DRAFT for USWG Review

Review of Current Stormwater Engineering Standards and Criteria for Rainfall and Runoff Modeling in the Chesapeake Bay Watershed

Photo: Green Street Retrofit, City of Lancaster

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Summary

The volume and distribution of precipitation is expected to change across the Chesapeake Bay watershed in the coming years as a result of climate change. These changing hydrologic conditions, especially when coupled with ongoing development, pose a risk to stormwater infrastructure and public safety. To date, state and local governments have used a series of precipitation volume-based engineering design criteria to manage risks to public health and safety as well as the performance of their stormwater BMPs. However, many stakeholders fear those criteria may not be well suited to address future precipitation.

This memo represents the second in a series of four memos dedicated to providing a clearer understanding of the current stormwater management approaches to climate resiliency. The series also identifies priority initiatives to allow managers to address their restoration and public safety functions under future climate conditions. This memo presents a review of the hydrologic models, precipitation data sources and state engineering criteria that underpin the design of the urban landscape across the Chesapeake Bay Watershed.

The following is a summary of the key takeaways from the review:

- Floodplain hazard maps are based on community participation in FEMA's National Flood Insurance Program (NFIP), which does not provide comprehensive coverage across the watershed. Even among NFIP participants, over 25% of communities have not had their floodplain maps updated by FEMA or a participating partner in the last 10 years.
- Hydrologic, hydraulic and rainfall-runoff models are used by engineers to convert precipitation volume to runoff volume and simulate how it will move through a watershed. The climate-based assumptions in these models have not been recently revisited. Recent evidence shows that variables such as the rainfall distribution curves, initial abstraction and antecedent runoff conditions may all be worth assessing.
- The precipitation data sources referenced in state design manuals vary significantly by age of record. TP-40 only covers a hydrologic record through 1958, while Atlas 14, the most recent precipitation data for the Chesapeake Bay Region, still only covers through 2000. A more thorough analysis comparing the precipitation projections to existing sources will be provided in Memo 3 of this series, but there are already significant increases in the 100-year storm volume observed between Atlas 14 and TP-40.
- Each state and the District of Columbia uses different design criteria. Further, within states, there are often differences in how design storms and precipitation data sources are discussed by departments of transportation, environmental regulatory agencies and the departments overseeing dam safety.
- With one or two exceptions, the most recent wave of state stormwater manual updates occurred between 2006-2013. To date, specific consideration of climate resilience has not been built into any state stormwater design manual in the form of revised sizing criteria or other specific design enhancements. Climate resilience efforts identified in the state Watershed Implementation Plans have focused on providing planning tools and risk assessments rather than regulatory levers that would drive changes to engineering design practice.

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Background

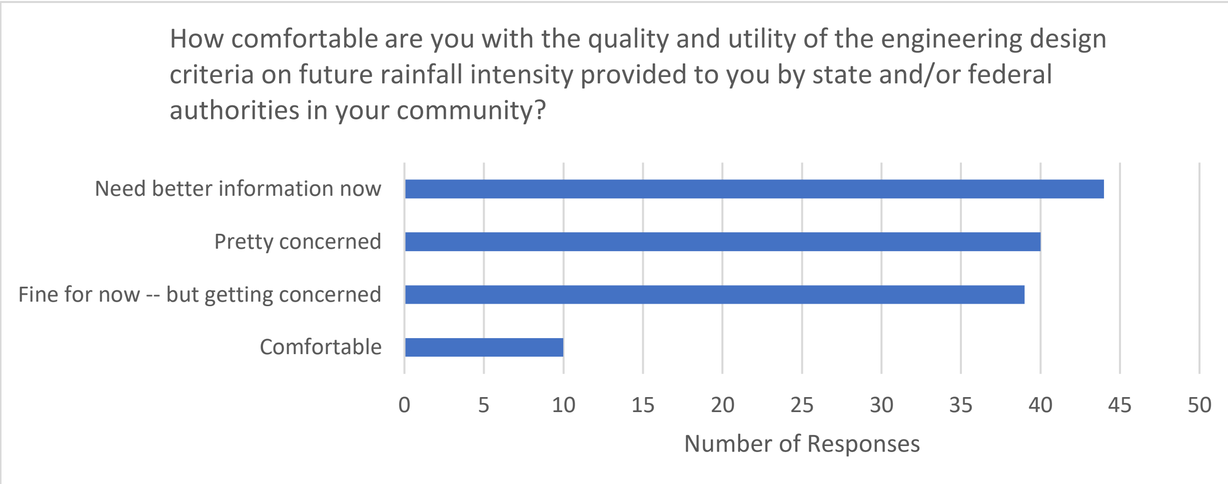
Preliminary analysis from the Chesapeake Bay Program estimates a 3.1% increase in rainfall volume across the Chesapeake Bay Watershed by 2025 (Linker et al. 2019). Further, it is expected that more rainfall will be concentrated in a series of high intensity events that can pose a risk to stormwater infrastructure and best management practices (NOAA 2018). Meanwhile, tidal communities are also experiencing increased occurrence of "blue sky flooding" that can inundate low lying areas, posing a public health risk and decreasing capacity in stormwater conveyance systems.

These changing hydrologic conditions, especially when coupled with ongoing development, pose a risk to stormwater infrastructure and public safety. BMPs and stormwater conveyance systems designed to capture, treat and safely move water through the urban environment may be undersized or ill-equipped to handle runoff from increasingly larger storm events, leading to failure or loss in performance.

To help address this challenge, the Chesapeake Stormwater Network (CSN) is seeking to clearly define the needs of local stormwater managers and identify the specific initiatives that will allow them to address their restoration and public safety functions under future climate conditions.

A recent survey of stormwater managers across the Chesapeake Bay Watershed identified concerns about the ability of current engineering and design guidance to address future climate change condition (Wood and Schueler 2020).

Figure 1. Summary of stakeholder concerns about current engineering design criteria (Wood and Schueler, 2020)



This memo assesses the site-based models and design calculations used to define BMP sizing for pollutant reduction, channel conveyance, flood control and the spatial dimensions of the urban floodplain. It also provides a state-by-state summary of the current stormwater engineering standards and criteria for rainfall and runoff modeling. The goal of this assessment is to provide the necessary information to allow watershed managers to identify opportunities to improve the resilience of their stormwater systems to increasing precipitation. The full series of memos on Maintaining the Resiliency of Stormwater and Restoration Practices in the Face of Climate Change in the Chesapeake Bay Watershed are detailed below:

- **Memo 1:** Summary of Stakeholder Concerns, Current Management and Future Needs for Addressing Climate Change Impacts on Stormwater Management
- **Memo 2:** Review of Current Stormwater Engineering Standards and Criteria for Rainfall and Runoff Modeling in the Chesapeake Bay Watershed
- **Memo 3:** Synthesis of Precipitation Analyses Used to Derive Intensity-Duration-Frequency (IDF) Curves
- **Memo 4:** Vulnerability Analysis of Urban Stormwater BMPs and Restoration Practices

Basics of Stormwater and Floodplain Management

Urban Watershed Basics

Surface runoff in urban watersheds is primarily driven by two variables: climate and physical factors (see Table 1). While climate has always been part of urban stormwater management and design, land use conditions – specifically impervious cover—has historically been the primary driver. As forests are cleared and farms are converted to developed land, permeable surfaces are replaced by rooftops, roads and parking lots. This increase in impervious cover fundamentally alters the watershed's hydrology. Rainfall, once intercepted by tree canopy and absorbed by the ground, is now converted to surface runoff. The impact of increasing impervious cover on the health of the urban stream network is summarized in Appendix B.

While existing stormwater runoff models make it easy to account for physical factors by allowing users to input new land use conditions, for example, the climate variables are more difficult to update. Users are often responsible for providing precipitation data for the models that may be decades old and which no longer represent current climate conditions.

Table 1. Factors affecting surface runoff

Climate	**Physical**
Rainfall intensity	Impervious Cover and Turf Cover
Rainfall amount	Topography
Rainfall duration	Soil Type
Rainfall location	Vegetation
Previous Rainfall	Watershed size
Rain or Snow	Ponds/Reservoirs

Basics of Floodplain Management

While not always thought of as part of the stormwater system, making decisions about floodplain management often falls within the role of watershed or stormwater professionals and can directly impact the performance of BMPs and the drainage network.

Floodplain delineation is the process of mapping the areas adjacent to waterbodies that are subject to recurring inundation. The boundary of the 100-year flood, or the flood with a 1% chance of annual occurrence, is commonly used in floodplain mitigation programs to identify areas where the risk of flooding is significant. These boundaries are established using a combination of field assessments, computer modeling and calibration to flow data from in-stream gages. A typical floodplain delineation involves (FEMA, 2014):

1. Using a site survey or photogrammetric methods to determine the channel and floodplain characteristics (i.e. channel cross-section, floodplain land use and topography, culverts).
2. Computer modeling (HEC-2 or similar) to calculate water surface elevations based upon hydrologic and hydraulic conditions.
3. Establishing the floodplain boundaries on aerial surveys or contour maps based on the computed water surface elevations.

Different from non-tidal flooding, most coastal flooding is driven by storm surge and wave action caused by coastal storms, usually hurricanes and nor'easters. However, rising sea levels are also subjecting coastal communities to more frequent "blue-sky flooding" – inundation of low-lying areas during high tide. Delineating coastal flood boundaries involves computer simulation based on data from past storms and past flood heights. The models typically use data on wind speeds, wind direction, and air pressure from historical hurricanes and correlate the results with the probability of the event occurring during high tide (FEMA, 2014).

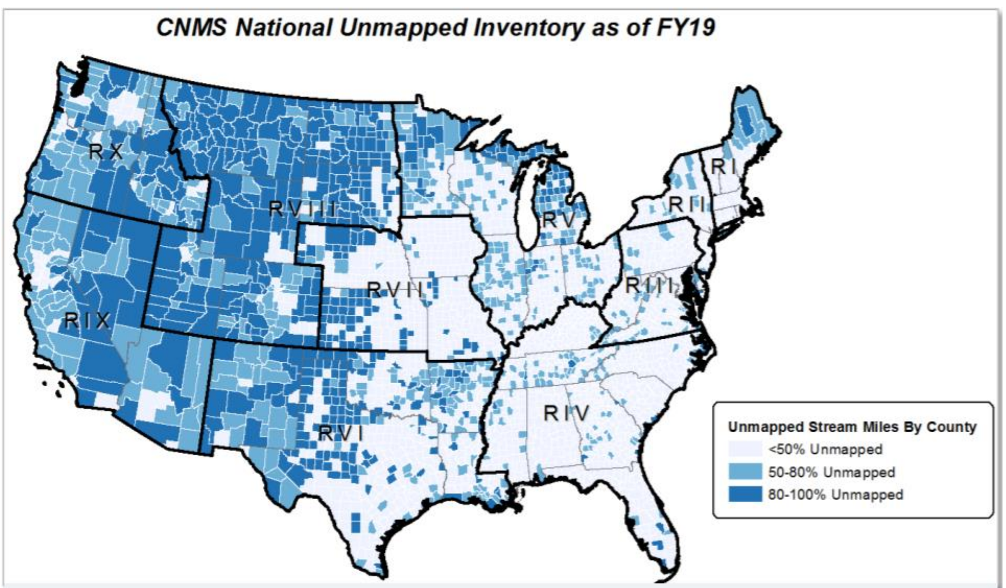
Floodplain mapping is typically done at a local scale and is driven by FEMA's National Flood Insurance Program (NFIP). The NFIP is a voluntary program that aims to reduce the impact of flooding on private and public structures by providing insurance to property owners and encouraging communities to adopt and enforce floodplain management regulations. The NFIP is a partnership with the local communities, and allows them access to flood insurance, grants and loans, and federal disaster relief.

Floodplain boundaries are constantly shifting due to human development and changes in climate. Urbanization makes stream systems more “flashy”, as runoff times decrease and the discharge rates increase. Further, artificial fill in the floodplain reduces the flood channel capacity and can increase the flood height (OAS, 1991). In addition to the changing physical factors, intensity and frequency of precipitation events in the Chesapeake Bay Watershed are expected to increase in the coming years, along with rising sea levels. One study on the impact of climate change and population growth on the NFIP indicated that by 2100, the 1% annual chance floodplain would increase in size by 45% in riverine areas (AECOM, 2013). Of that growth, 30% would be attributable to development and 70% to climate change. These climate variables will influence floodplain elevations and require more frequent updates to flood maps (ASFM, 2020).

FEMA, in coordination with their state and local partners, develops flood maps to show a community’s flood zone, floodplain boundaries, and base flood elevation to assess risk. These maps are updated continually, and represent the 100-year floodplain elevation. Because there are over 20,000 communities across the country that participate in the NFIP program, updates to flood hazard maps may be infrequent.

Across the six Chesapeake Bay states and the District of Columbia, there are 4,744 communities that participate in the NFIP program (including those outside the watershed). Due to differences in how communities are defined, it isn’t clear what proportion of the watershed is covered by the program. Of the communities in the NFIP program, 52% have not had their FEMA floodplain hazard map updated in the last five years and 26% have not been updated in the last 10 years (FEMA, 2020a). While some updates can be FEMA-initiated, most are community-initiated. Some communities work with state or regional technical partners to develop updated floodplain data and hydrologic and hydraulic modeling. Communities and their technical partners submit new data to FEMA following development or restoration activities to ensure the flood insurance maps are up to date (Guignet, 2019).

Figure 2. FEMA Coordinated Needs Management Strategy (CNMS) Unmapped Stream Miles (FEMA 2019).



FEMA Community Needs Management System (CNMS) Unmapped Stream Miles. Source: FEMA

Communities also have the option to participate in FEMA's Community Rating Systems (CRS). CRS is a voluntary incentive program that recognizes and encourages community floodplain management activities that exceed the minimum NFIP requirements. Points are awarded for 19 different activities related to public information, mapping and regulations, flood damage reduction and warning/response. A high score can earn a community discounts on their flood insurance premiums (FEMA, 2020b).

Table 2. Communities Participating in FEMA's National Flood Insurance Program (FEMA, 2020a)

State	Communities in NFIP	Communities in CRS
Delaware	50	11
District of Columbia	1	0
Maryland	147	15
New York	1,506	50
Pennsylvania	2,472	34
Virginia	290	25
West Virginia	278	10

Government officials use flood maps to (ASFM, 2020):

- establish zoning, land-use and building standards;
- support land use, infrastructure, transportation, flood warning, evacuation, and emergency management planning;
- prepare for and respond to floods.

Controlling the development that occurs within the floodplain boundaries helps ensure upland development does not increase the flood hazard to downstream properties. Floodplain development ordinances are produced at the local community scale, and therefore differ widely across the Chesapeake Bay Watershed. However, for communities participating in the NFIP, at a minimum, analysis must be conducted to demonstrate the proposed development or work will not cause any increase in the base flood elevation if it is located within the floodway.

That said, much of the development and infill that has occurred within the floodplain has been grandfathered into the existing codes and ordinances. As a result, many older communities have a mix of residential and commercial development, municipal buildings, roads and utilities within the 100-year floodplain. It is also likely that unless floodplain maps are updated, smaller, incremental land use changes would not be accounted for.

Understanding Current Stormwater Design

Risks and management objectives

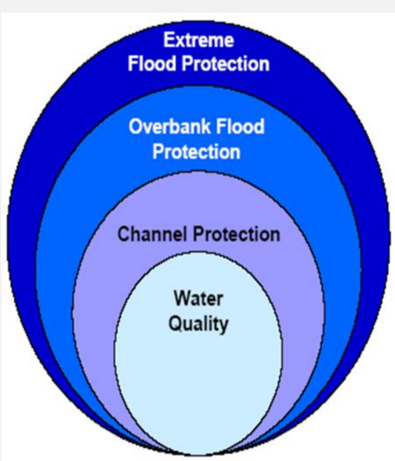
There is a wide-ranging set of risks that need to be managed through stormwater engineering design criteria. While the Chesapeake Bay TMDL places an emphasis on water quality improvement, managers must balance pollutant reduction requirements with other management objectives.

Table 3. Common municipal stormwater risks managed through engineering design criteria.

Physical Risks	Financial Risks
• Public safety (flash flooding, dam failure) • Interruption in public utility service (damage to water lines, road closure, etc.) • Damage to private property, especially in flood zones • Damage to public or private stormwater infrastructure (BMPs, stormwater conveyance, culverts) • Degradation of public open space and habitat conservation areas	• Increased long-term cost to maintain stormwater infrastructure • Loss of BMP function and subsequent loss of TMDL/MS4 permit reduction credit • Capital cost to relocate, replace or retrofit municipal stormwater infrastructure • Increased cost to manage public urban landscaping areas

To address risk and management objectives related to stormwater runoff, engineers use a series of volume-based targets. Stormwater infrastructure is designed to accommodate different storm event sizes tied to each different management objective. Traditional stormwater regulatory criteria required that stormwater quality, as well as increases in volume, velocity, and peak rates of discharge be managed to protect downstream aquatic resources. That created a hierarchy for BMP design within the site development process that nested smaller volumes to address water quality impacts, within the larger volumes that deal with physical impacts, such as flood control. (See Table 4).

Table 4. Summary of Unified Sizing Criteria for Stormwater Management

<table>
<tr><td rowspan="4">
</td><td>Water Quality criteria refers to the storage needed to capture and treat the runoff from a set storm event to remove pollutants such as nitrogen, phosphorus and sediment. For most states in the Chesapeake Bay watershed, this means capturing and treating the 90^{th} percentile, or approximately 1”, rainfall event.</td></tr>
<tr><td>Channel protection criteria are set to ensure that runoff can be stored and released in a gradual manner so that storm events will not cause erosion in downstream channels.</td></tr>
<tr><td>Channel Conveyance (Overbank Flood Protection) criteria are designed to prevent an increase in the frequency and magnitude of storm events that overflow the channels, causing flooding.</td></tr>
<tr><td>Extreme Flood Protection criteria is to prevent flood damage from large storm events, maintain the boundaries of the pre development 100-year FEMA floodplain, and protect the physical integrity of BMP control structures.</td></tr>
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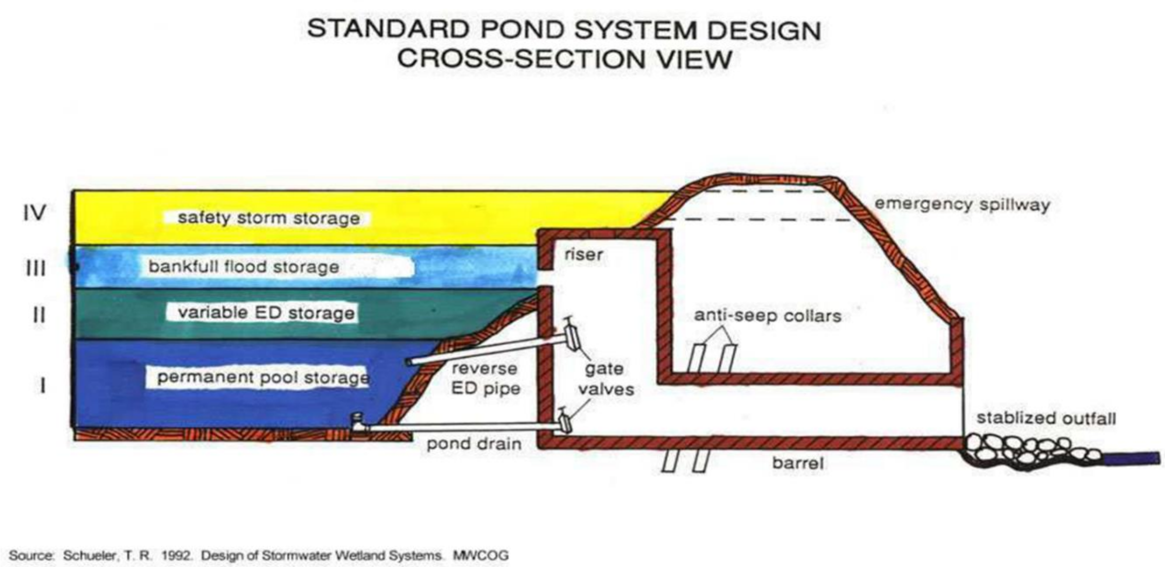
In older stormwater designs, larger pond facilities were used to meet multiple objectives within a single practice (See Figure 2). The predominant method used rate-control detention and extended detention facilities to comply with volume-based requirements, while water quality compliance was generally met through the inclusion of micro-pools, extended drawdown, or other design enhancements. With the most recent wave of state stormwater manuals, released about 10 years ago, there was a shift to more distributed, smaller practices designed to infiltrate runoff and emphasize water quality management. This approach meant site design that generates less runoff by maintaining pre-development hydrologic conditions, and implementing BMPs that effectively reduce runoff volume through processes, such as infiltration, extended filtration, and soil storage.

Figure 2. Stormwater Design to Meet Multiple Objectives



Historically, the volume-based targets were driven by subwatershed changes to impervious cover generated by land development. The Simple Method, a commonly applied model for determining water quality treatment requirements, uses volumetric runoff coefficients that are based on the percent impervious cover in the drainage area. Similarly, hydrologic models like TR-55, use runoff curve-numbers that calculate how much rainfall is converted to runoff based on changes in land use and soil characteristics. As the amount of impervious cover in the watershed increases and more precipitation is converted to surface runoff, the volume needed to be captured and treated increases. However, recent analysis of historic and projected precipitation data suggests that the size and distribution of precipitation events are becoming increasingly important to resilient stormwater design. It is expected that most of the increases to precipitation volume in the Chesapeake Bay region will occur in the largest 10% of storm events (Groisman et al., 2004). This change may lead to renewed interest in volume-driven stormwater practices and conveyance systems.

Understanding the Design Tools

To calculate the size of stormwater infrastructure, there are a number of models that can differ based on the primary objectives (Summarized in Table 5). Most of the models, while sometimes updated, still rely on basic hydrologic principles that haven't changed much over time, as well as climate inputs that can vary in age depending upon the source of data.

Rainfall-Runoff Calculation tools help designers determine the peak flow, runoff volume, and hydrograph functions needed for stormwater design. These tools take a combination of physical and climate factors into consideration to determine how much runoff will be generated for a given rainfall event. Depending on the tool, users select variables like the drainage area size, land cover, soil conditions and the size of the storm event they need to manage, and the tool will produce a hydrograph. From that hydrograph, users can determine the peak flow rate and runoff volume that their infrastructure must capture or safely convey to meet their design objectives.

Hydrologic models include rainfall-runoff simulations, but add in additional factors, such as reservoir and channel routing that can give a more accurate assessment of the hydrology at a site-scale. These tools may be used to evaluate flooding problems, alternatives for flood control (reservoirs, channel modification, and diversion), and impacts of changing land use on the hydrologic response of watersheds.

Hydraulic models include water surface profiles, flow rates, and flow velocities through waterways, structures and pipes. Many of these models also include green infrastructure, allowing users to assess how BMPs manage water through inflow, infiltration, evapotranspiration, storage and discharge. Based on the user's design objectives different specialized models can be selected.

Water Quality models analyze pollutant loading to surface waters or pollutant removal in a BMP. These models build upon the hydrologic and hydraulic models, but also incorporate information about pollutant loads and BMP removal efficiencies to provide site-scale estimates of water quality performance.

Each of these models require precipitation-based input data. Changes in the volume and intensity of storm events will influence the model results. The models also take into consideration factors such as the capacity of the conveyances system, which may be reduced by a rising groundwater table or backflow from tidal systems.

Table 5. Summary of Most Commonly Used Stormwater Models[1]

Model	Model Type	Description
Rational Method	Rainfall-Runoff	A simple hydrologic calculation of peak flow based on drainage area, rainfall intensity, and a runoff coefficient determined by the soil type and slope. Best for simple approximations of peak flow from small watersheds.
TR-55	Hydrologic	NRCS model to calculate storm runoff volume, peak rate of discharge, hydrographs and storage volumes in small urban watersheds. Hydrographs are routed downstream through channels and/or reservoirs. A rainfall-runoff analysis can be performed on up to ten sub-areas and up to ten reaches. The total drainage area modeled cannot exceed 25 square miles.
TR-20	Hydrologic	NRCS model that computes direct runoff and develops hydrographs resulting from any storm event. Developed hydrographs are routed through stream and valley reaches as well as through reservoirs. Best suited to predict stream flows in large watersheds. Users may import NOAA Atlas 14 rainfall data for site-specific applications.
HEC-RAS	Hydraulic	HEC-RAS is a river hydraulics model developed by the U.S. Army Corps of Engineers to compute one-dimensional water surface profiles for steady or unsteady flow. intended for floodplain studies and floodway encroachment evaluations.
SWMM	Hydrologic/Hydraulic/WQ	SWMM is a dynamic rainfall-runoff and water quality simulation model, developed by EPA, primarily for urban areas. Both single-event and continuous simulation can be performed on catchments having storm sewers, or combined sewers and natural drainage, for prediction of flows, stages and pollutant concentrations.
Simple Method	Water Quality	Used for estimating storm pollutant export delivered from urban development sites less than one square mile in area. Method is based on site area, rainfall depth, pollutant concentration, and a runoff coefficient.
Runoff Reduction Method	Water Quality	Similar to the Simple Method, but replaces the runoff coefficient -- which is based upon the percent impervious cover -- with a weighted treatment coefficient that reflects the different runoff coefficients assigned to impervious, managed turf (or disturbed soils), and forest.
[1]Summarized from MPCA (2019).		

Evaluating Climate Impacts on Model Parameters

Each of these tools allows users to adjust the inputs to analyze changing site characteristics. However, until recently, less emphasis has been placed on the climate variables and how changing precipitation conditions could affect the outputs of these modeling tools.

Many designers are using outdated precipitation data. In addition to increasing precipitation intensity, changes in the temporal distribution of storm events could have impacts on the runoff coefficients that make assumptions about antecedent rainfall conditions and soil storage volume.

Rainfall distribution

Rainfall distribution for engineering design is different from rainfall distribution in actual storm events. Actual storms can vary in duration from minutes to days, with periods of high intensity and low intensity within a single event. Design storms use synthetic distribution curves that start at low intensity and gradually increase then taper off over a 24-hour period. The most commonly applied rainfall distribution in the Chesapeake Bay watershed is the NRCS Type II rainfall distribution, developed based on TP-149 in 1973 (USDA-SCS, 1973). A 2011 analysis by NRCS of the Type II rainfall distribution found that when compared to the new Atlas 14 Vol 2 rainfall data, the Type II distribution is not generally applicable for the locations where it has been used in the past (Merkel et al 2011). NRCS now recommends the use of Atlas 14 data, which is available down to the 5-minute duration, in place of the old distribution curves (USDA NRCS, 2015). Documentation on how to import the data into TR-20 is available on their website, but it is unclear how widely known, or utilized, this method is in the stormwater engineering community. Further, many state stormwater manuals and dam safety regulations still reference or require use of the Type II rainfall distribution.

Soil Conservation Service Curve Number (SCS CN)

The CN method is the foundation for many of the rainfall-runoff models used in stormwater design (including the Rational Method, TR-55, and the Simple Method). The curve number is a coefficient that reduces the total precipitation to runoff potential after "losses" from evaporation, absorption, transpiration, and surface storage. The numbers were developed in 1954 and the original data sources are difficult to find. A recent assessment by NRCS showed that historical changes in climate are already affecting the curve-number (CN) method (Bonta 2015). The results suggest that temperature affects the evapotranspiration process by assigning a greater fraction of precipitation losses to initial abstraction, caused by a greater depletion of soil-water storage prior to a runoff event. This change has already been observed over the past several decades and thus the method may need occasional reevaluation if precipitation and temperature continue to increase.

The curve number method is also affected by antecedent runoff conditions (ARC). The curve number can be adjusted based on three ARC conditions: Dry, Average and Wet. For modeling purposes, the average condition is generally assumed, which is based on 1.4-2.0" of 5-day antecedent rainfall in the growing season and 0.5-1.0" in the dormant season (USDA SCS, 1972). The geographic basis, as well as the precipitation period of record for these values is unknown but they have been adopted for general use across the country (Ponce et al. 1996). A greater ARC condition would increase runoff generated from a rainfall event, and rainfall frequency data should be evaluated to consider increasing the default ARC for regional climate data.

Sea Level Rise Impacts on Hydraulic and Hydrologic Modeling

Tidal communities face a number of additional challenges to their stormwater infrastructure that may require new ways of thinking about how to model stormwater systems under changing climate conditions (NOAA, 2020). Some of these challenges are summarized below:

- Some stormwater drainage systems depend on gravity to help water move through the pipes. Flat topography can make this a difficult approach that is further compromised by flooding that causes outfalls to be partially or completely submerged. This combination can greatly prolong a flooding event.
- Coastal flooding at outfalls may drive backflow into the system, causing upland flooding through street drains and drainage ditches. The prolonged presence of saltwater can damage stormwater infrastructure.
- Shoreline erosion may expose stormwater infrastructure to potential damage.
- More frequent, higher, and longer-lasting high water events may drive up already high groundwater levels in some coastal communities. This change may reduce the soil's ability to absorb stormwater, thus increasing runoff.

Understanding the Climate Data Sources

TP-40

Technical Paper 40 (TP-40) was produced by NOAA in 1961 as a resource for hydrologists and water planners around the country. The paper presented analysis of precipitation frequency for durations ranging from 30-minutes to 24 hours and for return intervals from 1 to 100 years. Most of the precipitation frequency relationships developed in TP-40 were based upon a collection of 200 long-record stations that spanned from 1909-1958 (US Dept of Commerce, 1961). These relationships were commonly relied upon by stormwater engineers across the Chesapeake Bay watershed until NOAA's Atlas 14 was released over 40 years later. As such, some state design manuals still have outdated references to TP-40, and some engineers still rely on these values.

Atlas 14

Five of the Chesapeake Bay states, and the District of Columbia were covered in Atlas 14 volume 2, released in 2004 and updated in 2006 (NOAA, 2006). New York was updated more recently when Atlas 14 volume 10 was released in 2016 (NOAA, 2019). Atlas 14 supersedes the data presented in TP-40 and is now considered the current standard for precipitation frequency data across the United States. NOAA Atlas 14 Volume 2 greatly increased the amount of data used in its analysis, increasing the number of stations and the period of record. NOAA Atlas 14 Volume 2 also used more robust statistical analysis, including analyzing multiple distribution functions for each region and accounting for precipitation from nearby stations and topography.

While TP-40 used data up through 1958, Atlas 14 Volume 2 extends that record through 2000. In general, the additional data points show little change precipitation depths at low recurrence intervals when compared to results published in TP-40, but substantial increases at higher recurrence intervals (See Table 6).

Table 6. Comparison of precipitation totals for the 24-hour storm event from TP-40 and Atlas 14 Volume 2. All values are in inches per hour.

Recurrence Interval	Method	Harrisburg, PA	Annapolis, MD	Virginia Beach, VA	D.C.	Laurel, DE	Martinsburg, WV
2-Year	TP-40*	3.5	3.2	3.8	3.2	3.5	2.9
	Atlas 14**	2.67	2.97	3.37	2.89	3.14	2.61
10-Year	TP-40	4.7	5.2	5.9	5.2	5.6	4.7
	Atlas 14	4.29	4.97	5.58	4.77	5.28	4.06
100-Year	TP-40	6.8	7.5	8.9	7.5	7.8	6.7
	Atlas 14	7.41	8.63	9.37	8.28	9.16	6.37

*Data estimated by interpolating from TP-40 Maps
**AMS-based precipitation frequency estimates from NOAA Atlas 14 Volume 2

The precipitation data provided in TP-40 and NOAA Atlas 14 are included in engineering and design manuals for use by stormwater managers. While some engineers choose to go directly to Atlas 14 to obtain precipitation data, many use the rainfall volumes reproduced within their state stormwater design manual, or Chapter 4 of the NRCS National Engineering Handbook (USDA NRCS, 2019). More information on the state design manuals is included in the following section of this report.

The NRCS first published Chapter 4 (Storm Rainfall Depth and Distribution) of the National Engineering Handbook in 1964. Major revisions were published in 1993 and again in 2019. Chapter 4 applies to specific rain events and their analyses as well as monthly and annual rainfall. Chapter 4 also provides a brief account of the sources, variability, and preparation of storm rainfall or precipitation data (USDA NRCS, 2019). While past versions of the Handbook referenced TP-40 as the preferred precipitation frequency data, the most recent update refers users to Atlas 14 for all states in the Chesapeake Bay Watershed.

Updates to NOAA Atlas 14 are dependent upon external funding sources, and thus the timing of updates is unpredictable. There are still several states in the Pacific Northwest that are not covered by Atlas 14, and no timetable has been provided for an updated volume that would cover the Chesapeake Bay Watershed.

The Water Quality Storm

Unlike other management objectives, most states in the Chesapeake Bay watershed define the "Water Quality Storm" as controlling the 90th percentile, or 1 inch, rainfall event. This design is intended to improve water quality by capturing and treating runoff from small, frequent storm events that can contain high pollutant loads. The Rainfall Frequency Spectrum (Schueler 1992), sorted 50 years of hourly rainfall data from Washington National Airport and determined that a BMP sized to capture and treat the three month storm frequency storm (or 1.25" rainfall) effectively treats 90% of the annual average rainfall.

With climate change expected to bring larger, more infrequent storm events, there may be a need to revisit the 90th percentile storm event. A decrease in the number of storms, or an increase in the intensity of events may alter the size of the water quality storm.

Hydrometeorological Report No. 51 (HMR-51)

HMR-51 was published by the National Weather Service in 1978 to provide the Probably Maximum Precipitation (PMP) values for the eastern United States (NOAA, 1978). PMP, sometimes also referred to as the Probable Maximum Flood (PMF) is defined as the theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage area at a certain time of year. Funding is no longer available for the program, and thus updates are no longer occurring, despite NOAA's recognition that updates are needed (NOAA, 2017).

Both Pennsylvania and Virginia have conducted their own updates to the PMP values from HMR-51 and found that with an expanded storm record, improved climate data and more spatial and temporal resolution, that they were able to refine PMP estimates within their states (Kappel et al., 2015; Kappel et al., 2019). While the lack of notes and underlying data behind the original HMR-51 documents make direct comparisons difficult, both Virginia and Pennsylvania found average decreases in PMP depths when compared to HMR-51.

Summary of State Engineering Design Standards

Stormwater engineering design standards vary considerably across the Chesapeake Bay watershed states. This section summarizes the key takeaways from a review of the stormwater design standards and initiatives outlined by the states in the Phase III WIPs and in discussions with state agency representatives. Detailed summary tables are produced for each state in Appendix A, along with non-exhaustive lists of recent research in the state to understand climate projections, understand risks/vulnerabilities and provide guidance on resilience strategies related to stormwater management or floodplain protection. There are several key takeaways from this state-by-state review:

- Most states have not updated their stormwater manual in the last 5-10 years. A new round of updates would provide the opportunity to incorporate the latest precipitation data, provide consistency across agencies and design objectives, and explore new design options to improve resiliency while addressing water quality and volume. More discussion of options will be provided in Memo 4 of this series.
- In addition to the variety between states, similar variety is present within states. Transportation agencies, environmental regulatory agencies, and dam safety departments often all have separate design manuals, regulations and resources. There is a need for consistency in how precipitation data is discussed and how data sources are updated.
- In most states, water quality design is still based on the 90th percentile storm event rather than NOAA Atlas 14-based recurrence intervals. States should consider evaluating whether the 90th percentile storm event has changed, and whether it still provides the desired level of treatment volume to meet water quality objectives.
- There have been few examples of changes to policies, regulations or design standards to improve the climate resilience of stormwater infrastructure. To date, state climate resiliency initiatives have focused on developing planning tools, conducting risk assessments and developing resiliency plans, but there are few examples of changes being implemented that are directly linked to stormwater design and management.

Table 7. Summary or Manual Updates and Precipitation Data Sources

	Design Objective[1]	Date of Latest Publication	Precipitation Data
DE	Stormwater	2019	Reproduced from Atlas 14[2]
	Transportation	2008	Reproduced from Atlas 14
	Dam Safety	2004	TP-40; HMR-51[3]
D.C.	Stormwater	2013 (minor rev. 2019)	Atlas 14
	Transportation	2017	Atlas 14
MD	Stormwater	2009	Reproduced from TP-40
	Transportation	2009	Reproduced from TP-40
	Dam Safety	2000	No source referenced
NY	Stormwater	2015	Atlas 14
	Transportation	2018	Atlas 14 + NRCC Future Projections[4]
	Dam Safety	1989	TP-40; HMR-51
PA	Stormwater	2006	None referenced
	Transportation	2010	Reproduced from Atlas 14
	Dam Safety	2011	None referenced
VA	Stormwater[5]	2011	None referenced[6]
	Transportation	2019	Atlas 14
	Dam Safety	2018	PMP Study for Virginia (2015)
WV	Stormwater	2012	None referenced
	Transportation	2012	Reproduced from Atlas 14
	Dam Safety	2009	None referenced

[1] May refer to design manual or relevant regulation. In some states, regulations have been updated but are not yet reflected in an updated design manual.
[2] Relevant data are reproduced in the manual, as opposed to users obtaining it directly from Atlas 14.
[3] Hydrometeorological Report No. 51 (NOAA 1978)
[4] Northeast Regional Climate Center (http://precip.eas.cornell.edu/)
[5] A revised manual from 2013 is available, but still listed as DRAFT by VA DEQ. Virginia BMP Clearinghouse website links to NOAA Atlas 14.
[6] The Virginia Stormwater Management Program regulations prescribe the use of NOAA Atlas 14 data (VSMP Regulation, 2013).

Conclusion

Precipitation-based engineering design criteria is the foundation for stormwater management across the Chesapeake Bay Watershed. Increases in precipitation volume and intensity have already been observed, particularly for larger storm events, indicating an already-present risk that critical infrastructure designed to safely convey the 100-year storm event may be undersized. Further, climate change projections indicate that these trends will continue, underscoring the importance of providing stormwater managers with design criteria that are based on the latest science to improve the resilience of stormwater infrastructure.

Current engineering design criteria vary across the watershed, as well as within states depending on the management objectives. That variety creates additional challenges when it comes to developing unified guidance to address updates to precipitation data and tools. As new updates to precipitation data are available, it is important to understand how many agencies may need to update their manuals, and the history of how these updates have been made in the past. For example, many stormwater design manuals reference Atlas 14 precipitation data as the basis for stormwater design. Updating Atlas 14 would avoid the need to develop new stormwater manuals – a process that can take years – because engineers would still use Atlas 14, but would now have updated precipitation data. However, those updates would still be based on historical records that may themselves be outdated again in several years. Updating IDF curves is also only one potential option for improving the resilience of stormwater infrastructure.

Finally, floodplain management is an often-overlooked part of stormwater management and to date, participation in programs like FEMA's Community Rating System are very limited. Floodplain regulations are developed at a local scale, and those communities are dependent upon FEMA's NFIP program to provide access to flood insurance, grants and loans, and federal disaster relief. FEMA's floodplain maps are based on the 100-year storm, and updates to the floodplain boundaries can have significant implications for the local communities. While partnerships with states and other local partners has helped, many communities are using outdated floodplain maps.

Providing states and local governments with the most up-to-date precipitation data and science on the accuracy of their hydrologic tools is an important first step in building climate resilience. However, work is also needed to translate those updates into meaningful action through updates to regulations and design criteria. Further, a communication of the importance of those changes will be critical, as a cohesive message across state agencies and departments will result in more effective implementation.

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Appendix A. State Engineering Design Standards and Climate Resilience Initiatives

This appendix provides an overview of the stormwater design standards used by each state and the District of Columbia. Each summary also includes a non-exhaustive lists of recent research in the state to understand climate projections, understand risks/vulnerabilities and provide guidance on resilience strategies related to stormwater management or floodplain protection. While other climate resilience efforts, such as those focused on reducing temperature impacts or greenhouse gas emissions are important, they fall outside the scope of this report.

Delaware

Table 8. Delaware[1]

Range of Urban Stormwater Design Criteria Potentially Influenced by Future Changes in Rainfall Depths, Intensity or Hourly Distributions

Management Objective	**Design Storm**
Resource Protection Event	Treatment of a 1-inch runoff from a RPv, which is equal to a runoff volume generated by a 2.7" storm (1 year, 24 hr storm)
Channel Conveyance Construction-Site Management	2-year 24 hour
Channel Conveyance Post-Construction	10-year 24 hour
Extreme Flood Volume	100-year 24 hour storm
Road Drainage, Bridge and Culvert Design	Bridges and Culverts: • Interstates/Freeways/Expressways: 50-year • Principal and Minor Arterials: 50-year
Dam Safety[2]	Hazard Class 1: Probably Maximum Flood Hazard Class 2: 50% of the Probable Maximum Flood Hazard Class 3: 100-year, 24 hour, Type II distribution (or approved NRCS alternative)
Floodplain Delineation	100-year floodplain

NOTES
[1]Summarized from (7 DE Admin. Code 5101, 2019), (DelDOT, 2008), (7 DE Admin. Code 5103, 2004) and (DNREC, 2013)
[2] Represents the emergency spillway design storm.

Summary of Climate Resilience Initiatives Related to Stormwater Management (non-exhaustive):

- Delaware has completed a comprehensive Climate Change Impact Assessment, as well as a series of reports on Adapting for Sea Level Rise.
  - Delaware Climate Change Impact Assessment (2014)
  - Sea Level Rise Vulnerability Assessment (2012)
  - Recommendations for Adapting to Sea Level Rise in Delaware (2013)
  - Sea Level Rise Adaptation Worksheet and Interim Implementation Plan (2014)
- Delaware published a step-by-step guidance document with instructions for siting and design of state-funded projects to avoid and minimize flood damage.
  - Avoiding and Minimizing Risk of Flood Damage to State Assets: A Guide for Delaware State Agencies (2016)
- Delaware has developed the "Delaware Climate Projections Portal" to provide data and visualization tools based on analysis published in the Delaware Climate Change Impact Assessment (DNREC, 2014). The Portal allows users to view a variety of precipitation and temperature projections under low and high end emissions scenarios for 14 downscaled locations across the state.
- Delaware has developed a sea level rise map that overlays a projected 3 feet of sea level rise onto the 100-year FEMA flood elevation maps for use as a general planning tool (DE SLR Advisory Committee, 2012).

District of Columbia

Table 9. District of Columbia[1] Range of Urban Stormwater Design Criteria Potentially Influenced by Future Changes in Rainfall Depths, Intensity or Hourly Distributions	
Management Objective	**Design Storm**
Stormwater Retention Volume[2]	• Major land-disturbing activity (AWDZ[3] and District-wide): 90th percentile event (1.2 in.) • Major substantial improvement activity (AWDZ): 85th percentile event (1.0 in.) • Major substantial improvement activity (District-wide): 80th percentile event (0.8 in.)
Water Quality Treatment Volume	95th percentile rain event (1.7 inches)
Channel Protection	2-year 24 hour to the pre-development peak discharge
Channel Conveyance	15-year 24 hour to the pre-development peak discharge
Extreme Flood Volume	100-year 24 hour storm
Road Drainage, Bridge and Culvert Design	Road Drainage: • Interstate system = 25 year • Underpasses and depressed highways = 50 year • Bridge decks = 5 year • All other city streets = 15 year Culverts: • Freeways = 50 Year • Principal Arterials = 50 Year • Minor Arterial/Collectors = 25 Year • Local Streets = 10 Year Bridges: • Designed to withstand 100 year • Checked for 500 year or 1.7 times the 100 year. •
Dam Safety	100 year 24 hour storm
Floodplain Delineation	100-year floodplain
Hydraulics/Storm Sewer Pipes	15 year, 24 hours with pipe flowing full 50-year storm for pipes draining to a low point in a sag
NOTES [1] Summarized from (DOEE, 2020), (DDOT, 2017), (DC Mun Reg, 2010), (DC Water, 2018). [2] Major land-disturbing activity is defined as >5,000 sqft of disturbance; Major substantial improvement activity is defined as >5,000 sqft of disturbance and cost that equals or exceeds fifty percent (50%) of the market value of the structure before the improvement. [3] AWDZ = Anacostia Waterfront Development Zone	

Summary of Climate Resilience Initiatives Related to Stormwater Management (non-exhaustive):

- The District is the only Chesapeake Bay jurisdiction that committed to incorporating climate change projections into their nutrient planning targets in their Phase III Watershed Implementation Plan. In doing so, the District will further reduce its load by 6,000 pounds of nitrogen and 1,028 pounds of phosphorus by 2025 (DOEE, 2019).
- DOEE has developed a series of reports on anticipated climate change impacts on the District, as well as adaptation strategies:
  - Climate Projections and Scenario Development (2013)
  - Vulnerability and Risk Assessment (2016)
  - Climate Adaptation Plan (2016)
- DOEE is exploring revisions to its floodplain regulations to increase the District's resilience and account for sea level rise and more intense storms.
- As part of its MS4 permit requirements, DOEE will assess its stormwater performance standards established by the District's stormwater management regulations by 2020. The assessment will consider future precipitation forecasts.
- DOEE is developing Climate Resilient Design Guidelines that will provide parcel-scale recommendations for reducing the risk of climate impacts on property owners.
- DOEE is developing an integrated flood model for the city.
- DOEE is working with sister agencies to identify opportunities to use blue-green infrastructure and cloudburst management strategies that will reduce the city's risk of flooding from intense rainfall.
  - Blue Green Infrastructure: Cloudburst Management Strategies for the District of Columbia (2019)

Maryland

Table 10. Maryland[1] Range of Urban Stormwater Design Criteria Potentially Influenced by Future Changes in Rainfall Depths, Intensity or Hourly Distributions	
Management Objective	**Design Storm**
Recharge	90th percentile annual rainfall event multiplied by a hydrologic soil group recharge factor
Water Quality (WQv)	New development: Environmental Site Design (ESD) to the Maximum Extent Practical (MEP) for the 1-year, 24-hour storm event, which is 2.7 inches.[2] Redevelopment: Reduce existing imperviousness by 50%, or provide water quality treatment (i.e., runoff from 1" of rainfall) for 50% of existing imperviousness.
Channel Protection	1 year, 24 hour
Channel Conveyance	Western Shore: 10 year 24 hour Eastern Shore: 2 year, 24 hour
Road Drainage & Culvert Design	Culverts: • Principal Arterials: 100 year • Intermediate Arterials: 50 year • Minor Arterials: 50 year • Major and Minor Collectors: 25 year • Local Streets: 10 year
Dam Safety	Emergency spillway: 100 year
Floodplain Delineation	100-year
NOTES [1] Summarized from (MDE, 2009), (MDOT SHA, 2009) [2]ESD defined as using small-scale stormwater management practices, nonstructural techniques, and better site planning to mimic natural hydrologic runoff characteristics and minimize the impact of land development on water resources.	

Summary of Climate Resilience Initiatives Related to Stormwater Management (non-exhaustive):

- Maryland has published a Comprehensive Strategy for Reducing Maryland's Vulnerability to Climate Change that details strategies for coastal storms, sea level rise and resilience:
  - Phase I: Sea Level Rise and Coastal Storms (2008)
  - Phase II: Building Societal, Economic and Ecological Resilience (2010)

- Maryland published guidance for BMP siting and design to improve the resiliency of stormwater practiced:
    - Best Management Practices: Preserving Clean Water in a Changing Climate (2013)
- Maryland produced the Coastal Atlas, an online mapping and planning tool that allows state and local decision-makers to explore and analyze data for coastal and ocean planning activities.
- CoastSmart Communities is a program dedicated to assisting Maryland's coastal communities address short- and long-term coastal hazards, such as coastal flooding, storm surge, and sea level rise. CoastSmart connects local government staff and partners to essential information, tools, people, and trainings.
- MD DNR has worked with the Eastern Shore Land Conservancy and UMD on climate change projections and local policy and management options for eastern shore communities:
    - Preparing for Increases in Extreme Precipitation Events in Local Planning and Policy on Maryland's Eastern Shore (2020)
    - Mainstreaming Sea Level Rise Preparedness in Local Planning and Policy on Maryland's Eastern Shore (2019)

New York

Table 11. New York[1]

Range of Urban Stormwater Design Criteria Potentially Influenced by Future Changes in Rainfall Depths, Intensity or Hourly Distributions

Management Objective	**Design Storm**
Water Quality (WQv)	90^{th} percentile annual runoff event[2]
Channel Protection	1 year, 24 hour
Channel Conveyance	10 year 24 hour
Extreme Flood	100-year 24 hour
Road Drainage & Culvert Design[3]	Culverts: • Interstates and Freeways: 50 year • Principal Arterials: 50 year • Minor Arterials/Collectors/Local Roads: 50 year Drainage System: • Interstates and Freeways: 10 year • Principal Arterials: 10 year • Minor Arterials/Collectors/Local Roads: 5 year Ditches: • Interstates and Freeways: 25 year • Principal Arterials: 25 year • Minor Arterials/Collectors/Local Roads: 10 year
Dam Safety	Emergency spillway: Small Hazard Class A: 100 -year event Large Hazard Class A: 150% of the 100-year Small Hazard Class B: 250% of the 100 year storm Large Hazard Class B: 40% of PMF Small Hazard Class C: 50% of PMF Large Hazard Class C: PMF
Floodplain Delineation	100-year

NOTES

[1] Summarized from (NYS DEC, 1989), (NYS DEC, 2015), (NYS DOT, 2018)

[2]Currently the 1” storm.

[3]New NYSDOT Guidance: Current peak flows shall be increased to account for future projected peak flows for culvert design and natural channel relocations. Based on the USGS developed "Future StreamStats" tool, flows in Regions 1, 2, 7, 8, 9, 10, and 11, and Cortland and Oswego Counties in Region 3 shall be increased by 20%. Current peak flows in Regions 4, 5, and 6, and Cayuga, Onondaga, Seneca and Tompkins Counties in Region 3 shall be increased by 10%

Summary of Climate Resilience Initiatives Related to Stormwater Management (non-exhaustive):

- The Northeast Regional Climate Center developed downscaled future precipitation projections for New York under high and low emissions scenarios. The NYSDOT subsequently issued new guidance, increasing the peak flows used in culvert design to account for projected future precipitation.
- Adopted the Climate Risk and Resiliency Act in 2014 that adds mitigation of risk due to sea-level rise, storm surge, and flooding to the list of smart-growth criteria and requires the development of model local laws that include consideration of future risk due to sea-level rise, storm surge, and/or flooding.
- New York developed a series of guidance documents to help state agencies as they assess risks and identify mitigation opportunities to protect communities from sea-level rise, storm surge and flooding:
    - Guidance for Smart Growth Public Infrastructure Assessment (DRAFT)
    - Climate Smart Resiliency Planning: A Planning Evaluation Tool (2014)
- The Resilient NY flood studies will identify the causes of flooding within each watershed and develop, evaluate, and recommend effective and ecologically sustainable flood and ice-jam hazard mitigation projects. Proposed flood mitigation projects will be identified and evaluated using hydrologic and hydraulic modeling to quantitatively determine flood mitigation recommendations that will result in the greatest flood reductions benefits.

Pennsylvania

Table 12. Pennsylvania[1] Range of Urban Stormwater Design Potentially Influenced by Future Changes in Rainfall Depths, Intensity or Hourly Distributions	
Management Objective	**Design Storm**
Volume Control[2]	Guideline 1: 2 year, 24 hour event Or Guideline 2: Capture first 2" of runoff from contributing impervious surfaces and permanently remove[3] the first 1".
Peak Rate Control for Large Storms	100 year, 24 hour
Road Drainage & Culvert Design	Bridges/Culverts/Cross Pipes: • Interstate and Limited Access Highways: 50 year • Principal Arterial System: 50 year • Minor Arterial System: 25 year • Other Collector Systems: 10 year • Local Road and Street Systems: 10 year
Dam Safety	Emergency spillway: Class C4: 50 year to 100 year Class A4, B4, C2, C3: 100 year to 50% of PMF Class A1, A2, A3, B1, B2, B3, C1: 50% PMF to PMF
Floodplain Delineation	100-year
Notes: [1] Summarized from (PA DEP, 2006), (PennDOT, 2015), (25 Pa. Code, 2011) [2]Engineers may select either Control Guideline 1 or Control Guideline 2. For sites greater than 1-acre, they must use Control Guideline 1. [3] Refers to reuse, evaporation, transpiration or infiltration	

Summary of Climate Resilience Initiatives Related to Stormwater Management (non-exhaustive):

- Pennsylvania develops Climate Impact Assessments periodically, per the requirements of the Pennsylvania Climate Change Act of 2008. They also published two reports on risks and adaptation strategies, one for the entire state and one for PA DCNR lands:
  - Pennsylvania Climate Impact Assessment (2015)
  - Pennsylvania Climate Adaptation Planning Report: Risks and Practical Recommendations (2014)
  - Climate Change Adaptation and Mitigation Plan: PA DCNR (2018)

- The 2019 Climate Impact Assessment will include more direct focus on impacts to water quality goals and the resilience of critical infrastructure to extreme events.
- Pennsylvania revisited the PMP values from HMR-51 in 2019 and replaced them with new values (Kappel et al., 2019). Commonwealth-wide it was found that on average, PMP values for local storms showed reductions of between 10-57% in the average PMP volumes for the 10-sqmi drainage area compared to HMR-51, depending on the duration of the storm and the physiographic region.

Virginia

Table 13. Virginia[1] Range of Urban Stormwater Design Criteria Potentially Influenced by Future Changes in Rainfall Depths, Intensity or Hourly Distributions	
Management Objective	**Design Storm**
Water Quality (WQv)	90^{th} percentile annual rainfall event[2]
Channel Protection	Man-made channels: 2 year, 24 hour or Energy Balance (based on 1-year, 24 hour storm Natural Stormwater Conveyance Channels: Energy Balance (1-year, 24 hour)
Channel Conveyance	10 year 24 hour
Extreme Flood	100-year 24 hour
Road Drainage & Culvert Design[3]	Culverts/Road Drainage: • Interstate, Freeways: 50-year • Principal Arterial: 50-year • Urban Minor Arterial System: 50-year • Rural Minor Arterial System: 25 year • Rural Collector System, Major: 25-year • Rural Collector System, Minor: 10-year • Urban Collector System: 10-year • Local Street System: 10-yea
Dam Safety	Emergency Spillway: • Low Hazard: 100 Year • Significant: 0.5 PMF • High: PMF[2]
Floodplain Delineation	100-year
NOTES [1] Summarized from (VA DEQ, 2013), (VDOT, 2019), (VA DCR, 2016), (9 VAC, 2013) [2] Currently the 1” rainfall [3] Engineer must develop PMF hydrographs for 6-, 12-, and 24-hour durations	

Summary of Climate Resilience Initiatives Related to Stormwater Management (non-exhaustive):

- Executive Order 24: Increasing Virginia's Resilience to Sea Level Rise and Natural Hazard mandates the creation and implementation of a "Coastal Resilience Master Plan." The plan will detail specific actions to assist local governments in reducing flood risk through planning and implementation of large-scale flood reduction and adaptation initiatives.
- Developed the ADAPTVA portal that includes forecasting, case studies and policy tools to support sound decision-making related to climate change and resilience.
- The Virginia Coastal Zone Management Program has supported a number of locally-led climate adaptation efforts, including adaptation plans and risk assessments for Hampton Roads PDC, Middle Peninsula PDC, Northern Virginia Regional Commission and Accomack-Northampton PDC.
- Virginia revisited the PMP values from HMR-51 in 2015 and replaced them with new values (Kappel et al., 2015). Commonwealth-wide it was found that on average, PMP values for local storms showed reductions of 30% at 24-hour 200- square miles and 1000-square miles, and 25% at 72-hours 200-square miles and 1000-square miles
- Numerous resilience efforts have taken place at the local level in the Hampton Roads region. These include efforts to draft new design storm manuals for the City of Virginia Beach, new resilience zoning ordinances in Norfolk, and regional resiliency guidelines. These efforts are summarized in Appendix C.

West Virginia

Table 14. West Virginia[1] Range of Urban Stormwater Design Criteria Potentially Influenced by Future Changes in Rainfall Depths, Intensity or Hourly Distributions	
Management Objective	**Design Storm**
Water Quality (WQv)	90th percentile annual rainfall event[2]
Channel Protection	Locally determined. Likely to be 2 year, 24 hour
Channel Conveyance	Locally determined. Likely to be 10 year 24 hour
Extreme Flood	Locally determined. Likely to be 100-year 24 hour
Road Drainage & Culvert Design[3]	Storm Drainage: • Inlet Design: 10-year • Pipe Outlet: 10-year Channels/Culverts/Bridges: • Divided Highway and Principal Arterials: 50-year • Highways over 400 ATD[2]: 25-year • Highways under 400 ADT: 10-year Ditches • Roadside, Secondary, and Median: 10-year
Dam Safety	Emergency Spillway: Class 1: PMF for 6 hr storm Class 2: 50% PMF for 6 hr storm Class 3: 25% PMF for 6 hr storm Class 4: 100 year, 6 hr storm
Floodplain Delineation	100-year

NOTES

[1] Summarized from (WV DEP, 2012), (WV DOH, 2007) and (W. VA Code, 2009)

[2] Currently the 1" rainfall

[3] Average Daily Traffic Volume

Summary of Climate Resilience Initiatives Related to Stormwater Management (non-exhaustive):

- At this time, state and/or local climate strategies have not been developed in West Virginia. At the local level, communities are starting to emphasize hazard mitigation planning to address the adverse impacts from increasing storm frequency, volumes and intensities. These plans rely on voluntary green infrastructure retrofitting as a mechanism to co-benefit local flooding and CSO control issues.
- West Virginia is expects nutrient and sediment load increases due to climate change to be addressed numerically with the "freeboard" they created by developing a WIP that overachieves the planning targets.

Appendix B. Impacts of Impervious Cover on Stream Health

TABLE 1. IMPACTS OF IMPERVIOUS COVER ON STREAM HEALTH	
Changes in Stream Hydrology	
	• Produces more stormwater runoff volume during every storm event • Increases stream "flashiness" by delivering runoff more rapidly via curbs, ditches and pipes • Increases the frequency of extreme floods in the stream corridor • Increases the frequency of bank full floods that control the shape of the stream channel • Expands the height and width of urban floodplains, putting more people and structures at risk • Decreases stream flow during dry weather conditions, unless flows are augmented by leaks from urban pipe infrastructure
Loss of Stream Corridor Integrity	
	• Buries zero and first order streams and replaces them with a network of storm drain pipes and ditches • Encroaches into the existing floodplain via grading, sewers, buildings and other disturbances • Clearing of intact riparian forests along the stream corridor and interruption of fish and wildlife movement • Increases the number of stream crossings that can become barriers that prevent migration of resident and anadromous fish. • Disconnects the stream from its floodplain and degrades adjacent palustrine wetlands
Changes in Urban Stream Geomorphology	
	• De-stabilizes urban stream channels through enlargement or incision or both • Increases the severity of sediment export from stream bank erosion at the subwatershed level, particularly for headwater streams • May increase floodplain sediment storage in some reaches of larger streams and rivers • Sharply increases downstream sediment delivery especially when urban streams erode through extensive sediment deposits behind old mill dams
Degradation of Urban Stream Habitat	

	• Sharp declines in stream habitat quality scores • Simplifies and degrades stream pool-riffle structure • Reduces the amount of large woody debris found in stream channels • Changes how leaf litter and organic carbon are processed, which forms the base of the stream food chain • Increases stream temperature by 2 to 10 degrees F • Reduces streambed substrate quality by filling, fouling and microbial growth
Diminished Water Quality	
	• Increases salinity in streams, ponds and lakes due to road salting • Continuous violations of bacteria standards for water contact recreation after nearly every storm event and occasionally during dry weather • Sharp increases in nutrient loads that cause symptoms of eutrophication in streams, lakes, rivers and estuaries • Increases in pesticides, metal and hydrocarbon concentrations that cause toxicity to aquatic life • Contaminates bottom sediments of urban ponds, lakes, rivers and estuaries with toxic compounds • Increases loads of trash, debris and micro-plastics delivered to receiving waters
Loss of Stream Biodiversity	
	• Declines in aquatic insect diversity, especially stoneflies, mayflies and caddisflies • Decreases the number of fish species, especially "habitat sensitive" ones, such as trout and salmon • Declines in the abundance and diversity of amphibians along the stream corridor • Increases toxic accumulation in fish tissue and fish-eating raptors • Increases in the dominance of invasive plant species along the stream corridor

Appendix C. Hampton Roads Climate Change and Sea Level Rise (SLR) resilience efforts (6/18/19)

Hampton Roads has been addressing issues related to climate change and sea level rise as a step towards resiliency for a number of years. Early efforts were geared towards defining the problem and understanding the science behind the observed changes to weather patterns and our landscape. These summaries can be found in many of the reports below. Current work is further focused on detailing the specific types of flooding concerns and relating them to societal issues, emergency management, ecosystem restoration, water quality, stormwater, and economic vulnerability. Many tools and websites are currently available from federal, state, and local entities that provide existing data, allow for data input, and synthesize multiple types of data. Technical evaluations are still needed to further refine predictive models to determine when and where localized flooding will occur based on precipitation, wind events, tides, groundwater, infrastructure, and a combination of these factors. Data gathering, in the form of stormwater infrastructure specifications, water level elevations, land elevations, groundwater, and meteorological conditions, is needed to inform current stormwater and hydrodynamic models. Efforts are underway to provide management strategies with multiple benefits, in which management for flood control also has a positive impact on water quality, quality of living, and economic growth where possible. Finally, efficiency for any flood and stormwater controls in the form of best management practices (BMPs) or policy changes must be evaluated over time with respect to costs, maintenance, and overall feasibility.

Reports:

Climate Change in Hampton Roads (2008-2012)

- Phase I – potential impacts from climate change in Hampton Road, 2010, HRPDC. https://www.hrpdcva.gov/uploads/docs/Climate_Change_Final_Report_All.pdf
- Phase II – analyzing the impacts of storm surge flooding in the built environment and the economy, 2011, HRPDC.

https://www.hrpdcva.gov/uploads/docs/HRPDC_ClimateChange2010_FINAL.pdf

- Phase III – analyzing potential future impacts of sea level rise on the region's population, built environment, infrastructure, economy, and natural environment, 2012, HRPDC. https://www.hrpdcva.gov/uploads/docs/HRPDC_ClimateChangeReport2012_Full_Reduced.pdf

Coastal Resiliency: Adapting to Climate Change in Hampton Roads, 2013, HRPDC.

- Includes more accurate maps that include elevation datasets and recommendations to local governments.

https://www.hrpdcva.gov/uploads/docs/07182013-PDC-E9I.pdf

Land and Water Quality Protection in Hampton Roads (Phase II), 2013, HRPDC.

- Evaluates stormwater controls in the coastal plain, encourages multiple benefit BMPs to incorporate flood mitigation and TMDL compliance, offers policy change considerations https://www.hrpdcva.gov/uploads/docs/11212013-PDC-E3A.pdf

Hampton Roads Sea Level Rise Planning and Technical Assistance, 2015, HRPDC.

- Includes new inundation maps, an explanation of the methodology and scenarios used for the maps, and case studies for implementing local policies.

https://www.hrpdcva.gov/uploads/docs/Attachment_07_A_HRPDC_Sea_Level_Rise_FY_13_15.pdf

Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Pilot Project (Phase I & II), 2016, ODU. https://digitalcommons.odu.edu/hripp_reports/

Policy:

Adopted the Regional Sea Level Rise Planning Policy and Approach
Summary of Recommendations
- Localities should plan for sea level rise using 1.5 feet of relative sea level rise above current mean higher high water (MHHW) for near-term planning, 3 feet of relative sea level rise above current MHHW for medium-term planning, and 4.5 feet of relative sea level rise above current MHHW for long-term planning.
- For engineering and design, localities should calculate project-appropriate sea level rise scenarios by using a tool such as the U.S. Army Corps of Engineers Sea Level Change Calculator and conduct a benefit-cost analysis of various adaptation strategies to determine an appropriate amount of sea level rise for a specific project.
- These scenarios should be reevaluated as appropriate based upon new information developed by the National Oceanic and Atmospheric Administration, U.S. Army Corps of Engineers, or Virginia Institute of Marine Science.

Virginia Beach Sea Level Rise Policy Adaptation Report – Currently working on a draft design storm manual for the city

Websites/Tools:

Hampton Roads Resilience Projects – Maps completed, planned, proposed, under construction, and under design resilience projects. Includes costs and project categories (acquisition, beach replenishment, drainage improvements, elevations/flood proofing/buyouts, green stormwater management, natural shoreline management, road improvements, shoreline armoring/protection, stream restoration, structural flood protection, and wetland restoration)

StormSense Project – aid to predicting floods from storm surge, rain, and tides, hosts water level sensors used for predictive modeling

NOAA's Coastal Flood Exposure Mapper – Use this tool to create and share maps of sea level rise and flooding, and view the potential populations impacted.
NOAA's Ecosystem Services – Guidance, checklist, toolkit, data resources for evaluating cost/benefits of ecosystem services
AdaptVA – Includes multiples types of resources (forecasts, adaptations, tools, data, planning & policy) to inform those interested in planning in the face of climate change, specific to VA
Native Plants for Southeast Virginia – Guidance on native plant choices based on their tolerance to temperature, precipitation, flooding, etc.

Data and Data gathering exercises:

Precipitation/rain gauge data – Hampton Roads Sanitation District's rain gauge network (region-wide, on all pump stations), National Weather Service

Stormwater monitoring – Hampton Roads Regional Water Quality Monitoring Program

Water Level monitoring – Sensors specific to localities (VA Beach, Norfolk…), Storm Sense sensors, USGS sensors, NOAA water level, tide, and current stations

Groundwater monitoring – Army Corp of Engineers monitoring the growing season for wetlands, HRSD modeling and monitoring efforts (SWIFT), USGS groundwater monitoring network

Catch the King – Crowd source mapping for improving predictive mapping of nuisance flooding using sea level rise app

Coastal Flooding map book – The intent is to create a regional inventory of areas vulnerable to flooding through locality reporting (i.e. Norfolk Storm Mobile App), high water markers, work orders, locality-specific repetitive loss information, work in progress

First Floor elevation data – Gathering and mapping first floor elevation data to apply to coastal hazard vulnerability assessments

Individual Localities

VA Beach

- Comprehensive Sea Level Rise and Recurrent Flooding Analysis and Planning Study
- Analysis of Historical and Future Heavy Precipitation – led to change in local design storm standards
- Nature-based coastal flood mitigation strategies (2019)
- City-wide structural alternatives for coastal flood protection (2019)

Hampton – Resilient Hampton lays out the history and plans moving forward to identify vulnerable areas, causes of flooding, design considerations (less piping and draining, more slowing, storing, and discharging), and emphasizes multiple benefits with an evaluation tool tailored to prioritize projects

Norfolk

- Army Corp study on coastal storm risk management feasibility, recommendations for structural and nonstructural protections against flooding with environmental impact statements, green infrastructure plan evaluating infiltration and storage priority zones, assessing current land use for optimizing living shorelines
- Retain your rain program
- New zoning ordinance for resilience
- Ohio Creek Watershed Project – Combines green and gray stormwater infrastructure design for flood reduction, water storage, quality of life and water quality improvements

Portsmouth – Floodplain Management Plan, geared more towards repetitive loss but provides action items that include combining flood mitigation efforts with Chesapeake Bay, stormwater, erosion and sediment control, wetland regulations and zoning ordinances