# Flood Risk Management Planning Resources for Washington, DC

National Capital Planning Commission

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Cover Photo: The wake from a passing boat crashes over a flooded walkway on East Potomac Park during high tide on September 28, 2013. Credit: John Cochran



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www.ncpc.gov/docs/Flood_Risk_Management_Planning_Resources_Print_January_2018.pdf

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# 1. Introduction

## Document Purpose

Washington, DC and the surrounding National Capital Region (NCR) have experienced significant river, coastal, and interior floods that have negatively impacted federal and local operations, land and facility assets, and supporting infrastructure. As a result, flooding is one of the hazards that property and asset managers must consider to ensure a more secure and resilient capital.

This guide provides a short summary of key flood risks in the NCR, an overview of recent studies and tools that address current and future flood risks in the region, and brief descriptions of how these studies can be used in flood risk management. While much of the information addresses the entire NCR, the guide focuses on Washington, DC and its monumental core. The document will assist planners and facility managers and help inform their decisions on projects with flood risks.

## Intended Audience

The guide's primary audience is facility managers, asset planners, and building design professionals who are involved in the planning and design of facilities or land uses in or near floodplains in Washington, DC and its surrounding region. This document is not intended to be used by emergency management professionals, and is not a resource for what to do when a flood comes. The guide provides a high-level understanding of various studies and tools, and a common vocabulary to compare them. It is written with enough detail so that the reader can engage in discussions of work scope and findings with other professionals. Further analysis, beyond what is contained in the referenced studies and tools, will likely be required for detailed planning and development.

Left: Riverine flooding on the Potomac River caused by heavy rains along the Blue Ridge Mountains in March of 1936. Flood waters submerge parts of East Potomac Park and what is now Joint Base Anacostia-Bolling. Credit: National Archives

## Flooding in the National Capital Region

The National Capital Region is vulnerable to three types of flooding: riverine, coastal, and interior (described at right). Floods of each type have occurred in the recent past, including interior flooding in 2006; riverine floods in 1889, 1936, 1942, and 1996; and coastal floods in 2003 and 2010. These floods can have a significant impact on buildings and infrastructure. The 2006 Federal Triangle flood, for example, destroyed critical parts of the Internal Revenue Service headquarters' electrical and mechanical equipment and submerged the basement level under five feet of water. This resulted in millions of dollars of damage and required the building's 2,000 plus employees to be relocated for almost six months.[1] The 2006 flood exposed the priceless collections of Smithsonian museums, the National Gallery of Art, and National Archives as vulnerable to water damage and power outages. The same flood also had significant impacts to the regional transportation system, as the Washington Metropolitan Area Transit Authority shut down its Federal Triangle Metrorail Station for four days and spent millions of dollars to clean and replace critical train control and communication equipment.

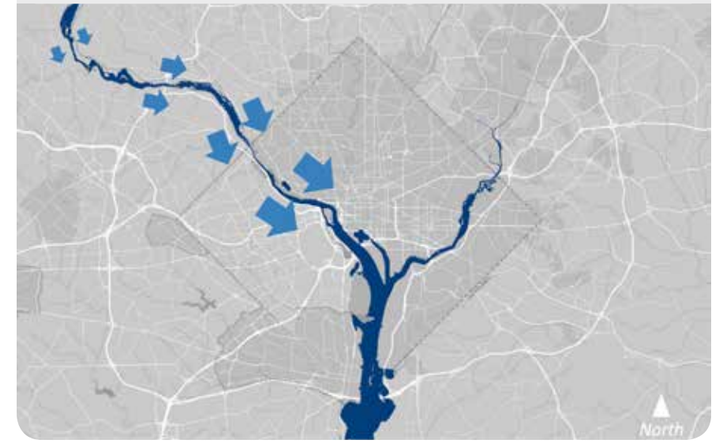
Some, but not all, of the District of Columbia's flood risk is mitigated by two primary levee systems: the Potomac Park Levee System and the Anacostia River Levee System. These levee systems (shown in white hatched lines on page 8) reduce risk to the District of Columbia from riverine and coastal flooding. They do not reduce the risk of interior flooding. Both levee systems were constructed by the U.S. Army Corps of Engineers (USACE). The Anacostia River Levee System is operated and maintained by the Department of the Navy and the National Park Service (NPS). The Potomac Park Levee System is operated and maintained by NPS.

The Anacostia River Levee System received an unacceptable rating by USACE due to several major deficiencies. The system is also not accredited by the Federal Emergency Management Agency (FEMA). After the USACE provided a positive levee system evaluation report for the Potomac Park Levee System in spring 2016, FEMA accredited the levee system and issued a revised Flood Insurance Rate Map (FIRM) for the District of Columbia. The revised FIRM shows that the Potomac Park Levee System will reduce riverine and coastal flood risk to communities behind the levee by containing flood waters that equate to the predicted 1 percent annual chance flood. When significant flooding is expected, NPS erects the 17th Street post and panel closure (see photo on page 10), which is a part of the Potomac Park Levee System and prevents flood waters from entering the city through 17th Street, a low point in the National Mall.

1 Government Accountability Office (GAO), *IRS Emergency Planning* (2007), 4-5. http://www.gao.gov/new.items/d07579.pdf



### Riverine Flooding




Riverine, or freshwater flooding, refers to overbank flooding on the Potomac River caused by its inability to contain the water collected in the Potomac River Basin. Heavy rainfall or snowmelt upstream can cause increased water levels downstream on the Potomac River hours or days later that also can cause backwater flooding on the Anacostia River.

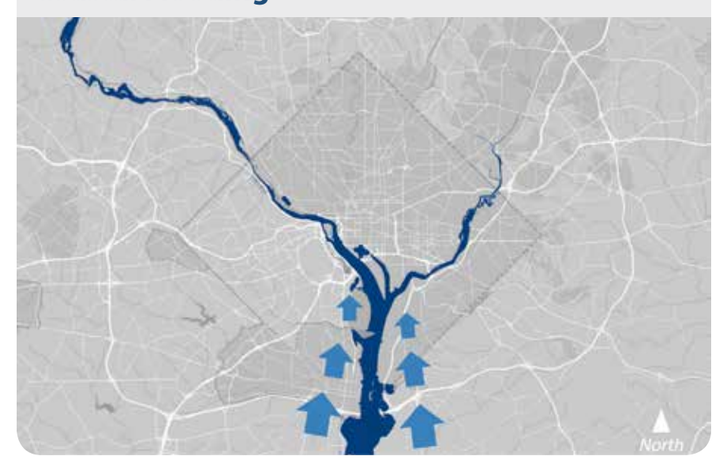
**Examples**: Floods in 1936 (page 4 photo), 1942, 1985 (page 36 photo), and 2010

### Interior Flooding

Interior floods, also known as flash floods, are caused by heavy rainfall that cannot be absorbed by the ground and then overwhelm the drainage system. Interior flooding can occur when river elevations are normal because interior floods are attributed to topography, development, localized weather, and the capacity of stormwater systems.

**Examples**: 2006 Federal Triangle Flood (page 43 map), 2012 Bloomingdale Floods, and minor flooding in 2010 as shown on page 40

### Coastal Flooding

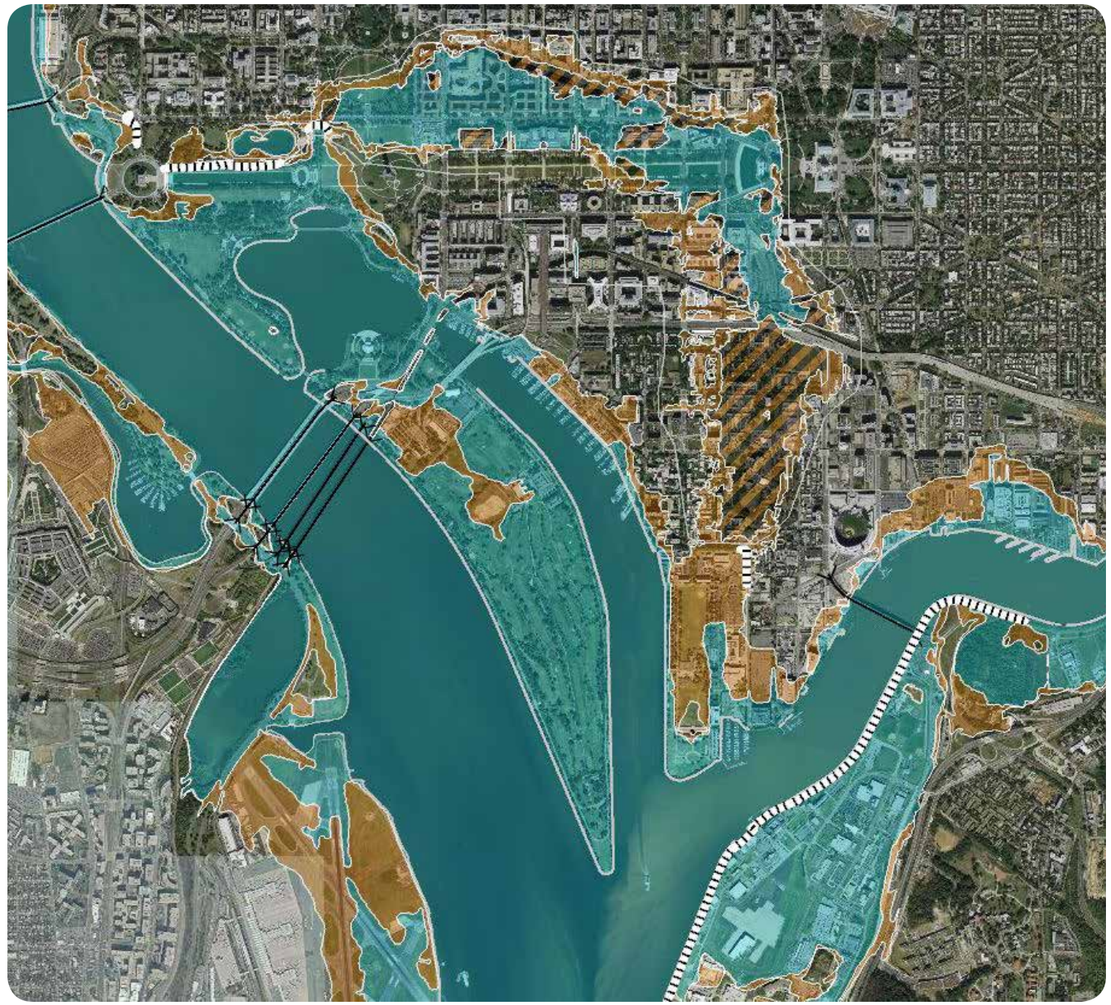



Coastal floods refer to inundation caused by the Potomac and Anacostia Rivers' connection to the Chesapeake Bay and ultimately to the Atlantic Ocean. Coastal flooding includes inundation resulting from high tides (often called tidal, nuisance, or sunny day flooding), but also from coastal storms like hurricanes that drive storm surge and waves up the Potomac River and into Washington, DC.

**Examples**: Nuisance floods (cover and page 44 photos), and Hurricane Isabel (2003)

## FEMA's Flood Insurance Rate Maps for Washington, DC

Though only intended to be insurance rating products, FIRMs are often used by government agencies as the primary sources to assess flood risk. FIRMs are available as PDFs in panels (an example is shown on page 28) at FEMA's Flood Map Service Center or as an interactive online map called the National Flood Hazard Layer, a screenshot of which is shown below.



Flood Hazard Zones
- 1% Annual Chance Flood Hazard
- Regulatory Floodway
- Special Floodway
- Area of Undetermined Flood Hazard
- 0.2% Annual Chance Flood Hazard
- Future Conditions 1% Annual Chance Flood Hazard
- Area with Reduced Risk Due to Levee

Levees

General Structures
- Flood Structure
- Bridge
- Dam, Weir, Jetty
- Other Structure

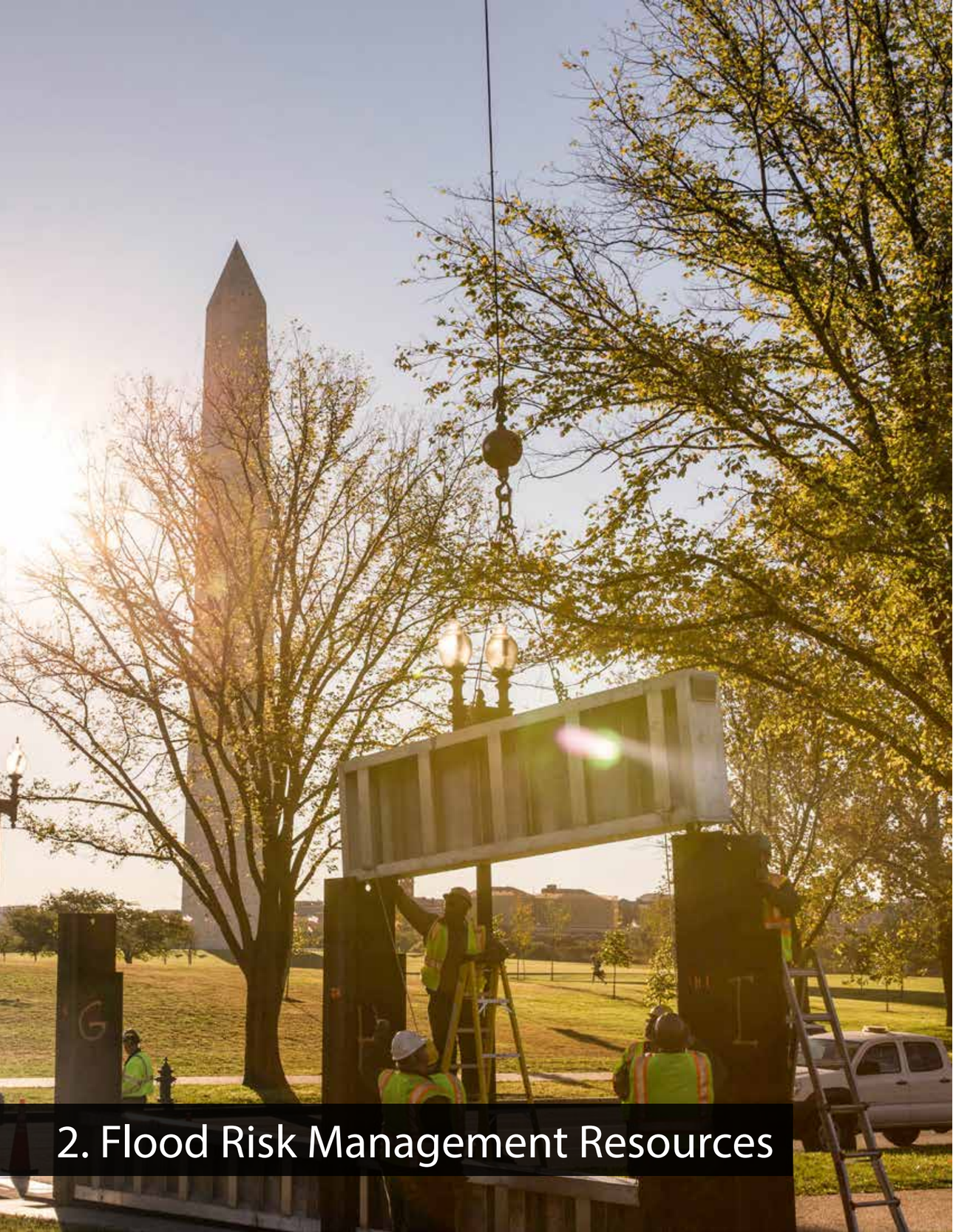


Even with certified levee systems in place, the city still has significant flood risk. A high enough flood may overtop the levees, while other areas of the city, like East Potomac Park, are not protected by the levee systems at all. The primary way agencies evaluate their flood risk in 2017 is by using FIRMs produced by FEMA (see pages 8 and 28 for two examples of the maps). These maps show areas that are in the 1 percent annual chance, and 0.2 percent annual chance floodplains, commonly referred to as 100-year and 500-year floodplains, respectively.[2] The maps are meant to be used for flood insurance rating purposes, and are not intended to be used for evaluating future flood risk, which may be impacted by changes in land use within the watershed and changes in precipitation and sea level. Planners and facility managers must use other tools and resources (which may vary depending on the type of flood risk) in order to understand and effectively respond to expected increases in future flood risk.

### Future Flood Risk

The current understanding of flood risk is primarily based on the FIRMs for Washington, DC. As described in more detail on pages 28-35, FIRMs are created using analyses of historic and existing data. While accurately reflecting this information, they do not consider how conditions that influence flooding may change in the future. This is intentional, as Section 44 of the Code of Federal Regulations states that FIRM "revisions cannot be made based on the effects of proposed projects or future conditions."[3] Planners and facility managers often use FIRMs to evaluate flood risks for long-term investments, which can be problematic because this assumes that historic and existing data (used in the creation of FIRMs) is a good predictor of the future, a concept often referred to as stationarity. Stationarity has proven to be a faulty assumption in hydrology due to climate change (i.e. sea level rise and extreme precipitation), as well as land use changes like urban development. As an example, the number of times that daily flow exceeded 1,000 cubic feet per second (cfs) on the Northeast Branch of the Anacostia River in Maryland increased from once or twice per year in the 1940s and 1950s, to as much as six times per year in the 1990s. This was due primarily to urban development that increased impervious surface and decreased the amount of rainfall that could be absorbed by soil,[4] but could also be attributed to lack of stormwater carrying capacity. To appropriately plan for and protect property, assets, operations, and other investments, which often have lifespans of 100 plus years, it is important to consider how future flood risks may be different from today.

2 More on defining the term "100-year flood:" http://water.usgs.gov/edu/100yearflood.html
3 Identification and Mapping of Special Hazard Areas, 44 C.F.R. § 65.6 (a) (3). https://www.gpo.gov/fdsys/granule/CFR-2011-title44-vol1/CFR-2011-title44-vol1-sec65-6
4 Konrad, C.P. (USGS), *Effects of Urban Development on Floods* (2003). http://pubs.usgs.gov/fs/fs07603/



# 2. Flood Risk Management Resources

## Document Structure

This chapter describes the studies and tools currently available to planners and facility managers in the NCR to consider both current and future flood risks. A useful comparison to many of these tools are the FIRMs, which are the primary maps used to evaluate flood risk today. Because of this, Chapter 3 is devoted to an in-depth explanation of the mapping and modeling processes used in their creation. In addition, many of these tools are not explicitly designed to account for future flood risks, a key consideration for investments with long lifespans. Chapters 4-6 describe both how future flood risks may change in the region and the methods and tools that can be used to evaluate these future risks; including how the tools described in Chapter 2 should or should not be used. Because future flood risks and the methods used to model its impacts depend on the *type* of flooding, one chapter will be devoted to answering these questions for each of the region's three types of flooding: riverine flooding (Chapter 4), interior flooding (Chapter 5), and coastal flooding (Chapter 6).

## One-Page Information Sheets

One-page information sheets that describe the resources (tools, data, and studies) that are currently available for the NCR begin on page 16. These resources represent the most widely accepted and used planning resources as determined by the co-leaders of the DC Silver Jackets. They do not include emergency management procedures or project proposals to reduce flood risk. The information sheets are meant to provide a quick overview of the resource and help users decide how it can be used to evaluate both current and future flood risks. The following pages provide two overview graphics to help organize the list of resources. Pages 12-13 include a list of all the information sheets organized by the type of flooding (riverine, interior, or coastal) for which they are best suited and by tool type (projection, map, or report). Some tools will be useful for more than one type of flooding or can be classified as multiple tool types. Because many of the resources described in the information sheets reference the same source data, an additional diagram on pages 14-15 has been included to show the relationship between source data and some of the resources. The eleven one-page information sheets begin on page 16.

Left: Employees of the National Park Service insert one panel of the 17th Street Levee Closure during a test installation on October 14, 2016. The closure protects the city from riverine and coastal flooding Credit: U.S. Army photo by Alfredo Barraza

# Flood Risk Management Resources for Washington, DC

The 11 resources described in this guide are listed below. Attributes of each study, Flood Type and Tool Type, are shown on page 13. Markers under **Flood Type** indicate that resource is useful for the specified types of flooding; riverine, interior, or coastal. Markers under **Tool Type** indicate what kind of resource to expect: "Projection" indicates that the resource has predictions about future climate conditions like sea level rise or precipitation, "Map" indicates that the resource includes a map or a model that can be used to visualize flood impacts, and "Report" indicates that the resource includes a written report with useful information on flood risk management.

| Page # | Resource Name | Last Update | Flood Type | | | Tool Type | | |
|---|---|---|---|---|---|---|---|---|
| | | | Riverine | Interior | Coastal | Projection | Map | Report |
| 16 | Flood Insurance Rate Maps (FEMA) | 2010[1] | ● | ●[2] | ● | | ● | ● |
| 17 | Flood Inundation Mapping Tool (USACE) | 2016 | ● | | ● | | ● | |
| 18 | North Atlantic Coast Comprehensive Study (USACE) | 2015 | | | ● | ● | ● | ● |
| 19 | Storm Surge Inundation Maps (USACE) | 2016 | | | ● | | ● | |
| 20 | Sea Level Rise Viewer (NOAA) | 2017 | | | ● | | ● | |
| 21 | Surging Seas Risk Finder (Climate Central) | 2017 | | | ● | ● | ● | ● |
| 22 | Sea Level Change Curve Calculator (USACE) | 2017 | | | ● | ● | | |
| 23 | Precipitation Modeling (DOEE) | 2015 | | ● | | ● | | ● |
| 24 | Federal Triangle Flood Study 2008 | 2008 | | ● | | | ● | ● |
| 25 | Federal Triangle Flood Study 2011 | 2011 | | ● | | | ● | ● |
| 26 | CMIP Climate Data Processing Tool (DOT) | 2010 | | ● | | ● | | |

[1] There have been six Letters of Map Revision (LOMRs) since 2010, which updated small areas within the map. The most recent revision was in February 2017. The analysis used to create the original Flood Insurance Rate Maps was from 2010.

[2] The Potomac Park Levee and 17th Street Closure LOMR changed the Flood Insurance Rate Map in that area to show interior flooding as well as the flooding that would occur if the closure structure was not in place. This is the only location in Washington, DC where interior flooding is mapped. The original 2010 Flood Insurance Rate Maps and associated Flood Insurance Study did not analyze interior flooding.

# Data Sources

Many of the tools described in the information sheets reference the same source data. This diagram attempts to show the cases where the same underlying data or models are used by multiple tools. The diagram only shows underlying data and models that are used by more than one tool. For example, the Federal Triangle Interior Drainage Analysis described on page 26 used USACE's HEC-HMS software to model the flow of surface water in Federal Triangle. Since the HEC-HMS software was only used by the 2008 Federal Triangle Flood Study, it is not included in this diagram.

| | 16 Flood Insurance Rate Maps (FEMA) | 17 Flood Inundation Mapping Tool (USACE) | 18 North Atlantic Coast Comprehensive Study (USACE) | 19 Storm Surge Inundation Maps (USACE) | 20 Sea Level Rise Viewer (NOAA) | 21 Surging Seas Risk Finder (Climate Central) | 22 Sea Level Change Curve Calculator (USACE) | 23 Precipitation Modeling (DOEE) | 24 Federal Triangle Flood Study 2008 | 25 Federal Triangle Flood Study 2011 | 26 CMIP Climate Data Processing Tool (DOT) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Stream and Tide Gage Data**<br>The United States Geological Survey and National Oceanic and Atmospheric Administration maintain national networks of gages that provide real-time and historic water level data that is used to predict future water surface elevations. | ● | ● | | | | ● | ● | | | | |
| **LIDAR Data**<br>LIDAR (Light Detection and Ranging) is a method to collect data on surface elevation. The data is used to create digital elevation models (DEM) upon which the flow of water over the surface can be modeled. LIDAR data varies in resolution. | ● | ● | ● | ● | ● | ● | | | ● | ● | |
| **CMIP Data**<br>The Coupled Model Intercomparison Project (CMIP) compiles data from 56 global climate models (GCMs). Given various carbon emissions scenarios, each GCM projects different changes in temperature and precipitation for a user-selected area. | | | | | | ● | | ● | | | ● |
| **Weather Station Data**<br>Historic temperature, precipitation, and humidity data from weather stations within the region are used as input data in climate models to predict future weather trends. | | | | | | | | ● | | | ● |
| **Sea Level Projections**<br>Sea level projections from sources such as NOAA and USACE are used as input data for modeling tools that show the vertical and horizontal extent of coastal inundation. | | | ● | | | ● | ● | | | | |
| **SLOSH Model**<br>SLOSH, or Sea, Lake, and Overland Surges from Hurricanes, is a National Weather Service model used to estimate storm surge heights resulting from historical, hypothetical, or predicted hurricanes. | | | ● | ● | | | | | | | |
| **HEC-RAS Model**<br>HEC-RAS (Hydrologic Engineering Centers River Analysis System) is a USACE software program used for hydraulic modeling of water flow. Given estimates of river flow or water surface elevation, it predicts the horizontal and vertical extent of flooding. | ● | ● | | | | | | | | | |

# Flood Insurance Rate Maps

## Federal Emergency Management Agency (FEMA)

**Purpose:** Provide maps that show the 1% annual chance (100-year) and 0.2% annual chance (500-year) floods. The maps are used by the local jurisdictions to regulate development in floodplains and are used by the National Flood Insurance Program to determine flood insurance requirements.

### Flood Type

- Riverine
- Interior
- Coastal

### Tool Type

- Projection
- Map
- Report

### Key Facts

**2004**
Topographic Data

**2010**
Maps Published

Available nationwide, though this page refers only to the DC maps

### Links

Online Map Viewer and DC Resources
https://msc.fema.gov/portal/search?AddressQuery=washington%20dc

2010 Flood Insurance Study
https://www.ncpc.gov/docs/DC_Flood_Insurance_Study_Pre-17th_Street_Levee.pdf

### Underlying Data and Modeling

**Modeling:** The maps are created through a complex process that is detailed in chapter "3. Mapping Current Flood Risk" on page 28. The process combines historical data analysis contained in the 2010 Flood Insurance Study with the USACE HEC-RAS software to model the water flow.

**Accuracy:** Washington, DC's floodmaps are derived from LIDAR data obtained in 1999, used to create a Digital Elevation Model (DEM) with 1 meter contours.

**NCR Specific:** Washington, DC's maps were recently updated to show the 17th Street Levee Closure as protecting against the 1% annual chance (but not the 0.2% annual chance) riverine or coastal flood. Much of the Federal Triangle area is still in the 1% annual chance floodplain because interior flooding risk remains. Federal Triangle is the only location in Washington, DC where interior flooding is mapped. The original 2010 Flood Insurance Rate Maps (FIRMs) and associated Flood insurance Study did not analyze interior flooding.

### Discussion

**Best Uses:** This tool is best used for screening of assets at a master planning level. It is unique because it shows inundation from an extreme water level perspective, with layers for the 1% annual chance (100-year) flood and the 0.2% annual chance (500-year) flood.

**Limitations:** The underlying DEM data and resulting limited horizontal resolution means that this tool should only be used for high-level screening. This tool does not incorporate future flood risks and projections of the 100 and 500-year floods are based on existing conditions as of the effective date of the FIRM.

**Comparisons:** Compare to "Surging Seas Risk Finder" on page 21, which can provide annualized risk from a different perspective. The user determines the height of flooding from 1 to 10 feet, and the viewer will provide the probablity that the selected flood will occur.



# Flood Inundation Mapping Tool

## U.S. Army Corps of Engineers (USACE) and National Weather Service (NWS)

**Purpose:** Provide digital maps that allow government leaders, emergency managers, and the public to view potential flood impacts during high-water events along the Potomac and Anacostia Rivers. The viewer provides access to multiple map layers that correlate to real-time forecasts from the National Weather Service.

### Flood Type

- Riverine
- Interior
- Coastal

### Tool Type

- Projection
- Map
- Report

### Key Facts

**2008**
Topographic Data

**2016**
Maps Published

Available in many locations; This page refers only to the Washington, DC study.

### Links

Online Map Viewer
http://www.weather.gov/lwx/PotomacInundationMaps

Main Website for Study
http://doee.dc.gov/service/fim

### Underlying Data and Modeling

**Modeling:** The viewer uses the NAVD88 datum as its base elevation, with available conversions to Mean Lower Low Water (MLLW) and Washington Mean Low Water (WMLW) stages. The water flow over the Digital Elevation Model (DEM) is modeled with USACE HEC-RAS software.

**Accuracy:** The underlying DEM data are from LIDAR data obtained in 2008, with a horizontal resolution of 1 meter. The grids used to show depth of water were downsized to 5 meter horizontal resolution for computational purposes.

**NCR Specific:** The Potomac Park levee system and the 17th Street levee closure are included. Privately-owned structures, DC Water flood control structures and the Anacostia levee system were not shown as providing protection.

### Discussion

**Best Uses:** This tool is best used for real-time emergency preparedness planning. Based on the forecast from the NWS, users can view a map that most closely resembles the predicted extent of the flood. For each of the three gages, there are approximately 20 layers depicting floods in about one foot increments, starting near the level of first inundation. These maps are also useful for planning "what-if" scenarios as you can select a potential flood, regardless of NWS predictions, and see the inundation extent. The NWS website that hosts the maps also has links to a real time hydrograph and text descriptions of the effects of various flood levels.

**Limitations:** The underlying DEM data and resulting limited horizontal resolution means that this tool should only be used for high-level screening. This tool does not account for sea level rise or wave run-up (see diagram on page 49) on top of predicted storm surge. Freshwater flooding of tributaries, including the Anacostia River, Rock Creek, and Cameron Run, is not considered in these maps. While these tributaries show inundation, it is only a result of "back water" from the Potomac River.

**Comparisons:** Compare to "Flood Insurance Rate Maps" on page 16 which use the same underlying model techniques. The FIRMs only shows two flood layers (100 and 500-year floods). Also compare to "Surging Seas Risk Finder" on page 21.

# North Atlantic Coast Comprehensive Study

## U.S. Army Corps of Engineers (USACE)

**Purpose:** Assess risk from storms and sea level rise post-Hurricane Sandy and support resilient coastal communities in the North Atlantic coast. Additional appendicies for states and the District of Columbia provide regional-scale risk maps and analyses along with coastal storm risk management strategies.

### Flood Type

- Riverine
- Interior
- **Coastal**

### Tool Type

- **Projection**
- **Map**
- **Report**

### Key Facts

**2014**
Data and Maps Created

**2015**
Report Published

Available for U.S. North Atlantic Coast

### Links

Main Website for Study
http://www.nad.usace.army.mil/CompStudy/

Washington, DC Appendix
http://www.nad.usace.army.mil/Portals/40/docs/NACCS/NACCS_Appendix_D.pdf

### Underlying Data and Modeling

**Modeling:** The District of Columbia appendix uses a variety of flood mapping techniques including the 1% and 10% annual chance floodplains, the 1% annual chance floodplain plus 3 feet, and a simulation of a Category 4 Hurricane as described in "Storm Surge Inundation Maps" on page 19.

**Accuracy:** Maps are based on an approximately 70m resolution grid. National datasets were used for resource mapping such as wetlands and infrastructure. Low resolution data was necessary because of the size of the NACCS study area.

**NCR Specific:** The 17th Street Levee Closure and the Anacostia Levee System are not shown as providing protection.

### Discussion

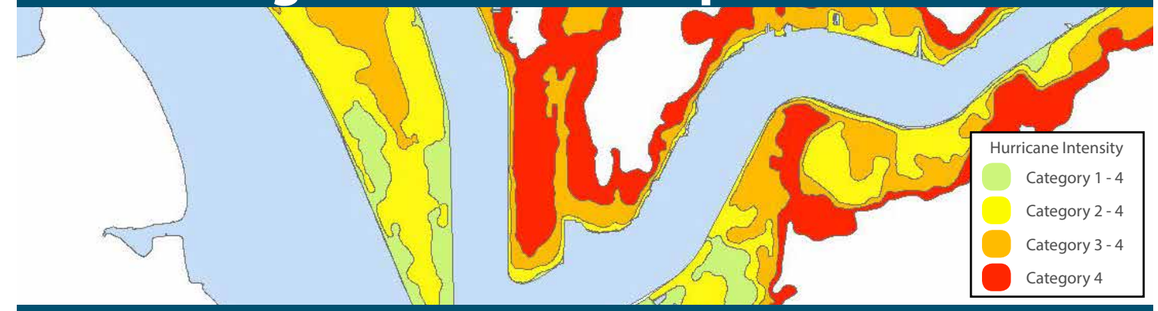
**Best Uses:** The District of Columbia appendix has two major resources. First are a series of maps showing various coastal floods (described in "Modeling"), social vulnerability, population density, infrastructure, environmental and cultural resources. The report is unique because it also combines these maps to describe risk (Probability of Occurence + Exposure to Hazards) for Washington, DC. Because these maps are low-resolution they cannot be used in master planning and are best suited to identifying neighborhood sized areas at risk. The second resource is a Risk Analysis that identified 6 key risk areas (i.e. "East of Georgetown," and "National Mall / Federal Triangle and Vicinity"). The District of Columbia appendix also evaluates the type of shorelines and potential coastal management solutions for each risk area. The overall NACCS report also provides detailed explanation of a number of coastal flood risk mitigation strategies.

**Limitations:** The scale of analysis and level of detail limit the map's usefulness.

**Comparisons:** The "Surging Seas Risk Finder" on page 21 also allows the combination of flood maps with other data like infrastructure, though its flood maps are created differently and have higher resolution. When evaluating sea level change, NACCS consulted projections from NOAA 2012, NASA 2012, and USACE 2013. The Coastal Hazards System web tool (described in Appendix C) provides access to the over 1,000 storm tracks (along with their predicted surge and wave heights) that were modeled for the NACCS: https://chswebtool.erdc.dren.mil/



# Storm Surge Inundation Maps




## U.S. Army Corps of Engineers (USACE)

**Purpose:** Determine the reasonable worst-case (peak) storm surge from the various intensities of hurricanes that could strike the region. The end product includes worst-case scenario storm surge mapping for each category hurricane (i.e., categories 1, 2, 3, and 4) that are used in Hurricane Evacuation Studies.

### Flood Type

- Riverine
- Interior
- **Coastal**

### Tool Type

- Projection
- **Map**
- Report

### Key Facts

**2014**
SLOSH modeling

**2016**
Map Published

Available in many locations; This page refers only to the Washington, DC study.

### Links

Online Map Viewer (DOEE)
http://doee.dc.gov/floodplainmap
(In Layers, check box for "Storm Surge")

Explanation of SLOSH
http://www.nhc.noaa.gov/surge/slosh.php
(Refer to "Composite Approach")

### Underlying Data and Modeling

**Modeling:** Water surface elevations for worst case storm surges are generated by a 2014 SLOSH model for the Chesapeake Basin (CP5), developed by NOAA's National Hurricane Center. The surges are added to the mean higher high water (MHHW) elevations. USACE overlaid these surge plus MHHW elevations from the SLOSH grid on a Digital Elevation Model (DEM) to create the extent and depth of flooding.

**Accuracy:** The underlying DEM is from 1 meter LIDAR data obtained in 2008 that was resampled to 10 feet. SLOSH grid cells range in size and are approximately 500 meters in the Washington, DC area.

**NCR Specific:** The 17th Street Levee Closure and the Anacostia Levee System are not shown as providing protection.

### Discussion

**Best Uses:** The primary purpose of this data is to support hurricane emergency management planning activities, including identification of evacuation zones. The map is meant to show the areas that are at risk for each hurricane category. For example, if the NWS predicts that a Category 4 (CAT4) hurricane is approaching Washington, DC, facility managers can refer to these maps to understand what areas might be flooded. In the event that the area experiences a CAT4 hurricane, it is likely that some areas identified in the maps as being inundated may actually experience less flooding since the maps represent the worst-case. The maps are useful in showing the areas that do not have storm surge flood risk (outside CAT4).

**Limitations:** This tool is only available as GIS shapefiles and there are no risk percentages (such as 1% annual chance) associated with the layers in this map. The map does not account for increased sea levels or for riverine flooding.

**Comparisons:** Compare to "Flood Insurance Rate Maps" on page 16 and "Flood Inundation Mapping Tool" on page 17. Instead of layers created by annual risk (FIRMs) or by elevation (FIMs) this tool has layers corresponding to Hurricane strength. This tool is an update to a previous study in 2009: https://www.ncpc.gov/docs/2009_USACE_Hurricane_SSIM.pdf. The following document futher describes how these maps compare with FIRMs: http://nhma.info/uploads/resources/flood/CoastalFloodMapsFactsheet_Final.pdf

# Sea Level Rise Viewer

## National Oceanic and Atmospheric Administration (NOAA)

**Purpose:** Provide a preliminary look at sea level rise and coastal flooding impacts along the entire United States coast. The viewer is a screening-level tool that shows the horizontal inundation of sea level rise using mapping layers of one foot increments from zero to six feet.

### Flood Type

- Riverine
- Interior
- **Coastal**

### Tool Type

- Projection
- **Map**
- Report

### Key Facts

**2008-14**
Topographic Data

**2017**
Nationwide viewer and projections updated

Available in continental U.S. and Hawaii

### Links

Online Map Viewer
https://coast.noaa.gov/slr/

NOAA FAQ Page
https://coast.noaa.gov/data/digitalcoast/pdf/slr-faq.pdf

### Underlying Data and Modeling

**Modeling:** The viewer uses mean higher high water (MHHW) as its base elevation and uses "bathtub modeling" that accounts for hydraulic connectivity.

**Accuracy:** The underlying Digital Elevation Model (DEM) used for the National Capital Region varies by jurisdiction. DC's DEM is from 2014 USGS LIDAR with 3m horizontal resolution. VA's DEM is from 2011 FEMA LIDAR with 3m horizontal resolution and MD's (Prince George's County) DEM is from the 2008 National Elevation Dataset with 10m horizontal resolution. NOAA has plans to update the MD DEM to 3m resolution from 2014 USGS LIDAR sometime in 2018.

**NCR Specific:** The 17th Street Levee Closure and the Anacostia Levee System are not shown as providing protection.

### Discussion

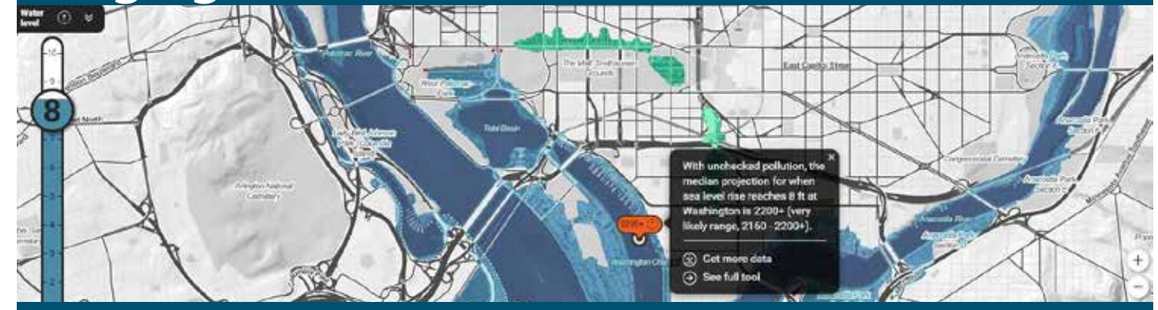
**Best Uses:** This tool is best used for screening of assets at a master planning level and is best suited to evaluate potential for nuisance flooding. For example, a planner might use this tool to understand what areas would experience high tide flooding given 1-6 feet of sea level rise. The planner would determine on his own when that given sea level rise elevation might occur. A unique and useful feature is the ability to download the underlying data (by state), including the DEM and sea level rise layers. This viewer is also unique because it displays inundation layers as either high or low confidence.

**Limitations:** The underlying DEM data and resulting limited horizontal resolution means that this tool should only be used for high-level screening. This tool does not map coastal storm surge, riverine flooding, erosion, or other coastal processes. While the underlying model incorporates low lying inland areas that are hydraulically connected to the rivers, the hydraulic modeling only captures the connections that appear in the elevation data and doesn't include other hydraulic connections like stormwater pipes.

**Comparisons:** Compare this tool to Climate Central's "Surging Seas Risk Finder" on page 21, which uses the same underlying elevation data but incorporates a more robust suite of analysis tools and displays inundation up to ten feet.



# Surging Seas Risk Finder




## Climate Central

**Purpose:** Help users understand and respond to the risks of sea level rise and coastal flooding. The tool includes a screening-level viewer that maps sea level rise and floods and provides high level analysis of impacts to population, buildings, and infrastructure. The tool also includes localized sea level rise projections.

### Flood Type

- Riverine
- Interior
- **Coastal**

### Tool Type

- **Projection**
- **Map**
- **Report**

### Key Facts

**2008**
Topographic Data

**2017**
Nationwide viewer and projections updated

Available in continental U.S.

### Links

Online Map Viewer
http://riskfinder.climatecentral.org/place/washington.dc.us

Comparison with NOAA SLR Viewer
http://sealevel.climatecentral.org/matrix/DC-metro.html?v=1

### Underlying Data and Modeling

**Modeling:** Mean higher high water (MHHW) is the base elevation and floods are depicted using "bathtub modeling" that accounts for hydraulic connectivity. Multiple SLR projections, which Climate Central modifies to include local data, are available.

**Accuracy:** Underlying data is the same as "Sea Level Rise Viewer" on page 20.

**NCR Specific:** The 17th street levee closure is shown as protecting against a 10 foot flood. The Anacostia Levee System is shown as offering no protection.

### Discussion

**Best Uses:** This tool is best used for screening of assets at a master planning level. This tool is unique in that it is organized to talk about risks of extreme flooding in addition to sea level rise. A user can set the height of a flood at 8 feet and charts provide additional analysis that state, for example, "There is a 5% single-year risk in 2050 of a flood 8 feet or more above the high tide line," based on a sea level rise projection chosen by the user. The tool also allows for easy visual comparison of multiple sea level rise projections, localized for Washington, DC. Also available are an auto-generated Local Fact Sheet and Local Report with key infromation on sea level rise and estimates of assets (such as number of homes) vulnerable to floods.

**Limitations:** The underlying Digital Elevation Model (DEM) data and resulting limited horizontal resolution means that this tool should only be used for high-level screening. The flood heights in this tool are for extreme still water levels, and do not include additional height from wave run-up. While the underlying model incorporates low lying inland areas that are hydraulically connected to the rivers, the hydraulic modeling only captures the connections that appear in the elevation data and doesn't include connections like stormwater pipes.

**Comparisons:** Compare this tool to NOAA's "Sea Level Rise Viewer" on page 20, which uses the same underlying elevation data but lacks the additional analysis tools and displays inundation only up to 6 feet.

# Sea-Level Change Curve Calculator

| | | | | | | |
|---|---|---|---|---|---|---|
| 2000 | 0.23 | 0.24 | 0.25 | 0.26 | 0.27 | 12.225 |
| 2005 | 0.28 | 0.30 | 0.33 | 0.35 | 0.37 | 12.315 |
| 2010 | 0.34 | 0.37 | 0.43 | 0.46 | 0.50 | 12.425 |
| 2015 | 0.39 | 0.44 | 0.54 | 0.59 | 0.66 | 12.553 |
| 2020 | 0.44 | 0.51 | 0.66 | 0.73 | 0.84 | 12.699 |
| 2025 | 0.49 | 0.59 | 0.80 | 0.90 | 1.05 | 12.864 |
| 2030 | 0.54 | 0.67 | 0.96 | 1.08 | 1.26 | 13.047 |
| 2035 | 0.60 | 0.76 | 1.12 | 1.28 | 1.54 | 13.249 |
| 2040 | 0.65 | 0.85 | 1.31 | 1.50 | 1.83 | 13.47 |
| 2045 | 0.70 | 0.95 | 1.50 | 1.74 | 2.13 | 13.709 |
| 2050 | 0.75 | 1.05 | 1.71 | 2.00 | 2.47 | 13.966 |
| 2055 | 0.80 | 1.16 | 1.94 | 2.28 | 2.83 | 14.243 |
| 2060 | 0.86 | 1.27 | 2.18 | 2.57 | 3.22 | 14.537 |
| 2065 | 0.91 | 1.38 | 2.43 | 2.88 | 3.63 | 14.85 |
| 2070 | 0.96 | 1.50 | 2.70 | 3.21 | 4.07 | 15.182 |
| 2075 | 1.01 | 1.62 | 2.98 | 3.56 | 4.53 | 15.532 |
| 2080 | 1.06 | 1.75 | 3.28 | 3.93 | 5.02 | 15.901 |

## U.S. Army Corps of Engineers (USACE)

**Purpose:** Help users apply USACE guidance requiring considerations for sea level change (SLC) to be incorporated in civil works programs and projects. The tool acheives this by offering localized SLC projections for a selected NOAA tide gage along with graphs and charts to understand how SLC may impact a proposed project.

### Flood Type

- Riverine
- Interior
- **Coastal**

### Tool Type

- **Projection**
- Map
- Report

### Key Facts

**2013**
USACE projections

**2017**
Last update to the calculator

Available for entire U.S.

### Links

Online Calculator
http://www.corpsclimate.us/ccaceslcurves.cfm

User Manual (2015)
http://www.corpsclimate.us/docs/Sea_Level_Change_Curve_Calculator_User_Manual_2015_46_FINAL.pdf

### Underlying Data and Modeling

**Modeling:** The user can view SLC based on projections from NOAA or USACE. See "Relative Sea Level (RSL) Projections for Washington, DC" on page 54 for more details. Projections start in 1992 from 0 feet Local Mean Sea Level (LMSL).

**Accuracy:** Since all SLC projections have inherent uncertainty, the viewer provides projections as a range of scenarios; low, intermediate, and high.

**NCR Specific:** The projections are based on the SW Waterfront Gage. The default setting shows sea level elevation in feet relative to NAVD88. Users can set the "Output Datum" to "LMSL" so that SLC in 1992 (the baseline year) is 0 feet which would allow users to simply add the SLC projections to their critical elevations. Keeping the datum in NAVD88, however, allows for direct comparisons to FEMA maps and local flood emergency manuals.

### Discussion

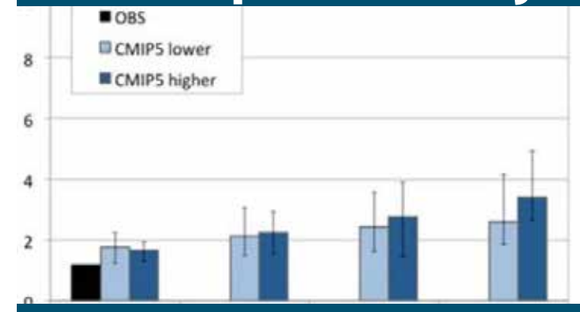
**Best Uses:** Providing numerical values for sea level change. For example, by selecting the "Washington, DC" gage, and keeping all the default settings, the user will see three values (low, intermediate, and high) for SLC for every 5 years from 1995 to 2100. For more detailed analysis, users can also make changes to the settings, including changing the source of the projections (from USACE to NOAA 2012, CARSWG 2016, or NOAA 2017), changing the source used to localize the projections, changing the time horizons, and adding in critical elevations (such as the elevation of an emergency generator). The user can also plot various extreme water levels to be added on top of the SLC curves. For example, users can add the height of a 10-year, 50-year, or 100-year storm to the "high" scenario SLC curve.

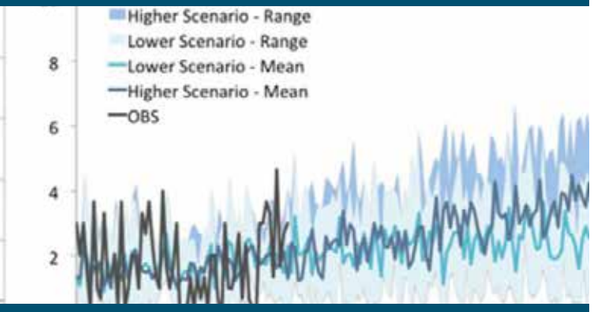
**Limitations:** The above example (100-year plus SLC) is just an estimate and should not be used for detailed site planning. Projecting the future 100-year flood elevation requires more analysis than simply adding SLC to the existing 100-year flood since SLC isn't the only factor (i.e. storm intensity and higher tidal range) that would increase the future 100-year flood.

**Comparisons:** Compare this tool to Climate Central's "Surging Seas Risk Finder" on page 21, which displays SLC projections from different sources.



# DC Precipitation Projections




## District Department of Energy and Environment (DOEE)

**Purpose:** Provide downscaled precipitation projections for Washington, DC that can be used to inform engineering calculations for drainage infrastructure. The precipitation projections, which are most relevant to discussions on flooding, are just one part of the report that includes temperature projections as well.

### Flood Type

- Riverine
- **Interior**
- Coastal

### Tool Type

- **Projection**
- Map
- **Report**

### Key Facts

**2012**
Precipitation data used for modeling from 1950 - 2012

**2015**
Report Published

Available only for Washington, DC.

### Links

Precipitation Projections Report
http://doee.dc.gov/sites/default/files/dc/sites/ddoe/publication/attachments/150828_AREA_Research_Report_Small.pdf

DOEE Climate Projections Website
http://doee.dc.gov/node/1110407

### Underlying Data and Modeling

**Accuracy:** The projections are downscaled using regional weather stations and can be used anywhere in Washington, DC. Site scale projections are not practical.

**Modeling:** The downscaled projections were created by incorporating historical observations from local weather stations with 9 global climate models (GCMs). The output was daily precipitation totals for three planning horizons (2020s, 2050s, 2080s). Using the projected precipitation values, statistical modeling was applied to determine design storm values, similar to the process used to determine peak river floods for the Flood Insurance Rate Maps.

### Discussion

**Best Uses:** The projections are best used to see future changes in regional precipitation trends. By extrapolating the data and adding some uncertainty, they can also be used for detailed engineering calculations to determine the size of future stormwater facilities. Precipitation changes are measured by three indicators in the analysis: the number of annual days with more than 1 and 2 inches of rain in a 24-hour period; the estimated rainfall depths associated with 24-hour design storms for 1-, 2-, 15-, 25-, 100-, and 200-year recurrence intervals and 6-hour design storms for 2-, 15-, 100-, and 200-year recurrence intervals; and projections of future 80th, 90th, and 95th percentile events.

**Limitations:** As with any climate projection, there is inherent uncertainty because of natural variability of the climate system, uncertainty in scientists' ability to model the response of climate systems, and uncertainty in future emissions of greenhouse gases (GHGs). Using multiple GCMs and using two different GHG emission scenarios in the projections helps to mitigate some uncertainty, though there is always greater uncertainty when predicting extreme events.

**Comparisons:** Compare this tool to "CMIP Climate Data Processing Tool" on page 26 which provided some of the source data but did not provide downscaling.

# Federal Triangle Interior Drainage Analysis

## Tetra Tech for DC Office of Planning

**Purpose:** Assess the interior flooding impacts in the Federal Triangle area protected by the Potomac Park Levee system. The analysis was submitted as part of the Conditional Letter of Map Revision used to update the 1% annual chance floodplain boundary in FEMA's Flood Insurance Rate Maps.

### Flood Type

- Riverine
- **Interior**
- Coastal

### Tool Type

- Projection
- **Map**
- **Report**

### Key Facts

**2008**
Topographic Data

**2008**
Analysis Published

Available only for Washington, DC.

### Links

Interior Drainage Analysis
https://www.ncpc.gov/docs/TETRATECH_Interior_Drainage_Analysis.pdf

### Underlying Data and Modeling

**Modeling:** USACE's HEC-HMS software was used to model the flow of surface water over streets and through detention basins in the Federal Triangle watershed. The software also determined the elevation of water that would pond at the watershed's low point in the Federal Triangle given certain conditions.

**Accuracy:** 2008 LIDAR data with a horizontal resolution of 100 feet was used to generate a Digital Elevation Model (DEM) with 2-foot contours. The analysis notes that there are elevation discrepancies between the 2004 and 2008 LIDAR data, but that difference would have little effect on the elevation or extent of ponding in Federal Triangle.

### Discussion

**Best Uses:** The maps provided in this report can be used in site planning analyses for buildings within Federal Triangle and along Constitution Avenue. The maps show the horizontal extent of interior flooding through four plausible scenarios. Scenarios 1 through 3 simulate the ponding extents of a 100-year rainfall in combination with the river surface at a 100-year elevation. Each scenario uses different assumptions for how much water enters into sewer system catch basins and whether water that ponds in Federal Triangle is pumped out. The fourth scenario uses a joint probability analysis of river surface elevation and 24-hour rainfall to determine the ponding elevation in Federal Triangle that has a 1% annual chance of occuring. The report contains maps for each scenario, a map of the Federal Triangle watershed and its sewersheds, and various other figures.

**Limitations:** The study area is limited to the Federal Triangle and Constitution Avenue and does not account for future precipitation trends.

**Comparisons:** The ponding area predicted in Scenario 4 is larger than the area predicted by a 1992 USACE study. Compare this study to "Federal Triangle Stormwater Drainage Study" on page 25 which uses updated modeling in addition to suggesting potential mitigation actions.





# Federal Triangle Stormwater Drainage Study

## Greely and Hansen for Federal Triangle Stormwater Study Working Group

**Purpose:** Create an accurate model of the Federal Triangle stormwater system and predict Federal Triangle ponding levels that would occur for various storm frequencies. Propose system-wide flood control alternatives ranging from traditional infrastructure improvements to more innovative mitigation actions to mitigate interior flooding risk.

### Flood Type

- Riverine
- **Interior**
- Coastal

### Tool Type

- Projection
- **Map**
- **Report**

### Key Facts

**2011**
Topographic Data and Models recalibrated.

**2011**
Report Published

Available only for Washington, DC.

### Links

Summary Report
https://www.ncpc.gov/docs/Federal_Triangle_Stormwater_Drainage_Study_Companion_Report.pdf

Full Study
https://www.ncpc.gov/docs/Federal_Triangle_Stormwater_Drainage_Study_Full.pdf

### Underlying Data and Modeling

**Modeling:** The study combined a hydrologic runoff model (modeling how water flows into catch basins) with a hydraulic "pipe" model (modeling how and how much water flows through sewer pipes) and a surface flow model (modeling ponding elevations of water that exceed sewer capacity). The hydraulic and hydrologic models were recalibrated for this study from their original 2006 form. The Digital Elevation Model (DEM) for the surface flow model was also recalibrated as described below. Once calibrated to existing conditions and data from the 2006 flood, the model was used to predict ponding elevations of the 5, 15, 50, 100, 200, and 500-year storms.

**Accuracy:** The underlying DEM for the surface flow and ponding is based on the 2008 2-foot contour interval data (from the DC Office of the Chief Technology Officer) that was revised based on spot elevations produced in an April 2010 survey. Only pipes greater than 24 inches were included in the hydraulic model.

### Discussion

**Best Uses:** This tool not only provides elevations of flooding for various storm events that can be used to design individual flood-proofing solutions, it also evaluates the effectiveness and cost of possible alternative flood control measures. Study results may be used to implement flood-proofing measures for individual sites and to adopt best practices.

**Limitations:** While a helpful predictive tool, the study area is limited to the Federal Triangle and Constitution Avenue. Additionally, the Stormwater Study recognizes that factors outside of the study scope that must be considered when analyzing the costs and benefits of identified alternatives. Further, the storm models used (i.e. 100-year storm) are based on historic data and do not account for the fact that future rain storms will likely be more intense and more frequent.

**Comparisons:** This study built upon the previous studies. The predicted ponding level for a 100-year storm event (approximately 8.2 feet for a 12-hour duration) occupies a smaller area than what was predicted by the 2008 Tetra Tech Study (described on page 24). A previous 2007 GSA study (by Setty & Associates) only examined underlying causes of the 2006 flood and did not conduct modeling.

This information sheet is part of a series documenting the flood risk resources specific to the National Capital Region.
This information sheet was last updated 1/24/2018.

# CMIP Climate Data Processing Tool

| Click column headings for additional info | Baseline (1950-1999) | | 2020s (2010-2040) | | | | | 2050s (2040-2070) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Observed Value | Modeled Value | Projected Value | Change from Baseline | % Change from Observed | Model Uncertainty Range (95% Confidence Interval) Low | High | Projected Value | Change from Baseline | % Change from Observed | Model Uncertainty Range (9 Confidence Interval) Low | High |
| Average Total Annual Precipitation | 41.8 inches | 41.8 inches | 43.9 inches | 2.1 inches | 5% | 43.2 inches | 44.6 inches | 45.4 inches | 3.6 inches | 9% | 44.6 inches | 46.2 inche |
| "Very Heavy" 24-hr Precipitation Amount (defined as 95th percentile precipitation) | 0.8 inches | 0.6 inches | 0.8 inches | 0.0 inches | 4% | 0.8 inches | 0.8 inches | 0.8 inches | 0.0 inches | 0% | 0.8 inches | 0.8 inche |
| "Extremely Heavy" 24-hr Precipitation Amount (defined as 99th percentile precipitation) | 1.4 inches | 1.1 inches | 1.4 inches | 0.1 inches | 6% | 1.4 inches | 1.5 inches | 1.4 inches | 0.1 inches | 5% | 1.4 inches | 1.5 inche |
| Average Number of Baseline "Very Heavy" | 10.5 times | 15.9 times | 12.1 times | 1.6 times | 16% | 11.5 times | 12.7 times | 13.0 times | 2.5 times | 24% | 12.3 times | 13.7 time |
| Average Number of Baseline "Extremely Heavy" | 2.1 times | 3.2 times | 2.8 times | 0.7 times | 34% | 2.6 times | 3.0 times | 3.4 times | 1.3 times | 63% | 3.1 times | 3.7 time |
| Average Total Monthly Precipitation | | | | | | | | | | | | |
| January | 3.1 inches | 3.0 inches | 3.2 inches | 0.1 inches | 5% | 3.1 inches | 3.3 inches | 3.3 inches | 0.2 inches | 7% | 3.1 inches | 3.4 inche |
| February | 2.8 inches | 2.9 inches | 2.9 inches | 0.1 inches | 4% | 2.8 inches | 3.1 inches | 3.0 inches | 0.2 inches | 8% | 2.9 inches | 3.2 inche |
| March | 3.8 inches | 3.7 inches | 4.1 inches | 0.3 inches | 7% | 3.9 inches | 4.2 inches | 4.3 inches | 0.5 inches | 13% | 4.1 inches | 4.4 inche |

## U.S. Department of Transportation (USDOT)

**Purpose:** Process climate data from global climate models (GCMs) from the Coupled Model Intercomparison Project (CMIP) into relevant, local-level temperature and precipitation statistics for transportation planners. CMIP data can be used to understand the observed and expected changes in frequency and intensity of future precipitation events.

### Flood Type

- Riverine
- **Interior**
- Coastal

### Tool Type

- **Projection**
- Map
- Report

### Key Facts

**2013**
Date of Publication for GCMs used in CMIP5

**2016**
Date of last update to USDOT Excel tool

Available in continental U.S.

### Links

USDOT User Guide (PDF)
https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/modules/user_guide/cmip_user_guide.pdf

Download CMIP Data
http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/#Welcome

### Underlying Data and Modeling

**Modeling:** CMIP compiles data from 56 GCMs. Given certain green house gas emissions scenarios (Representative Concentation Pathways), each GCM projects different changes in termperature and precipitation across the globe. The USDOT processing tool (an interactive excel spreadsheet that processes CMIP data) allows users to view the observed record and projections for a selected geographic area.

**Accuracy:** GCMs available for selection in the Processing tool have varying resolutions from 0.18° to 5° latitude-longitude resolutions. GCM outputs are downscaled to 1/8° or 1/16° latitude-longitude (~14km or ~7km) resolutions in the USDOT processing tool. Since all GCMs are models, there is an inherent level of scientific uncertainty in the output, which is mitigated somewhat by averaging their outputs as USDOT does in this tool.

### Discussion

**Best Uses:** This tool provides regional-level data on future precipitation and temperature changes. However, USDOT does not recommend using the outputs directly in designing for built infrastructure without further downscaling. Precipitation changes are measured by the following variables: average total annual precipitation, 95th and 99th percentile precipitation amounts (and how often they occur on average in a given year), average total monthly precipitation, average total seasonal precipitation, and the largest 3-day precipitation event per season.

**Limitations:** Subject expertise is necessary to receive utility from this tool, particularly to translate outputs into climate protection levels for the intended asset and for the risk tolerance of the stakeholder. To select relevant data and to obtain output from the data archive, users must follow a lengthy site tutorial to request data, indicate how the data will be used and agree to terms of use.

**Comparisons:** Many of the other tools source and/or synthesize data from CMIP. For example, in DC's precipitation projections (on page 23), DC downscaled CMIP data by using long-term historical observations at the Dalecarlia Reservoir, National Arboretum, and Reagan National Airport weather stations. GCMs from CMIP are also used in many of the reports described on page 53 to create global mean sea level projections.



This information sheet is part of a series documenting the flood risk resources specific to the National Capital Region.
This information sheet was last updated 1/24/2018.

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# 3. Mapping Current Flood Risk

## Flood Insurance Rate Maps

Though only intended to be insurance rating products, Flood Insurance Rate Maps (FIRMs) are often the primary tool used by planners and facility managers to understand flood risk in the region. Newer tools, such as the 2016 Flood Inundation Maps (described on page 35), use updated modeling and topographic data, but are less well known. FIRMs are often used because they show the horizontal extent (see figure on page 33) of the 1 percent annual chance, and 0.2 percent annual chance floods. The underlying data used to create FIRMs comes from flood insurance studies (FIS). Both FIRMs and FIS are updated infrequently and are a joint effort of the State Floodplain Manager, USACE, and FEMA. FIRMs for Washington, DC, for example, were updated in 1985 and in 2010. Smaller map revisions occur more frequently and do not require a reissuance of the Washington, DC FIRMs.[5]

In the NCR, there is an FIS for each jurisdiction, including Montgomery County, Prince George's County, Arlington County, and the District of Columbia. Each jurisdiction's FIS (see figure on page 30) analyzes major rivers and streams within their borders. The District of Columbia's FIS, for example, includes individual analyses for the Potomac and Anacostia Rivers, as well as smaller tributaries such as Broad Branch, Rock Creek, Oxon Run, and Watts Branch. Creating flood analyses for rivers and streams is a complex and unique process. Following is an overview of the creation of the FIS analysis only for the Potomac River within Washington, DC. The detailed explanation that follows is intended to provide an understanding of how the FIRMs can and cannot be used to predict future flood risk.

5 FEMA's term for this is Letter of Map Revision (LOMR). https://www.fema.gov/letter-map-revision

Left: One panel of the FIRMs for Washington, DC showing the confluence of the Potomac and Anacostia Rivers. FIRMs are available as PDFs in panels (shown here) or as an interactive online map that can be seen on page 10. Both types of maps are available at FEMA's Flood Map Service Center.

# Multiple Flood Studies in the National Capital Region

Currently there are multiple studies that analyze flooding potential on the Potomac River. Flood Insurance Studies (FIS) are created for each jurisdiction and are the underlying data for the Flood Insurance Rate Maps. The 2016 Flood Inundation Maps depict a portion of the Potomac and Anacostia Rivers that cross multiple jurisdiction boundaries.

**Flood Insurance Studies by Jurisdiction**

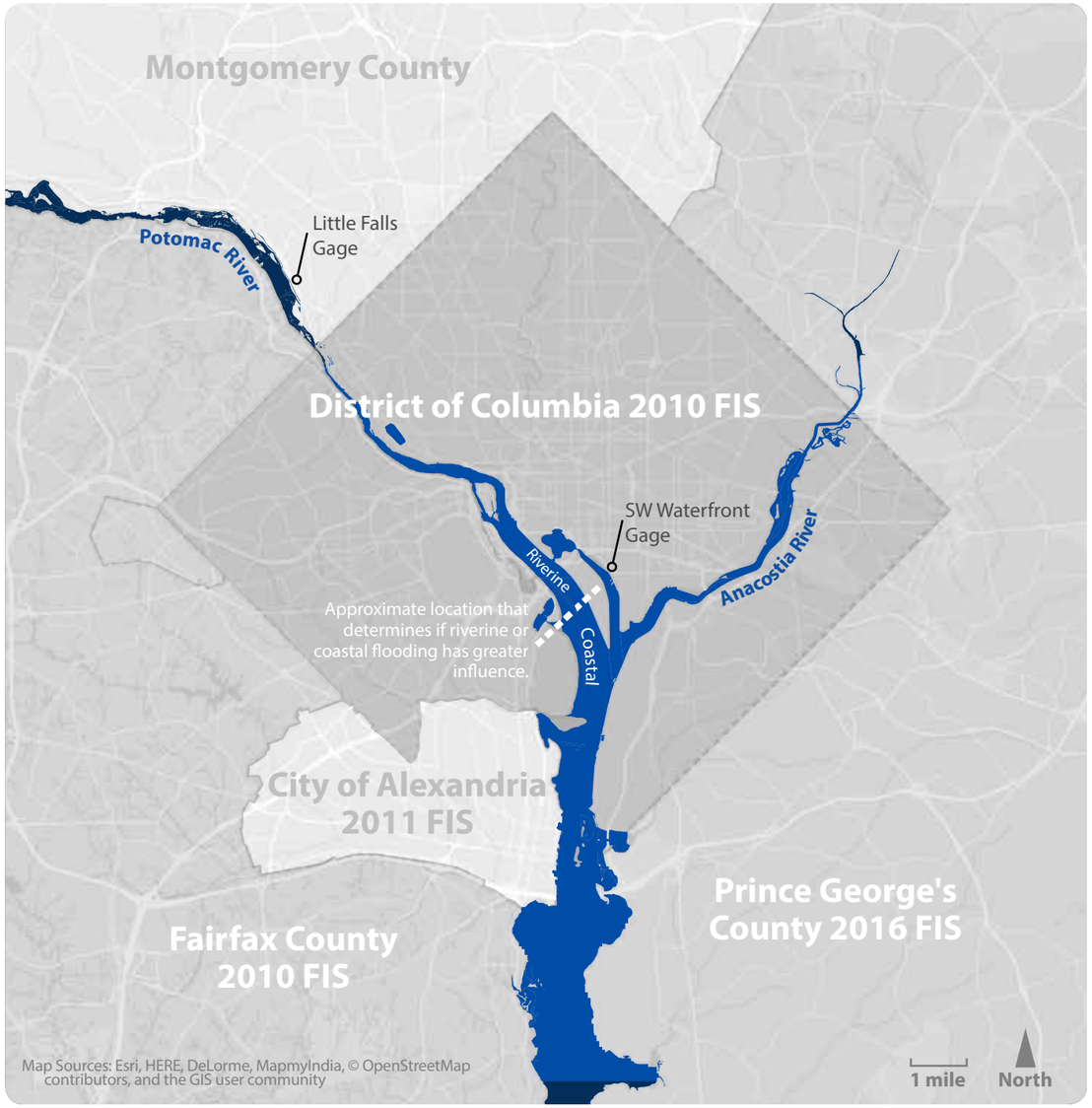
District of Columbia 2010 FIS | City of Alexandria 2011 FIS | Fairfax County 2010 FIS | Prince George's County 2016 FIS

Arlington County: Used data from the District of Columbia 2010 FIS.

Montgomery County: No analysis was conducted for the Potomac River in the Montgomery County 2006 FIS.

**2016 Flood Inundation Maps Extent** (shown by river color)

Not included in 2016 Flood Inundation Maps  Included in 2016 Flood Inundation Maps






## District of Columbia FIRMs

FIRMs for the Potomac River within the District of Columbia (see figure on page 30) are created by combining two different analyses from the *2010 Flood Insurance Study for the District of Columbia* (2010 FIS),[6] which uses water gage[7] data to predict floodplains and create FIRMs. The first analysis is based on data from the Little Falls Gage and can be considered a riverine-only analysis, since the gage's location is not tidally influenced[8] and the data only measures water flowing downstream. The second analysis, based on data from the SW Waterfront Gage, does not distinguish between riverine and coastal flooding as it measures water surface elevation (which is influenced by both river flow and storm surge). Both analyses and how they work in conjunction to represent existing flood risk in Washington, DC are described below.

## Little Falls Gage Analysis

The extent of a 1 percent annual chance, and 0.2 percent annual chance riverine flood are based on an analysis of historic data measuring the quantity of water flow from a nearby gage. The data for the Potomac River near Washington, DC is collected at the Little Falls Gage, which has measured water flow, also called discharge, since 1931 (see figure on page 33). Using what is called a flood frequency analysis,[9] historic "peak flow" flood events are used to project the river flow of the 1 percent annual chance and 0.2 percent annual chance river floods. For example, the 2010 FIS estimates that the 0.2 percent annual chance Potomac River flood has a peak discharge of 698,000 cubic feet per second at the Little Falls Gage. The fact that a peak flow of this quantity hasn't occurred since the data began to be recorded there reinforces that this peak flow value is statistically extrapolated. When historic data is limited, statistical analysis must be used to estimate these extreme events, like the 0.2 percent annual chance (1-in-500 chance) flood, that have recurrence

6 Referred to in document as "2010 Flood Insurance Study." Full Citation: FEMA, *Flood Insurance Study – District of Columbia Washington, D.C.* (2010). https://www.ncpc.gov/docs/DC_Flood_Insurance_Study_Pre-17th_Street_Levee.pdf

7 Water gages are scientific instruments that measure the depth or quantity of water at a certain point.

8 The Little Falls Gage is located just upstream of the Little Falls Dam which was constructed to divert water to the Washington Aqueduct for the city's water supply. The dam height, at 14 feet, means that tidal flows or most storm surges will not reach the Little Falls gage. The gage is also located within part of the Potomac River fall line, the point at which rivers plunge in elevation. Fall lines also represent the inland limit of navigation for most rivers, past which vessels cannot continue without the help of lock systems. Little Falls is the first barrier to navigation going upstream on the Potomac River. Great Falls, five miles further upstream, is often also considered the fall line for the Potomac River.

9 More info on statistical analysis can be found on page 37 of this document: Federal Highway Administration, *Highways in the River Environment – Floodplains Extreme Events, Risk and Resilience* (2016): https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif16018.pdf#page=37

intervals greater than the length of time that data was recorded. See the 2010 FIS for more information on the statistical analysis process, and hydrologic analyses for the Anacostia River, Watts Branch, and Rock Creek.[10]

Maps depicting peak flow events are determined through *hydraulic* modeling[11] which provides estimates of flood elevations and horizontal extents for the 1 percent annual chance and 0.2 percent annual chance riverine floods. The 2010 FIS for Washington, DC used HEC-RAS,[12] a software program, to model the water flow over the ground surface.[13] Hydraulic modeling requires a 3D representation of the terrain, often referred to as a digital elevation model (DEM), and a computer program to predict how water will move over the terrain. Based on the HEC-RAS model outputs, the extent of the 1 percent annual chance, and 0.2 percent annual chance floods are mapped and used as layers in the FIRMs (see pages 8 and 28 for two examples of the maps for Washington, DC).[14]

### SW Waterfront Gage Analysis

The SW Waterfront Gage, located on a pier in the Washington Channel, has collected water-surface elevation data since 1931. This water surface elevation data is influenced both by river flow and coastal storm surge, and reflects riverine floods, coastal floods, and combined riverine/coastal floods. This is an important distinction: while the Little Falls Gage analysis is riverine only, the SW Waterfront gage analysis cannot be considered coastal only, since it does not distinguish between coastal and riverine floods.

In coastal areas, FEMA typically uses ADCIRC,[15] a modeling tool, to determine coastal flooding risks. In the NCR, ADCIRC modeling is used for areas along the Potomac River downstream of the Fairfax County border. For areas upstream of the Fairfax County border, statistical analysis of water surface elevations at the SW Waterfront Gage is used in lieu of ADCIRC modeling.[16]

Using a flood frequency analysis, water-surface elevations from historic flood events are used to extrapolate the water-surface elevations of the 1 percent annual chance and 0.2 percent annual chance floods. For example, the 2010 FIS[17] notes the 0.2 percent annual chance

10 2010 Flood Insurance Study, 14.
11 Hydrologic models are those that estimate the quantity of water flowing past a gage. Hydraulic models are those that approximate how water will flow over land, creating depth and horizontal extent of a given quantity of water.
12 HEC-RAS (Hydrologic Engineering Centers River Analysis System) is a USACE software program used for hydraulic modeling.
13 2010 Flood Insurance Study, 29.
14 The FIRMs are available from FEMA's Online Map Portal: https://msc.fema.gov/portal
15 ADCIRC, or the Advanced Circulation Model, is a sophisticated computer program used to predict storm surge flooding from coastal storms. The model uses historic and synthetic storm tracks to predict the horizontal extent of the 1% and 0.2% chance coastal storms. Results from the ADCIRC analysis are combined with other data to produce FIRMs. More on coastal flood mapping in a 2011 Fact Sheet, *Region III Coastal Analysis and Mapping*, produced by FEMA. https://www.ncpc.gov/docs/R3_Coastal_Technical_Fact_Sheet.pdf
16 Based on conversations with Robert Pierson (FEMA) and contractors who worked on the analysis.
17 2010 Flood Insurance Study, 14.



## Extents of Flooding Defined

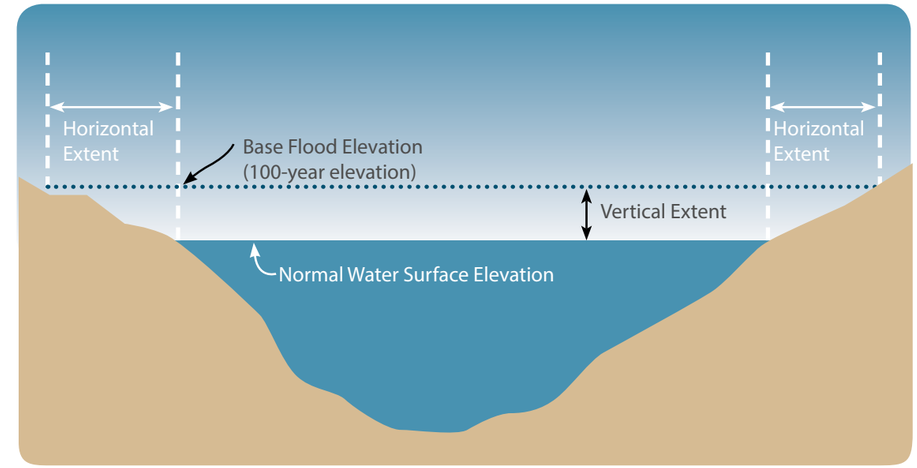
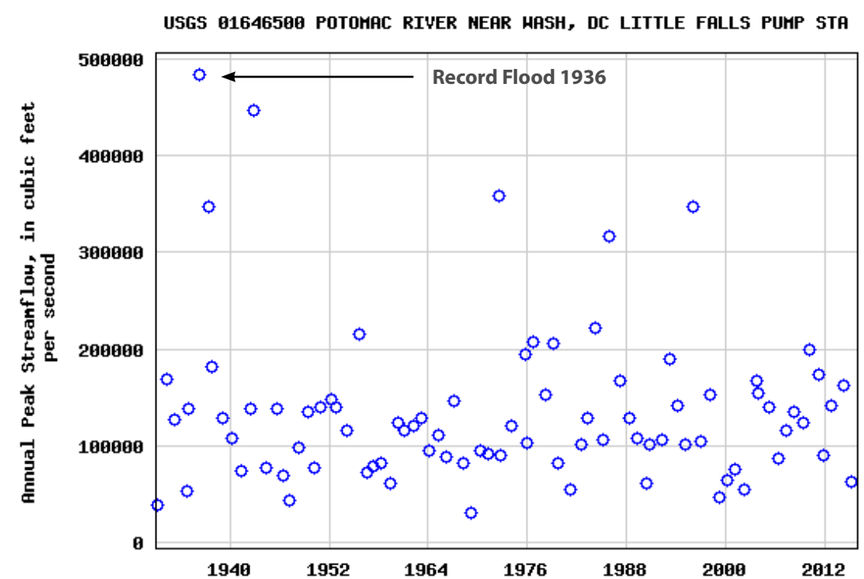



Diagram showing horizontal and vertical aspects of the 100-year flood adapted from EO: 11988 Implementing Guidelines.

## Little Falls Gage Historic Data




This graph depicts historic data in cubic feet per second (cfs) that measures Potomac River discharge at the Little Falls Gage. The highest recorded peak discharge is slightly under 500,000 cfs, while the 500-year flood is estimated to have a discharge of 698,000 cfs.

Historic data for the Little Falls Gage available on the USGS website.

(1-in-500 chance) flood would reach a water surface elevation of 14.7 feet (NAVD88).[18] The highest flood ever recorded at the SW Waterfront Gage was 9.65 feet (NAVD88) on October 17, 1942. The fact that the actual record flood for the SW Waterfront Gage is lower than the modeled 0.2 percent annual chance flood reinforces that the 0.2 percent annual chance flood analysis is a statistical extrapolation. It is also important to point out that this statistical analysis for the SW Waterfront Gage does not differentiate between riverine and tidal floods. It simply projects water-surface elevations based on historical data that includes high water events from both riverine and coastal flooding. The 1942 record flood, for example, was a riverine flood.

These projected elevations from the flood frequency analysis are then combined with a digital elevation model (DEM) to determine the horizontal extents for the 1 percent annual chance and 0.2 percent annual chance floods, which are then used as layers in FEMA's Flood Insurance Rate Maps for Washington, DC.

### Combining the Two Analyses

The Little Falls Gage and SW Waterfront Gage analyses result in separate maps for the Washington, DC region, which are combined to form Washington, DC's FIRMs. The two maps are merged at the point on the Potomac River where the elevation of the 1 percent annual chance riverine flood (as determined by the Little Falls Gage analysis) equals the elevation of the 1 percent annual chance flood (as determined by the SW Waterfront Gage analysis). For the Potomac River, that point is just south, or downstream, of the 14th Street Bridges (see figure on page 30).[19] This merging is necessary to reflect the fact that riverine floods have a greater influence upstream of this location on the Potomac River, while coastal floods have greater influence downstream. When looking at a location upstream of the 14th Street Bridge, such as Georgetown Waterfront Park, the elevation of the 1 percent chance riverine flood (based on the Little Falls Gage data analysis) is *higher* than the elevation of the 1 percent chance flood based on the SW Waterfront Gage data analysis. The reverse is true for areas downstream of the 14th Street Bridge. The elevation of the 1 percent chance riverine flood will be *lower* than the elevation of the 1 percent chance flood (based on the SW Waterfront Gage) at the same location in Joint Base Anacostia-Bolling.

## 2016 Flood Inundation Maps

While the FIRMs continue to be the standard tool for depicting existing flood risk, the 2016 Flood Inundation Maps (see the information sheet on page 17) can also be used for current (and future – see page 38) flood risk planning. These maps, which use more recent topographic data and modeling than the FIRMs, were developed as a DC Silver Jackets[20] project and released in November 2016 for the Washington, DC area. The 2016 Flood Inundation Maps are non-regulatory maps for the Potomac and Anacostia Rivers (the map on page 30 shows the extent of the analysis) intended to help communities view flood risks in real time. Once the National Weather Service issues a flood forecast, users can view a map that most closely resembles the predicted extent of the flood. Instead of producing just two layers (like the 1 percent and 0.2 percent annual chance layers in the FIRMs), the Flood Inundation Maps include multiple layers to show flooding extent and depth at approximately 20 different water elevations, including some which are above the 0.2 percent annual chance flood. Even when there is not an imminent flood, the maps are available online and can be used to answer hypothetical questions like: "What is the horizontal extent of a riverine or coastal flood with an elevation of 11 feet at the SW Waterfront Gage?" The 2016 Flood Inundation Maps are created with the same hydraulic modeling process as the 2010 FIRMs, but use a more recent digital elevation model (DEM) and updated HEC-RAS program.

18 Refers to the North American Vertical Datum of 1988. NAVD88 serves as an elevation reference system so that heights of various points can be standardized to a common point of zero elevation.

19 2010 Flood Insurance Study, Map 35P.

20 The DC Silver Jackets is an interagency team that leverages resources to identify and implement comprehensive, resilient, and sustainable solutions to reduce flood risks around Washington, DC. Their website: http://silverjackets.nfrmp.us/State-Teams/Washington-DC

# 4. Riverine Flooding

## Current Methods to Evaluate Riverine Flood Risks

As described in the Chapter 3, FEMA's Flood Insurance Rate Maps (FIRMs) are the primary method used to evaluate today's riverine flood risks. These maps are based on existing conditions only, and do not take into account any future conditions. As of November 2016, regional Flood Inundation Maps offer another way to view flood risk, although the map layers (in elevation increments) do not assign probabilities of occurrence, like the FIRMs do by only mapping the 1 percent and 0.2 percent annual chance floodplains.

## How Future Riverine Flood Risks May Change

Future riverine flooding is expected to be impacted as a result of precipitation and land use changes in the Potomac and Anacostia River watersheds. In Washington, DC specifically, data indicates that precipitation changes are expected to include an increase in average annual rainfall and an increase in the intensity *and* frequency of severe storms.[21] Increasing intensity and frequency of severe storms is of particular concern, as severe storms are the primary cause of major flooding. In riverine flooding, severe storms refer to regional-scale weather events that have a significant impact on water levels in the Potomac River, as opposed to microbursts which are too small in scale to cause rivers to rise but can cause interior flooding. With more frequent and severe storms predicted for Washington, DC, and the Potomac River Watershed by extension,[22] riverine flooding is also expected to

21 Based on projections created for the District of Columbia. See information sheet on page 23.

22 There are no data for precipitation trends in the entire Potomac River Watershed, but data for regions in and around the watershed all point to increased severe precipitation events. This includes the projections in footnote 20, and projections in the National Climate Assessment (NCA) for both the Northeast and Southeast regions of the United States. The Potomac River Watershed straddles the border of these two regions. http://nca2014.globalchange.gov/

Left: Riverine flooding from heavy rains in the Potomac River Watershed on Election Day in 1985. The cyclist is standing on Ohio Drive just south of Memorial Bridge. Credit: Britt Leckman

increase in frequency and severity in the future. Changes in land use can also play a role in frequency of floods. As areas become more urbanized, their capacity to absorb rainfall diminishes, resulting in more frequent floods.[23] In 1985, 11.6 percent of land area in the Potomac River Watershed was urbanized.[24] By 2011, urbanized areas represented 14 percent of the land area in the Potomac River watershed, with the remaining land uses identified as 54 percent forest, 26 percent agriculture, and 6 percent wetland.[25] National and regional development trends[26] point to continuing urbanization within this watershed, suggesting that riverine flooding in Washington, DC will become more frequent and severe.

## Methods to Evaluate Future Riverine Flood Risks

Currently, there are no available tools to show what the extents of the 1 percent or 0.2 percent annual chance riverine floods will look like in the future. Since riverine flooding analysis for the Potomac River is based on flow readings at the Little Falls Gage, modeling future riverine flooding would require estimation of how those flow readings would change as a result of increased precipitation and urbanization. Since riverine flooding on the Potomac River is affected by areas upstream, precipitation and land use projections would have to reflect the entire Potomac River watershed upstream of Washington, DC. To date, no such analysis has been conducted. Once complete, however, such an analysis might say, "the 0.2 percent annual chance river flood in 2050 will have a flow of 800,000 cfs at Little Falls Gage." Planners could then use one of the layers in the 2016 Flood Inundation Maps that most closely reflects 800,000 cfs and use that map to approximate the future 0.2 percent annual chance floodplain.

23 Konrad, C.P. (USGS), *Effects of Urban Development on Floods* (2003). http://pubs.usgs.gov/fs/fs07603/

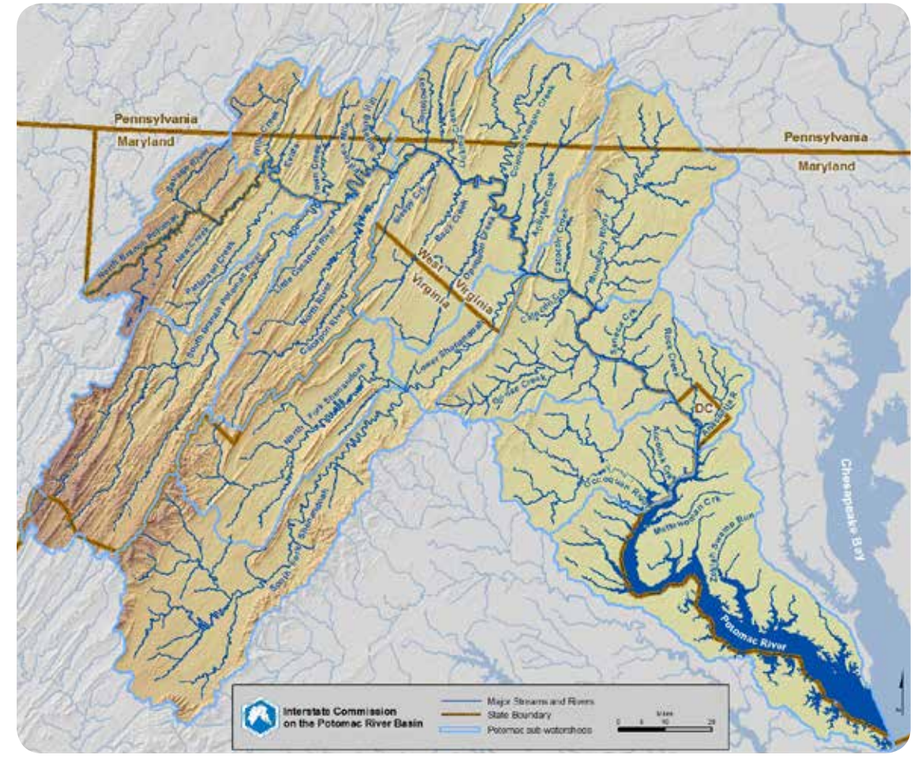
24 Camacho, Rodolfo, *Potomac River Basin Land Use Data: Evaluation and Methodology to Determine Basin Land Use from Non-Digitized County Land Use Data* (1989). https://www.potomacriver.org/wp-content/uploads/2014/12/ICP89-8_Camacho.pdf

25 Interstate Commission on the Potomac River Basin, *Potomac Basin Facts* (Accessed November 2016). https://www.potomacriver.org/potomac-basin-facts/

26 Land area in the United States classified as urban increased from 2.6% in 2000 to 3.1% in 2010. See Table 5 in *United States Summary: 2010. Population and Housing Unit Counts* (2012) by the U.S. Census. http://www.census.gov/prod/cen2010/cph-2-1.pdf



## Potomac River Watershed




Left: Map of the Potomac River Watershed from the Interstate Commission on the Potomac River Basin.

# 5. Interior Flooding

## Current Methods to Evaluate Interior Flood Risk

There is an information gap in the ability to evaluate current interior flooding risks in Washington, DC. Aside from specific mapping done in the Federal Triangle as a result of the 2006 flood,[27] there are few maps that depict areas of interior flooding in the rest of Washington or the NCR for reasons described below. Initial efforts were made by the DC Silver Jackets to use available agency data as a proxy to map interior flooding, such as DC Water's data on calls for service due to standing water.[28] When the locations of the service calls are plotted on a map it can be a useful, though unscientific, proxy for where interior flooding occurs in Washington, DC.

Interior flooding is often difficult to map because it requires hydrologic and hydraulic modeling (like the methods described in creating the FIRMs), but also an "all-pipes" model of the storm sewer infrastructure. This is necessary because interior flooding is about the flow of water over ground, *and* its interaction with the storm sewer system's capacity. In many cases, interior flooding occurs as a result of rainfall overwhelming the storm sewer system. All-pipes models must contain information on the location and size of storm sewer inlets and pipes, as well as how the pipes are hydraulically connected to other areas of the city. As this data can be sensitive, utilities often do not provide all-pipes data. In some cases, data for storm sewer inlets and pipes lack information or the appropriate level of detail such as elevation, size, or material.

The lack of data on interior flooding should not be mistaken for a lack of risk. In the Federal Triangle, the one area in the NCR that has been modeled, the likelihood of interior flooding is greater than the likelihood of riverine or coastal flooding.[29] Many other areas of Washington, DC, including the Bloomingdale neighborhood, are known areas of interior flooding but have not been officially identified on maps.

## How Future Interior Flood Risks May Change

Like riverine flooding, interior flooding risk is expected to increase primarily as a result of changes in precipitation. These changes include both an increase in average annual rainfall and an increase in the intensity and frequency of severe storms. The increased intensity and frequency of heavy rainfall has been observed across the United States, with some of the larger changes occurring in the Northeast (which includes Washington, DC).[30] Precipitation projections from the recent District Department of Energy and Environment (DOEE) report, *Climate Projections and Scenario Development,* include data on expected change in annual rainfall, and also how the frequency and severity of storms might change over time. For example, DOEE estimates that today's 100-year storm will be more like a 15-year storm by the 2080s.[31] More information is available on the information sheet on page 23 and in the figure on page 43.

27 This mapping effort is described in the information sheet on page 25 and was also incorporated into the 2010 FEMA FIRMs.

28 DC Silver Jackets, *Interior Flooding in Washington, DC,* (2017). https://silverjackets.nfrmp.us/Portals/0/doc/DC/Interior_Flooding_Report_20170825.pdf?ver=2017-09-01-175909-267

29 This can be seen in the revised FIRMs. With the 17th Street Levee closure now accredited, facilities like the National Archives are protected from the 1 percent annual chance river or coastal flood, but are still vulnerable to the 1 percent annual chance interior flood.

30 U.S. Global Change Research Program (USGCRP), *Climate Science Special Report: Fourth National Climate Assessment, Volume I*, 2017: https://science2017.globalchange.gov/

31 District Department of Energy and Environment (DOEE), *Climate Projections and Scenario Development* (2015). http://doee.dc.gov/sites/default/files/dc/sites/ddoe/publication/attachments/150828_AREA_Research_Report_Small.pdf

Left: Heavy rain comes down faster than the stormwater sewers can drain on 9th Street NW in 2015.

Sea level rise is also expected to make interior flooding more frequent and severe (see the next chapter for more information on sea level rise). As sea levels rise, the fresh water table will rise as well,[32] leaving a smaller volume of soil that is capable of absorbing stormwater runoff. With higher sea levels and more frequent nuisance or "sunny day" flooding events, there will also be more days where the storm sewer outlets are below the water surface elevation. When this occurs, stormwater that normally drains directly to the rivers (MS4 areas)[33], will be unable to leave the storm sewer system and may cause additional flooding in areas that are connected to these pipes.

Interior flooding is heavily influenced by the built environment, so changes in land use play a role in flood frequency. Changes in the amount of pervious surface in a storm sewer drainage area can significantly impact the quantity and timing of water entering the storm sewer system. Projecting future interior flooding risk should therefore consider how land use might change around existing facilities. The addition of low impact development features, such as green roofs and sidewalk stormwater infrastructure, or improvements to existing infrastructure (i.e. enlarging pipes to increase capacity) will help reduce interior flooding risk, while greenfield development or additional pavement will likely increase interior flooding risks. DC Water's Clean Rivers Project[34] could have a significant impact on interior flooding once complete. While its primary purpose is to reduce combined sewer overflows to District waterways, many of its interventions, such as underground stormwater storage pipes and green infrastructure solutions, will reduce the amount of runoff produced during intense rains and decrease the risk of interior floods.

## Methods to Evaluate Future Interior Flood Risks

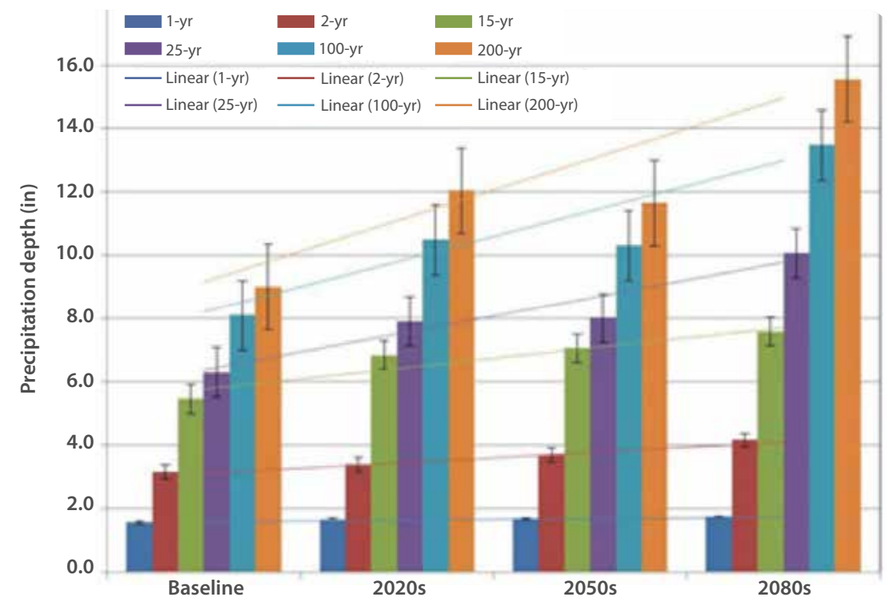
Even though the District of Columbia has recently developed rainfall projections that incorporate climate change,[35] modeling impacts of future rainfall requires additional information. Rainfall projections must be included in a hydraulic model and map to be useful for facility managers. For example, the District of Columbia's precipitation projections show that today's 100-year six-hour storm results in 5.1 inches of rainfall.[36] However, one cannot simply add 5.1 inches above ground level to determine the flood elevation during a 100-year six-hour storm. Flood elevations for interior flooding are affected by storm sewer system capacity, the size of the storm sewer drainage area, and local topography. If the facility is at the bottom of the storm sewer system drainage area, the flood elevation will be much higher than if the facility is on high ground within the drainage area. This type of mapping and modeling has not been completed for the District of Columbia, with the exception of Federal Triangle.

The relative ease of evaluating future interior flooding risks depends on data availability. For facilities in the Federal Triangle area where hydraulic and "all-pipes" modeling has already been completed, (see the information sheet on page 25) simulating future interior flooding impacts by running the model again with the projected rainfall amounts would be relatively easy. In other areas of the NCR where mapping and modeling does not exist, a much greater effort would be required to acquire and stitch together storm sewer infrastructure and urban topography data.

32 USGS, *Coastal Groundwater Systems* (2015). https://woodshole.er.usgs.gov/project-pages/sea-level-rise_hazards/physical-systems/coastal-groundwater.html
33 MS4 areas, or Municipal Separate Storm Sewer Systems, are areas of the city where stormwater drains directly to the rivers. In other areas of the city, stormwater flows into a combined sewer system that sends both stormwater and sewage through underground tunnels to the Blue Plains Wastewater Treatment Plant.
34 DC Water, *Clean Rivers Project* (Accessed 2018). https://www.dcwater.com/clean-rivers-project
35 DOEE, *Climate Projections and Scenario Development* (2015).
36 Ibid.



## 24-Hour Design Storm Comparison




Comparison of precipitation depth and return interval (i.e. 15-year vs. 100-year) from the District of Columbia's Precipitation Projections. See page 23 for source.

## 2006 Federal Triangle Floods

A model re-creation of the 2006 Federal Triangle Flood that caused major damage to the National Archives, Internal Revenue Service, Environmental Protection Agency and Department of Justice buildings. See page 25 for source.

# 6. Coastal Flooding

## Current Methods to Evaluate Coastal Flooding

Coastal floods refer to inundation caused by the Potomac and Anacostia Rivers' connection to the Chesapeake Bay and ultimately to the Atlantic Ocean. Coastal flooding includes two types of inundation. The first type, called nuisance or sunny day flooding, results from high tides that flood low-lying areas. Nuisance flooding does not typically result in significant damage, and is mostly an inconvenience due to flooded sidewalks and roadways, as is the case on East Potomac Park pictured at left. The second type of flooding, often called storm surge flooding, is a result of coastal storms, like hurricanes, that drive storm surges up the Potomac River toward Washington, DC. The 1 percent and 0.2 percent annual chance coastal floods are exclusively caused by storm surge flooding in combination with tides, which can result in floods with much higher water elevations than nuisance floods.

Extreme water levels from coastal flooding result from four major components (see figure on page 47).

1. **Increases in mean sea level**: Increased sea level, which has already been observed and is expected to continue,[37] raises the normal water surface elevation upon which the three components below are added.

2. **Tidal variability above mean sea level:** In Washington, DC the tidal range at Hains Point is about three feet, but that range can change as a result of monthly and seasonal variability.

3. **Storm surge:** Increased water levels as a result of storm surge are produced by low barometric pressure and wind from coastal storms.[38] When the first three components of coastal flooding (sea level rise, tidal variability, and storm surge) combine during a storm event, the water surface elevation is called the Extreme Still Water Level.

4. **Wave run-up**: Wave run-up tends to be greatest on areas that are near the open ocean and with steep slopes, like the Pacific Islands. Areas like Washington, DC, where the shoreline is sheltered, do not typically experience breaking waves or significant wave run-up.[39]

37 Referred to in document as "NOAA 2017". Full Citation: Sweet, William V., Robert E. Kopp, Christopher P. Weaver, Jayantha Obeysekera, Radley M. Horton, E. Rovert Thieler, and Chris Zervas. *Global and Regional Sea Level Rise Scenarios for the United States.* NOAA Technical Report NOS CO-OPS 083 (2017). https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf

38 Federal Highway Administration, *Highways in the Coastal Environment: Assessing Extreme Events* (2014) 33. http://www.fhwa.dot.gov/engineering/hydraulics/pubs/nhi14006/nhi14006.pdf

39 Referred to in document as "CARSWG 2016". Full Citation: Hall, J.A., S. Gill, J. Obeysekera, W. Sweet, K. Knuuti, and J. Marburger, *Regional Sea Level Scenarios for Coastal Risk Management: Managing the Uncertainty of Future Sea Level Change and Extreme Water Levels for Department of Defense Coastal Sites Worldwide* (U.S. Department of Defense, Strategic Environmental Research and Development Program, 2016), 43. https://www.serdp-estcp.org/content/download/38961/375873/file/CARSWG%20SLR%20April%202016.pdf

Left: Nuisance flooding on East Potomac Park during high tide in 2010. Credit: Flickr user TrailVoice

Facility managers and planners primarily use FEMA's FIRMs to identify coastal flooding risk. As described in Chapter 3, the flood extents shown in the FIRMs below the 14th Street Bridge are based on analysis of data from the SW Waterfront Gage. When high water surface elevations during coastal floods are recorded, they are measures of Extreme Still Water Level (sea level rise, tidal variability and storm surge). The 2016 Flood Inundation Maps can also be used to depict coastal floods, though the map layers (in elevation increments) do not assign a probability of occurrence like the FIRMs do by labeling the 1 percent and 0.2 percent annual chance floodplains.

In addition to the FIRMs and 2016 Flood Inundation Maps, there are other mapping products that depict flood risk from modeled hurricane tracks. USACE's Storm Surge Inundation Maps (described on page 19) is one example. This particular map uses SLOSH,[40] a modeling tool, to show four layers of flood extents, one each for the worst case scenario of category 1-4 hurricanes.[41] These maps, while informative to planners, are primarily used to inform emergency evacuation route planning, and typically overestimate flood extents as a result of the SLOSH modeling process.

## How Future Coastal Flood Risks May Change

Climate change is expected to increase future coastal flooding in two ways. First, in all plausible future conditions, mean sea levels are expected to rise in Washington, DC,[42] thereby making nuisance flooding more frequent, and also increasing the normal water surface elevation upon which storm surge and wave run-up are added. Second, increased global temperatures are expected to create more intense coastal storms, which means Washington, DC can expect higher storm surges during these events.[43] The net result of all these factors is that with sea level rise, the future 1 percent annual chance coastal storm will have higher water surface elevations than today's 1 percent annual chance coastal storm. Because changes in sea level are such a critical factor in how this region will be affected by future coastal flooding, further detail is provided below.

40 SLOSH, or Sea, Lake, and Overland Surges from Hurricanes, is a National Weather Service Model used to estimate storm surge heights resulting from historical, hypothetical, or predicted hurricanes. Maps for the NCR are created using the "composite approach" described on this webpage: National Hurricane Center, *Sea, Lake, and Overland Surges from Hurricanes (SLOSH)* (Accessed November 2016). http://www.nhc.noaa.gov/surge/slosh.php.

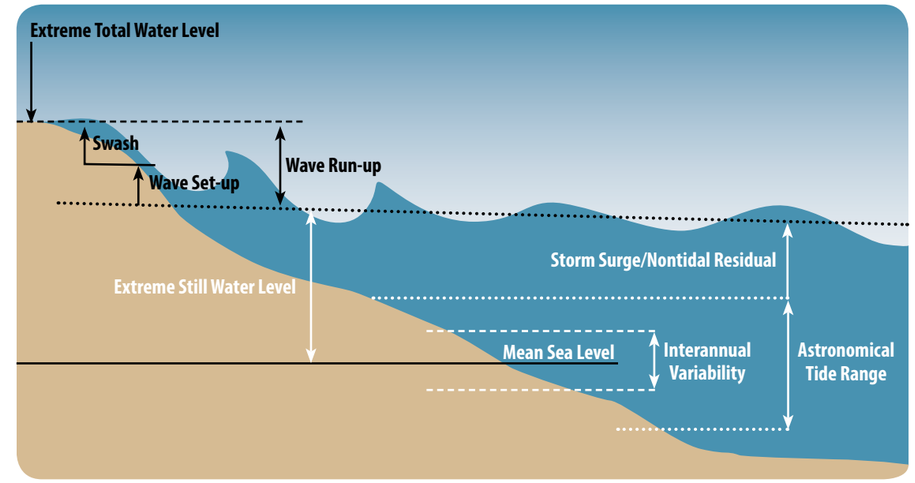
41 SLOSH products do not include category 5 hurricanes north of the North Carolina – Virginia border as thermodynamic factors become unfavorable. More information: http://journals.ametsoc.org/doi/full/10.1175/WCAS-D-14-00049.1

42 NOAA 2017, Section 3.

43 Referred to in document as "Maryland 2013". Full Citation: Boesch, D.F., L.P. Atkinson, W.C. Boicourt, J.D. Boon, D.R. Cahoon, R.A. Dalrymple, T. Ezer, B.P. Horton, Z.P. Johnson, R.E. Kopp, M. Li, R.H. Moss, A. Parris, C.K. Sommerfield. 2013. *Updating Maryland's Sea-level Rise Projections. Special Report of the Scientific and Technical Working Group to the Maryland Climate Change Commission* (2013) 14. https://www.pwrc.usgs.gov/SeaLevelRiseProjections.pdf



## Components of Extreme Water Levels




Graphic depicting the components of extreme water levels adapted from the Coastal Assessment Regional Scenario Working Group's 2016 report.

## Top 10 Cities with Increased Nuisance Flooding

| | Average Nuisance Flood Days | | |
|---|---|---|---|
| **Location** | **1957–1963** | **2007–2013** | **Increase** |
| Annapolis, MD | 3.8 | 39.3 | 925% |
| Baltimore, MD | 1.3 | 13.1 | 922% |
| Atlantic City, NJ | 3.1 | 24.6 | 682% |
| Philadelphia, PA | 1.6 | 12 | 650% |
| Sandy Hook, NJ | 3.3 | 23.9 | 626% |
| Port Isabel, TX | 2.1 | 13.9 | 547% |
| Charleston, SC | 4.6 | 23.3 | 409% |
| **Washington, DC** | **6.3** | **29.7** | **373%** |
| San Francisco, CA | 2 | 9.3 | 364% |
| Norfolk, VA | 1.7 | 7.3 | 325% |

**Nuisance Flooding Defined:** "During extremely high tides, some locations along coasts experience shallow coastal flooding: the sea literally spills onto land, indundating low-lying areas with seawater until high tide has passed. Because these floods causes public inconveniences such as road closures, overwhelmed storm drains, and deterioration of roads and infrastructure from exposure to salt water, the events are referred to as nuisance flooding."
- From the U.S. Climate Resilience Toolkit webpage on Nuisance Flooding.

Summary table detailing the increase in days of nuisance flooding in ten different U.S. cities. Data is from a 2014 NOAA Technical Report.

## Relative Sea Level Change

Relative sea level (RSL) change is a combination of global mean sea level (GMSL) rise and local factors that further influence sea levels. In some cases, these local factors result in an overall decrease in RSL, which is why "change" is often used when referring to local and relative sea levels as opposed to "rise." While globally sea levels are rising,[44] some areas, such as the Alaskan coast, are experiencing falling sea levels; in these cases, local factors such as land uplift, outweigh GMSL rise.[45] In Washington, DC and the broader Mid-Atlantic region, sea levels are expected to rise faster than the global average. Understanding the factors that contribute to Washington, DC's RSL is important for evaluating available tools and projections for the region. Page 49 contains more detailed information on how global and local factors combine to affect RSL.

### *Global Mean Sea Level Rise*

GMSL rise is principally caused by 1) "warming the oceans, which causes sea water to expand, increasing ocean volume, and (2) melting land ice, which transfers water to the ocean."[46] Melting land ice is typically broken into two categories: glaciers and ice caps, and the Greenland and Antarctic ice sheets. Recently, changes in land water storage, such as groundwater being removed faster than it can be recharged (resulting in more water being stored in the ocean rather than underground) was identified as a factor in GMSL.[47]

In 2014, GMSL was measured at 2.6 inches above the 1993 average.[48] While today's increased GMSL is scientifically supported, it remains difficult to project the future rate of sea level rise. The National Oceanic and Atmospheric Administration (NOAA) describes the challenge this way; "As global temperatures continue to warm, sea level will continue to rise. How much it will rise depends mostly on the rate of future carbon dioxide emissions and future global warming. How fast it will rise depends mostly on the rate of glacier and ice sheet melting."[49] Current models for GMSL predict a range of scenarios. For example, the Global Sea Level Rise Scenarios published by NOAA's 2017 report estimates GMSL to be between 12 inches and 8.2 feet by 2100.[50] As with most global models, the high scenario reflects rapid melting of the Greenland and Antarctic ice sheets. The different methods for projecting sea level rise are discussed in the paragraph titled *Methods to Evaluate Future Coastal Flood Risks* on page 50.

### *Local Sea Level Rise*

While GMSL is rising, local factors such as vertical land motion, and global factors that have disproportionate local impacts (i.e. ocean dynamics and ice-melt fingerprinting) influence whether sea level rise at specific locations may be more or less than the global average. A brief discussion of how these local factors contribute to RSL rise in Washington, DC is below.

A primary local factor that influences RSL is vertical land motion, which describes how local geology and hydrology interact with the sea level. The weight of the glaciers from the last ice age that covered the Northeast raised a bulge at the edge of the glaciers in

44 Referred to in document as "IPCC 2014". Full Citation: IPCC, *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (2014) 42. https://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full.pdf
45 NOAA, *Sea Level Trends* (2013). https://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml
46 Referred to in document as "NRC 2012". Full Citation: National Research Council, *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future* (2012). https://www.nap.edu/read/13389/chapter/3
47 IPCC, *Climate Driven Change in Land-Water Storage* (Part of the IPCC Fourth Assessment Report: Climate Change 2007). https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch5s5-5-5-3.html
48 Lindsey, Rebecca (NOAA), *Climate Change: Global Sea Level* (2016). https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level
49 Ibid.
50 NOAA 2017, Section 5.



## Understanding Relative Sea Level Change

Relative sea level (RSL) change is a combination of global and local factors.

**Global Factors**

**Thermal Expansion**
Warming the oceans causes sea water to expand, and thus increases the ocean volume. Thermal expansion has been one of the dominant contributers to global mean sea level rise over the past decades.

**Land-Water Storage**
Changes in the amount of water stored on land (such as in groundwater, soils, snowpack, rivers, or lakes) affect global mean sea level. Over extraction of groundwater, for example, means that more water is stored in oceans than underground, causing global mean sea level to rise. Impoundment of water behind dams, on the other hand, removes water from the ocean and lowers the global mean sea level.

**Glaciers & Ice Caps**
This factor represents one component of land ice, the melting of which adds freshwater to the ocean and raises global mean sea level. Glaciers and ice caps refer to all land ice that is not part of the Greenland or Antarctic ice sheets, including ice on mountain tops and glacial formations that are distributed all over the world.

**Greenland & Antarctic Ice**
This is the other component of land ice. Greenland and Antarctic ice scheets have significant water stored in them, and when they melt, the water will be added to the ocean raising global mean sea level. Their rate of ice melt is one of the toughest factors to predict and is a primary cause of variance in global projections.

+

**Local Factors**

**Vertical Land Motion**
Vertical Land Motion refers to movement of the ground relative to sea level. This includes Glacial Isostatic Adjustment (which can raise or lower land depending on the location), sediment compaction, and groundwater or hydrocarbon extraction. Both compaction and extraction will lower land and RSL as a result.

**Ocean Dynamics**
Ocean currents and coastal geography both affect RSL. Strong currents, like the Gulf Stream, influence sea levels. As the strength of currents change, the sea levels along coast lines can change as well. When sea levels change the size and shape of bays and rivers, tidal range can also be affected.

**Ice-Melt Fingerprinting**
As glaciers melt, they have a disproportionate impact on sea levels accross the globe. Areas near melting glaciers will experience falling sea levels while farther locations will experience sea level rise associated with that particular ice melt.

=

**RSL Change**

**Relative Sea Level Change**
When global and local factors are combined, projections for relative sea level change can be made for a specific location. The Washington, DC region can not only expect rising sea levels, but levels that rise faster than the global average due to local factors.

the Mid-Atlantic. Now that the glaciers are gone, that bulge is subsiding (called Glacial Isostatic Adjustment), resulting in land subsidence in the Mid-Atlantic States, including Washington, DC. Glacial Isostatic Adjustment is the primary cause of land subsidence in this area, but land subsidence can also be caused by sediment compaction over time or by groundwater or hydrocarbon extraction. In the Norfolk, Virginia area, for example, the high groundwater use by nearby paper mills caused land subsidence in surrounding areas.[51] A 2010 study estimated that Washington, DC has experienced land subsidence of approximately 1.11 millimeters per year between 1976 and 2007.[52]

Local topography and bathymetry, a component of ocean dynamics, also play a role in how sea level rise affects the coastline. Generally, tidal range (the difference in water surface elevations between high and low tide) in a semi-enclosed water body like the Chesapeake Bay decreases with shallower water depth. Higher sea levels would mean a deeper Chesapeake Bay, which could increase the tidal range in Washington, DC.[53] Therefore, in addition to sea level rise raising the normal water surface elevation, a *higher* high tide (caused by sea level rise) would increase water levels further.

Ocean currents, another component of ocean dynamics, also affect RSL in Washington, DC. The entire Atlantic coastline is heavily influenced by the Gulf Stream current. Because strong currents change sea levels, sea level on the East Coast (west of the Gulf Stream) is 3-5 feet lower than water offshore (east of the Gulf Stream). Recent research has shown that short-term weakening of the Gulf Stream results in higher than normal water levels along the Virginia coast. Global climate warming is expected to weaken the Gulf Stream current north of Cape Hatteras, thereby increasing sea level on that area of the East Coast.[54]

Research called ice-melt fingerprinting explains that added water from ice sheet melting is not evenly distributed across the globe. "When the Amundsen Sea sector of the West Antarctic Ice Sheet is totally gone, the average global sea level will rise four feet. But the East Coast of the United States will see an additional 14 to 15 inches above that average."[55] Various glacier and ice-sheet melting, and their distribution throughout the world must be accounted for in projections for RSL in Washington, DC.

51 Eggleston, Jack and Jason Pope (USGS), *Land Subsidence and Relative Sea-Level Rise in the Southern Chesapeake Bay Region* (2013). http://pubs.usgs.gov/circ/1392/pdf/circ1392.pdf

52 Boon, J.D., J.M. Brubaker and D.M. Forrest. *Chesapeake Bay Land Subsidence and Sea Level Change: An Evaluation of Past and Present Trends and Future Outlook. Special Report No. 425 in Applied Marine Science and Ocean Engineering.* (Virginia Institute of Marine Science, Gloucester Point, Virginia, 2010).

53 Zhong, L., M. Li and M.G. Foreman, "Resonance and Sea Level Variability in Chesapeake Bay," *Continental Shelf Research*, 28, (2008) 2565-257. https://www.researchgate.net/publication/222682991_Resonance_and_sea_level_variability_in_Chesapeake_Bay

54 Maryland 2013, 12.

55 Rasmussen, Carol (NASA), *The Fingerprints of Sea Level Rise* (2015). http://www.jpl.nasa.gov/news/news.php?feature=4701



## Methods to Evaluate Future Coastal Flood Risks

### Evaluating Relative Sea Level Change

There are many RSL projections for the Washington, DC area. In order to compare them properly, it is important to understand what factors were included. All RSL projections start by projecting GMSL, usually by using global climate models or synthesizing previous research. Global models that are used in Washington, DC's *local* projections are described on page 53. Once a global mean sea level projection is selected, local factors are then introduced to come up with projections for RSL at a particular location. This process of adjusting global projections with local data is standard practice and recommended by NOAA: "Additional information should be combined with the global scenarios to incorporate regional and local conditions when conducting risk analysis. These factors include regional mean sea level variability, local and regional vertical land movement, coastal environmental processes (geological, ecological, biological, and socio-economic), and the effect of extreme weather and climate on regional sea level."[56]

A comparison chart of current RSL projections that have been localized for Washington, DC are presented on pages 54-55. This guide does not select or recommend any particular approach; instead it compares the underlying information for each. Though all projections are focused on the National Capital Region, many use different data sources to measure the same factor, such as vertical land motion. Some projections include ocean dynamics and ice-melt fingerprinting while others don't. As new projections and models are released, the comparison chart can also help users understand how they differ from existing projections.

As shown in the RSL comparison chart, RSL projections for Washington, DC vary substantially. Projections for the year 2100, for example, range from 0.3 meters (USACE 2013 low scenario) to 3.6 meters (NOAA 2017 high scenario). A wide range can be found even comparing high scenarios among the different projections. The range for the year 2100 in high scenarios varies from 1.7 meters (USACE 2013 and Maryland 2013) to 3.6 meters (NOAA 2017). The fact that well-respected scientific studies offer such a range makes it difficult to select a single number for RSL that can be used in site designs.

Uncertainty in RSL projections requires a nuanced approach when designing facilities to account for future coastal flood risk. Most attempts to deal with this uncertainty promote a scenario approach where varying RSL projections (usually a low and high scenario but also frequently including a "most likely" or central estimate) are applied to a design. A scenario is selected depending on the exposure, sensitivity, adaptive capacity and life-cycle of the project (i.e. a facility that performs irreplaceable functions and is meant to last indefinitely

56 Referred to in document as "NOAA 2012". Full Citation: Parris, A., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, K. Knuuti, R. Moss, J. Obeysekera, A. Sallenger, and J. Weiss, *Global Sea Level Rise Scenarios for the United States National Climate Assessment* (2012). https://scenarios.globalchange.gov/sites/default/files/NOAA_SLR_r3_0.pdf

would be designed[57] to adapt to the highest RSL rise scenario). A new approach, identified in the 2014 Kopp et al. study,[58] offers an alternative way to use quantified probabilistic estimates of RSL rise, but the nature and limitations of these estimates must be well-understood before incorporating into real world decision making. One limitation, for example, is that the value of probabilistic projections declines as planning horizon extends beyond 2050. Applying projections of future flood risk in site design (as opposed to identifying them as this document does) is a complex process that is beyond the scope of this document, and should be considered in future NCPC or DC Silver Jackets discussions. A 2014 USACE publication[59] and NOAA's 2017 report[60] provide excellent overviews on the subject.

### Evaluating Future Nuisance Flooding

Currently, the Washington, DC region has several tools to evaluate how coastlines will change and the extent of *future* nuisance flooding at a screening level. There are a number of tools available that depict still water conditions associated with sea level rise (without any other type of flooding). They include NOAA's Sea Level Rise Viewer (page 20), Climate Central's Surging Seas Risk Finder (page 21), and USACE's Sea Level Change Curve Calculator (page 22). Tools for future nuisance flooding are available because they only require the addition of RSL projections, of which Washington, DC has many, to existing water levels.

### Evaluating Future Storm Surge Flooding

There are no easy-to-access tools that directly project future coastal flooding from storm surge. In addition to applying RSL projections to storm surge, users must also consider that sea level rise is only one component of future coastal flood risk. More intense future storms, even without rising seas, would increase coastal flood risks. As a result, simply adding RSL on top of existing storm surge studies would not be accurate. Existing tools (such as the Flood Inundation Mapping Tool (page 17) and the Storm Surge Inundation Maps (page 19) do not consider how future conditions may affect flood risk. The North Atlantic Coast Comprehensive Study (NACCS) described on page 18 does show future coastal floods by including a map of the 100 year plus 3-foot flood, but the map is in low resolution and therefore minimally useful to planners.

Similar to how they might be used in depicting future riverine flooding, the 2016 Flood Inundation Maps could be used in conjunction with a future analysis. Once complete, such an analysis might say, "the 0.2 percent annual chance storm surge flood in 2050 will have a water surface elevation of 16 feet at the SW Waterfront Gage." Planners could then use one of the layers in the 2016 Flood Inundation Maps that most closely reflects the 16 foot elevation and use that map to approximate the *future* 0.2 percent annual chance floodplain.

57 This could include a static design where the facility is built ready to withstand 10 feet of additional sea level rise well before it occurs, or a design with adaptive management and adaptation pathways in mind. An example of the latter type of design is a levee built to a height of 5 feet to account for current risk, but with a footing that is able to support a height of 10 feet to account for potential future conditions.

58 Referred to in document as "Kopp et al. 2014". Full Citation: Kopp, R. E., Horton, R. M., Little, C. M., Mitrovica, J. X., Oppenheimer, M., Rasmussen, D. J., Strauss, B. H. and Tebaldi, C. "Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites." *Earth's Future,* 2 (2014): 383–406. http://onlinelibrary.wiley.com/doi/10.1002/2014EF000239/full

59 USACE, *Technical Letter No. 1100-2-1 Procedures to Evaluate Sea Level Change: Impacts, Responses, and Adaptation* (2014), Chapter 3. http://www.publications.usace.army.mil/Portals/76/Publications/EngineerTechnicalLetters/ETL_1100-2-1.pdf

60 NOAA 2017, Section 6.



## Global Mean Sea Level Change Projections

All relative sea level (RSL) projections (shown on the following page) start with a global mean sea level (GMSL) projection. The GMSL projections (shown on this page) are created by various working groups and agencies. They use global climate models (GCMs) and peer reviewed science to project global sea levels based on factors such as thermal expansion, land-water storage, and ice-melt. The following GMSL projections represent some of the most well known and frequently used GMSL projections. The GMSL projections that are used to in local RSL projections for Washington, DC on the next page are indicated with an asterisk.

| Reference | Detailed Information |
|---|---|
| NRC 1987* | **Title:** Responding to Changes in Sea Level: Engineering Implications<br>**Author:** The National Research Council (NRC)<br>**Link:**https://www.nap.edu/catalog/1006/responding-to-changes-in-sea-level-engineering-implications |
| IPCC 2007 | **Title:** Climate Change 2007: The Physical Science Basis (Part of the Fourth Assessment Report)<br>**Author:** The Intergovernmental Panel on Climate Change (IPCC)<br>**Link:** https://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html |
| NRC (2012)* | **Title:** Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future<br>**Author:** The National Research Council (NRC)<br>**Link:**https://www.nap.edu/catalog/13389/sea-level-rise-for-the-coasts-of-california-oregon-and-washington |
| NASA (2012)* | **Title:** Adapting to a Changing Climate: Federal Agencies in the Washington, DC Metro Area<br>**Author:** National Aeronautics and Space Administration (NASA)<br>**Link:** https://www.ncpc.gov/docs/Adapting_to_a_Changing_Climate_November2012.pdf |
| NOAA (2012)* | **Title:** Global Sea Level Rise Scenarios for the United States National Climate Assessment<br>**Author:** Parris, Adam et al. - published by the National Oceanic and Atmospheric Administration (NOAA)<br>**Link:** https://scenarios.globalchange.gov/sites/default/files/NOAA_SLR_r3_0.pdf |
| IPCC (2013) | **Title:** Climate Change 2013: The Physical Science Basis (Part of the Fifth Assessment Report)<br>**Author:** The Intergovernmental Panel on Climate Change (IPCC)<br>**Link:** https://www.ipcc.ch/report/ar5/wg1/ |
| NOAA (2017)* | **Title:** Global and Regional Sea Level Rise Scenarios for the United States<br>**Author:** Sweet, William et al. - published by the National Oceanic and Atmospheric Administration (NOAA)<br>**Link:** https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf |

*Indicates that the GMSL projection was used in one of the RSL projections for Washington, DC shown on the next page.

# Relative Sea Level (RSL) Projections for Washington, DC

Relative sea level (RSL) projections specific to Washington, DC are summarized below. All RSL projections start with a global model that projects global mean sea level (GMSL). These GMSL projections are then modified by one or more local factors to create RSL projections. GMSL projections that underly RSL projections are noted under "Global Factors." The chart simplifies a very complex process of how projections are created, which typically involves consideration of a combination of historical data, output from climate models, and expert judgement. The chart should not be used to determine which projection is best, but as an "apples-to-apples" comparison of all local projections and their underlying global models available as of January 2018.

**Note on Projections:** Only lowest and highest projections are shown for 2050 and 2100, though many of the RSL projections include intermediate scenarios as well. Projections that follow with a year in superscript indicate a particular study that did not publish projections for the years 2050 or 2100, and used an alternate time horizon instead. For example, NASA's low projection of "+0.2m (2050s)" indicates that NASA projects +0.2m of sea level rise in the years 2050-2059. All projections in this chart are standarized to start at zero in 1992. This year is often used because it is the mid-year of the NOAA National Tidal Datum Epoch (NTDE) of 1983–2001. Pojections are rounded to one decimal place.

| | | RSL Projections = | | Global Factors + | | | | | Local Factors | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2050 Low / High | 2100 Low / High | GMSL Projection (see page 55) | Thermal Expansion | Land-Water Storage | Glaciers & Ice Caps | Greenland & Antarctic Ice | Vertical Land Motion | Ocean Dynamics | Ice-Melt Fingerprinting |
| **NASA (2012)** | NASA's RSL projections are based on NASA's own GMSL projections that incorporate 7 global climate models and 3 emissions scenarios. Only the high GMSL projections incorporate rapid ice-melt. Local sea level changes due to ocean dynamics were derived from the global models. Vertical land motion data was derived from the Peltier database. | +0.2m (2050s)<br>+0.7m (2050s) | +0.3m (2080s)<br>+1.4m (2080s) | NASA (2012) | ● | | ● | ● | ● | ● | |
| **USACE (2013)** | USACE's RSL projections for the low scenario are based on the historic rate of GMSL rise. Intermediate and high GMSL projections are from the 1987 NRC report that USACE modified using the most recent IPCC and NRC projections. GMSL projections are localized with vertical land motion based on data from NOAA's Sea Level Trends website. (This text represents the default settings) | +0.2m<br>+0.6m | +0.3m<br>+1.7m | NRC (1987) | ● | ● | ● | ●* * Projections do not include rapid ice-melt scenarios | ● | | |
| **NOAA (2013)** | NOAA's RSL projections are found on the USACE SLC curve calculator by modifying the default settings (which show USACE 2013 RSL). Select "NOAA" as output agency and "Regionally Corrected" as SLC Rate. GMSL projections are based on the NOAA 2012 report and then localized with vertical land motion based on data from a 2013 NOAA technical report. | +0.2m<br>+0.7m | +0.3m<br>+2.1m | NOAA (2012) | ● | | ● | ● | ● | | |
| **Maryland (2013)** | The Maryland Climate Change Commission's RSL projections use the GMSL projections from the 2012 NRC report as a starting point. The GMSL projections are then adjusted for local factors by the Scientific and Technical Working Group using peer reviewed science that uses data approporiate to Maryland's location. | +0.3m<br>+0.7m | +0.7m<br>+1.7m | NRC (2012) | ● | | ● | ● | ● | ● | ● |
| **Climate Central (2017)** | Climate Central (CC) allows users to view RSL projections based on six global models (NRC 2012, NOAA 2012 (National Climate Assessment), IPCC 2013, Kopp et al. 2014, Kopp et al. 2017, and NOAA 2017). CC then localizes the projections that aren't already localized. Projections at right are CC's localization of GMSL projections in the NOAA 2012 report. | +0.2m<br>+0.6m | +0.4m<br>+2.0m | Multiple | ● | ●* | ● *Depends on which model selected | ● | ● | ●* | ●* |
| **CARSWG (2016)** | RSL projections for DOD installations by the Coastal Assessment Regional Scenario Working Group (CARSWG) used GMSL projections in the NOAA 2012 report and then localized them with peer reviewed science and local data. Only the process for creating RSL projections is publically available in the CARSWG Report. DC projections shown here were provided as an exception. | +0.2m (2035)<br>+0.5m (2035) | +0.3m<br>+2.4m | NOAA (2012) | ● | ● | ● | ● | ● | ● | ● |
| **NOAA (2017)** | The process for creating NOAA's RSL projections as well as the actual GMSL projections they derive from are described in the NOAA 2017 report. The regionalization process is similar to that used in CARSWG 2016 but differs by using new data sets slightly modified from Kopp et al. 2014. Data (.csv format) for multiple locations is provided in low, medium, and high scenarios. | +0.2m<br>+1.1m | +0.3m<br>+3.6m | NOAA (2017) | ● | ● | ● | ● | ● | ● | ● |

# 7. Summary

## Summary

The Washington, DC region is vulnerable to riverine, coastal, and interior floods, all of which have affected communities and infrastructure, buildings, and operations in the recent past. Planners and asset managers must manage these current risks, and anticipate that risks for all flood types may increase in the future due to climate and land use changes. Considering current and future flood risks is necessary to protect land, facility, and infrastructure investments, many of which are meant to last for generations, especially given the quantity and importance of assets already prone to flooding in the NCR.

This guide explores the available tools and resources to evaluate current and future regional flood risks, including their limitations. All resources described in this study are useful at a screening level to provide a basic understanding and order of magnitude estimates for how current and future flood risks may impact facility and infrastructure assets, though these resources vary in their accuracy and applicability to future flood conditions. The available mapping resources, however, do not provide enough detail or degree of accuracy to be used in site planning. Agencies will likely need to hire an expert to make informed flood risk management decisions on matters of site selection, design and development, and related operations. In addition, new resources could be developed to fill current information gaps.

## Opportunities

Currently, tools to depict future riverine and interior flooding risks are not available. There are opportunities to take advantage of existing studies to develop this information. In the case of interior flooding, the detailed hydrological model for the Federal Triangle developed for the 2011 Federal Triangle Study could be run again with the District of Columbia's 2015 precipitation projections to provide a map of *future* interior flood risk in the Federal Triangle. In the case of riverine flooding, if modeled estimates for future Potomac River flows (based on precipitation and land development changes) are generated, that information could be used with the 2016 Flood Inundation Maps prepared by the USACE to show the extent of future riverine flood risks. Similarly, the 2016 Flood Inundation maps could be used once modeled estimates of future storm surge flooding are generated.

Coastal flooding has the most data available for understanding future flood risk. Since sea level rise estimates are given in a range, and all buildings and infrastructure may not require the same risk protection, applying projections of future flood risk to site design is still a difficult and complex process. There is an opportunity, with coastal flooding risk especially, for agencies to work together to create approaches for planning facilities in or near floodplains that can account for the uncertainty in future conditions.

At Left: Paddleboats docked on the Tidal Basin, when no flooding is present. Credit: Catalina Calachan

# 8. Appendices

## Appendix A: Acronyms

| | |
|---|---|
| ADCIRC | Advanced Circulation Model |
| CARSWG | Coastal Assessment Regional Scenario Working Group |
| CC | Climate Central |
| cfs | cubic feet per second |
| cm | centimeters |
| CMIP | Coupled Model Intercomparison Project |
| CMIP5 | Coupled Model Intercomparison Project Phase 5 |
| DC | District of Columbia |
| DEM | Digital Elevation Model |
| DOD | Department of Defense |
| DOEE | District Department of Energy and Environment |
| DOT | Department of Transportation |
| EO | Executive Order |
| ETL | Engineer Technical Letter |
| FEMA | Federal Emergency Management Agency |
| FFRMS | Federal Flood Risk Management Standard |
| FHWA | Federal Highways Administration |
| FIM | Flood Inundation Mapping |
| FIRMs | Flood Insurance Rate Maps |
| FIS | Flood Insurance Study |
| GCM | Global Circulation Models |
| GIA | Glacial Isostatic Adjustment |
| GIS | Geographic Information Systems |
| GMSL | Global Mean Sea Level |
| GSA | General Services Administration |
| HEC-HMS | Hydrologic Engineering Center's Hydrologic Modeling System |
| HEC-RAS | Hydrologic Engineering Center's River Analysis System |
| IPCC | Intergovernmental Panel on Climate Change |
| JBAB | Joint Base Anacostia-Bolling |
| LIDAR | Light Detecting and Ranging |
| LMSL | Local Mean Sea Level |
| m | meters |
| MD | Maryland |
| MHHW | Mean Higher High Water |
| MS4 | Municipal Separate Storm Sewer Systems |
| NACCS | North Atlantic Coast Comprehensive Study |
| NASA | National Aeronautics and Space Administration |
| NAVD88 | North American Vertical Datum |
| NCA | National Climate Assessment |
| NCPC | National Capital Planning Commission |
| NCR | National Capital Region |
| NFIP | National Flood Insurance Program |
| NOAA | National Oceanic and Atmospheric Administration |
| NRC | National Research Council |
| NTDE | National Tidal Datum Epoch |
| NWS | National Weather Service |
| RCP | Representative Concentration Pathways |
| RSL | Relative Sea Level |
| RSLC | Relative Sea Level Change |
| SERDP | Strategic Environmental Research and Development Program |
| SLC | Sea Level Change |
| SLOSH | The Sea, Lake and Overland Surges from Hurricanes model |
| SLR | Sea Level Rise |
| USACE | United States Army Corps of Engineers |
| USGCRP | United States Global Change Research Program |
| USGS | United States Geological Survey |
| VA | Virginia |
| VLM | Vertical Land Motion |

At Left: Riprap on the Potomac River shoreline of West Potomac Park looking north towards Memorial Bridge.

# Appendix B: Washington, DC RSL Projections from the 2017 NOAA Report "Global and Regional Sea Level Rise Scenarios for the United States"

The table below represents the RSL projections for Washington, DC as they appear in the NOAA 2017 report. Projections for multiple locations in the United States are available online in a .csv format. They have been filtered here to only show projections for Washington, DC.

**Notes on the tables:** All numbers on these pages (60-61) represent centimeters above the 1991-2009 mean sea level datum, and are roughly 3 centimeters lower than if they were standardized to the National Tidal Datum Epoch (NTDE). The numbers highlighted in red were adjusted to the NTDE for use in the RSL Projection comparison chart on pages 54-55.

**Suggested Citation:** Sweet, W.V., R.E. Kopp, C. P. Weaver, J. Obeysekera, R. M. Horton, E.R. Thieler and C. Zervas (2017), Global and Regional Sea Level Rise Scenarios for the United States. NOAA Tech. Rep. NOS CO-OPS 83. https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf

**Descriptions of Data Columns from Data Authors:**

E) Scenario: For each of the six Global Mean Sea Level (GMSL) scenarios (identified by the height in meters in 2100), there is a low, medium and high sub-scenario, corresponding to the 17th, 50th, and 83rd percentile of the climate-related sea level projections consistent with the GMSL.

F) Background RSL rate (mm/yr): Applied as a constant linear trend. The mean estimate, mean estimate - 1 standard deviation, and mean estimate + 1 standard deviation are respectively applied to the medium, low and high sub-scenarios.

G-T) Relative Sea level (RSL) rise: GMSL scenario rise amounts and associated RSL changes (both in cm) projected at tide gauge and grid locations by decade from 2000 to 2100 and also for years 2120, 2150 and 2200.

*Numbers highlighted in red boxes are those that were used in the comparison chart on pages 54-55.*

| E | F | G | H | I | J | K | L | M |
|---|---|---|---|---|---|---|---|---|
| **Scenario** | **Background RSL rate (mm/yr)** | **2000** | **2010** | **2020** | **2030** | **2040** | **2050** | **2060** |
| 0.3 - MED | 1.35 | 0 | 5 | 11 | 15 | 20 | 26 | 31 |
| 0.3 - LOW | 1.21 | 0 | 2 | 6 | 11 | 14 | **16** | 19 |
| 0.3 - HIGH | 1.49 | 0 | 6 | 14 | 20 | 28 | 34 | 42 |
| 0.5 - MED | 1.35 | 0 | 5 | 13 | 18 | 25 | 32 | 38 |
| 0.5 - LOW | 1.21 | 0 | 4 | 8 | 14 | 19 | 24 | 29 |
| 0.5 - HIGH | 1.49 | 0 | 7 | 15 | 22 | 30 | 38 | 46 |
| 1.0 - MED | 1.35 | 0 | 8 | 17 | 27 | 37 | 49 | 63 |
| 1.0 - LOW | 1.21 | 0 | 6 | 12 | 21 | 29 | 39 | 51 |
| 1.0 - HIGH | 1.49 | 0 | 9 | 20 | 31 | 43 | 57 | 72 |
| 1.5 - MED | 1.35 | 0 | 10 | 22 | 35 | 49 | 68 | 87 |
| 1.5 - LOW | 1.21 | 0 | 6 | 13 | 24 | 36 | 51 | 67 |
| 1.5 - HIGH | 1.49 | 0 | 12 | 24 | 39 | 56 | 76 | 99 |
| 2.0 - MED | 1.35 | 0 | 12 | 26 | 43 | 63 | 89 | 118 |
| 2.0 - LOW | 1.21 | 0 | 11 | 23 | 40 | 58 | 80 | 104 |
| 2.0 - HIGH | 1.49 | 0 | 13 | 27 | 46 | 68 | 94 | 124 |
| 2.5 - MED | 1.35 | 0 | 14 | 28 | 47 | 70 | 101 | 138 |
| 2.5 - LOW | 1.21 | 0 | 6 | 13 | 27 | 45 | 67 | 96 |
| 2.5 - HIGH | 1.49 | 0 | 14 | 28 | 49 | 75 | **107** | 145 |



| E | F | N | O | P | Q | R | S | T |
|---|---|---|---|---|---|---|---|---|
| **Scenario** | **Background RSL rate (mm/yr)** | **2070** | **2080** | **2090** | **2100** | **2120** | **2150** | **2200** |
| 0.3 - MED | 1.35 | 36 | 41 | 44 | 46 | 53 | 61 | 73 |
| 0.3 - LOW | 1.21 | 20 | 23 | 24 | **25** | 31 | 32 | 33 |
| 0.3 - HIGH | 1.49 | 48 | 54 | 59 | 65 | 74 | 88 | 110 |
| 0.5 - MED | 1.35 | 44 | 50 | 55 | 60 | 71 | 87 | 112 |
| 0.5 - LOW | 1.21 | 34 | 40 | 44 | 48 | 57 | 65 | 74 |
| 0.5 - HIGH | 1.49 | 52 | 59 | 65 | 71 | 85 | 106 | 147 |
| 1.0 - MED | 1.35 | 77 | 93 | 109 | 126 | 145 | 199 | 293 |
| 1.0 - LOW | 1.21 | 63 | 77 | 91 | 105 | 123 | 168 | 242 |
| 1.0 - HIGH | 1.49 | 88 | 106 | 125 | 145 | 170 | 232 | 356 |
| 1.5 - MED | 1.35 | 110 | 136 | 163 | 196 | 238 | 346 | 560 |
| 1.5 - LOW | 1.21 | 85 | 107 | 129 | 154 | 196 | 283 | 441 |
| 1.5 - HIGH | 1.49 | 124 | 152 | 183 | 218 | 283 | 407 | 662 |
| 2.0 - MED | 1.35 | 149 | 185 | 227 | 274 | 364 | 545 | 905 |
| 2.0 - LOW | 1.21 | 131 | 165 | 202 | 245 | 328 | 485 | 814 |
| 2.0 - HIGH | 1.49 | 157 | 198 | 240 | 288 | 388 | 570 | 945 |
| 2.5 - MED | 1.35 | 179 | 223 | 276 | 336 | 448 | 686 | 1121 |
| 2.5 - LOW | 1.21 | 129 | 168 | 212 | 259 | 370 | 570 | 1005 |
| 2.5 - HIGH | 1.49 | 188 | 235 | 288 | **353** | 509 | 751 | 1228 |

# Appendix C: Additional Resources

In addition to the resources described in Section 2, the following list of resources may also be useful to planners and facility managers in the National Capital Region. Any future editions of this guide may consider a more detailed discussion of these and any other resources that may be released after this document is published.

**Climate Data for the Mid Atlantic** from the Mid-Atlantic Regional Integrated Sciences and Assessments (MARISA) program: NOAA established the program in 2016 and it is now led by the non-profit RAND Corporation, in partnership with researchers at Penn State University, Johns Hopkins University and Cornell University. The MARISA Climate Data Portal provides access to the ChesWx gridded climate datasets that contain daily interpolations of precipitation and temperature observations for the Chesapeake Bay watershed.

Source: https://www.marisa.psu.edu/data/

**Climate Resilience Toolkit** from USGRCP and NOAA: This website provides a compilation of tools, resources, data and projections, as well as case studies to help increase understanding of how to address climate risks across many sectors.

Source: https://toolkit.climate.gov/

**Coastal Flood Exposure Mapper** from NOAA: This is a collection of visualization tools and maps to assess vulnerability to sea level rise and other coastal flood hazards. Some of the layers in the map are the same as the Sea Level Rise Viewer described on page 20, but this tool also provides layers such as ecosystem exposure and infrastructure exposure.

Source: https://coast.noaa.gov/digitalcoast/tools/flood-exposure.html

**Coastal Hazards System** from USACE: This online tool provides access to over 1,000 storm tracks (along with their predicted surge and wave heights) that were modeled for the North Atlantic Coast Comprehensive Study.

Source: https://chswebtool.erdc.dren.mil/

**National Stormwater Calculator** from the U.S. Environmental Protection Agency: This online calculator uses a selection of low impact development controls to estimate local area annual rainwater and runoff frequency.

Source: https://www.epa.gov/water-research/national-stormwater-calculator

**National Climate Assessment** from USGCRP: This is an interactive, online report on the impact of climate change on the United States, with detailed regional information.

Source: https://www.globalchange.gov/nca4/

**Nonstationarity Detection Tool** from USACE: This online tool aids users in assessing stationarity of streams, creeks, and rivers in the continental United States. Stationarity assumes that historic data (used in hydrologic analyses) is a good predictor of the future, so if there are nonstationarities in the data it could affect design decisions.

Source:https://cwbiviz.usace.army.mil/t/CCAdaptation/views/ETL_DETECTIONTOOL_NSD_PROD/NonstationarityDetector?:embed=y&:toolbar=yes&:display_count=no



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# Flood Risk Management Planning Resources for Washington, DC

January 2018

Published by:

**Washington, DC Silver Jackets**
The DC Silver Jackets is an interagency team comprised of members from federal, District of Columbia and regional agencies, as well as academia dedicated to reducing flood risk in the District. More information can be found on their homepage: http://silverjackets.nfrmp.us/State-Teams/Washington-DC.

**National Capital Planning Commission**
The National Capital Planning Commission (NCPC) is the federal government's central planning agency for the National Capital Region. More information can be found on their homepage: www.ncpc.gov.

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Photo: The Lincoln Memorial and Washington Monument as viewed from the Potomac River during a sunset in November 2017. Credit: Flickr user Plum109

National Capital Planning Commission