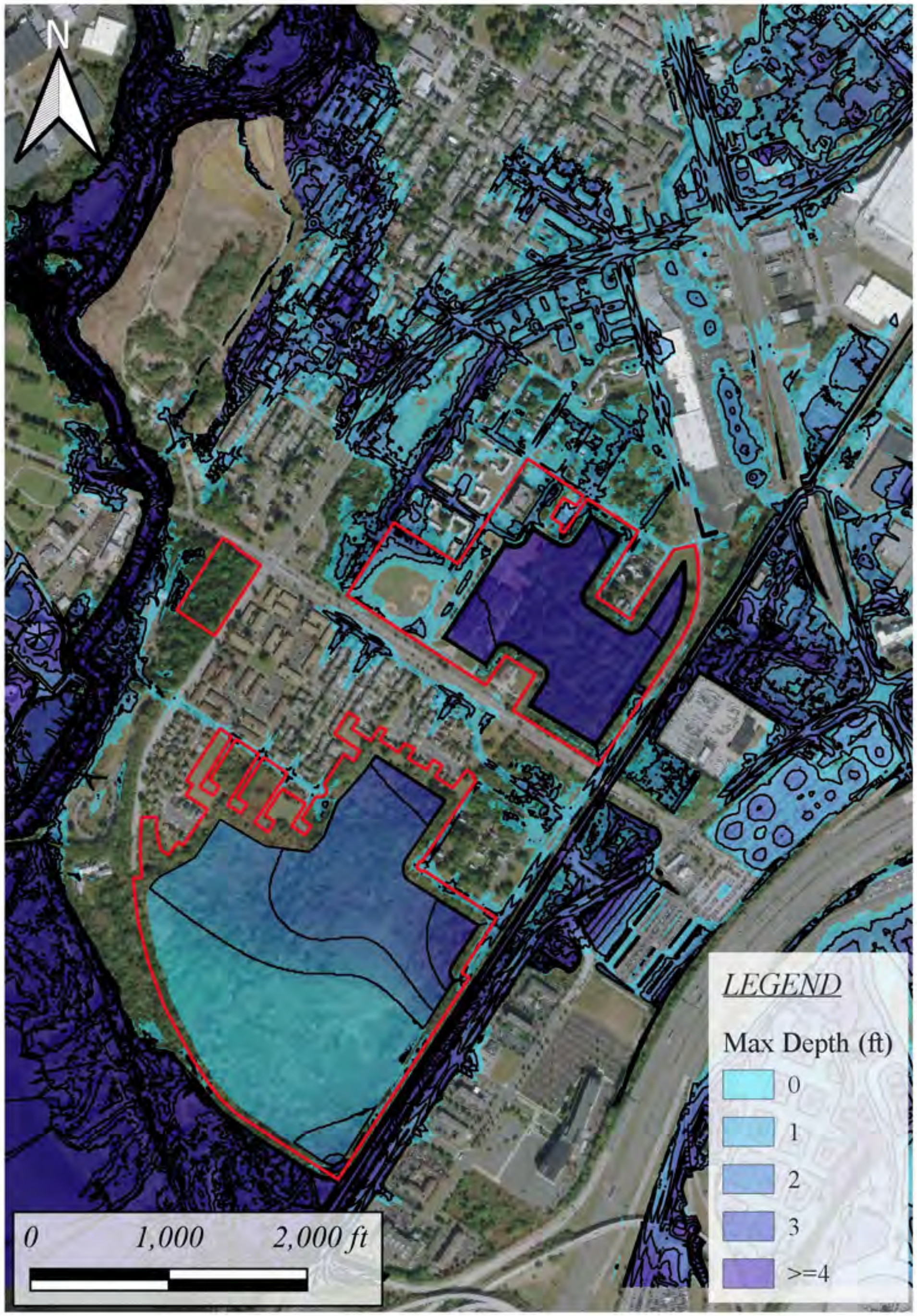


LEPLS Reuse Concepts - Maximum Depth (ft)

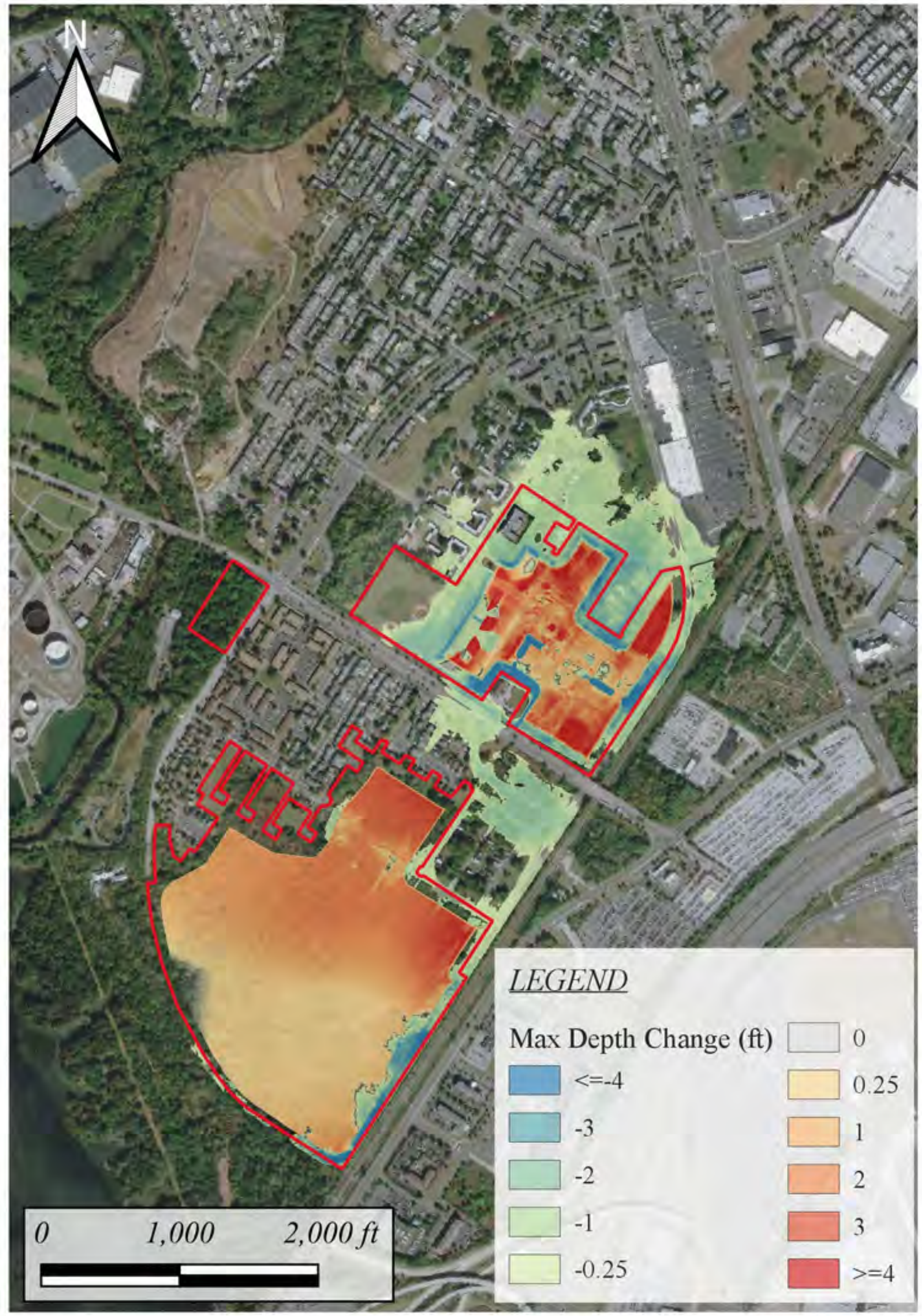
LEPLS Reuse Concepts - Change in Maximum Depth from Existing Conditions (ft)

ATTACHMENT D – CONSTRUCTED WETLANDS AND STORAGE BASINS CONCEPT MODEL RESULTS

Attachment D-1. Hurricane Isaias Constructed Wetlands and Storage Basins Model Results

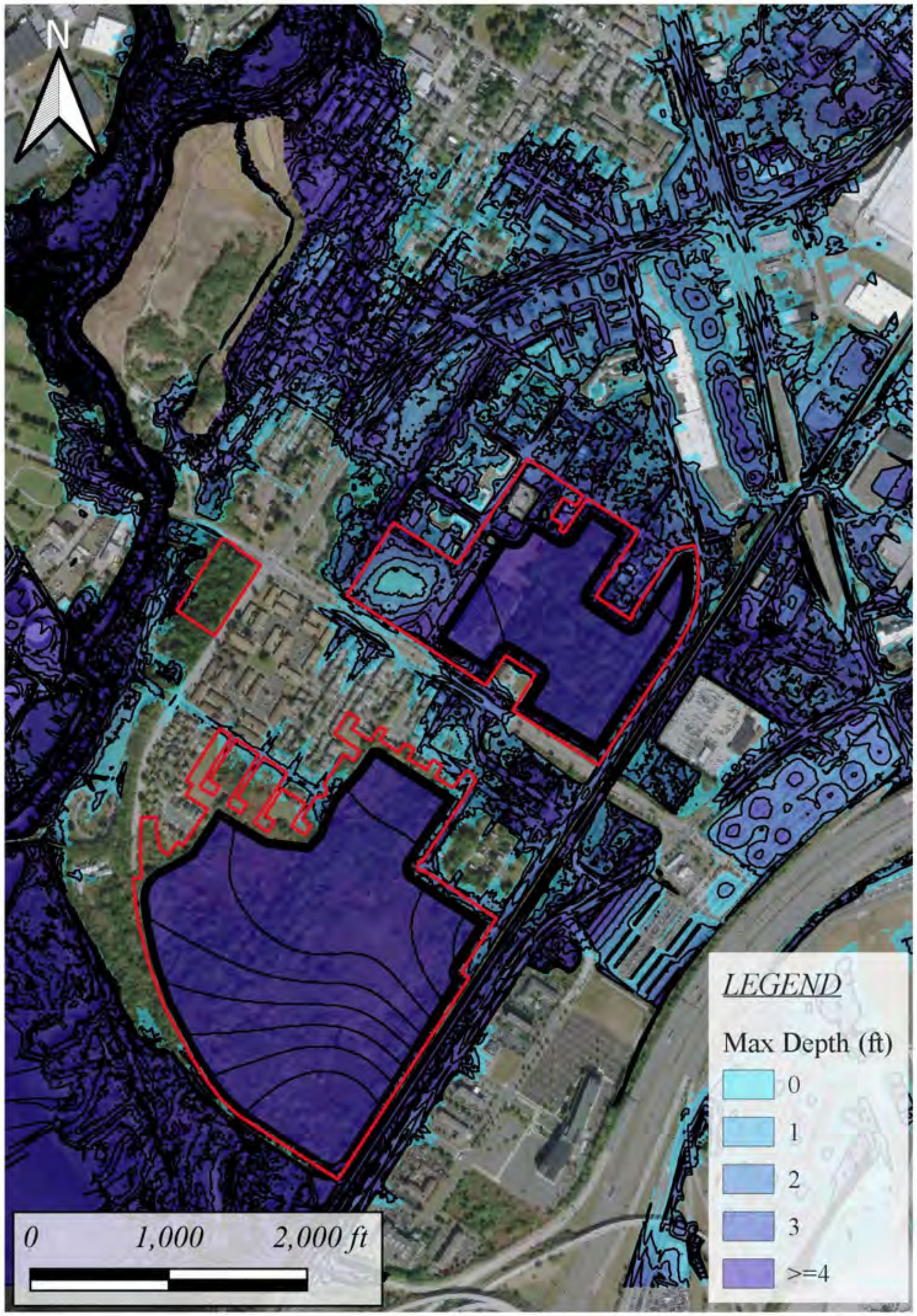


Scenario 1 - Maximum Depth (ft)

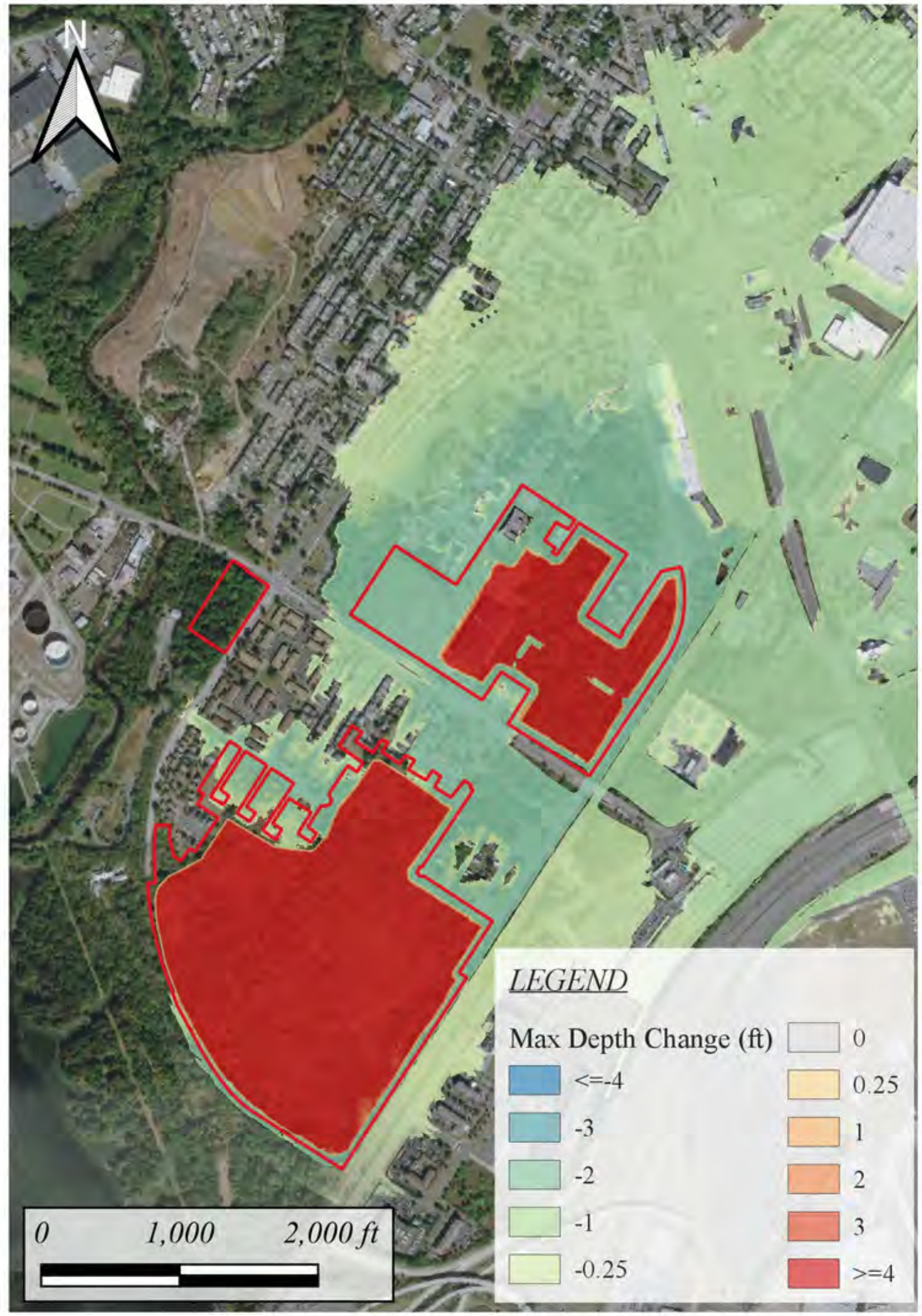


Maximum Restoration Scenario - Change in Maximum Depth from Existing Conditions (ft)

Attachment D-2. 100-Year Terrestrial Maximum Ecological Restoration Model Results

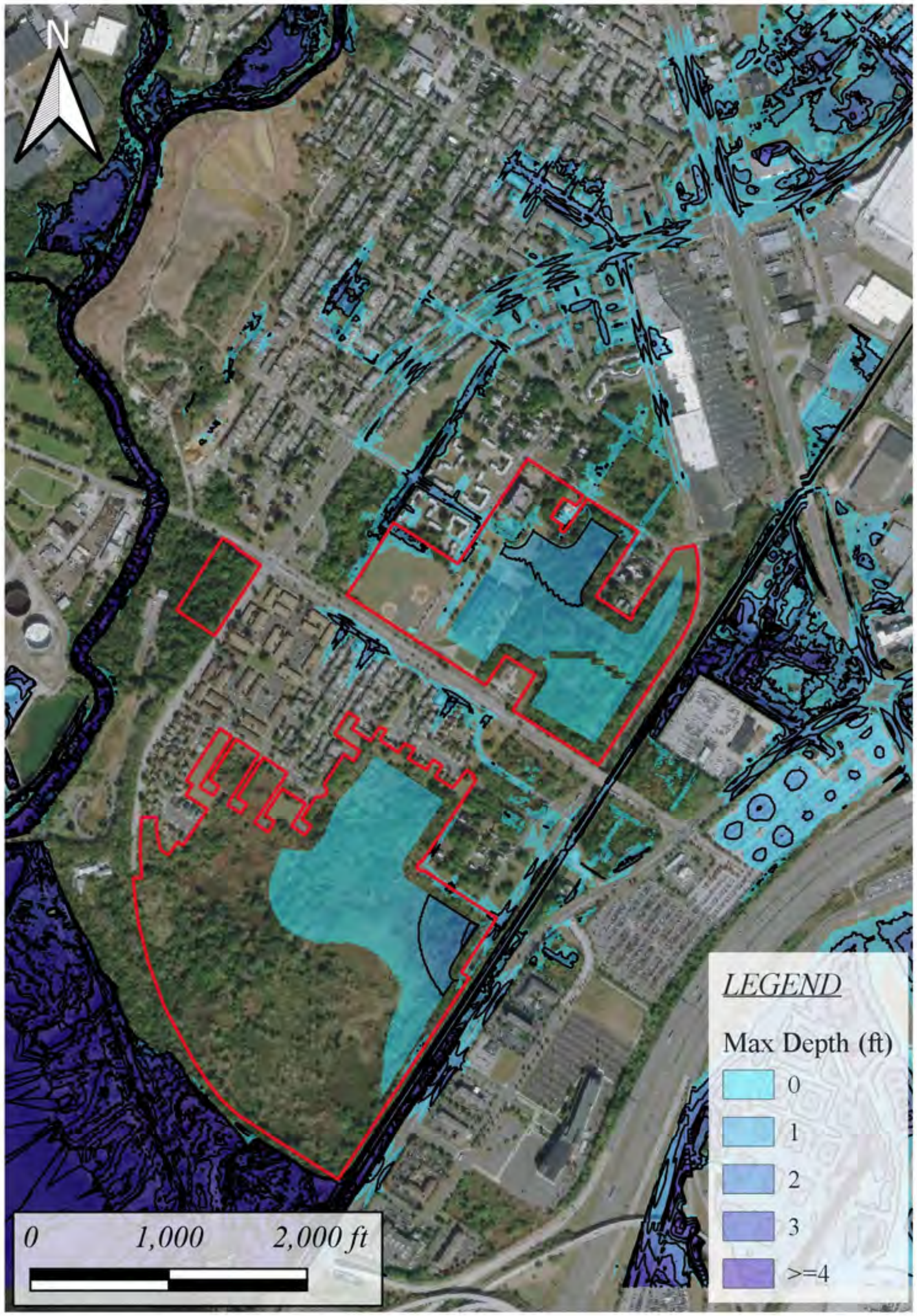


Maximum Restoration Scenario - Maximum Depth (ft)



Maximum Restoration Scenario - Change in Maximum Depth from Existing Conditions (ft)

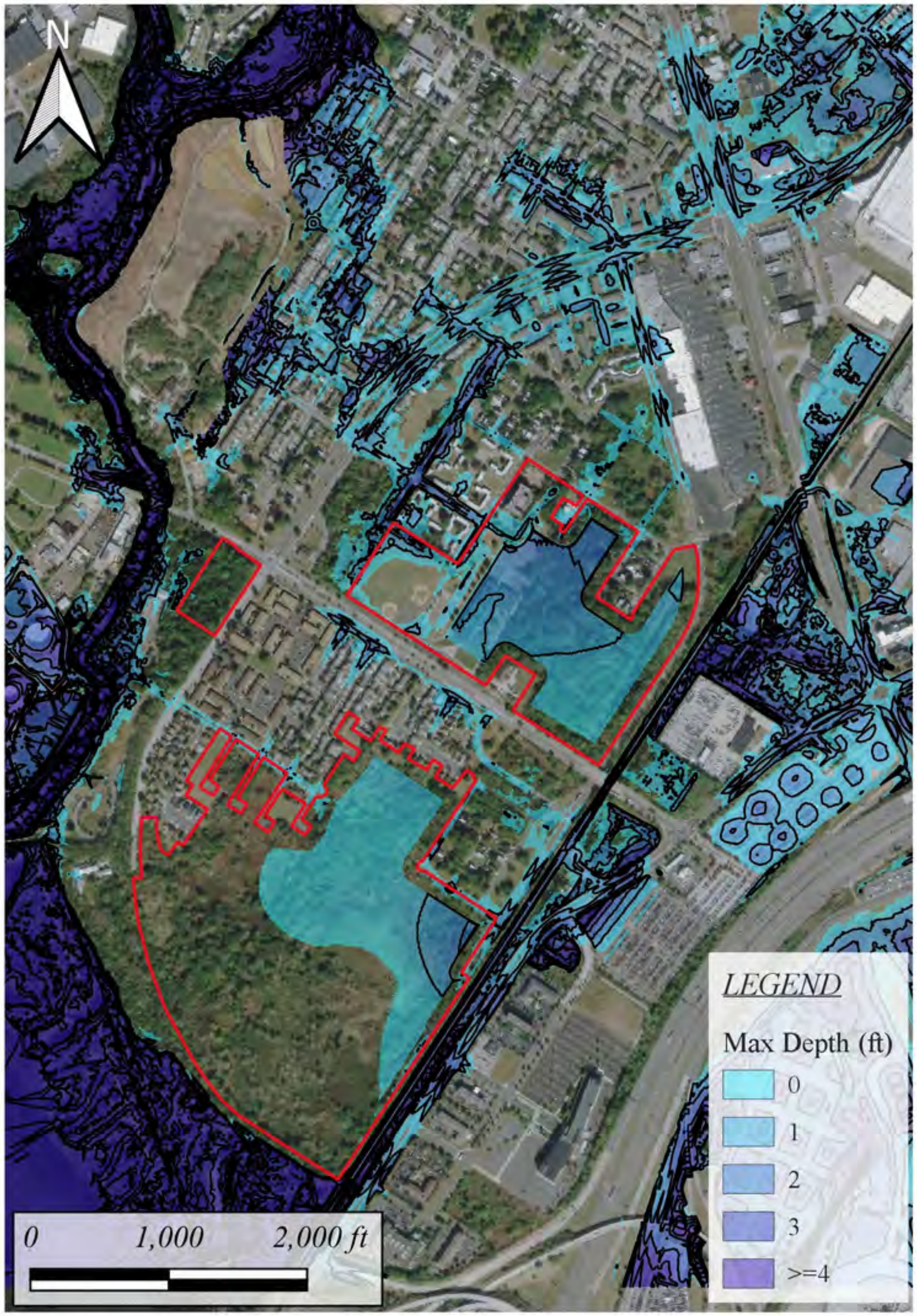
Attachment D-3. Hurricane Sandy Constructed Wetlands and Storage Basins Model Results



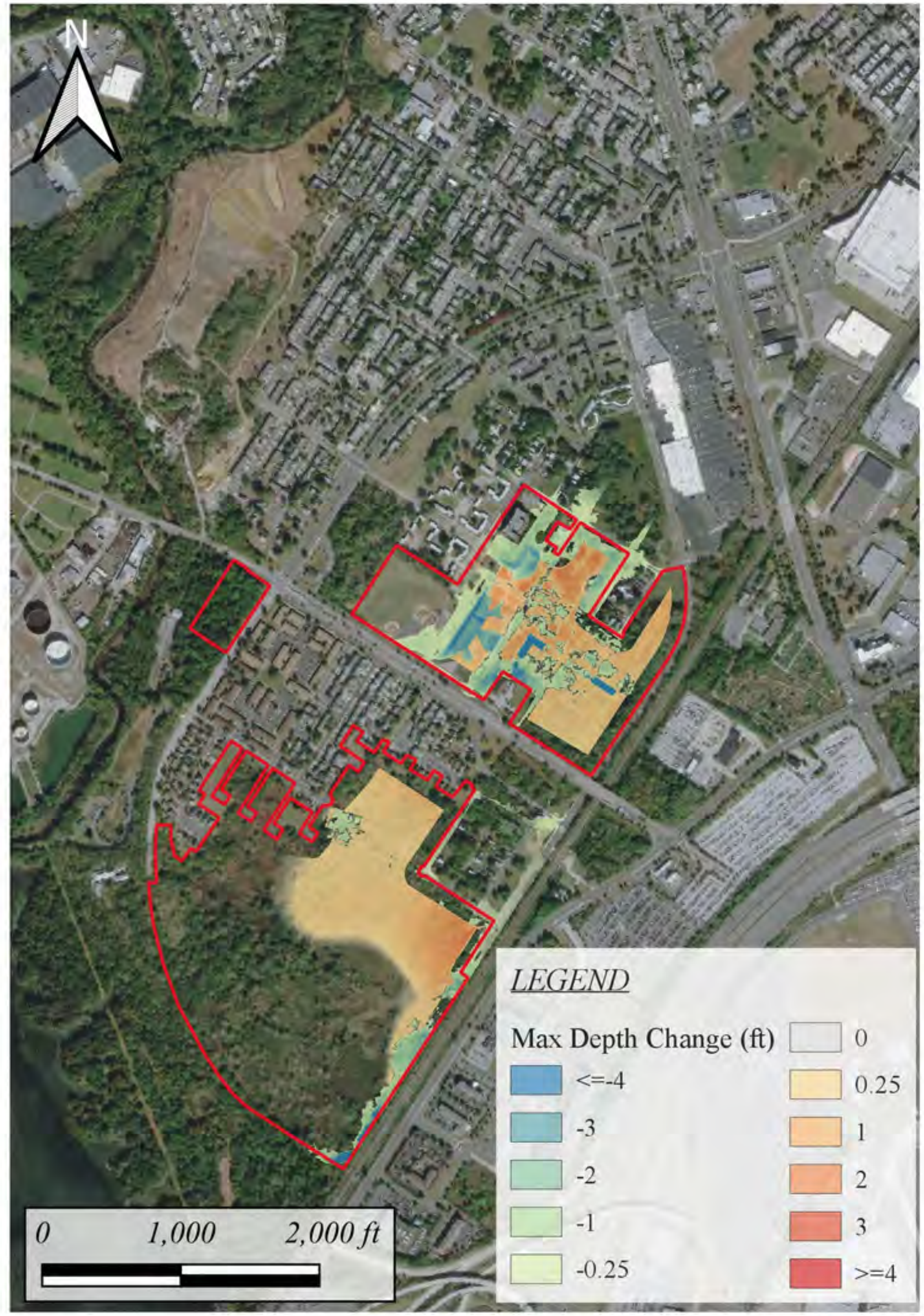
Scenario 1 - Maximum Depth (ft)

Maximum Restoration Scenario - Change in Maximum Depth from Existing Conditions (ft)

Attachment D-4. 1950 Great Appalachian Storm Adjusted to 2020 Constructed Wetlands and Storage Basins Model Results

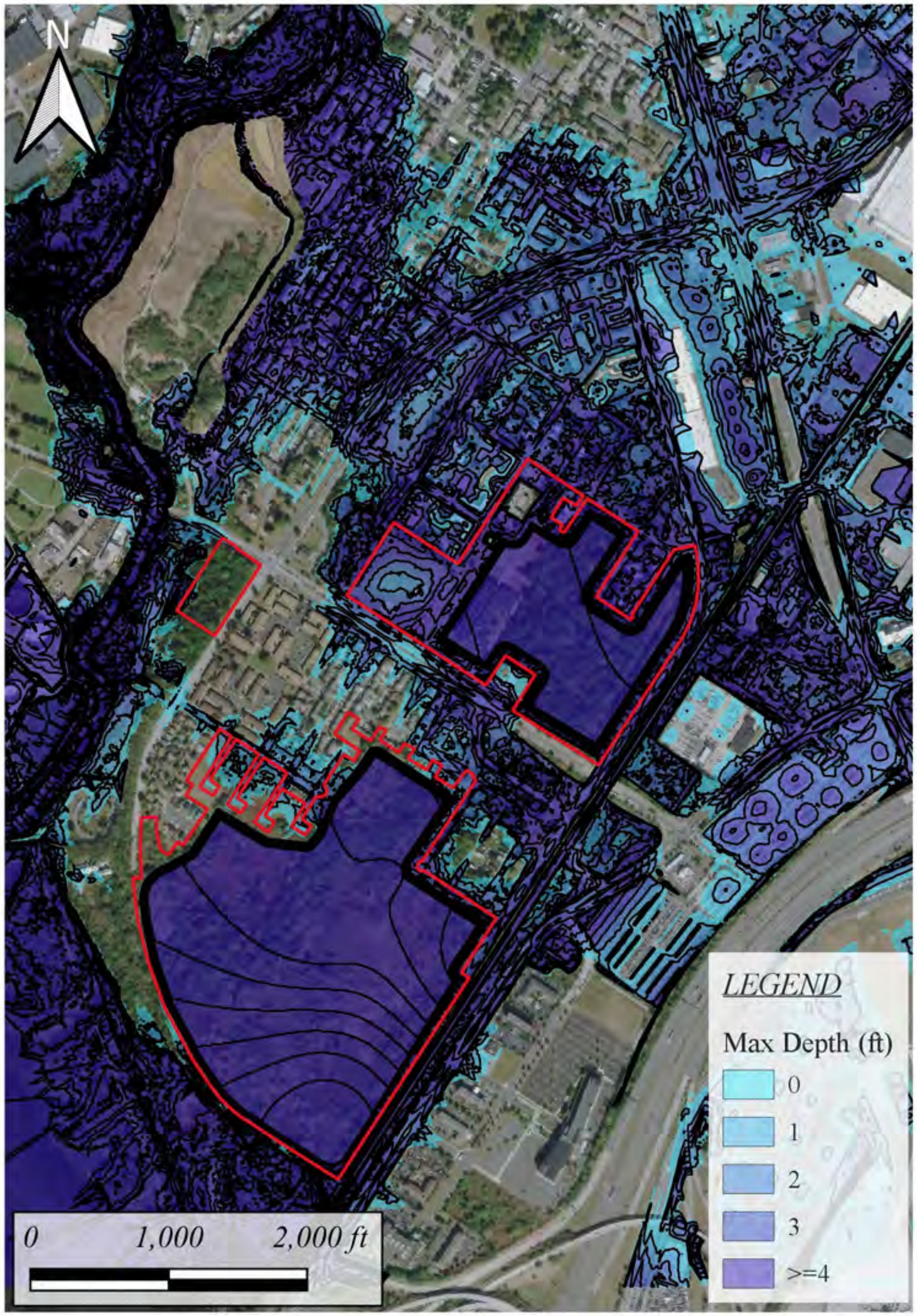


Scenario 1 - Maximum Depth (ft)

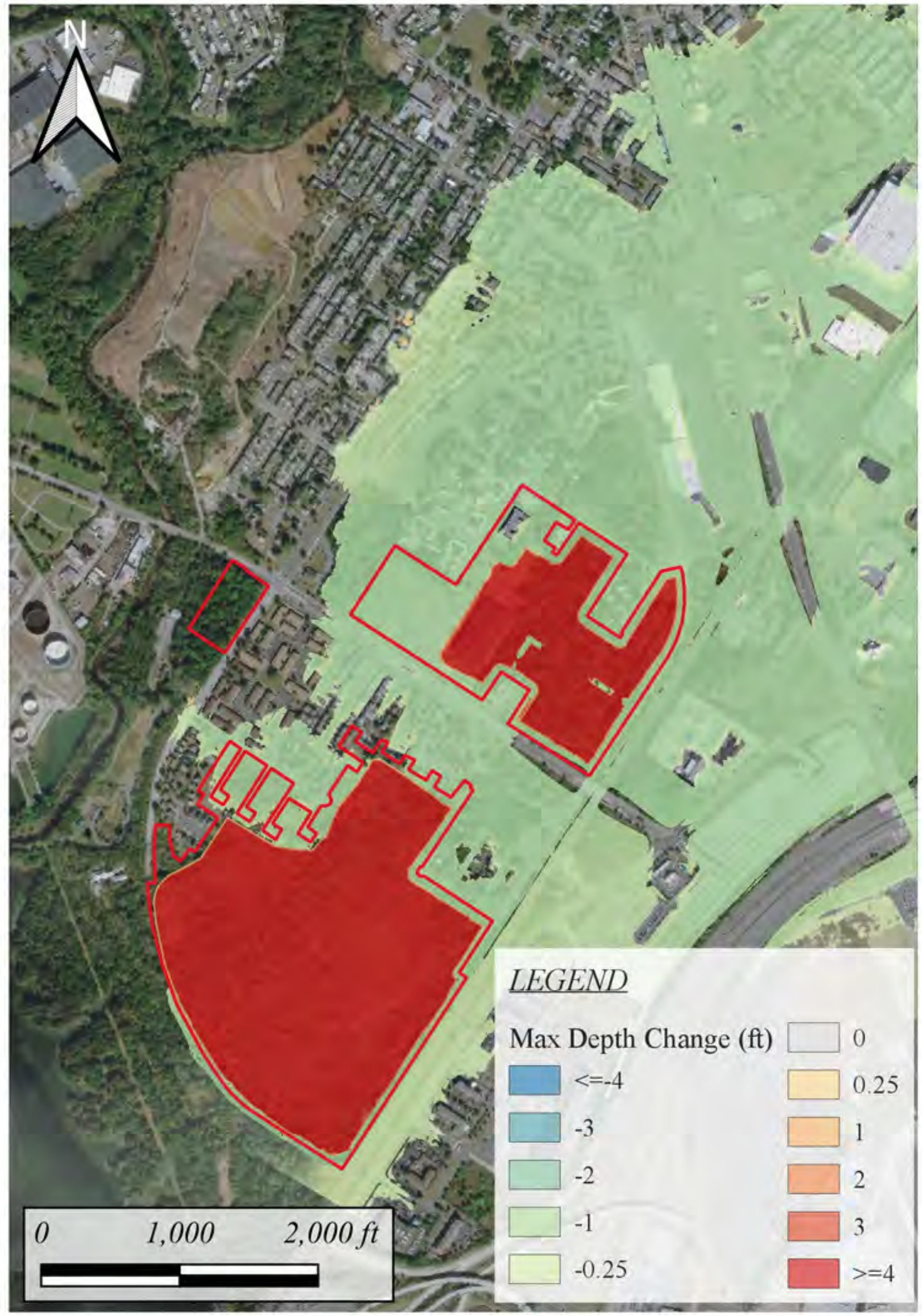


Maximum Restoration Scenario - Change in Maximum Depth from Existing Conditions (ft)

Attachment D-5. 100-Year Terrestrial at 2100 Constructed Wetlands and Storage Basins Model Results

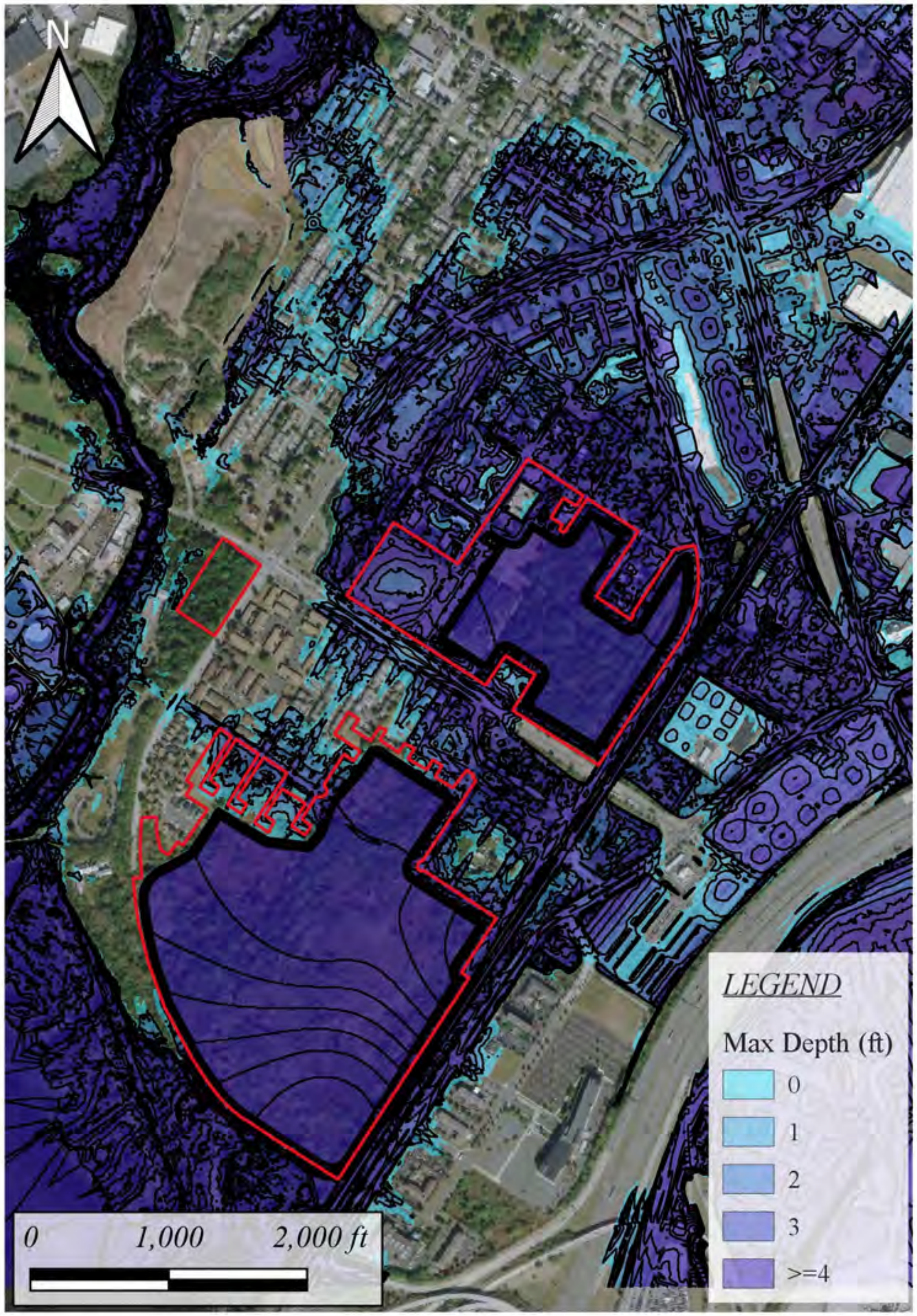


Scenario 1 - Maximum Depth (ft)

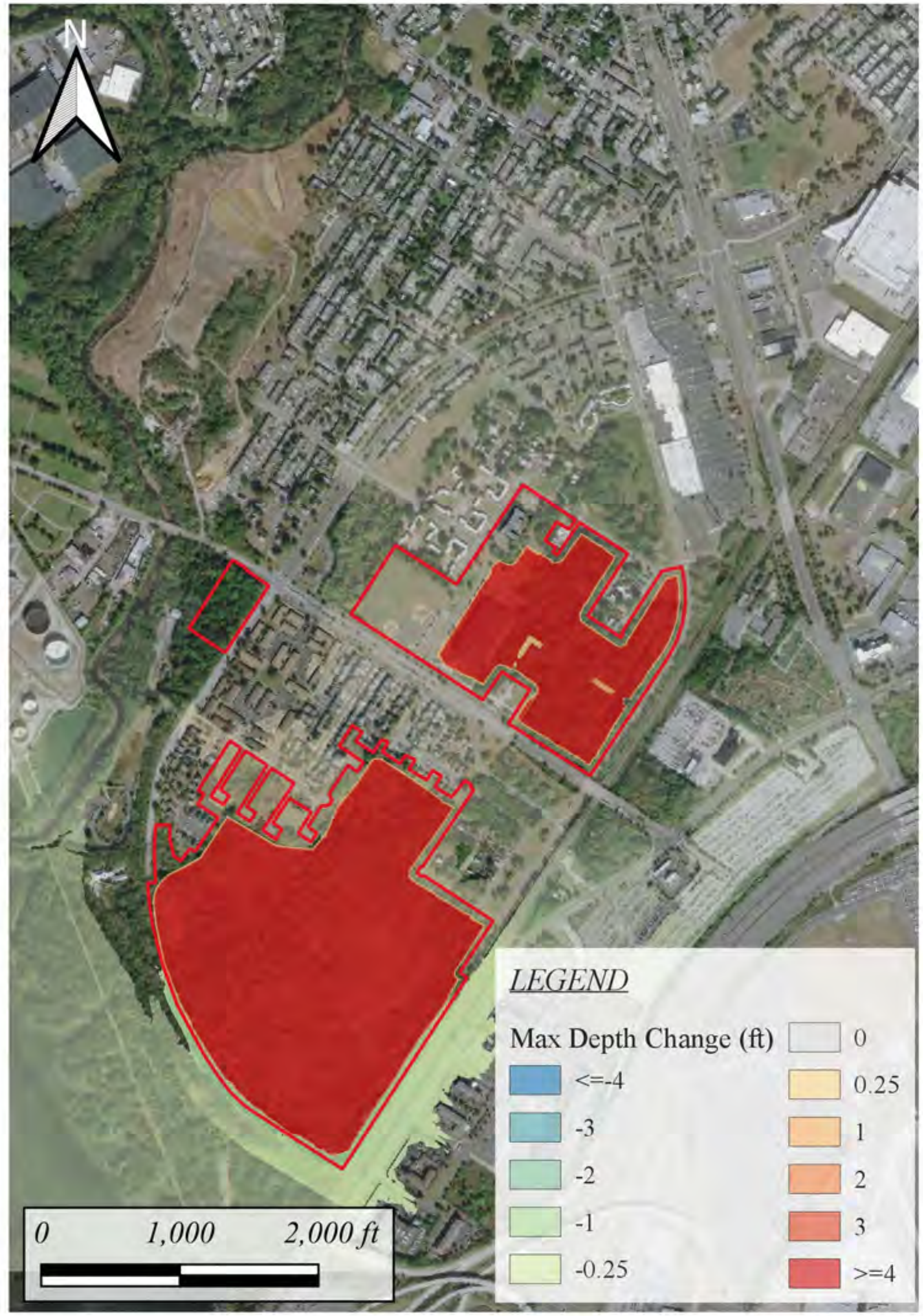


Maximum Restoration Scenario - Change in Maximum Depth from Existing Conditions (ft)

Attachment D-6. 1950 Great Appalachian Storm Adjusted to 2100 Constructed Wetlands and Storage Basins Model Results

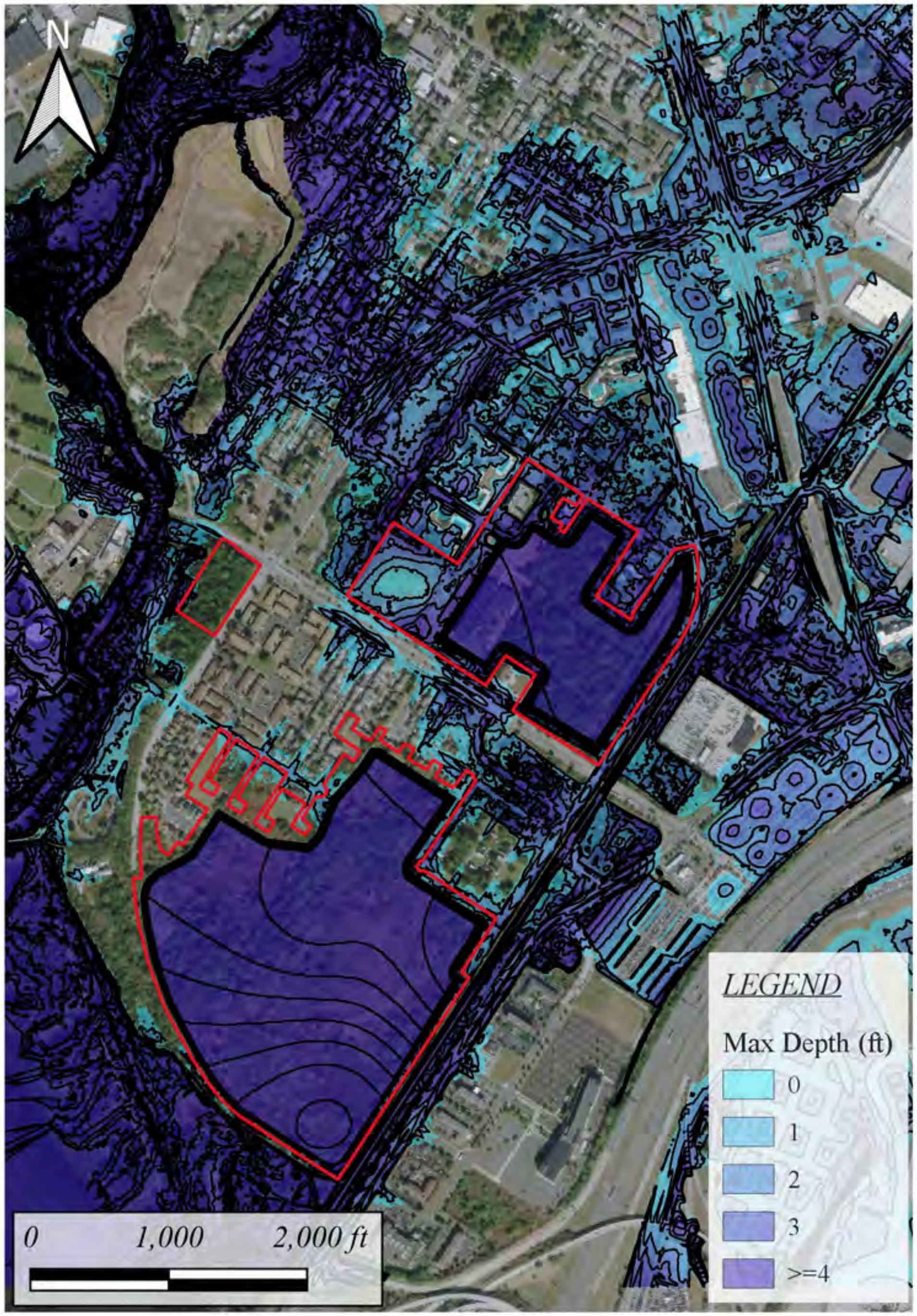


Scenario 1 - Maximum Depth (ft)

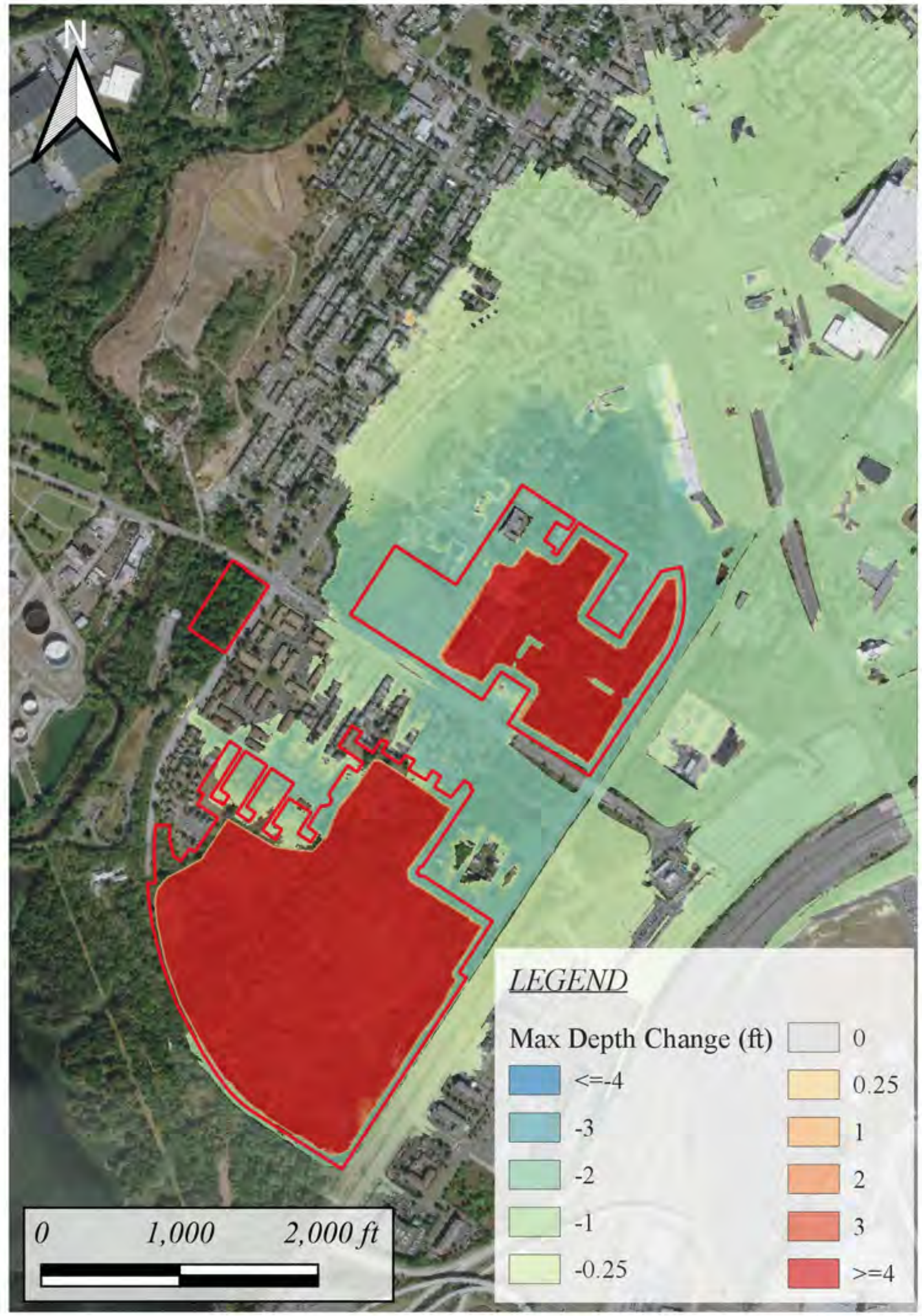


Maximum Restoration Scenario - Change in Maximum Depth from Existing Conditions (ft)

Attachment D-7. The 100-year Terrestrial Event & 10-year Tidal Event Constructed Wetlands and Storage Basins Model Results

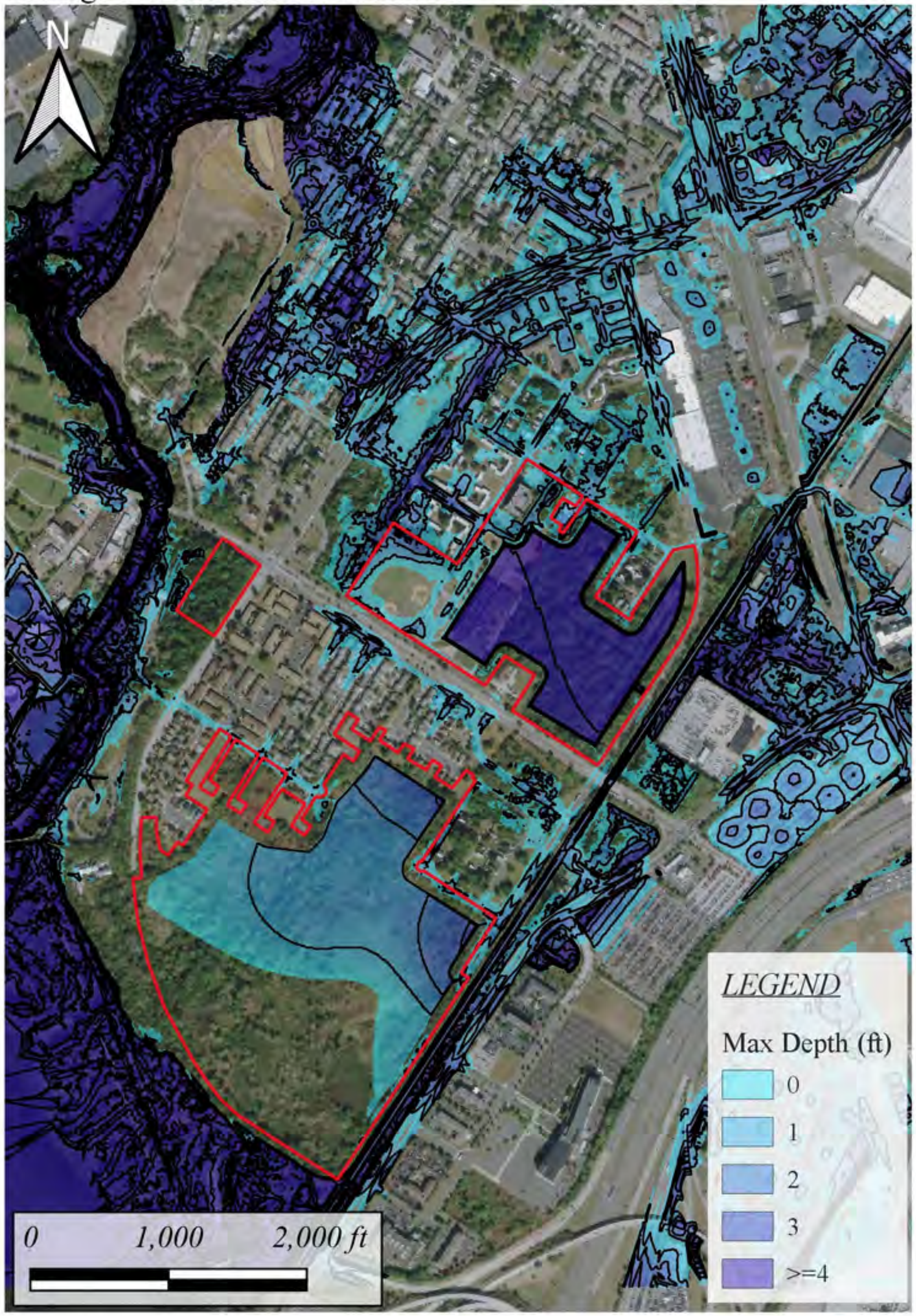


Scenario 1 - Maximum Depth (ft)

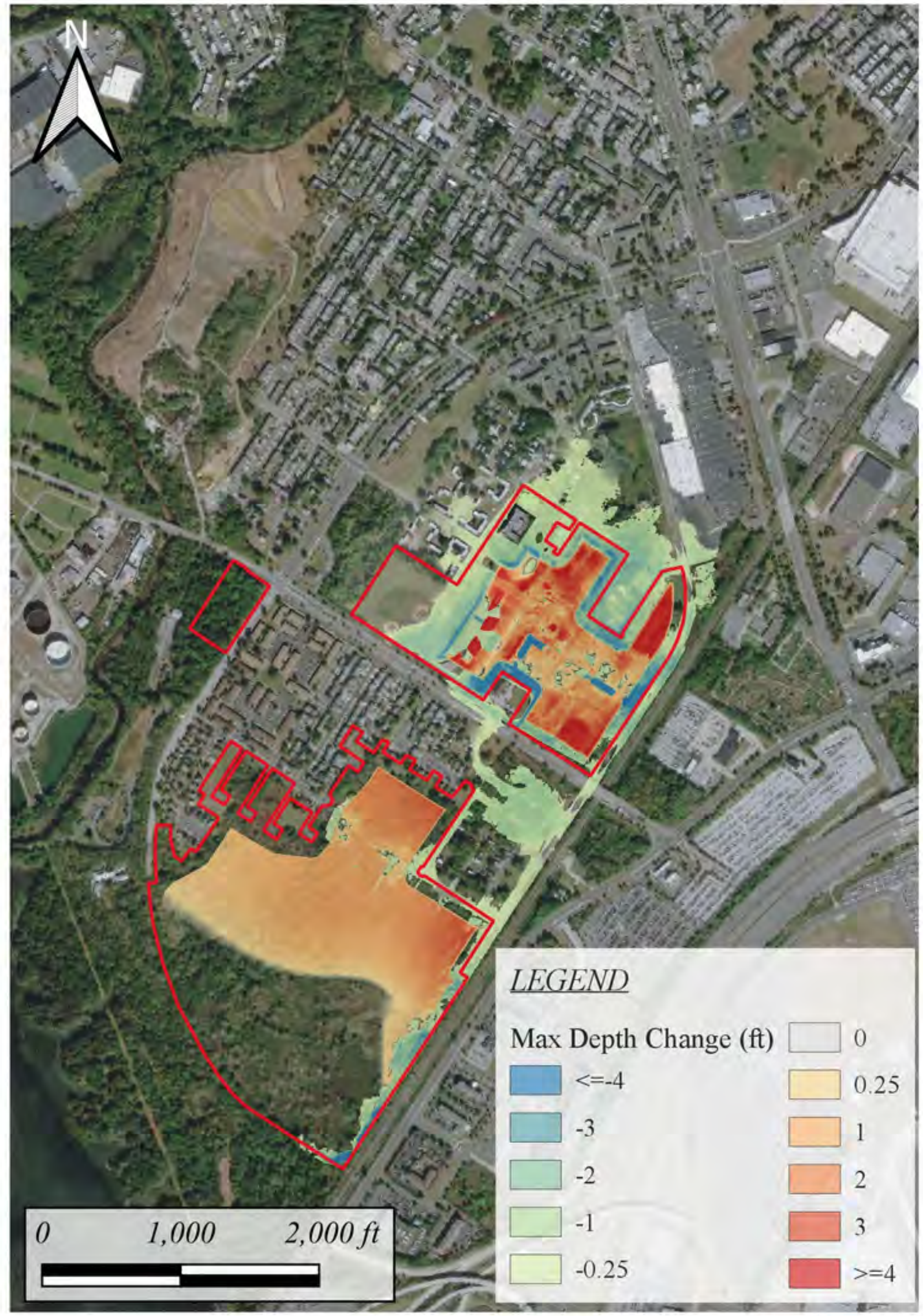


Maximum Restoration Scenario - Change in Maximum Depth from Existing Conditions (ft)

Attachment D-8. The 10-year Terrestrial Event & Great Appalachian Storm of 1950 Adjusted to 2020 Constructed Wetlands and Storage Basins Model Results



Scenario 1 - Maximum Depth (ft)



Maximum Restoration Scenario - Change in Maximum Depth from Existing Conditions (ft)