Sea Level Rise Adaptation Recommendations for the Delaware Avenue Extension Project

City of Philadelphia, Pennsylvania

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Prepared via EPA Brownfields Area-Wide Planning Technical Assistance for:

EPA United States Environmental Protection Agency

City of Philadelphia

Prepared by:

ICF

S/G/A

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1. Introduction

Background

FIGURE 1: AWP STUDY AREA, WITH DELAWARE AVENUE EXTENSION SITE APPROXIMATED IN RED.

The City of Philadelphia has requested technical assistance to determine the potential impacts of sea level rise and storm surge on the proposed Delaware Avenue Extension and how this information can be used to help ensure that sea level rise is considered in the project design and construction. The proposed site runs along the tidal Delaware River and crosses over Old Frankford Creek. The extension is one of the priority goals of the *Lower Frankford Creek Watershed Brownfields Area Wide Plan (AWP)* (Figure 1).[1] The Delaware Avenue Extension from Orthodox to Tacony Streets would promote access to two major AWP catalyst sites[2] – Rohm & Haas / Dow Chemical Co. and Philadelphia Coke / National Grid.

ICF has completed an analysis of potential flooding from future sea level rise and storm surge at the Delaware Avenue Extension site. This report summarizes findings on potential flooding and its consequences and provides recommendations for adaptation strategies to address these impacts.

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[1] Philadelphia City Planning Commission, 2015. Lower Frankford Creek Watershed Brownfields Area Wide Plan (AWP). https://www.phila.gov/media/20190517135734/Lower_Frankford_Creek_Area_Wide_Plan_2015.pdf

[2] Catalyst sites are "parcels or groups of contiguous parcels that can be leveraged through redevelopment to create a broader economic impact on an area or neighborhood" (Philadelphia City Planning Commission, 2015).

2. Sea Level Rise Findings

Sea level rise scenarios, design life, and risk tolerance

ICF reviewed the most current sea level rise literature, local sea level rise projections, and available data sets to select the following projections[3] for the site-specific analysis.

- 2050: 1.1 feet of sea level rise from 2018 base year
- 2100: 3.1 feet of sea level rise from 2018 base year

These sea level rise projections were selected based on a combination of the best available science on the range of potential sea level rise over the design traffic life of the roadway and design life of the bridge, and a discussion with the City of Philadelphia of the risk tolerance for flooding at the site. The review is summarized below and detailed in Appendix A: Sea Level Rise Scenarios and Risk Tolerance. While the flood analysis utilizes a single sea level rise scenario per time period for the purposes of planning and designing, ICF recognizes uncertainty in future sea levels and recommends adaptive management (discussed under adaptation strategies below) to address a range of possible sea level rise amounts.

When determining the most appropriate sea level rise projections for use in site design, the first requirement is to select the appropriate design life. The assumed design traffic life for the Delaware Ave Extension roadway is 30 years, and the design life of the bridge is at least 100 years. It is also important to consider sea level rise projections associated with the actual expected lifetime of the asset, in addition to its design traffic life or design life, since assets often remain in service beyond their expected useful lives.

The next step is to establish the managing agency's sea level rise risk tolerance and to use that decision to determine the sea level rise projections associated with the design horizon years. Selecting a risk tolerance is necessary because there is significant uncertainty about how much sea levels will rise, and that uncertainty increases further into the future. This uncertainty is due to policy uncertainty (i.e., how much global emissions are curtailed), scientific uncertainty (i.e., scientific understanding of ice sheet melt and other feedback loops), and modeling uncertainty (i.e., how well global models represent natural processes). An agency or project with a low risk tolerance may select to design for the "worst case" while an agency with a high risk tolerance may design for more moderate rates of sea level rise.

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[3] DVRPC. 2019. Coastal Effects of Climate Change in Southeastern PA. https://dvrpcgis.maps.arcgis.com/apps/MapSeries/index.html?appid=8080c91a101d460a9a0246b90d4b4610. Citing data from Kopp, et al. 2016 but with the sea level rise baseline year updated from 2000 to 2018. Assessing New Jersey's Exposure to Sea-Level Rise and Coastal Storms: Report of the New Jersey Climate Adaptation Alliance Science and Technical Advisory Panel. https://rucore.libraries.rutgers.edu/rutgers-lib/50714/PDF/1/play/

Risk tolerance is usually selected based on the criticality of the assets and the overall risk tolerance of the agency that will be constructing and operating it. As summarized in Appendix A, there are a range of sea level rise risk tolerances recommended by different cities, Philadelphia departments, and preliminary national transportation guidance. Although this decision on risk tolerance can only be made by PennDOT and the City of Philadelphia, the 50% probability of exceedance sea level rise scenarios for 2050 and 2100 used in the exposure assessment for this project (see Table 1) generally falls within the set of best practices in the literature. However, for more critical sections of the transportation network (e.g., I-95) a lower risk tolerance may be appropriate, which would result in designing for higher sea level rise values. See Table ES-1 in the Rutgers 2019 report[4] for the sea level rise values associated with alternative risk tolerance thresholds (e.g., 83% or 17% probability of exceedance).

TABLE 1: SEA LEVEL RISE INCREMENTS ASSOCIATED WITH DELAWARE AVE EXTENSION COMPONENTS DESIGN LIFE (FROM A 2018 BASELINE)

Delaware Ave Extension Component	Estimated Design Life	Sea Level Rise at Design Horizon Year	Likelihood of Exceedance (under high emissions scenario)
Roadway	30 years	1.1 feet	50%
Bridge	100+ years	3.1+ feet	50%

[4] Kopp, R.E., C. Andrews, A. Broccoli, A. Garner, D. Kreeger, R. Leichenko, N. Lin, C. Little, J.A. Miller, J.K. Miller, K.G. Miller, R. Moss, P. Orton, A. Parris, D. Robinson, W. Sweet, J. Walker, C.P. Weaver, K. White, M. Campo, M. Kaplan, J. Herb, and L. Auermuller. 2019. *New Jersey's Rising Seas and Changing Coastal Storms: Report of the 2019 Science and Technical Advisory Panel*. Rutgers, The State University of New Jersey. Prepared for the New Jersey Department of Environmental Protection. Trenton, New Jersey. https://climatechange.rutgers.edu/images/STAP_FINAL_FINAL_12-4-19.pdf

Potential flooding

ICF analyzed the extent of potential flooding at the proposed roadway site under the following flood events given sea level rise and storm surge for current day (2018), 2050, and 2100:

- Daily high tide flooding (i.e., mean higher high water [MHHW])
- Chronic flooding (i.e., flooding occurring 26 times per year)
- A 10% annual chance flood
- A 4% annual chance flood
- A 1% annual chance flood (Figure 2)

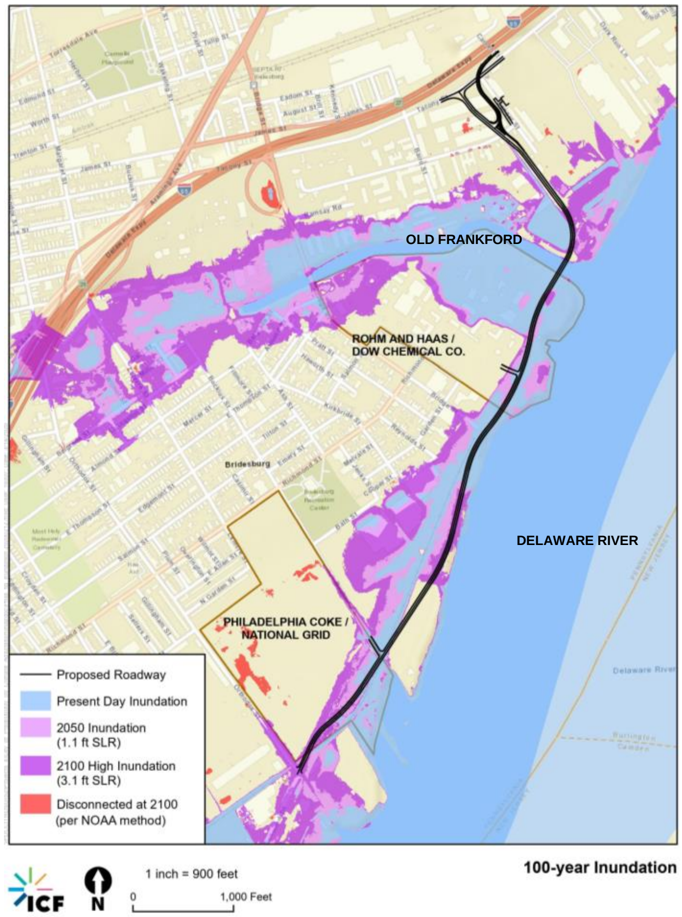

FIGURE 2: EXTENT OF 1% ANNUAL CHANCE FLOOD FOR PRESENT DAY (LIGHT BLUE), 2050 (PINK), AND 2100 (PURPLE)

As represented in Figure 2 and summarized in Table 2, in the present day, portions of the roadway site along the Delaware River, the Dow site, the National Grid site, and the adjacent community along the Old Frankford Creek are in the floodplain associated with a 10%, 4%, and 1% annual chance flood. In 2050, storm surge flooding will be greater in extent in these areas. Small portions of the edges north of Old Frankford Creek are expected to experience daily high tide flooding and chronic flooding by 2050. By 2100, most of the Dow site and portions north of Old Frankford Creek are projected to experience daily high tide flooding. Many sections along the proposed roadway and a portion of the National Grid site are projected to experience chronic flooding by 2100.

TABLE 2: SUMMARY SEA LEVEL RISE INUNDATION RESULTS ALONG THE PROPOSED DELAWARE AVE EXPANSION ALIGNMENT (WATER ELEVATIONS RELATIVE TO NAVD88 ARE IN PARENTHESES)

	High Tide Flooding (MHHW)	Chronic Flooding	10% Annual Chance Storm	4% Annual Chance Storm	1% Annual Chance Storm
Today (2018)	No Flooding (3.9 ft)	No Flooding (5.0 ft)	Limited Flooding (7.0 ft)	Limited Flooding (7.9 ft)	Significant Flooding (8.1 ft)
2050 (1.1 ft sea level rise)	No Flooding (5.0 ft)	No Flooding (6.1 ft)	Significant Flooding (8.1 ft)	Significant Flooding (9.0 ft)	Significant Flooding (9.2 ft)
2100 (3.1 ft sea level rise)	Limited Flooding (7.0 ft)	Significant Flooding (8.1 ft)	Significant Flooding (10.1 ft)	Significant Flooding (11.0 ft)	Significant Flooding (11.2 ft)
"Limited" flooding defined as greater than 0 and less than ~3000 linear feet inundated. "Significant" flooding defined as greater than ~3000 linear feet inundated.					
This analysis uses annual exceedance probability levels (i.e., water levels for annual chance storms) from the National Oceanic and Atmospheric Administration (NOAA). NOAA does not model wave action (e.g., wind-driven waves), while the Federal Emergency Management Agency (FEMA) does. This results in the FEMA annual chance storm water elevations being higher than the NOAA water elevations. PennDOT is required to evaluate the FEMA published 100-year flow for regulatory purposes.					

Under PennDOT's current design guidelines, the roadway would be designed such that, at a minimum, a present day 4% annual chance flood event (7.9 feet relative to NAVD88 based on NOAA models) would not overtop the asset. However, as can be seen in red in Table 2, that elevation would be exceeded during more and more common flood events in the future. By the end of the roadway's approximate design traffic life of 30 years (i.e., 2050), the roadway could be overtopped during a 10% annual chance flood event if designed to the present-day minimum. The bridge over Old Frankford Creek, likely to have a design life of 100+ years, should consider at minimum the potential 2100 flood elevations. It is also important to consider potential inundation to the roadway and bridge from sea level rise projections beyond 2050 and 2100 respectively since assets often remain in service beyond their expected useful lives.

The full set of flood extent maps and flood depth profiles are included in Appendix B. The flood extent mapping methodology is summarized in Appendix C.

Coastal erosion and groundwater elevation

Both coastal erosion and groundwater elevation may be altered by sea level rise and could impact the project site and surrounding areas.

With higher tides and more frequent storms in the future due to climate change, the Delaware River shoreline will likely face greater risks from erosion. In several locations, the proposed roadway alignment runs very close to the river, which could present problems if the shoreline erodes.

Sea level rise will impact local aquifers by raising groundwater elevations. Higher groundwater levels will reduce the local area's ability to capture and store freshwater flows during precipitation events, which will increase the risk of impacts to the project site from inland flooding. The rise in groundwater levels from sea level rise will be compounded by an increase in the severity and frequency of extreme precipitation events from climate change.

Additionally, higher groundwater levels increase the likelihood of longer subgrade saturation. Even if the roadway does not experience standing water, the saturated subgrade results in weakened pavement that will degrade faster with routine traffic levels. This increase in the frequency and elevation of saturation also increases the possibility of mobilizing hazardous materials present within the subgrade of the brownfield sites adjacent to the proposed Delaware Avenue Extension.

3. Potential Consequences

The sea level rise impacts of flooding, coastal erosion, and groundwater rise could lead to consequences for the roadway extension as well as the broader AWP study area, including the brownfield sites and surrounding communities. Many of the potential roadway flooding consequences identified in the City of Philadelphia's draft Infrastructure Design and Planning Guidelines for Flood Resilience for the I-95 corridor are applicable to the Delaware Avenue Extension project. If unaddressed, projected sea level rise impacts on the roadway and surrounding sites may ultimately affect the proposed reuse and revitalization of this area.

Consequences for the asset

- Damage to physical infrastructure, such as:
    - Washout and erosion of the roadway (e.g., chronic and daily overtopping of portions by 2100; overtopping from flood events under current and future conditions)
    - Damages to culverts, pumps, and drains
    - Bridge scour
    - Subsurface utility damage
- Increase in needs for operations and maintenance or repair and replacement, such as:

- Operational and communication challenges (e.g., electronic signage outage)
    - Additional drainage and pumping requirements
    - Shortened infrastructure life
- Increase in costs associated with operations, maintenance, repair and replacement

Consequences for roadway users and the broader area

- Loss of services for direct users of the roadway (e.g., commuters, truck drivers, emergency responders) and indirect users (e.g., adjacent industrial sites, communities), such as:
    - Delays and traffic disruptions
    - Inaccessibility and stranding issues
    - Need for detours and alternative routes to the catalyst sites
    - Slower travel times
- Safety impacts, such as:
    - Increased number of accidents
    - Potential loss of life
    - Impacts to public health and the environment if higher groundwater levels and flooding of the brownfield sites leads to possible mobilization of contaminants in the subgrade and release of hazardous substances into floodwaters
- Economic impacts, such as:
    - Costs for direct users associated with delays and detours (e.g., gasoline, time)
    - Economic loss for neighboring sites that the roadway is meant to serve (e.g., industrial sites)
- Loss of service at proposed neighboring sites that the roadway is meant to serve, such as:
    - Inundation of the Dow and National Grid sites (e.g., most of the Dow site will experience daily inundation by 2100 if unaddressed)
    - Inundation of the proposed adjacent North Delaware Greenway Trail and riverfront public parks (e.g., portions of the riverfront will experience daily inundation by 2100 if unaddressed)

4. Adaptation Strategies

Importance of adaptive management

There will likely remain a possibility that sea level rise will exceed the selected design value prior to the end of the useful life of the roadway and bridge, regardless of the risk tolerance selected, given uncertainty in future conditions. And even if it does not, the assets put in place today are likely to be reconstructed in-place at the end of their useful life. For these reasons, during the initial design, it is valuable to consider how the assets can be modified for additional protection in the future. Thinking through this topic during the design can make future modifications easier and more cost effective by ensuring that actions taken in the short term do not preclude future adaptation actions. Adapting over time, as needed, is commonly referred to as adaptive management.

Adapting the assets

There are two primary strategies for addressing sea level rise as part of the Delaware Ave Extension project: protect and accommodate. Due to the extensive future floodplain in the project area, a minor realignment of the roadway was not considered viable for reducing sea level rise risk for this analysis. A significant relocation away from the Delaware River and Old Frankford Creek would be required to remove the roadway from the floodplain.

Protect – elevate and harden the roadway, bridge, and associated infrastructure

Designing to protect the asset from sea level rise will require multiple adaptation actions.

Elevate the roadway and bridge to account for sea level rise. Integrating sea level rise into design elevations typically follows a simple formula:

Base Flood Elevation + Freeboard[5] *+ Sea Level Rise Projection = Design Flood Elevation*

PennDOT typically designs minor arterials to avoid overtopping in at least a 25-year (4% annual chance) design storm,[6,7] and bridge foundations to withstand a 100-year (1% annual chance) design storm or highest velocity overtopping event. The Pennsylvania Department of Environmental Protection (PA DEP) requires design of public infrastructure in urban areas to evaluate the 100-year event. The City's Building Code recommends using FEMA's 100-year (1% annual chance) design storm.[8] There is a two foot elevation difference between the 25-year storm water elevation using NOAA's data and the 100-year storm water elevation using FEMA's flood insurance rate maps.

PennDOT will ultimately evaluate several scenarios in the design process in accordance with PennDOT and PA DEP requirements and FEMA regulations. The PennDOT Design Manual Part 2 requires that PennDOT evaluate updated flows and water surface elevations considering

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[5] The City's Building Code recommends a freeboard addition of 18 inches for roads constructed in the floodplain.

[6] PennDOT Design Manual Part 2, Chapter 10, Table 10.6. https://www.dot.state.pa.us/public/Bureaus/design/PUB13M/Chapters/Chap10.pdf

[7] According to NOAA, the 4% annual chance flood has an historical elevation of 7.9 feet in Philadelphia (NAVD88 datum).

[8] Using the 2015 FEMA 1% annual chance flood insurance rate maps, the base flood elevation along the project site would be 9.9 feet (NAVD88 datum).

current and future conditions. Additionally, if the updated hydrology is different than the published FEMA 100-year flow, PennDOT is also required to evaluate the FEMA published flow.

If PennDOT decides to elevate the roadway and the bridge, the City and private landowners that are inland of the project should not rely on the roadway to provide flood protection benefits unless the roadway embankment is specifically designed and certified as a levee. According to the Federal Highway Administration (FHWA):

- "Highway embankments do not include design features, such as internal impervious core and freeboard, required for a levee or other flood control structures;
- The fill material used in the construction of a typical highway embankment is not a sufficient barrier against water; therefore, a highway embankment is subject to piping, seepage, and infiltration; and
- Typical highway embankment construction does not require the same level of geotechnical engineering analysis as required for flood control structures."[9]

Design the embankment to withstand future loads. Even without designing the embankment as a levee, the embankment should be designed and constructed to withstand loads associated with the projected higher storm surge water levels.

Consider changes in design of drainage and water conveyance structures. In addition to elevating the primary project components, designing to protect the project from sea level rise may require a different design of the drainage and water conveyance structures. This may entail the installation of backflow prevention devices to limit the amount of water that reaches inland areas during storm events. PennDOT should also ensure proper design of conveyance structures so that stormwater will not be inadvertently pooled in low-lying areas on the landward side of the project. In the long term, pumps may be required to sufficiently drain the area following precipitation events.

Design for flexibility for additional protection. In addition to designing to the Design Flood Elevation that accounts for likely sea level rise, PennDOT should consider designing for flexibility so that the assets can be modified for additional protection in the future. As such, during the project design process, PennDOT should explore the possibility of significantly increasing the elevation of the roadway in the future (e.g., as sea levels near the elevations assumed in the project design) to protect against ever increasing sea levels. Raising the roadway would require expanding its footprint, which would need to be accounted for in the

[9] FHWA. 2008. *Highway Embankments versus Levees and other Flood Control Structures*. https://www.fhwa.dot.gov/engineering/hydraulics/policymemo/20080910.cfm

design, including how future increases in elevation may impact the surrounding land uses and road network.

Likewise, the bridge foundation and drainage structures should be designed to accommodate future increases in bridge height.

Minimize impacts on adjacent network and land uses. Beyond the broader geotechnical and hydrologic engineering implications of elevating the Delaware Avenue Extension, there are also resultant impacts on the surrounding road network and land uses to consider. If Delaware Avenue is elevated to address the flood risk, the portions of the street grid connecting to Delaware Avenue will have to transition up to that elevation. While the roadway tie-ins themselves will be straightforward from a vertical profile perspective, it will be important to consider second-order effects, like the need for additional right-of-way acquisition and impacts on the adjacent land uses, which will have limitations on frontage opportunities as a result.

Maintain public riverfront access. Raising the elevation of the roadway can also have an impact on the physical and psychological connection to the Delaware riverfront. If PennDOT pursues a protection strategy, the elevated roadway design should still ensure that the public can access the riverfront. Taking the constraints of the right-of way into consideration, the final design will have to balance the limited footprint available for the roadway and its associated embankment with efforts to prevent the road from becoming a physical and mental barrier to the riverfront. This will mean softening the transition between the landward side of the roadway and the roadway itself, whether through strategic adjustments to grading or through the use of vegetation and other natural and architectural elements to prevent the roadway embankment from effectively walling off the riverfront.

Accommodate – design and operate the asset for continued performance during future flood events

As an alternate adaptation strategy to protection, PennDOT and the City could rely on operational and maintenance-based approaches to accommodate more and more frequent roadway flooding. The consequences of this approach to roadway users would be significantly higher than the protection strategy and would increase over time as sea levels rise.

Actions to accommodate roadway flooding are outlined in the City's Building Code and the draft City of Philadelphia Infrastructure Design and Planning Guidelines for Flood Resilience, and summarized below. If this strategy to accommodate flooding is undertaken, PennDOT and the City should proactively plan, design, and allocate resources for continued performance during future flood events of increasing frequency.

Plan proactively for operations during flood events of increasing frequency.

- Flood Emergency Operations Plan, including:

- Plans for the temporary installation of flood barriers (e.g., panels, sand bags, inflatable bags)
- Warning time for staff and community members to respond/evacuate
- Staff, equipment, and materials required to mitigate flood effects
- Detour routes that are not vulnerable to the same flood events
- Communication/coordination systems
- Maintenance/inspection

Design proactively for continued performance.

- Drainage
    - Back-flow valves for drainage systems
    - Pumps to remove floodwaters and emergency power for those pumps
    - Easy maintenance design
    - Watertight manhole covers and alternate venting
    - Operations and maintenance plan
- Mechanicals
    - Design to a depth sufficient to prevent movement, separation, or loss due to flooding and erosion
    - Design to withstand flood-related loads, including the effects of buoyancy, hydrodynamic forces, and debris impacts
- Bridge deck
    - With an accommodation approach, it is particularly important that the bridge deck be designed to account for potential buoyant forces during future storms to prevent any potential damage from uplift
- Lighting
    - If typical electric lighting is used, design upland lighting to be on separate circuits from floodplain lighting. This will allow upland lighting to remain functional should a flood event damage the electrical lines in the floodplain
    - Install non-wired lighting, such as solar or wind powered lighting, where possible
- Conduits
    - Locate conduits at higher elevations on the site
    - If below flood elevation, assure they are floodproof
    - Explore solar- or wind-powered components to avoid subsurface conduits

Allocate resources for future flood events of increasing frequency.

- Increase budget for:
    - Pre-event drainage system cleaning
    - Debris clean-up
    - Repair/replacement of damages

- Evacuation

The adaptation strategies to accommodate and protect are not mutually exclusive. If the accommodate strategy is selected, PennDOT and the City could consider supplementing near-term operational and maintenance-based approaches with a strategy to protect in the long-term, when the accommodate strategy can no longer be effectively and efficiently applied. This adaptive management approach to incorporate protection as sea levels rise will require upfront design for the flexibility to elevate in the future. However, retrofitting for flood resilience once the asset is built may be less cost efficient than incorporating protection into the upfront design of a new asset.

Adapting at a broader scale

Adaptation strategies at a broader scale could protect the roadway and other assets in the AWP study area. To adapt at this scale, the City of Philadelphia could consider:

Protect coastal edges from increased erosion due to sea level rise. As mentioned earlier, sea level rise can increase rates of coastal erosion. To help stabilize the waterfront, the City of Philadelphia could:

- Construct, monitor, and maintain nature-based solutions (e.g., marsh, wetland, living shorelines in coastal and estuarine environments) along the coast. FHWA recently published *Nature-Based Solutions for Coastal Highway Resilience: An Implementation Guide*,[10] which is designed to help transportation practitioners understand how and where nature-based and hybrid solutions can be used to improve the resilience of coastal roads and bridges. Nature-based solutions offer many benefits in addition to stabilizing the shoreline, including reducing coastal flooding, increasing habitat, improving water quality, and creating recreational benefits.
    - Note: Several of the blue/green infrastructure recommendations from the Brownfield AWP (e.g., creating native landscape riparian buffers) – although geared towards managing stormwater – could be applied for resilience to future flooding of the tidal riverfront. They also provide a soft edge that can serve as a recreational and educational feature in a riverfront park, as proposed in the AWP.
- Harden the river shoreline (e.g., sills, breakwaters, bulkheads, revetments, seawalls, deployable protection measures).

[10] FHWA. 2019. *Nature-Based Solutions for Coastal Highway Resilience: An Implementation Guide.* Federal Highway Administration. FHWA-HEP-19-042. https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/green_infrastructure/implementation_guide/

- Employ a hybrid of structural and nature-based solutions (e.g., marsh plus breakwater). Particularly in active waters like the Delaware River where tidal fluctuations and wakes from passing watercraft must be considered, nature-based solutions include built features (e.g., breakwaters and sills) to dissipate wave energy and allow the natural feature to flourish and serve its purpose of reducing erosion while improving the overall health of the waterway.
    - The use of a hybrid solution is especially attractive in areas like the waterfront parks proposed in the AWP, as it allows for a natural connection and interaction with the river while still offering the protection provided by the structural features.

Elevate the riverfront parks. The City of Philadelphia could design the riverfront parks as a first line of defense for flood resilience. This could provide added flood protection of the roadway and community since the parks will be sited on the river-facing side of the roadway. The New York City Parks department published *Design and Planning for Flood Resiliency: Guidelines for NYC Parks*[11], which covers useful design concepts.

Coordinate flood protection with the City, PennDOT, and Belt Line & Conrail. The City of Philadelphia should continue to play a coordinating role in discussions of flood protection within the broader project area. A consistent and mutually beneficial flood protection strategy between the City parks, PennDOT, Belt Line and Conrail will help ensure comprehensive resilience in this segment of Philadelphia.

Disclose increasing catalyst site flood risks. Since the catalyst sites are increasingly vulnerable to flooding due to sea level rise, EPA and the City could facilitate discussions with current and future owners of the Dow and National Grid sites (i.e., vulnerable catalyst sites that the roadway would serve) and other stakeholders to:

- Disclose future flood risks at the brownfield sites and potential consequences (e.g., hazardous waste exposure).
- Promote future reuse of the site in a manner consistent with the AWP proposed reuse concepts. These concepts account for the existing high flood risks to the Dow site.
- Identify opportunities to elevate, accommodate, protect, relocate, or remove constrained materials to ensure resilient redevelopment of the catalyst sites.

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[11] NYC Parks. *Design and Planning for Flood Resiliency: Guidelines for NYC Parks.* https://www.nycgovparks.org/pagefiles/128/NYCP-Design-and-Planning-Flood-Zone__5b0f0f5da8144.pdf

5. Recommendations for Additional Analyses

The various stakeholders should consider undertaking additional analyses during the design of the roadway.

Select risk tolerance/timeframe for adaptation and select adaptation strategies for the roadway and bridge. The design stage of the new roadway asset is one of the ideal opportunities to efficiently incorporate adaptation strategies into project development. Once the window of opportunity is closed, flood resilience redesign and retrofitting of an existing asset may be costly and inefficient. PennDOT, in coordination with the City, should select the preferred risk tolerance for the project site, consider the full range of potential adaptation strategies, and integrate the preferred strategy into the current design phase. The design should also account for future enhancements to the sea level rise and storm surge protections.

Coordinate the design of the roadway and bridge with interdependent infrastructure. The interdependency of the roadway with other systems, if vulnerable, creates the potential for cascading impacts. Infrastructure designed to support the roadway and the surrounding community, such as utilities and drainage, may face similar exposure to future flooding. Additionally, infrastructure that will be built contingent on the roadway, such as underground utilities and the greenway, may also be vulnerable. The City's building code (appendix G) has numerous recommendations for designing floodproof mechanical systems.

Conduct further analyses on additional sea level rise impacts. As mentioned, sea level rise could affect coastal erosion and groundwater elevation. The rise in groundwater levels, compounded with projected increases in extreme precipitation events, could increase the risk of subgrade saturation and inland flooding. Additional analyses of these impacts could inform the resilient design of the Delaware Avenue Extension and development plans in the broader AWP area.

Analyze potential inundation of the broader AWP study area given proposed construction of the roadway. The sea level rise analysis conducted as part of this technical assistance does not consider how construction of the Delaware Avenue Extension will modify the geographic extent and depth of flooding over the rest of the AWP study area. A hydrologic and hydraulic (H&H) analysis that accounts for sea level rise should be conducted as part of the site design to assess the extent to which fill (or alternative adaptation strategies) may affect future inundation of the project itself and adjacent properties.

Consider vulnerability of the roadway to additional climate change hazards. As recommended in the Brownfield AWP, investments in infrastructure should consider temperature and precipitation changes. For example, Philadelphia is expected to experience up to 4 days a year above 100°F by mid-century (2045-2065) and as many as 16 days a year above 100°F by end-of-century (2081-2099), up from baseline conditions (1950-1999) of fewer than one day a year.[12] Extreme high temperatures may increase the need for maintenance to repair rutting of pavement and thermal expansion of bridge joints.

[12] Miller, Rawlings, Choate, Anne, Wong, Angela, Snow, Cassandra, Snyder, John, Jaglom, Wendy, and Biggar, Sarah. "Useful Climate Information for Philadelphia: Past and Future." Prepared by ICF International for the Philadelphia Mayor's Office of Sustainability, March 2014.

Appendix A: Sea Level Rise Scenarios and Risk Tolerance

This appendix contains the contents of a memorandum delivered to EPA, the City, and PennDOT on January 30, 2020, summarizing the recommended sea level rise scenarios. This appendix provides the contents delivered as-is, with only minor adjustments.

Background

The City of Philadelphia has requested technical assistance to determine the potential impacts of sea level rise and storm surge on the proposed Delaware Avenue Extension and how this information can be used to help ensure that sea level rise is considered in the project design and construction. The Delaware Avenue Extension from Orthodox to Tacony Streets would directly impact the two major AWP catalyst sites.

ICF has completed a review of the most current sea level rise literature, local projects using sea level rise projections, and available data sets. Based on this information, ICF has prepared the following memorandum. It includes our findings and our recommendations for the sea level rise and storm surge scenarios to be used in the site-specific analysis.

Scenarios Precedent

Several other studies have been conducted in the Philadelphia region, all of which use varying sea level rise scenarios. The following sections provide a summary of the precedent set by the various groups.

Growing Stronger: Towards a Climate Ready Philadelphia

The sea level rise scenarios analyzed in *Growing Stronger: Towards a Climate Ready Philadelphia*[13] considered 2013 projections from the U.S. Department of Energy (DOE)[14] and the Climate & Urban Systems Partnership (CUSP).[15] Table 3 provides a summary of the projections.

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[13] City of Philadelphia. 2015. *Growing Stronger: Towards a Climate Ready Philadelphia*. https://www.phila.gov/media/20160504162056/Growing-Stronger-Toward-a-Climate-Ready-Philadelphia.pdf

[14] Storm Surge/Sea Level Rise Information courtesy of Energy Infrastructure Modeling and Analysis, Office of Electricity Delivery and Energy Reliability, U.S. Department of Energy. Original data produced by NOAA with analysis by ICF.

[15] Climate & Urban Systems Partnership. 2013. Philadelphia Climate Projections. http://www.cuspproject.org/uploads/ files/485063842785882816-philadelphia-cmip5.pdf

TABLE 3: GROWING STRONGER SEA LEVEL RISE PROJECTIONS FOR PHILADELPHIA (RELATIVE TO 2000-2004)[16]

Source	Timeframe	Scenario			
CUSP		**Low (10th %)**	**Mid (25th %)**	**Mid (75th %)**	**High (90th %)**
	2050	< 1 ft	< 1 ft	2 ft	3 ft
	2100	1 ft	1-2 ft	3 ft	4-5 ft
DOE		**NCA Low**	**NCA Int-Low**	**NCA Int-High**	**NCA High**
	2050	<1 ft	1 ft	1-2 ft	< 2 ft
	2100	< 1 ft	2 ft	4 ft	6 ft

Using the conservative (i.e., upper end) of the column highlighted in orange, the Growing Stronger analysis considered 2 feet of sea level rise in 2050 and 4 feet in 2100. The report also considered the potential for a Category 1 storm (combined with sea level rise) to directly hit the Philadelphia region.

Philadelphia Water Department

The Philadelphia Water Department (PWD) uses 2017 sea level rise projections from the National Oceanic and Atmospheric Administration (NOAA) in their internal planning work.[17] Table 4 shows the NOAA range of scenarios typically used by PWD. The sea level rise increments in Table 4 for the Intermediate-Low and Intermediate-High scenarios are notably higher than those in Table 3 due to advances between 2013 and 2017 in our scientific understanding of sea level rise dynamics.

The 2050 Intermediate-High scenario is PWD's primary planning scenario while the other two provide an envelope of the range of potential sea level rise. The Intermediate-High scenario is a relatively low risk tolerance scenario. This is appropriate for PWD because they operate critical infrastructure very close to the river's edge. While PWD only designs their infrastructure for sea level rise out to 2050, they plan to use an adaptive management approach to increase protection levels, as needed.

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[16] Base year period for CUSP sea level rise values is 2000-2004. Unable to confirm base year for DOE sea level rise values utilized for *Growing Stronger*.

[17] Sweet, et al. 2017. Global and Regional Sea level Rise Scenarios for the United States. https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf

TABLE 4: NOAA 2017 SEA LEVEL RISE PROJECTIONS FOR PHILADELPHIA (RELATIVE TO 2000)

Year	Intermediate-Low	Intermediate-High	Extreme
2050	1.0 feet	2.2 feet	3.3 feet
2100	1.9 feet	6.4 feet	11.1 feet

Delaware Valley Regional Planning Commission

The Delaware Valley Regional Planning Commission (DVRPC), recently produced an online story map on the "Coastal Effects of Climate Change in Southeastern PA".[18] The sea level rise increments used by DVRPC in their story map are drawn from a paper by Kopp et al.,[19] which was produced by many of the same authors as the data set PWD is relying upon and uses a similar methodology. However, while PWD has selected to use sea level rise projections that correspond with the higher end of the range of possible sea level rise futures due to their low risk tolerance, DVRPC has selected to use projections that correspond with the central estimate. In other words, DVRPC has selected scenarios that have a 50% probability of sea level rise meeting or exceeding them within the specified time frame.

DVRPC, following the Kopp et al. methodology, sought to acknowledge that there is increasing uncertainty in sea level rise projections further out in time. For this reason, they included both a low and high 2100 emissions scenario. The low emissions scenario represents intensive global action to reduce greenhouse gas emissions. The high emissions scenario represents a much hotter future, caused by "business-as-usual" greenhouse gas emissions, whereby unsubstantial efforts are made to reduce emissions.

Table 5 provides a summary of the DVRPC sea level rise projections.

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[18] DVRPC. 2019. Coastal Effects of Climate Change in Southeastern PA. https://dvrpcgis.maps.arcgis.com/apps/MapSeries/index.html?appid=8080c91a101d460a9a0246b90d4b4610. More information on DVRPC's methodology is available here: https://drive.google.com/file/d/1BwzFUM8GxqKgEtmeFNhHLkye8aL7JnTW/view

[19] Kopp, et al. 2016. Assessing New Jersey's Exposure to Sea-Level Rise and Coastal Storms: Report of the New Jersey Climate Adaptation Alliance Science and Technical Advisory Panel. https://rucore.libraries.rutgers.edu/rutgers-lib/50714/PDF/1/play/

TABLE 5: DVRPC SEA LEVEL RISE PROJECTIONS FOR PHILADELPHIA (RELATIVE TO 2000, FROM KOPP ET AL. 2016)

Year	Sea Level Rise (50th percentile)
2050	1.4 feet
2100 Low Emissions Scenario (RCP 2.6)	2.3 feet
2100 High Emissions Scenario (RCP 8.5)	3.4 feet

In addition to sea level rise, DVRPC considered three flooding scenarios. These scenarios are developed on top of the baseline sea level rise inundation scenarios presented above.

1. A "chronic flooding" scenario developed by the Union of Concerned Scientists.[20] Chronic flooding is described as the flood level that occurs approximately 26 times per year (i.e., every other week).
2. A 10% annual chance flood scenario developed by NOAA.[21]
3. A 1% annual chance flood scenario developed by NOAA.[22] NOAA's and FEMA's 1% floodplain are similar, however, NOAA does not model wave action (e.g., wind-driven waves), while FEMA does. This results in the FEMA base flood elevation at the project site being two feet higher than the NOAA 1% flood levels at the project site. DVRPC elected to use the NOAA model rather than FEMA because the NOAA outputs are more readily combined with sea level rise projections.

Comparison of PWD and DVRPC scenarios

Both PWD and DVRPC are using the most up-to-date sea level rise projections available. While the results are presented differently in their two source documents, the underlying methodology is extremely similar. However, the PWD source (Sweet et al.) considers a wider range of sea level rise scenarios, including a much more extreme ice sheet melt scenario. A comparison of the two data sets are provided in Figure 3 and Figure 4.

[20] Dahl, K.A., Spanger-Siegfried, E., Caldas, A. and Udvardy, S. 2017. Effective inundation of continental United States communities with 21st century sea level rise. *Elem Sci Anth*, 5, p.37. DOI: http://doi.org/10.1525/elementa.234

[21] National Oceanic and Atmospheric Administration (NOAA). 2019. "Exceedance Probability Levels and Tidal Datums 8545240 Philadelphia, PA." NOAA Tides & Currents. Accessed December 2019. https://tidesandcurrents.noaa.gov/est/stickdiagram.shtml?stnid=8545240

[22] Ibid.

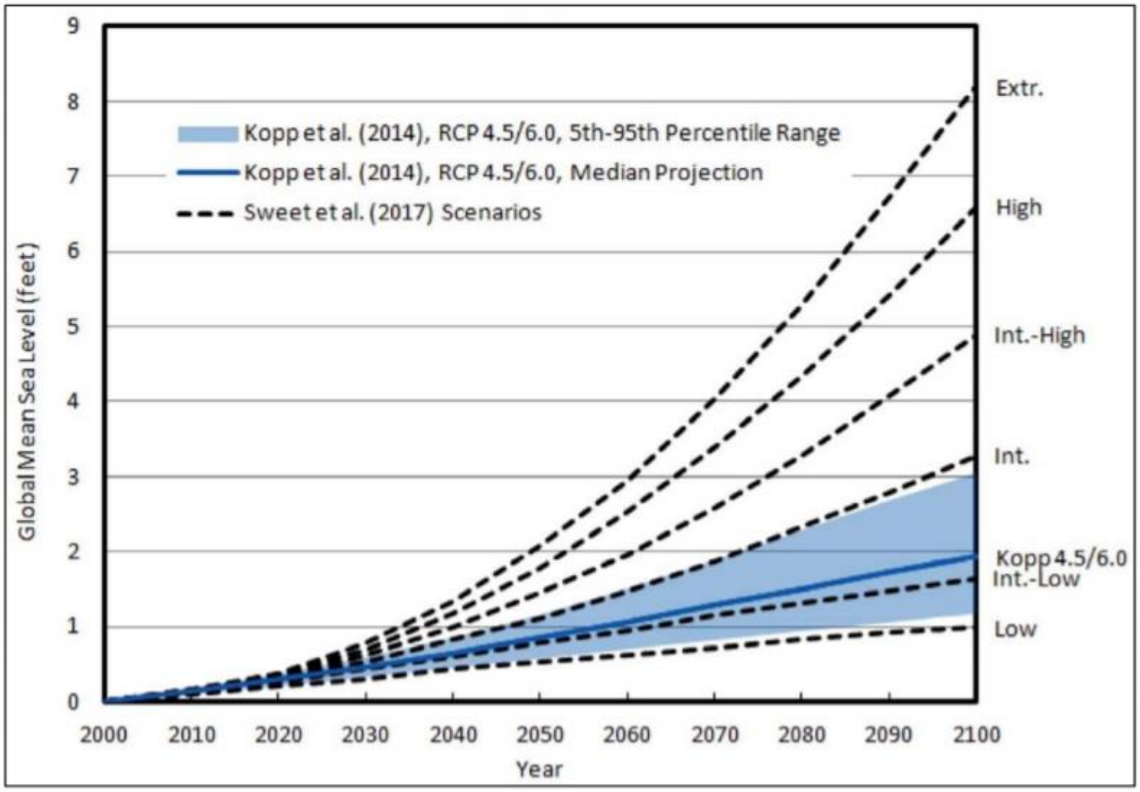

FIGURE 3: KOPP ET AL (2014) RCP4.5 GLOBAL MEAN SEA LEVEL RISE PROJECTIONS (BLUE SHADING AND MEDIAN LINE), RELATIVE TO THE SCENARIOS PRESENTED IN SWEET ET AL. (2017).[23]

[23] Kilgore et al. 2019. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure: Design Practices. https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4046

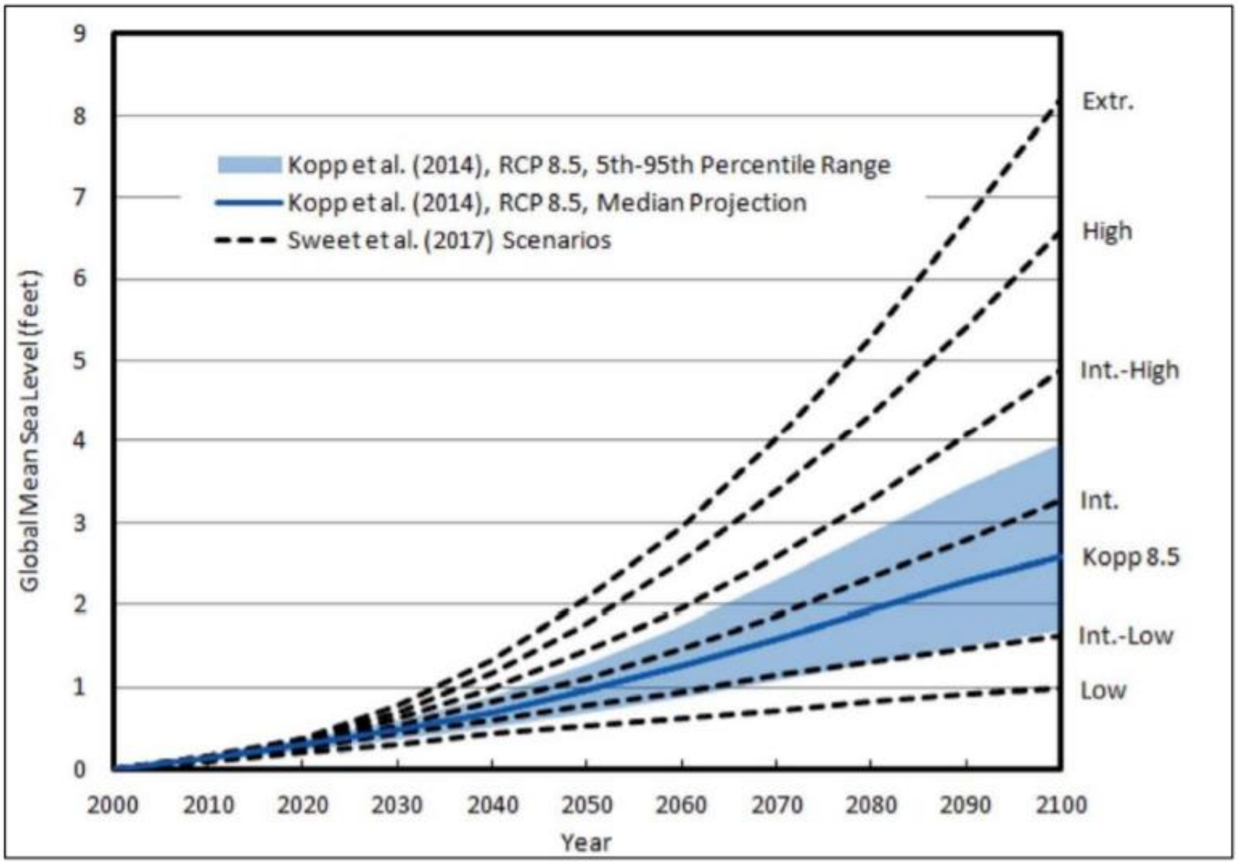

FIGURE 4: KOPP ET AL (2014) RCP8.5 GLOBAL MEAN SEA LEVEL RISE PROJECTIONS (BLUE SHADING AND MEDIAN LINE), RELATIVE TO THE SCENARIOS PRESENTED IN SWEET ET AL. (2017).[24]

Since both data sets are highly respected and up-to-date resources, the largest decision to make is the risk tolerance appropriate for a roadway. PWD has selected a low risk tolerance (i.e., higher sea level rise scenarios represented by the Int.-High in the figures) due to the criticality of their assets, while DVRPC has selected a moderate risk tolerance level (i.e., middle-of-the-road sea level rise scenarios, represented by the solid blue lines in the figures). Risk tolerances can vary between infrastructure types (e.g., critical vs. non-critical), locations, agency/department perspective, etc.

A summary of the sea level rise scenarios used by Growing Stronger, PWD, and DVRPC are provided in Table 6.

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[24] Kilgore et al. 2019. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure: Design Practices. https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4046

TABLE 6: COMPARISON OF SEA LEVEL RISE SCENARIOS

Year	Growing Stronger (relative to 2000-2004)	PWD (relative to 2000)	DVRPC (relative to 2000)
2050	2 feet	2.2 feet	1.4 feet
2100	4 feet	6.4 feet	2.3 – 3.4 feet

External Examples of Selecting Scenarios

As a point of reference, other cities and transportation research groups have selected the following risk tolerance scenarios:

- **New York City**: 50th percentile sea level rise projections, merged across moderate- and high-emissions scenarios.[25] This is very similar to the DVRPC approach.
- **Boston**: Although not explicitly stated, Boston recommends a scenario that averages moderate- and high-emissions 5% probability of exceedance sea level rise scenarios. This is closer to the PWD Intermediate-High scenario approach.[26]
- **National Cooperative Highway Research Program (NCHRP)**: New national guidance recommends transportation infrastructure be designed to at least the moderate-emissions (RCP 4.5) median sea level rise projections.[27] This scenario is a little higher than the low-emissions scenario in the DVRPC analysis, and close to PWD's Intermediate-Low scenario. For critical transportation infrastructure, the report recommends considering a scenario that falls between DVRPC's high emissions scenario and PWD's Intermediate-high scenario.

[25] New York Mayor's Office of Recovery and Resiliency. Climate Resiliency Design Guidelines. March 2019.
https://www1.nyc.gov/assets/orr/pdf/NYC_Climate_Resiliency_Design_Guidelines_v3-0.pdf

[26] Boston Public Works Department. 2018. Climate Resilient Design Standards & Guidelines.
https://www.boston.gov/sites/default/files/imce-uploads/2018-10/climate_resilient_design_standards_and_guidelines_for_protection_of_public_rights-of-way_no_appendices.pdf

[27] Kilgore et al. 2019. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure: Design Practices.
https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4046

Recommended Scenarios

In an ideal situation, we would be using recent sea level rise projections specific to Philadelphia that have already been modeled/mapped in an easy-to-use format. However, we unfortunately do not have all of those components. Table 7 outlines the pros and cons of using the various sea level rise projections covered in this memo.

TABLE 7: PROS AND CONS OF VARIOUS SEA LEVEL RISE PROJECTIONS

Projections	Pros	Cons
PWD/ Sweet et al. 2017	Sea level rise projections are specific to the Philadelphia tide gauge and come from a highly respected scientific source.	There is no detailed mapping of these scenarios for the region. Analysis of sea level rise impacts at a specific site would require either: • Relying on existing tool such as the NOAA sea level rise viewer or Climate Central to approximate the impacts, but their sea level rise maps are only available in 1 foot increments, thus negating the benefits of using highly localized sea level rise projections. • Conducting custom bathtub modeling, which may be harder for the City and PennDOT to replicate in other locations.
DVRPC/ Kopp et al. 2016	DVRPC has produced a robust set of maps for all of Philadelphia (and beyond) using the most accurate digital elevation data available. Using this data set will increase the replicability of the analysis. Sea level rise projections come from a highly respected scientific source.	Kopp et al. developed the sea level rise projections based on the Atlantic City, NJ tide gauge. Kopp et al. found this tide gauge data to be transferable to the tidal Delaware River, but it is less localized than the Sweet et al. data. The 2100 low emissions sea level rise scenario is lower than national guidance for designing transportation infrastructure.[28]
Growing Stronger/ DOE 2013	Consistency with existing City of Philadelphia reports and data sets. We have access to existing mapping,	Although the sea level rise projections are not materially different than the other options being considered, their source data is considered out of date.

[28] Kilgore et al. 2019. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure: Design Practices. https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4046

Projections	Pros	Cons
	though it uses a less refined digital elevation model.	

To increase the replicability of the process used in this analysis, ICF recommends taking advantage of the DVRPC data set for this analysis. The DVRPC mapping uses a very high quality digital elevation model, thus providing one of the most robust sets of inundation data currently available for the region. By utilizing this existing resource, we would be establishing a protocol that can be easily replicated in other areas in Philadelphia. Additionally, it would free up resources under the contract to focus more on adaptation considerations. However, since the DVRPC 2100 low-emissions scenario falls below the new national recommendations for transportation infrastructure, we recommend dropping that scenario and focusing in on the 2050 scenario and the 2100 high-emissions scenario.

If the City and PennDOT agree to using the DVRPC scenarios, we would provide maps and inundation depth information under the following scenarios for 2050 and 2100 high-emissions scenarios:

- Daily high tide flooding (i.e., mean higher high water [MHHW])
- Chronic flooding (i.e., flooding occurring 26 times per year)
- A 10% annual chance flood
- A 1% annual chance flood

The sea level rise increments associated with these time frames and flood scenarios using various datums are provided in Table 8 through Table 10. These tables also include the 4% annual chance flood, which equates to a 25-year return period. This flood probability is commonly used by PennDOT in designs for local arterials, such as the Delaware Ave. extension.

TABLE 8: FLOOD SCENARIOS USING THE NAVD 88 DATUM (FEET)

Scenario	2050	2100 High Emissions
Sea Level Rise (relative to 2000)	1.4	3.4
Daily High Tide (MHHW)	5.3	7.3
Chronic Flooding	6.4	8.4
10% Flood Water Level	8.4	10.4
4% Flood Water Level	9.3	11.3
1% Flood Water Level	9.5	11.5

There is a difference of -4.63 feet between the NAVD88 datum and the datum used by the City of Philadelphia Fifth Survey District. For example, elevation 10.00' NAVD88 = Elevation 5.37' City of Philadelphia.

TABLE 9: FLOOD SCENARIOS USING THE CITY OF PHILADELPHIA 5TH SURVEY DISTRICT DATUM (FEET)

Scenario	2050	2100 High Emissions
Sea Level Rise (relative to 2000)	1.4	3.4
Daily High Tide (MHHW)	0.7	2.7
Chronic Flooding	1.8	3.8
10% Flood Water Level	3.8	5.8
4% Flood Water Level	4.7	6.7
1% Flood Water Level	4.8	6.8

There is a difference of +5.71 feet between the City of Philadelphia Fifth Survey District and NGVD29. For example, elevation 10.00' City of Philadelphia = Elevation 15.71' NGVD29.

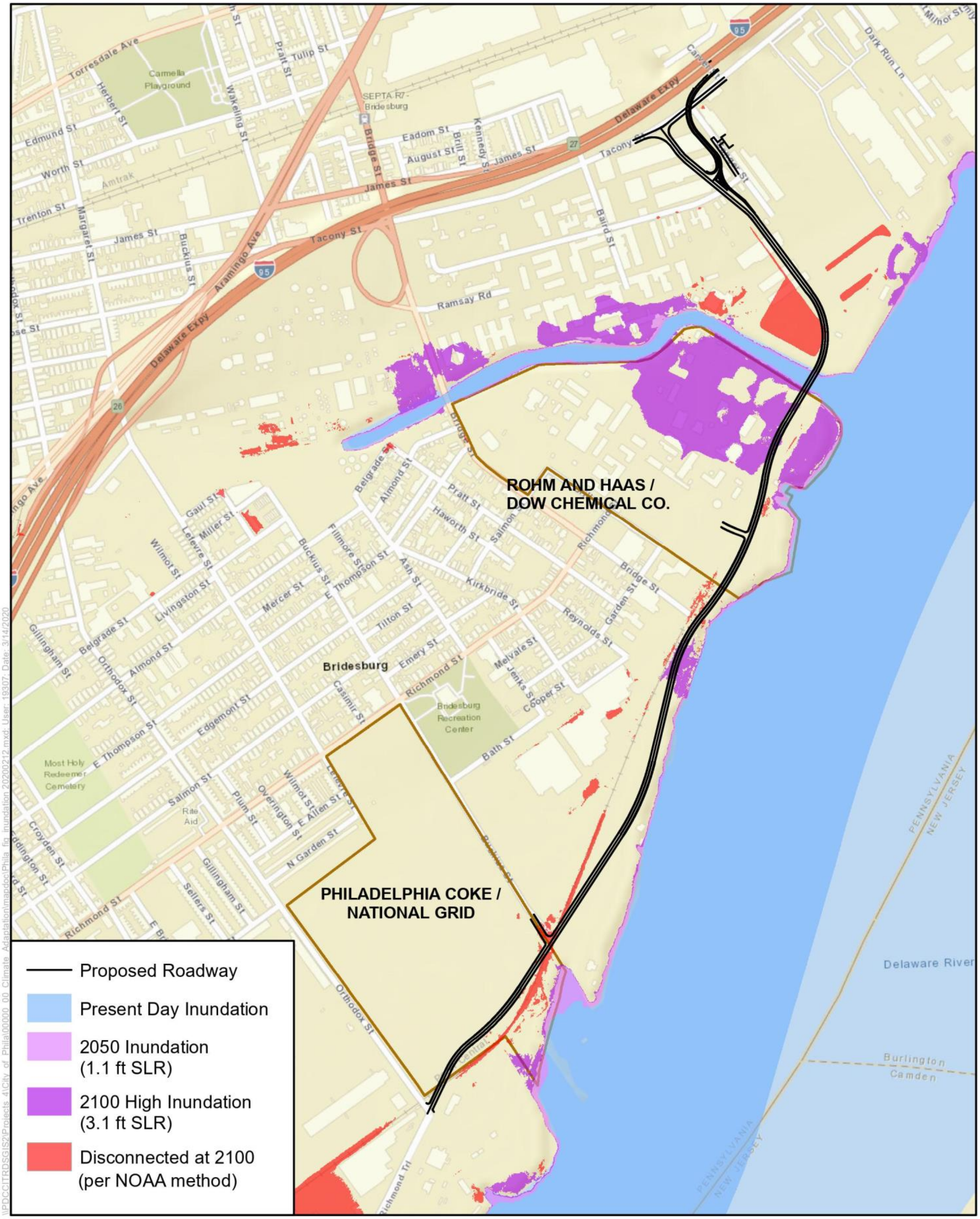
TABLE 10: FLOOD SCENARIOS USING THE NGVD 29 DATUM (FEET)

Scenario	2050	2100 High Emissions
Sea Level Rise (relative to 2000)	1.4	3.4
Daily High Tide (MHHW)	6.4	8.4
Chronic Flooding	7.5	9.5
10% Flood Water Level	9.5	11.5
4% Flood Water Level	10.4	12.4
1% Flood Water Level	10.6	12.6

Appendix B: Inundation Maps and Profiles

This appendix contains:

- Maps of inundation extent
    - The mapping methodology is detailed in Appendix C.
- Elevation profiles of inundation depth
    - The profiles of the proposed roadway alignment reflect the bare ground elevation from PennDOT's engineering data since the elevation of the proposed road has not yet been determined.
    - These diagrams help demonstrate where there are points in the alignment that are lower than the potential flood elevations. These profiles do not account for hydrologic connectivity – they simply identify low points in the profile. This is equivalent to a simple bathtub flooding model.
- Map of proposed roadway alignment and distance from northern origin point, that correspond to the alignment and distances in the elevation profiles

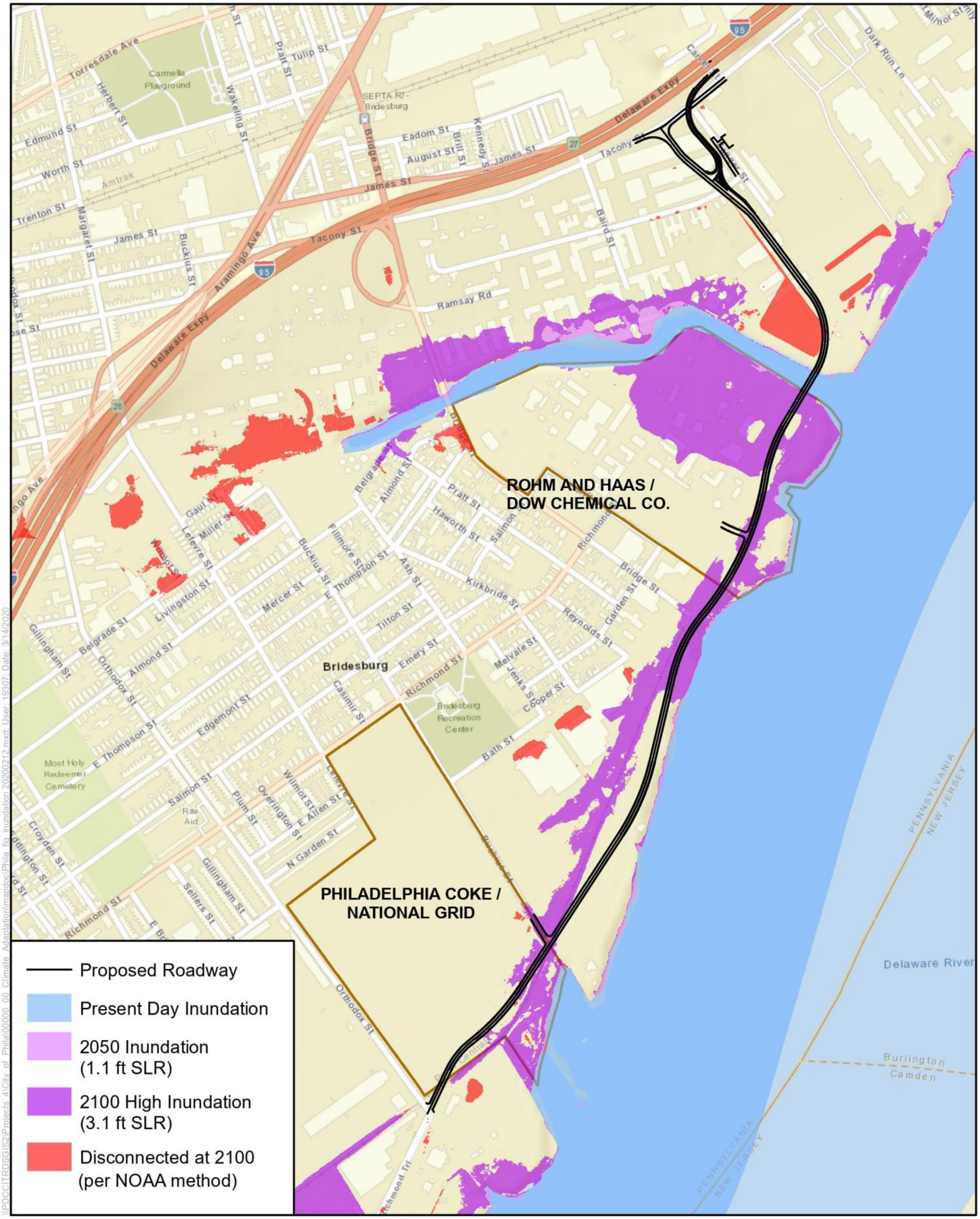


Daily Inundation

1 inch = 900 feet

0 1,000 Feet

N

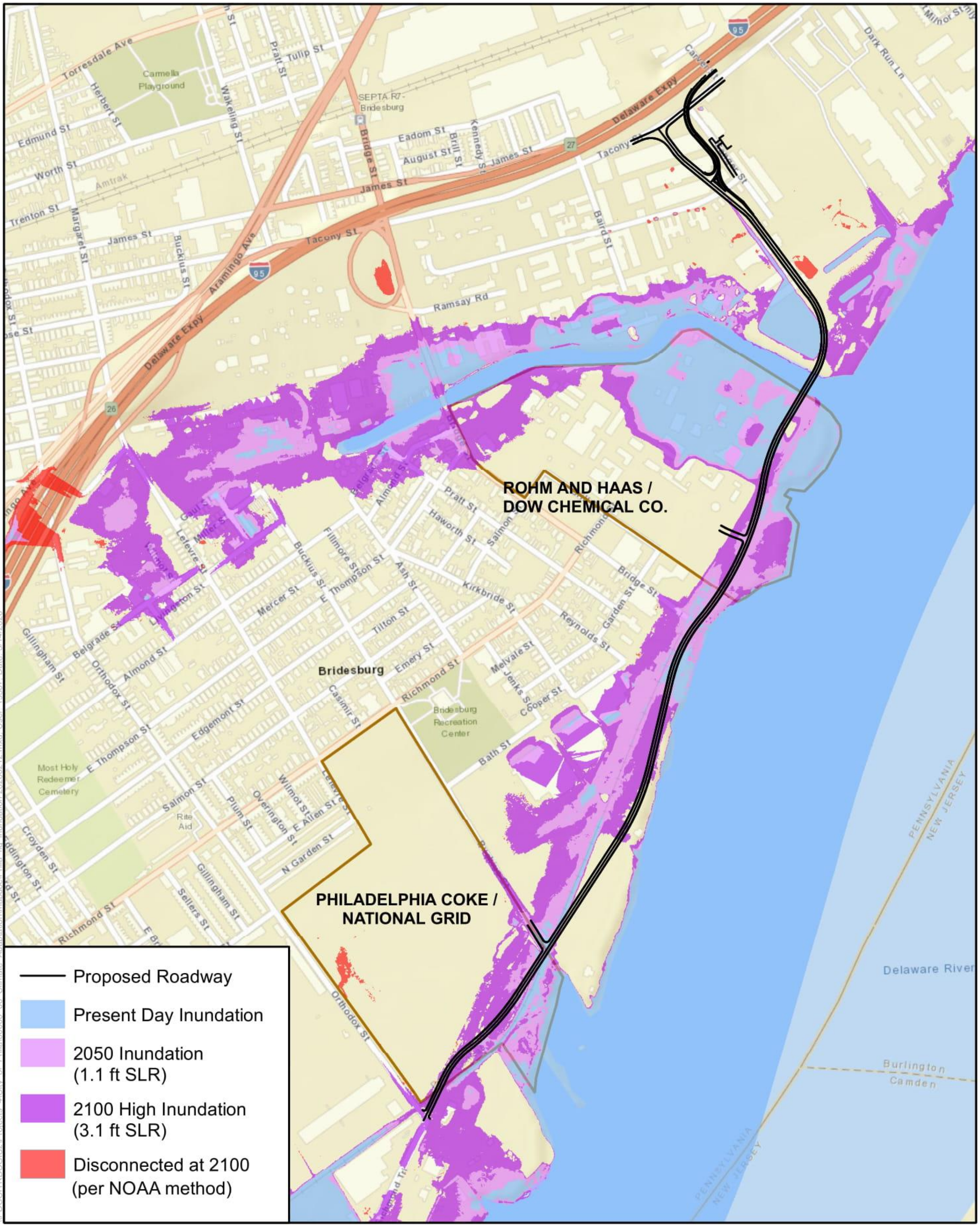


Chronic Inundation

N

1 inch = 900 feet

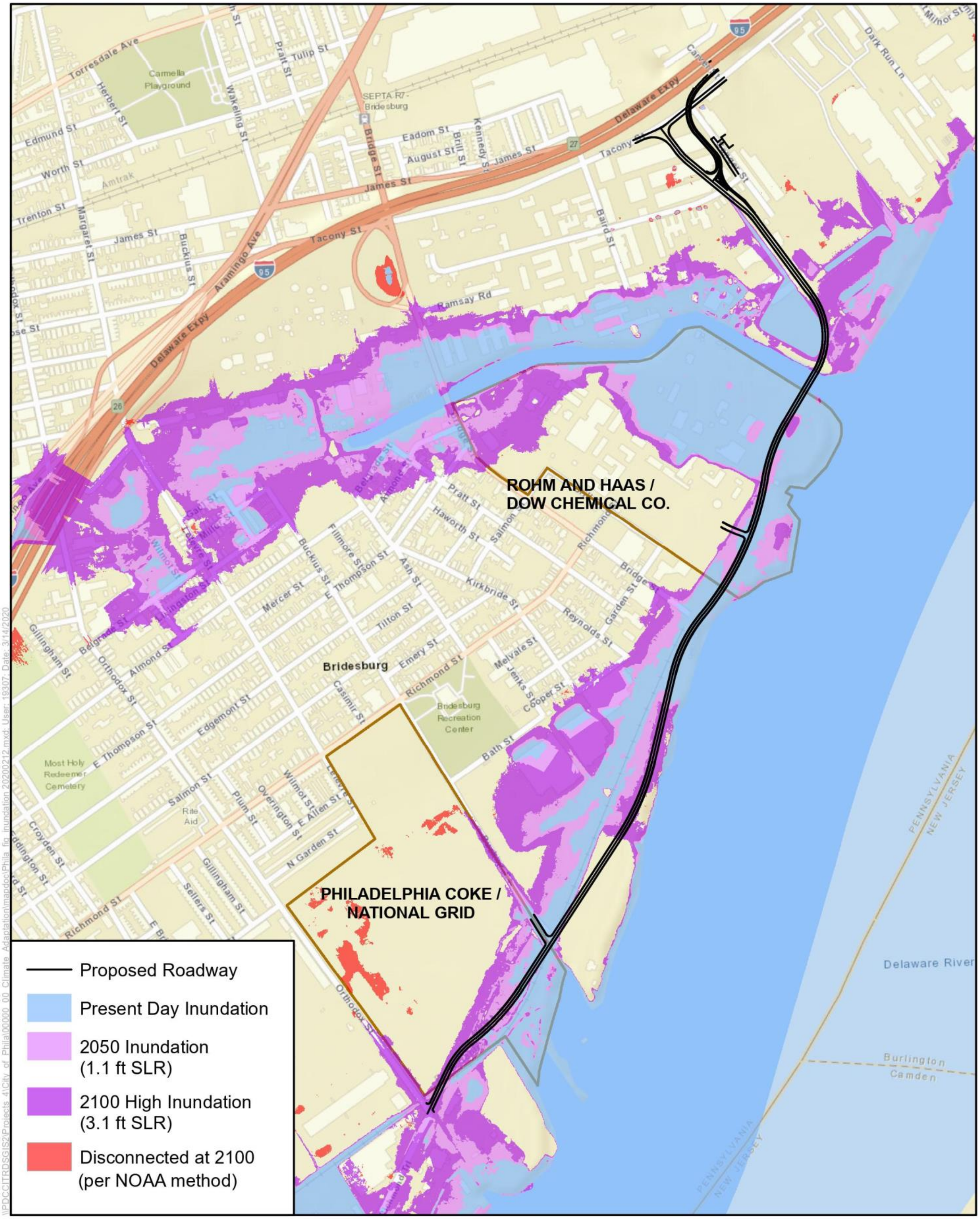
0 1,000 Feet



10-year Inundation

1 inch = 900 feet

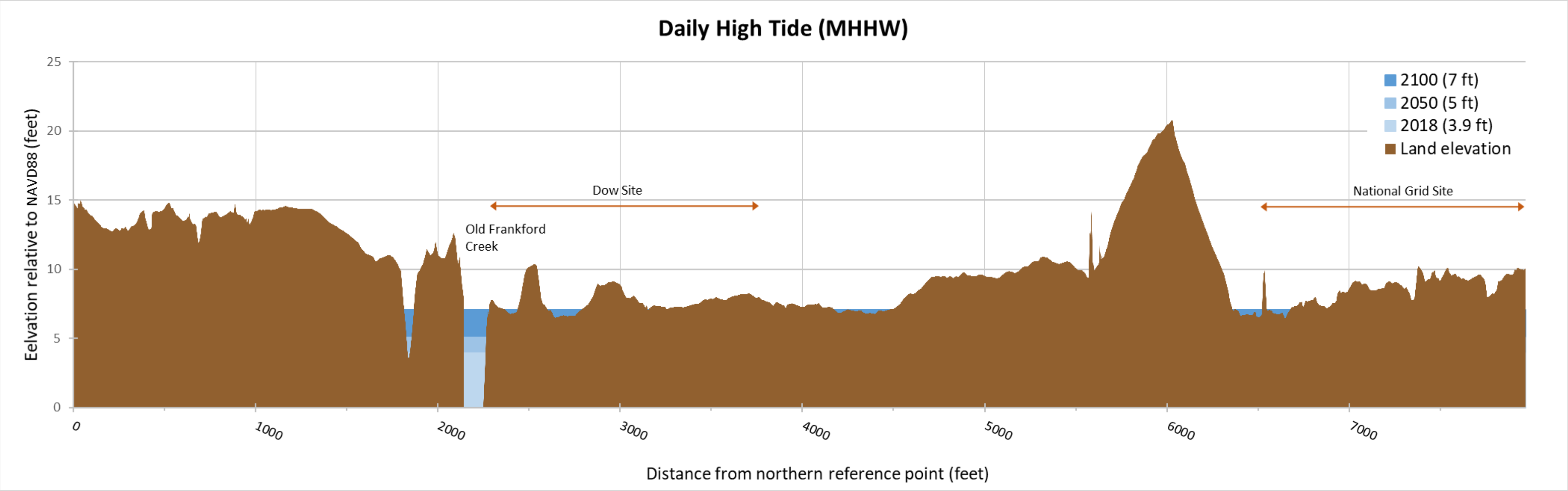
0 1,000 Feet

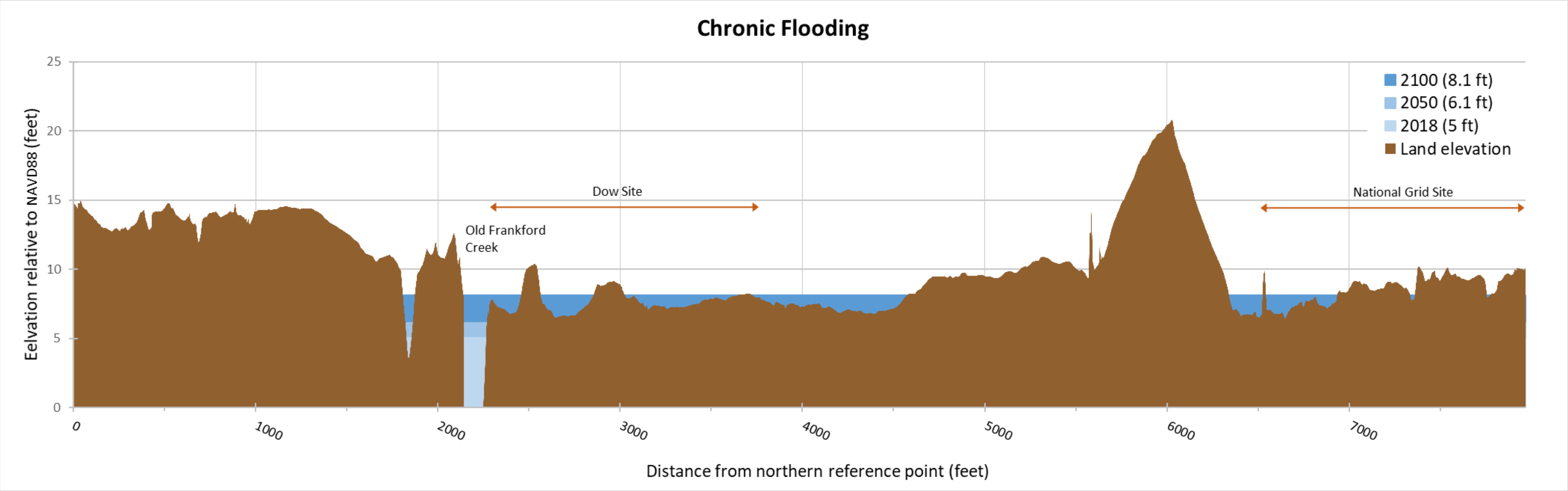


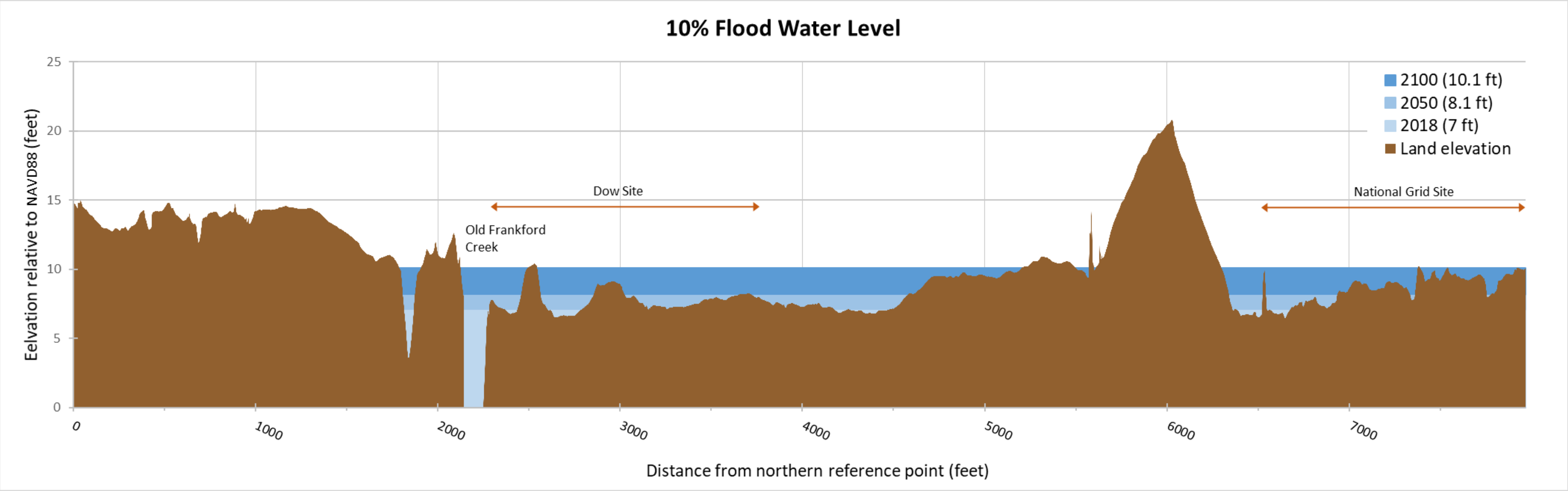
100-year Inundation

1 inch = 900 feet

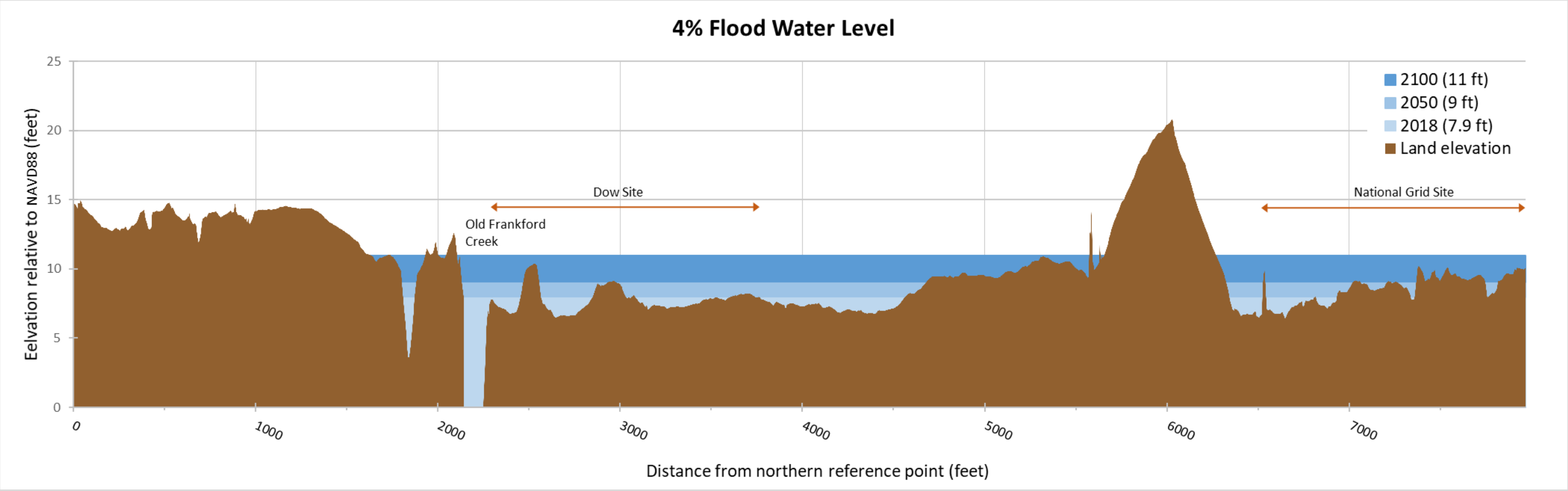
0 1,000 Feet


Daily High Tide (MHHW)
2100 (7 ft)
2050 (5 ft)
2018 (3.9 ft)
Land elevation
Dow Site
National Grid Site
Old Frankford
Creek
Eelvation relative to NAVD88 (feet)
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
6000
7000
Distance from northern reference point (feet)

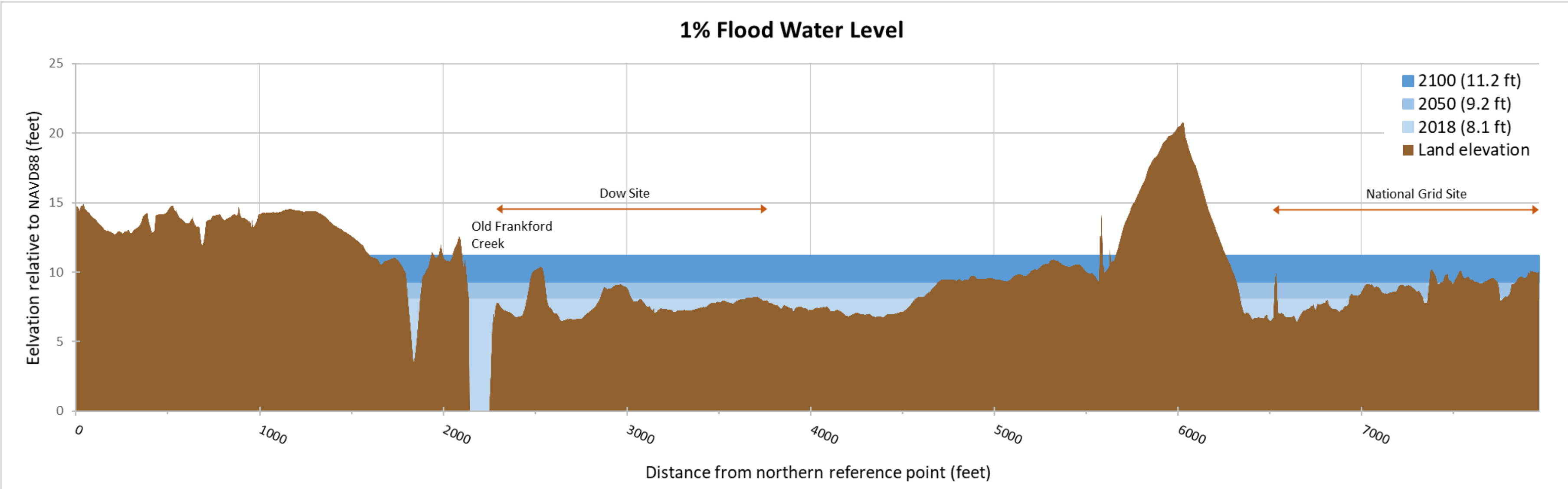

Chronic Flooding
2100 (8.1 ft)
2050 (6.1 ft)
2018 (5 ft)
Land elevation
Dow Site
National Grid Site
Old Frankford
Creek
Eelvation relative to NAVD88 (feet)
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
6000
7000
Distance from northern reference point (feet)



10% Flood Water Level
2100 (10.1 ft)
2050 (8.1 ft)
2018 (7 ft)
Land elevation
Dow Site
National Grid Site
Old Frankford
Creek
Eelvation relative to NAVD88 (feet)
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
6000
7000
Distance from northern reference point (feet)



4% Flood Water Level
2100 (11 ft)
2050 (9 ft)
2018 (7.9 ft)
Land elevation
Dow Site
National Grid Site
Old Frankford
Creek
Eelvation relative to NAVD88 (feet)
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
6000
7000
Distance from northern reference point (feet)



1% Flood Water Level
Eelvation relative to NAVD88 (feet)
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
6000
7000
Distance from northern reference point (feet)
2100 (11.2 ft)
2050 (9.2 ft)
2018 (8.1 ft)
Land elevation
Dow Site
Old Frankford
Creek
National Grid Site

ICF

N

1 inch = 900 feet

0 1,000 Feet

Proposed Road Centerline

Appendix C: Mapping Methodology

This appendix contains the contents of a memorandum, delivered February 19, 2020, summarizing the mapping methodology. This appendix provides the contents delivered as-is, with only minor adjustments.

Introduction

In our memo on sea level rise scenarios and risk tolerance, ICF recommended using the Delaware Valley Regional Planning Commission (DVRPC), "Coastal Effects of Climate Change in Southeastern PA"[29] sea level rise inundation data set for mapping impacts to the Delaware Avenue extension project to increase the replicability of the process. The DVRPC mapping uses a high-quality digital elevation model, thus providing one of the most robust sets of inundation data currently available for the region. One of the goals of utilizing this existing resource was to establish a process that could be easily replicated in other areas in Philadelphia. This memo seeks to provide insight on that process.

Overview of the DVRPC Data Set and Limitations

Overview of Methods and Assumptions

DVRPC provided geospatial information on the extent of potential inundation under the following sea level rise and storm surge scenarios for current day (2018), 2050, and 2100:

- Daily high tide flooding (i.e., mean higher high water [MHHW])
- Chronic flooding (i.e., flooding occurring 26 times per year)
- A 10% annual chance flood
- A 1% annual chance flood

DVRPC has prepared a very thorough write-up[30] that outlines their methodology, data sources, assumptions, answers to key questions, and limitations to their approach for developing the scenarios and the inundation maps. Rather than recreating that document, we recommend the City of Philadelphia and PennDOT review DVRPC's documentation to better understand their approach.

Limitations

DVRPC acknowledges three core limitations to their modeling approach:

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[29] DVRPC. 2019. Coastal Effects of Climate Change in Southeastern PA. https://dvrpcgis.maps.arcgis.com/apps/MapSeries/index.html?appid=8080c91a101d460a9a0246b90d4b4610

[30] DVRPC. 2019. Coastal Effects of Climate Change in Southeastern PA. About Our Analysis. https://drive.google.com/file/d/1BwzFUM8GxqKgEtmeFNhHLkye8aL7JnTW/view

- **Hydrological connectivity**: DVRPC maps show all low-lying areas as flooded, regardless of whether there is a flow path by which water could reach that area. In other words, it does not account for the natural and man-made topographical features that might impede the flow of water to a low-lying area. ICF corrected for this limitation using the methodology outlined below.
- **Map interpretation:** While DVRPC used a high-resolution digital elevation model (1-meter horizontal resolution) to produce their results, the resolution is still not high enough to be accurate at the parcel level. Their analysis is appropriate for neighborhood-scale analyses, such as the review of the full Delaware Avenue extension corridor.
- **Riverine flooding:** DVRPC's mapping does not account for the hydrodynamics of precipitation-driven riverine flooding following a storm as this is a very complex topic to model. ICF is not aware of any models that capture the combined dynamics of sea level rise, coastal storm surge flooding, and riverine flooding in the Philadelphia region.

In addition to these limitations, there are three more that ICF is aware of:

- **Low-emissions 2100 scenario:** As described in the January 2020 memo, DVRPC includes a low-emissions and a high-emissions 2100 sea level rise scenario. Based on our review of the literature, the low-emissions scenario is considerably lower than what is generally recommended for use in design (see the earlier memo for more information on this topic). For this reason, ICF opted to only use the 2100 high-emissions scenario in our analysis.
- **Tide gauge selection**: The sea level rise projections used by DVRPC are based on the Atlantic City tide gauge rather than the Philadelphia tide gauge. Atlantic City was used because it is the reference point in the Kopp et al. [31] paper, which presents sea level rise projections in an easy-to-use format. Sweet et al.[32] provides sea level rise projections specific to Philadelphia, but the presentation can be harder for a lay person to interpret. Regardless, the sea level projections for the two tide gauges are very similar.
- **Groundwater table rise**: The scope of the DVRPC modeling does not capture the impact of groundwater changes due to sea level rise, which could be a highly relevant concern for brownfield sites.

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[31] Kopp, et al. 2016. Assessing New Jersey's Exposure to Sea-Level Rise and Coastal Storms: Report of the New Jersey Climate Adaptation Alliance Science and Technical Advisory Panel. https://rucore.libraries.rutgers.edu/rutgers-lib/50714/PDF/1/play/

[32] Sweet, et al. 2017. Global and Regional Sea level Rise Scenarios for the United States. https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf

Methodological Options for Flagging Low-Lying, Disconnected Inland Areas

Sea level rise inundation models may show areas of inundation that are disconnected (i.e., not hydrologically connected to the open water), as shown on Figure 5 in red. These low-lying inland areas do not have a clear path for water to reach them horizontally due to natural or man-made topographical features. However, it is possible that culverts or other water conveyance systems, which are not included in this type of flood modeling (i.e., bathtub approach), could result in flooding in those locations.

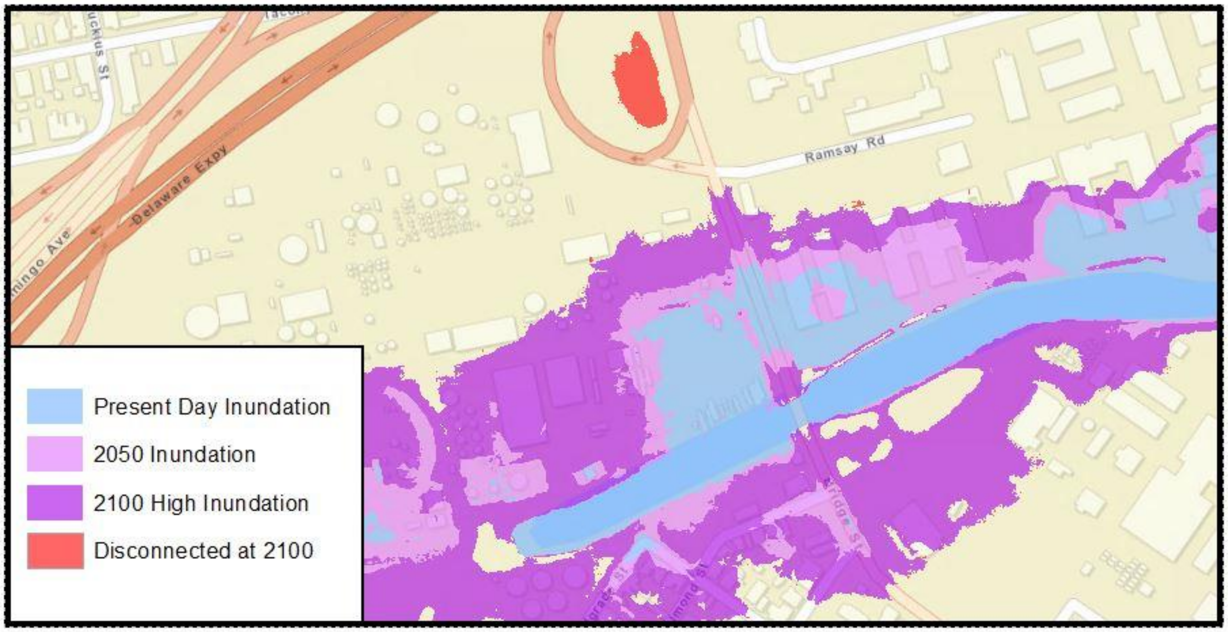

FIGURE 5: DISCONNECTED LOW-LYING AREA

Disconnected low-lying areas can be identified and isolated through use of GIS software and methods for the purposes of 1) symbolizing them on maps in ways that distinguish them from the larger contiguous area of flooding connected to the ocean or open water; or 2) including or excluding them in GIS spatial analysis methods, such as exposure modeling.

The purpose of this section of the memo is to briefly describe and compare three methods for identifying disconnected low-lying areas in GIS to facilitate display and analysis goals, in particular for use on the Delaware Avenue Extension project and other projects, as needed. The methods are:

1) NOAA's Detailed Method for Mapping Sea Level Rise Inundation;[33]
2) a visual identification of disconnected areas; and

[33] NOAA Office for Coastal Management. January 2017. Detailed Method for Mapping Sea Level Rise Inundation. https://coast.noaa.gov/data/digitalcoast/pdf/slr-inundation-methods.pdf

3) a polygon selection method that mimics the NOAA method on polygonal data.

NOAA Method

NOAA's document, referenced in the link above, describes the sea level rise inundation mapping process used by the NOAA Office for Coastal Management. The Detailed Mapping Process section (pages 3-5 in the document) provides a set of step-by-step instructions, which are applied in ArcMap Spatial Analyst software, to calculate flood inundation extent and depth. Steps 1 and 2 of this process are used to calculate water depth from: a ground elevation digital elevation model (DEM, which we obtained from DVRPC), tidal surface, and sea level rise amount (i.e., the extent of flooding as provided by DVRPC). The remaining Steps 3-7 are applied to identify and display disconnected low-lying areas; these are the steps that are specifically addressed in this document.

The NOAA method assumes that inputs are in the format of Esri raster (grid cell) files. The basic premise of NOAA's method is that the inundated area that is connected hydrologically to open water will be represented in GIS by the largest (in terms of land area) single contiguous collection of inundated grid cells. All other areas of inundation (i.e., of smaller land area than the maximum) will be considered disconnected. The method, in Step 4, uses the Spatial Analyst Region Group tool to identify contiguous areas (i.e., collections of contiguous grid cells), which are saved in a new raster (named "clumped"). In Step 5, the user interactively queries the results of Region Group to identify the largest contiguous area (i.e., with the largest number of grid cells); the Extract-by-Attributes tool is then used to extract this area and save it in a new raster (named "connect").

The NOAA method provides additional steps that appear to be optional depending on user needs. Step 6 derives low-lying areas greater than one acre in size (it is not clear from NOAA's document why this step is performed and what the basis is for the one-acre threshold). Step 7 is used to mask the SLR depth raster with the connected inundated area for the purpose of displaying inundation only on land. Two additional post-processing steps (1 and 2) are provided for optionally displaying the results of Step 7.

For any organization applying the NOAA method, ICF recommends the creation of a model in Esri's ArcGIS ModelBuilder environment to implement the sequence of NOAA's analysis steps in a way that makes the process repeatable, reusable, editable, and well-documented.

NOAA Method Implementation

ICF implemented the NOAA method steps 4-6 for the Delaware Avenue Extension project for the 2050 and the 2100 High daily, chronic, 10-year, and 100-year flooding scenarios. An Esri model was built to perform the analysis, a portion of which is shown on Figure 6 for illustration purposes. The NOAA approach was modified slightly to accommodate the specific inputs received from DVRPC; namely, DVRPC provided polygon feature classes (rather than rasters) representing inundation extent, and it was therefore not necessary to calculate flood extent and depth from DEM ground elevation, sea level rise elevation, and water level raster files.

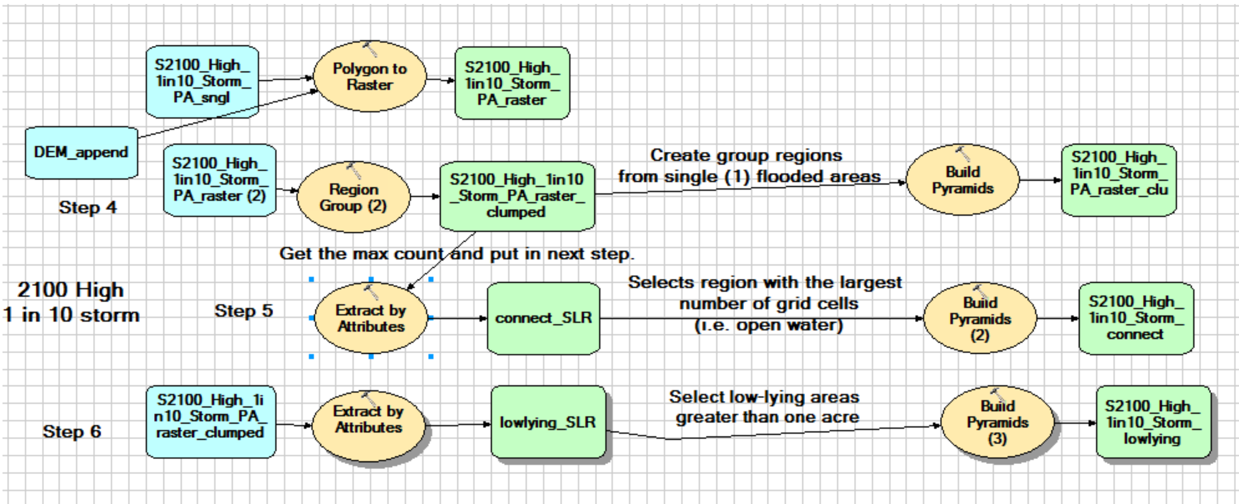

FIGURE 6: GIS MODEL OF NOAA METHOD

To follow the NOAA method, it was necessary to create raster files of inundation extent from the polygon feature classes provided by DVRPC. The Polygon to Raster tool shown in Figure 6 performs this function; one-meter grid cell raster files conforming to DVRPC's DEM data resolution were created. These files were used as input into the Step 4 Region Group process and form the basis for the identification of disconnected low-lying areas.

Once the GIS model outputs (rasters named "clumped" and "connect") are generated, standard ArcMap tools were used to display them. ICF created a set of maps that display the connected flood areas for present day, 2050, and 2100, and that separately show in a different symbol the disconnected areas for 2100. Separate maps were created for each of the Daily Conditions, Chronic Conditions, 10-year storm, and 100-year storm scenarios. The basic display technique is to order the map layers in the following specific way. The "clumped" layer draws first (these are the grouped regions) in a single color; next the "connect" layer is drawn (this is the large connected flood area) in a single color, leaving the disconnected areas visible; next the 2050 and present-day flood areas (which fall within the larger flood areas previously drawn) are displayed in a third and fourth color, respectively.

Application of the NOAA method appeared to accurately identify and allow effective display of disconnected flood areas in the project area.

Manual Visual Method

A manual, visual method is also available for identifying disconnected low-lying areas. This method was employed by ICF, prior to implementing the NOAA method, to develop a set of maps quickly and at low cost for early project team review and comment. The basic approach entails the creation of an ArcMap project (mxd file) that logically orders and displays the inundation layers for each scenario. For this project, the 2100 flood layer was drawn first, followed by the 2050 and present-day layers. An attribute field was added to each inundation layer for the purpose of storing a binary value (e.g. 1 or 0; yes or no; Y or N) to indicate whether each polygon feature in the layer is hydrologically connected or disconnected. The newly-created attribute field was populated for each polygon to identify whether it was connected or disconnected to open water, thereby allowing them to by symbolized differently on a map, or to be selectively used for further analysis, if desired.

This method is relatively quick and easy to implement, although it may introduce some subjectivity and potential for human error in the process.

Polygon Selection Method

During this analysis, a possible third method for identifying disconnected low-lying areas emerged. As previously mentioned, the NOAA method described above assumes that raster files will be used as input to the process, and that regional groups/clusters will be formed by grouping grid cells through use of the Spatial Analyst Region Group tool. The group or cluster with the largest count of grid cells (i.e., the largest geographic area) is designated as the hydrologically-connected flood area.

For this project, inundated areas are represented as polygon feature classes rather than as raster files. Instead of identifying clusters through a tool such as Region Group, each polygon might be considered a "cluster." As a substitute for counting grid cells, the area of the polygon might be used to identify connected and disconnected flood areas (i.e., the single polygon with the largest area is the connected polygon, and all other polygons are disconnected). A new attribute field may be added to each polygon feature class to identify it as connected or disconnected.

Although this method has not been implemented by ICF, it appears to be a reasonable application of the NOAA method, whereby a polygon data structure is used in place of a raster data structure. This method does carry some caveats. For example, the polygon features must be stored as "single-part" features, rather than "multi-part" (an Esri tool is available to make this conversion, if necessary). And each polygon must stand alone and not be subdivided into more than one polygon. Other potential limitations may apply.

Method Comparison and Summary

A summary comparison of the three methods is provided below.

NOAA Method

Pros:

1. Authoritative. Carries the stamp of approval of NOAA.

2. Quantitative. Counts contiguous grid cells to identify the group/cluster with the largest area.
3. User documentation is provided by NOAA.
4. Method can be modelled in Model Builder to allow revision, re-use, and sharing.

Cons:

1. May take longer to implement than other methods.
2. Requires GIS resources – staff, knowledge, software (Spatial Analyst).
3. Can require long computer processing time.

Manual Visual Method

Pros:

1. Relatively easy and quick to implement.
2. Short computer processing time.

Cons:

1. Can be subject to human error.
2. Qualitative and subjective. May not be regarded as rigorous as NOAA method.

Polygon Selection Method

Pros:

1. Relatively easy and quick to implement if inundation data stored as polygons.
2. Short computer processing time.

Cons:

1. Not yet tested by ICF.
2. Not specifically documented or recommended by NOAA.