FINAL
Review of Recent Research on Climate Projections for the Chesapeake Bay Watershed

Photo: Chesapeake Bay Program

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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 use 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 third in a series of four memos dedicated to providing a clearer understanding of the current stormwater management approaches to climate resiliency and identifying priority initiatives to allow managers to address their restoration and public safety functions under future climate conditions. This memo presents a review of recent research to downscale global and regional precipitation projections and develop local intensity-duration-frequency curves that can be used to design more resilient stormwater infrastructure.

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

- Global and regional climate models are in general agreement about expected changes in temperature and sea level rise. Projections out to the middle of this century predict approximately 2-3°F of warming and 1-2 feet of sea level rise.
- Streamflow still appears more heavily influenced by human activity (land use, water management) than by climate change, but that dynamic is shifting. Streamflows are projected to increase across the region as a whole, though the increases may not be uniform across urban areas due to other factors like impervious cover and leaky infrastructure impacting groundwater recharge.
- Global and regional climate models agree that precipitation volume is increasing and so is the intensity of storm events. Downscaled models are needed to provide stormwater managers with the temporal and spatial resolution to design and engineer stormwater infrastructure, but there are many different approaches and the results are variable.
- Four published studies in the Chesapeake Bay watershed have downscaled regional climate projections to local intensity-duration-frequency (IDF) curves. These downscaled projections show that precipitation intensity is generally expected to increase by 5-35% by the middle of the century. These projections also indicate that more frequent storms are expected to intensify more than less frequent storms, and that longer duration events will intensify more than shorter duration events.
- Multiple studies demonstrated that the climate is not stationary, indicating that the use of IDF curves based on historic precipitation analysis are likely to underestimate future precipitation.
- Application of projected precipitation data to inform stormwater management and design remains limited.

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Setting the Stage

Background on this Memo

Models are used to help understand future climate by characterizing outcomes and uncertainties under specific assumptions about future greenhouse gas emissions scenarios. New models are constantly under development to improve the spatial resolution and better represent processes that are important in simulating the carbon cycle of the Earth.

In 2018, the International Panel on Climate Change (IPCC) released its most recent report on global, long-term climate change projections. The report draws on data collected as part of CMIP5, a worldwide coordination of earth system modeling experiments. Different climate models provide alternative representations of the Earth’s response to greenhouse gases, aerosols, and of natural climate variability. Looking at ensembles of models, climate scientists simulate the response to a range of different scenarios, mapping out a range of possible futures, and helping us understand their uncertainties.

These global-scale general circulation models generally do a very good job of reproducing spatial patterns, climate zones, important climate processes and reproducing the historical record with accuracy. However, the resolution of General Circulation Models (GCMs) make it difficult to simulate microclimates in a way that is needed for local and regional policy and planning. Regional climate models (RCMs) use boundary conditions from CMIP5 global projections to develop regional models to better inform managers on climate impacts and implications for decision-making, but still fall short of the resolution needed for local hydrologic and hydraulic modeling conducted by stormwater engineers.

Of critical importance is understanding climate projections for the Chesapeake Bay Watershed and how they can be used to inform changes to stormwater design, floodplain management and coastal resiliency. Local engineers and stormwater managers need a method to translate GCM and RCM results into actionable mechanisms for stormwater infrastructure sizing at a finer scale. This requires downscaling raw climate projection data to specific gauge stations across the watershed using a variety of statistical and dynamical approaches to produce intensity-duration-frequency curves (IDF curves) used by engineers for BMP and infrastructure sizing.

This memo will provide an overview of the forecasted climate conditions for the Mid-Atlantic region for 2025 and out as far as 2100. It will then summarize the efforts to take those global and regional climate forecasts and downscale them for use by local stormwater managers and engineers. This summary will compliment the prior memos in this series evaluating the current stormwater engineering standards, providing necessary context for the importance of using the latest precipitation data in the development of stormwater design standards, and the challenges and data gaps that must be filled to shift to using future climate projections for those purposes. 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

Understanding Climate Projections

This memo will walk through findings from a variety of different climate projections at varying scales. It will introduce global projections from the IPCC, regional projections from the National Climate Assessment (NCA), and watershed projections from the Chesapeake Bay Program Office. A glossary of terms used throughout the report to describe the modeling and downscaling processes is included in Appendix A for reference.

The IPCC is the standard-bearer for climate projections. The IPCC developed the CMIP5 series of global models, as well as the RCP scenarios, that feed nearly all other climate modeling efforts. The reports from the IPCC focus on global climate change, however, and therefore the specific outputs reported upon in their reports may not always be applicable to the Chesapeake Bay Watershed Region.

The National Climate Assessment authors were provided with statistically downscaled CMIP5 projections, allowing them to make statements about a series of regions in the United States (USGCRP 2018). Most of the Chesapeake Bay watershed jurisdictions fall within the Northeast region of the NCA, though Virginia falls into the Southeast region.

The Chesapeake Bay Program partnership’s climate assessment was based on a combination of historical trend analysis and modeled projections. The recommendation of the Bay Program’s Scientific and Technical Advisory Committee (STAC) was to use long-term observed precipitation trends instead of climate model projections to assess expected changes in precipitation for the year 2025, as the uncertainty of the models introduced more variability for this near future than extrapolation of the trend. For 2050 precipitation estimates, STAC recommended an ensemble of GCMs based on CMIP5 (Johnson et al., 2016).

Modeling Future Precipitation for Stormwater Management

Stormwater infrastructure is designed to accommodate different storm event sizes tied to different management objectives. Typically, the 24-hour storm event is used to establish the engineering design criteria, and engineers use intensity duration frequency (IDF) curves to determine the sizing of the stormwater infrastructure needed to accommodate the volume associated with the 24-hour storm event.

However, to properly design stormwater infrastructure, engineers need more than just the 24-hour storm. High-resolution precipitation data is input into hydrologic and hydraulic models, often down to the 15-minute intervals and relatively precise geographic scales, to simulate different events to ensure the stormwater infrastructure safely conveys runoff. More information on commonly used H&H models and stormwater design basics can be found in Memo 2 of this series.

Regional Temperature Projections

TEMPERATURE PROJECTIONS AT-A-GLANCE

- **As temperatures rise, the air holds additional moisture, leading to more infrequent, but more intense rainfall events. According to the IPCC, global precipitation will increase, likely 1-3% per °C of warming.**
- **Increasing temperatures will also likely impact water quality, though not all impacts will necessarily be negative. For example, bacteria management may become more difficult, road salt management may become less difficult.**
- **Stormwater BMPs that depend on vegetation are most vulnerable to temperature impacts – tree BMPs, bioretention, etc.**

The United States is already observing increases in average annual temperature, as well as more frequent extreme heat events. The Northeast region (as defined by the NCA) has seen a 1.43°F increase in present-day temperature (1986–2016) compared to the average for the first half of the last century (1901–1960). Over the next few decades, annual average temperature over the contiguous United States is projected to increase by another 2.2°F relative to 1986–2015, regardless of future scenario. By the end of the century much larger increases are projected: 2.3°–6.7°F under a lower scenario (RCP4.5) and 5.4°–11.0°F under a higher scenario (RCP8.5) (Hahoe et al., 2018).

Further, daily extreme temperatures are projected to increase substantially in the contiguous United States, particularly under the higher scenario (RCP8.5). In the Northeast, the warmest day of the year is expected to increase by 6.51°F by the end of the century (Dupigny-Giroux et al., 2018).

The Chesapeake Bay Program's 2019 Climate Assessment projected temperature using historical trend data for 2025, and an ensemble of GCMs moving further out in time. Their projections were largely in alignment with those from the IPCC and NCA, finding that by the middle of the century, temperatures across the Chesapeake Bay watershed are expected to increase by 3.7°F under RCP4.5, relative to 1995 (Table 1).

Table 1. Change in temperature (°F) as compared to 1995 (Source: CBP, 2019)

Geography	**Year 2025**	**Year 2035**	**Year 2045**	**Year 2055**
Delaware	1.85	2.45	2.97	3.47
Maryland	1.96	2.57	3.13	3.62
Virginia	1.93	2.54	3.11	3.55
Pennsylvania	2.11	2.72	3.40	3.82
District of Columbia	1.98	2.59	3.17	3.65
West Virginia	2.03	2.66	3.28	3.73
New York	2.14	2.77	3.47	3.92
CB Watershed	**2.02**	**2.65**	**3.26**	**3.71**

The increase in temperature can have several potential impacts on stormwater management. The first involves the relationship between temperature and precipitation. As temperatures rise, the air holds additional moisture, leading to more infrequent, but more intense rainfall events. According to the IPCC, global precipitation will increase, likely 1-3% per °C of warming (Hahoe et al., 2018).

Increasing temperatures will also likely impact water quality, though not all impacts will necessarily be negative. Temperature is widely recognized as an important controlling factor in influencing bacterial growth. Rising water temperatures may signal better conditions for rapid bacterial growth (WHO, 2003). A recent study found that an observed increase in the number of *Vibrio* infections in the human population in recent years could be a direct consequence of dramatic ocean warming over the last few decades (Vezzulli et al. 2016). Alternatively, the observed changes in seasonality in the Northeastern United States -- winters have warmed three times faster than summers and are expected to get milder by the middle of the century – could lead to a reduction in the number of storms requiring road salt application, a potential positive for water quality. Road salt has been identified as an emerging contaminant of concern with potentially significant impacts on stream biology (Corsi et al. 2015).

Meanwhile, the changing temperature will also influence the best management practices used by stormwater managers to capture and treat runoff. Though not traditional stormwater practices, street tree plantings and urban forestry initiatives are both frequently utilized Chesapeake Bay restoration practices. Increasing temperatures and reduced seasonality are likely to significantly impact these forest and tree canopy programs. While milder winters may lead to longer growing seasons, it also has the potential to leave trees vulnerable to hard freezes after an early budbreak. Early insect emergence and shifting herbivore ranges are also threats to forest health.

Temperature also plays a role in the performance of green infrastructure practices. Soil microorganism activity may be impacted by increasing temperatures, as will plant selection and maintenance needs. These factors will be further explored in Memo 4 of this series.

Regional Precipitation Projections

PRECIPITATION PROJECTIONS AT-A-GLANCE

- **The volume of annual rainfall is expected to increase in the Chesapeake Bay Watershed by approximately 6.5% by 2055 under a mid-range emissions scenario.**
- **The distribution of rainfall events is also expected to shift, meaning more intense downpours and longer dry periods between rain events.**
- **Assuming that historical climate data will be representative of future conditions may lead to the underestimation of extreme precipitation by as much as 60%, increasing the flood risk and failure risk in infrastructure systems. This includes the more than 7 out of 10 dams in the United States that will be over 50 years old in 2025.**
- **Intense storm events are more likely to bypass treatment in stormwater BMPs. They also increase the need for frequent maintenance to address erosion at inlets, clogging of filter media, and other potential performance-altering impacts.**

The Chesapeake Bay Program's Climate Assessment evaluated projected changes in rainfall volume across the Chesapeake Bay Watershed. The volume of annual rainfall is expected to increase by approximately 6.5% by 2055 under RCP4.5 (Table 2).

Table 2. Percent change in rainfall volume as compared to 1995 (CBP, 2019)

Geography	**Year 2025**	**Year 2035**	**Year 2045**	**Year 2055**
Delaware	2.06%	3.10%	4.14%	6.23%
Maryland	3.09%	4.13%	4.92%	6.70%
Virginia	2.56%	3.68%	5.23%	6.50%
Pennsylvania	3.28%	4.46%	5.07%	6.32%
District of Columbia	3.14%	4.11%	5.07%	6.83%
West Virginia	2.72%	3.73%	5.23%	6.53%
New York	5.00%	6.09%	5.99%	6.24%
CB Watershed	**3.11%**	**4.23%**	**5.19%**	**6.44%**

While the expected increases in total annual rainfall is important, the expected changes in rainfall intensity may be more significant from a stormwater design perspective. According to the IPCC, while it is virtually certain that global precipitation will increase in the coming years, it is also anticipated that there will be a shift to more intense individual storms and fewer weak storms as temperatures increases. This could mean more intense downpours -- it is expected that the 20-year, 24 hour precipitation event could become the 10-year, 24 hour event by the end of the 21st century – as well as longer dry periods between rain events (Collins et al. 2013).

The National Climate Assessment further added that the trends in increasing precipitation intensity in the Northeast exceeds those in other regions in the United States. These increases are expected to be greatest in the winter and spring, with monthly precipitation in the Northeast projected to be about 1 inch greater for December through April by end of century (2070–2100) under RCP8.5 (Dupigny-Giroux et al., 2018).

Current infrastructure design is based on local rainfall Intensity-Duration-Frequency (IDF) curves. IDF curves use historical rainfall data where rainfall intensities corresponding to particular durations (e.g., 1-hr, 2-hr, 6-hr, 24-hr) are obtained by fitting a theoretical probability distribution to annual extreme rainfall amounts.

Current IDF curves are based on the concept of temporal stationarity, which assumes that the occurrence probability of extreme precipitation events is not expected to change significantly over time (Simonovic and Peck 2009). However, climate change is expected to alter the intensity, duration or frequency of climatic extremes over time, something called non-stationarity. Given non-stationarity, current IDF curves can substantially underestimate precipitation extremes and thus, may not be suitable for infrastructure design in a changing climate. Cheng and AghaKouchak (2014) showed that a stationary climate assumption may lead to underestimation of extreme precipitation by as much as 60%, increasing the flood risk and failure risk in infrastructure systems.

This concept is particularly important for the highest risk infrastructure, such as dams, which are typically designed to safely convey the 100-year, 24-hour storm event. More than 15,000 dams in the United States are listed as high risk due to the potential losses that may result if they failed, and yet by 2025, seven out of 10 dams in the United States will be over 50 years old (ASCE, 2017).

Increasing storm volume and intensity will also impact the performance green infrastructure practices. High intensity events are designed to bypass BMP treatment, but are also more likely to cause maintenance issues that may affect long term performance for smaller events (Hathaway et al., 2014). High intensity events are more likely to deliver excess sediment loads, potentially clogging inlets or filter media (Sharma et al, 2011). They are also more likely to erode inlet and outlet structures, leading to potential failure. These impacts will be covered in more detail in Memo 4 of this series.

Regional Stream Flow Projections

STREAM FLOW PROJECTIONS AT-A-GLANCE

- **Over the last 60 years, climatic trends have caused a change of 50 percent or more in one or more streamflow attributes at two-thirds of USGS stream gaging sites.**
- **Annual streamflow for the Chesapeake Bay Watershed is projected to increase by 4.5% by 2055, but changes in streamflow are not uniform across all urban watersheds. Impervious cover can make systems more "flashy" and reduce groundwater recharge, while inputs from leaky infrastructure further complicates this dynamic.**
- **Higher streamflow impacts nutrient and sediment transport and delivery from headwater systems to the Chesapeake Bay. It also creates risk to developed urban floodplains, and "on-line" BMPs such as stream restoration practices.**

Streamflow is affected by both climate change and other human activities, such as irrigation for agriculture and increasing impervious cover. In fact, the USGS found that land and water-management practices have exerted a stronger effect on streamflow than climate has in recent decades (Carlisle et al., 2019). That said, the climate influence in streamflow may be increasing, and the impacts are already being seen across the Chesapeake Bay Region. Over the last 60 years (1955–2014), climatic trends have caused a change of 50 percent or more in one or more streamflow attributes at two-thirds of USGS stream gaging sites (Carlisle et al., 2019).

Although the annual minimum streamflows have increased during the last century, late-summer warming could lead to decreases in the minimum streamflows in the late summer and early fall by mid-century (Demaria et al 2016). The dynamics are complicated in urban systems, where high flows tend to be higher than normal due to impervious cover generating more surface runoff and making the system "flashy". On the other end of the spectrum, low flow elevations can vary based on the setting. In some cases, low-flow elevations are higher than normal due to leaky water infrastructure providing recharge. In other cases, low-flow elevations are below normal because impervious cover prevents infiltration and groundwater recharge.

The Chesapeake Bay Program's Climate Assessment projected changes in annual streamflow for the watershed as described in Table 3.

Table 3. Percent change in simulated flow as compared to 1995 (1991-2000) (CBP, 2019)

Geography	**Year 2025**	**Year 2035**	**Year 2045**	**Year 2055**
Delaware	0.99%	2.46%	2.46%	3.79%
Maryland	2.56%	3.91%	3.91%	4.60%
Virginia	1.73%	3.11%	3.11%	5.56%
Pennsylvania	2.30%	3.67%	3.67%	3.70%
District of Columbia	0.59%	0.83%	0.83%	1.06%
West Virginia	0.76%	2.00%	2.00%	4.27%
New York	4.98%	5.97%	5.97%	4.49%
CB Watershed	2.37%	3.70%	3.70%	4.48%

Streamflow in the context of stormwater management has several implications. High flow events pose a risk to public and private infrastructure and increases in high flow events would require adjustments to floodplain maps (see Memo 2 for more detail). Streamflow also directly impacts nutrient and sediment transport and delivery. Higher streamflows mean more pollutants being delivered downstream and to the Chesapeake Bay, but also a greater risk of failure for stream restoration practices. Stream restoration is one of the most commonly used BMPs for the Chesapeake Bay TMDL, but is also at great risk of failure because they are "on-line" and subject to the greatest flow events.

Regional Sea Level Rise Projections

SEA LEVEL RISE PROJECTIONS AT-A-GLANCE

- **Sea level rise is expected to average approximately 2 feet across the Mid-Atlantic by 2100 under a mid-level emissions scenario, with Hampton Roads experiencing nearly twice the global rate.**
- **"Blue-sky" or high tide flooding has increased by a factor of 10 over the past 50 years, and is expected to exceed 30 days per year in over 20 cities in the Northeast by 2050 under the most conservative emissions scenario.**
- **Rising sea levels contribute to accelerated shoreline erosion, prevents the use of infiltration BMPs in areas with high water tables, and may result in new load sources from frequently inundated urban areas.**

Sea level rise is projected to further exacerbate flooding in tidal regions across the Northeast and Chesapeake Bay Watershed. Under RCP 4.5, sea level rise of 2 feet on average is expected in the region by 2100. The worst-case scenario, however, projects that sea levels in the region would rise upwards of 11 feet on average by the end of the century (Lynch et al., 2016).

The Chesapeake Bay Program Office used the following projected Sea Level Rise in their 2019 Climate Assessment, projecting 0.53 m (1.7 ft) of SLR by 2055 under RCP4.5.

Table 4. Sea Level Rise (ft) used in the 2019 CBP Climate Assessment (CBP, 2019)

Geography	**Year 2025**	**Year 2035**	**Year 2045**	**Year 2055**
Chesapeake Bay	0.7	1.0	1.4	1.7

According to the NCA, high tide flooding has increased by a factor of 10 or more over the last 50 years for many cities in the Northeast region and will become increasingly synonymous with regular inundation, exceeding 30 days per year for an estimated 20 cities by 2050 even under a very low scenario (RCP2.6) (Dupigny-Giroux et al., 2018).

Local studies are already showing the effects of sea level rise, with Virginia Beach stations in particular indicating that their rate of sea level rise is nearly twice the global rate, and the highest rate of sea level rise on the east coast. Projections in this region are between 1 and 4 ft between now and 2100 (City of Virginia Beach, 2020).

Sea level rise in the Chesapeake Bay Region creates significant challenges for stormwater and floodplain managers. In addition to impacts on floodplain maps, discussed in Memo 2, 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. Further, coastal flooding at outfalls may drive backflow into the system, causing upland flooding through street drains and drainage ditches.

From a water quality perspective, seal level rise accelerates shoreline erosion processes (Leatherman et al., 2000; Oppenheimer et al., 2019), while also raising the groundwater table, reducing the effectiveness of infiltration practices, some of the most implemented stormwater BMPs. New research from citizen monitoring data also suggests that “blue-sky” flooding may contribute significant pollutant loads to local waterways, as the falling high tides carry nutrients, sediments and other pollutants back into the estuary (Mulholland, 2019).

Creating Downscaled IDF Curves

DOWNSCALED IDF CURVES AT-A-GLANCE

- **To provide information useful to inform stormwater design, more geographic and temporal specificity is needed than is produced by global and regional climate models. Stormwater engineering models require precipitation data down to 15-minute durations, while rainfall patterns often differ dramatically within the same city.**

- **There are many methods for downscaling global and regional precipitation data to better inform stormwater management, but selecting a different technique can lead to considerable, and sometimes significant, differences in the expected percent change in rainfall. Therefore, it is generally recommended that testing and comparison of the approaches be undertaken.**

- **Over the past several years, five studies have been completed or are underway to project localized rainfall data in the Chesapeake Bay Watershed. Each study used slightly different methodologies.**

- **The projections show that precipitation intensity is generally expected to increase by 5-35% by the middle of the century under a high-end emissions scenario. These projections also indicate that more frequent storms are expected to intensify more than less frequent storms, and that longer duration events will intensify more than shorter duration events.**

- **Application of projected precipitation data to inform stormwater management and design remains limited. Three examples currently exist in the Chesapeake Bay Watershed:**

    - **The New York State Department of Transportation has revised their highway design manual to account for future projected peak flow in culvert design. The change was a 20% increase.**

    - **The City of Virginia Beach has revised their stormwater regulations to increase in their design storm by 20%.**

    - **The Virginia Department of Transportation (VDOT) has also revised its bridge design manual to account for climate change. VDOT has implemented a 20% increase in rainfall intensity and a 25% increase in discharge in design of bridges.**

Introduction to Downscaling Climate Projections

Taking low-resolution models and translating them into higher-resolution projections involves a process called downscaling. Downscaled precipitation data is necessary to use climate projections to inform future stormwater design. However, there are a number of ways that downscaling can be done, and a number of decisions that must be made about the specific questions that need to be answered, including:

1. Select GCM Ensembles
2. Select one or more emission scenarios (e.g. RCP4.5, RCP8.5)
3. Select time periods of interest (planning horizon)
4. Select GCM grid cells relevant to study and nearest rain gage and download daily data
5. Select analytical downscaling technique (statistical, dynamical, analog, etc.)

Depending upon the objectives of the study, some researchers may choose to pull regionally downscaled climate projections from an existing database rather than raw GCM projections. These projections exist at approximately a 50km grid scale and may be appropriate to help understand changes in the frequency of different 24-hour storm events. While methods are needed to bias-correct those data (remove systematic climate model errors at regional scales), further downscaling may not be needed.

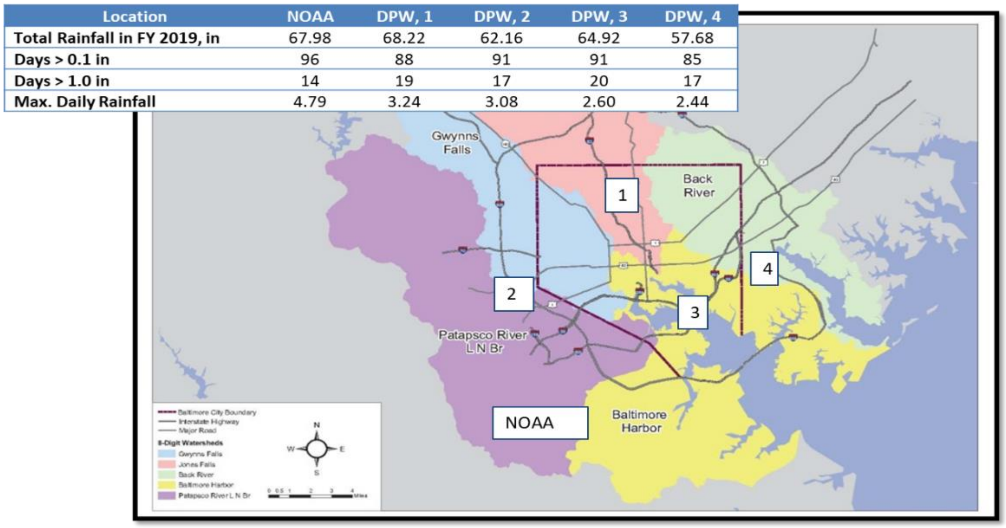
Decisions about emissions scenarios, grid cells and time periods of interest are all related to the specific management objectives. One way to think about emissions scenarios is risk management. Projecting future precipitation under RCP8.5 may overestimate future emissions, and therefore changes in temperature and precipitation if mitigation steps are taken in the coming years to reduce greenhouse gas emissions. However, it also provides a protective baseline if trends continue on their current trajectory.

While one spatial resolution does not always produce higher values than another, generally, finer resolutions have been shown previously to better represent daily extreme rainfall patterns and spatial distributions that are more consistent with real-world tendencies (Cooke et al., 2020).

The time-period chosen for analysis may be related to specific management objectives. For example, if the purpose of the projections is to inform the design of infrastructure with an anticipated lifespan of 50 years, it would make sense to develop climate projections out to 2070 and beyond. However, long-range projections carry more uncertainty, which requires managers to make decisions about how to interpret results with a large range of potential outcomes.

To provide information useful to inform stormwater design, more geographic and temporal specificity is needed than is produced by GCMs and RCMs. Hydraulic and hydrologic models require temporal resolution as fine as 15-minute duration, and cities often see rainfall patterns that differ dramatically within the same city (see Figure 1 for an example).

Figure 1. Precipitation gauge data from Baltimore, MD (Source: Grove, 2020)



Location	NOAA	DPW, 1	DPW, 2	DPW, 3	DPW, 4
Total Rainfall in FY 2019, in	67.98	68.22	62.16	64.92	57.68
Days > 0.1 in	96	88	91	91	85
Days > 1.0 in	14	19	17	20	17
Max. Daily Rainfall	4.79	3.24	3.08	2.60	2.44

Many different downscaling methods have been developed to take RCM and GCM projection data down to a gauge-station scale. Broadly, those methods are lumped into Dynamical and Statistical downscaling approaches, as summarized below.

Dynamical Downscaling: Regional climate models (RCMs) are run at finer resolution and driven by atmosphere–ocean general circulation models. The result is a data product that is dynamically consistent, both internally and with the boundary conditions. Further downscaling is generally needed to take gridded precipitation values to point values.

Statistical Downscaling: Involves the development of statistical relationships between long term, historic, observations of local climate surface variables, and large-scale atmospheric variables. These relationships are applied to projected output of GCMs for selected future time windows to simulate local and regional climate variables (Hoar and Nychka, 2008). There are many different types of statistical downscaling, including the "delta method" and the "analogue method":

- **Delta Method:** Compares model-simulated precipitation extremes between historical and future periods (at GCM resolution) (Cannon et al., 2015). In other words, future downscaled recurrence interval precipitation amounts are estimated by calculating the percent change in precipitation extremes between simulated daily precipitation for historical and future periods, and then this factor is applied to the observed precipitation extremes at the corresponding station (DeGaetano and Castellano, 2017).
- **Analogue Method:** Using coarse resolution data, the method identifies analogous days in the historical record and uses the associated fine-resolution historical data to produce fine-resolution outputs. Analogue days are chosen by minimizing the differences between predictor variables commonly associated with heavy precipitation. (Castellano and DeGaetano, 2015).

When comparing downscaling approaches, there are strengths and weaknesses to each. The primary benefit to dynamical downscaling is that is does not assume stationarity, allowing the models the ability to respond in a physically consistent way to different external forcing signals, such as land surface or atmospheric chemistry changes. However, they are computationally demanding and the climate signals, while physically consistent, may not always be accurate and must be analyzed.

Statistical downscaling approaches are less computationally demanding, and are generally good at reproducing historical data, but the relationship is “stationary” in the sense that it does not change when the statistical model is applied to future GCM data (Berg, 2018). Therefore, the method tends to underestimate the variance of climatic patterns.

The decision on use of statistical versus dynamical downscaling is not universal and will vary based on the geographic and climactic conditions – one technique does not systemically bias results to be higher or lower. However, selecting a different technique can lead to considerable, and sometimes significant, differences in the expected percent change in rainfall (Cooke et al., 2020). Therefore, it is generally recommended that testing and comparison of the approaches be undertaken. The following section outlines several different downscaling approaches to produce IDF curves in the Mid-Atlantic.

Summary of Chesapeake Bay Region Downscaled Projections

This review summarizes six studies that downscaled precipitation projections for local stormwater management application. Each of the studies are located within the Chesapeake Bay watershed and five of them projected downscaled precipitation depth or intensity estimates with the goal of producing projected IDF curves. The sixth downscaling study was conducted for the District of Columbia, but only included 6 hr and 24 hr storm durations, and therefore did not produce IDF curves. Methods from all five studies are compared in Table 5 and more details are provided in Appendix A.

Table 5. Summary of downscaling methodologies in Chesapeake Bay studies[1].

Study Location (citation)	**Downscaling Method**	**RCPs Analyzed**	**Temporal and Geographic Scale**
New York (DeGaetano and Castellano, 2017)	Dynamical Delta Analogue	RCP4.5 RCP8.5	*Temporal:* 2010-2039, 2040-2069, 2070-2099 *Geographic*: Gauge
Virginia Beach (Smirnov et al., 2018)	Dynamical	RCP4.5 RCP8.5	*Temporal:* 2026-2065, 2056-2095 *Geographic:* 11km grid (RCP8.5); 44km grid (RCP4.5)
Maryland Eastern Shore (Charochak and Bass, 2019)	Delta	RCP8.5	*Temporal:* 2041-2070 *Geographic:* 750m grid
Virginia (Wang, 2020)	Delta	SRES A2 emissions (Roughly comparable to RCP8.5)	*Temporal:* 2035-2070 *Geographic:* Gauge
Maryland (Butcher, 2020)	Statistical (Modified Delta)	RCP 4.5 RCP 8.5 10th and 90th percentile	*Temporal:* 2040-2069, 2070-2099 *Geographic:* Gauge
District of Columbia (DOEE, 2015)	Statistical	RCP 4.5 RCP 8.5	*Temporal: 2040-2070, 2070-2100* *Geographic: Gauge*
[1] Summarized from DeGaetano and Castellano (2017), Smirnov et al (2018), Charochak and Bass (2019), Wang (2020), Butcher (2020), DOEE (2015) and Hayhoe and Stoner (2015). More detail provided on methodologies in Appendix A.			

While methods differed, most studies developed mid-century projections and for the RCP8.5 (or equivalent) emissions scenario. For the sake of comparison, the findings of those studies are summarized in Table 6. More details are provided in the following sections.

Table 6. Summary of Select Mid-Century Rainfall Intensity Projections (in/hr) in downscaling studies[1].

Study (Projection Location)[2]	**Duration**	**Frequency**	**Atlas 14**	**Mid-Century Projection**	**Percent Change**
New York (Elmira)	1hr	2yr	1.02	1.10	8%
		10yr	1.51	1.53	1%
		100yr	2.34	2.56	9%
	24hr	2yr	0.10	0.12	20%
		10yr	0.16	0.17	6%
		100yr	0.24	0.28	17%
Maryland Eastern Shore (Easton)	1hr	2yr	1.47	2.1	9%
		10yr	2.15	3.0	16%
		100yr	3.16	4.5	27%
	24hr	2yr	0.139	0.2	44%
		10yr	0.217	0.3	32%
		100yr	0.375	0.5	33%
Virginia Beach	1hr				
	24hr	2yr	3.37	4.4	31%
		10yr	5.58	6.5	16%
		100yr	9.37	11.9	27%
District of Columbia (National Arboretum)	1 hr				
	24 hr	2yr	3.18	3.73	17%
		15yr	5.27	6.95	32%
		100yr	8.43	10.15	20%

[1] More information on methods and scenario details are provided in Appendix A, along with links to the complete reports.

[2] Gauge station locations were chosen at random from stations within the Chesapeake Bay watershed for summary purposes.

New York (Degaetano and Castellano, 2017)

Full Report: http://ny-idf-projections.nrcc.cornell.edu/idf_tech_document.pdf

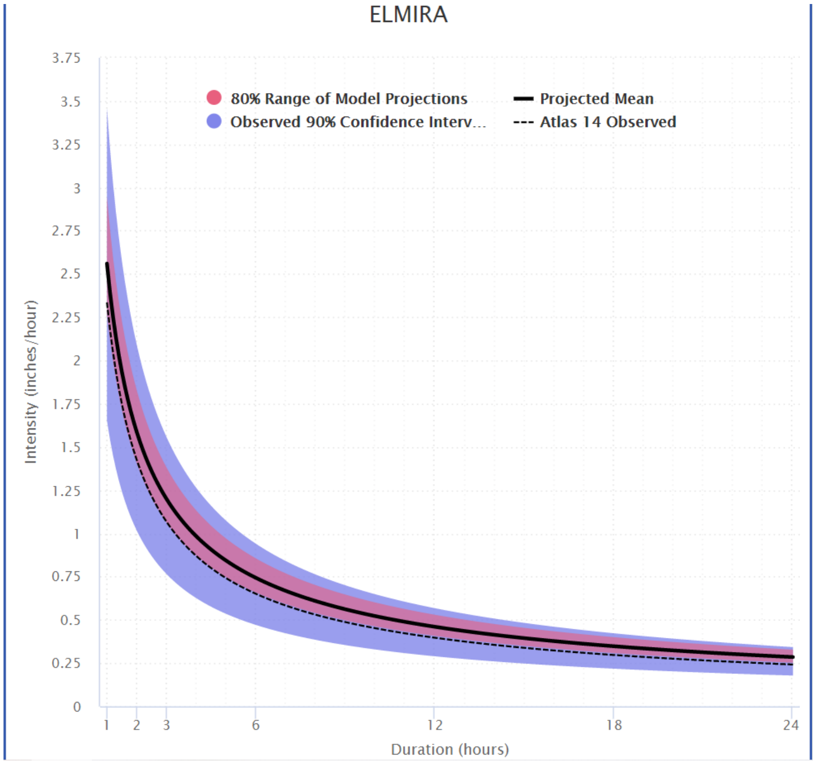
Summary of Projections

In the 2010–2039 period, the 100-year precipitation amounts exhibit a median increase of between 5 and 10% across the 157 stations. By mid-century (2040–2069), the effect of the concentration pathway becomes more pronounced. The median increase in 100- year precipitation amounts is less than 10% for all downscaling methods under RCP4.5, but increases to 10–20% under the high concentration case (RCP8.5). In the 2070–2099 period, regardless of downscaling method, 100-year precipitation amounts are expected to increase at all stations. Median changes range from 10–20% under RCP4.5, but vary considerably from 15% for the analog method to over 35% in the dynamically downscaled simulations under RCP8.5

There is little consistency in the geographic variation in extreme precipitation change. Averaged across all climate model-downscaling method combinations, the projected change in 100-year recurrence interval extreme precipitation amounts by the 2070–2099 period (RCP 8.5) is between 15 and 25% across the state of New York (including areas outside the Chesapeake Bay Watershed).

A sample output projection is provided in Figure 2.

Figure 2. 2040-2069 IDF curve projection for the 100-year storm event in Elmira, NY under RCP 8.5



Application of Projections

While the projected IDF curves developed by DeGaetano and Castellano (2017) have not been directly utilized to replace existing design standards, there are several examples in New York of this work influencing future design criteria. In 2018, the New York State Department of Transportation revised their highway design manual to account for future projected peak flow in culvert design (NYSDOT 2018). Peak flows in some regions of the state (including those falling within the Chesapeake Bay Watershed) were increased by 20%, while other regions were increased by 10%.

As another example, New York City has not adjusted its design manual, but has issued the "Climate Resiliency Design Guidelines" (NYC Mayor's Office of Recovery and Resiliency, 2019). Among the guidelines provided is the recommendation that the current 50-year IDF curve be used as a proxy for the future 5-year storm (projected for the 2080s). The guidelines suggest that designers plan to use on-site detention/retention systems to retain the volume associated with that size storm event though it is not yet a requirement.

Virginia Beach (Smirnov et al. 2018)

Full Report: https://www.vbgov.com/government/departments/public-works/comp-sea-level-rise/Documents/anaylsis-hist-and-future-hvy-precip-4-2-18.pdf

Summary of Projections

Projected IDF curves are higher than the historical curve across all return periods for both the 2045 and 2075 periods. However, due to increasing uncertainty for less frequent events, a statistically significant separation is limited to only the higher frequency events (through the 10-year event for 2045 projection and the 20-year event for 2075).

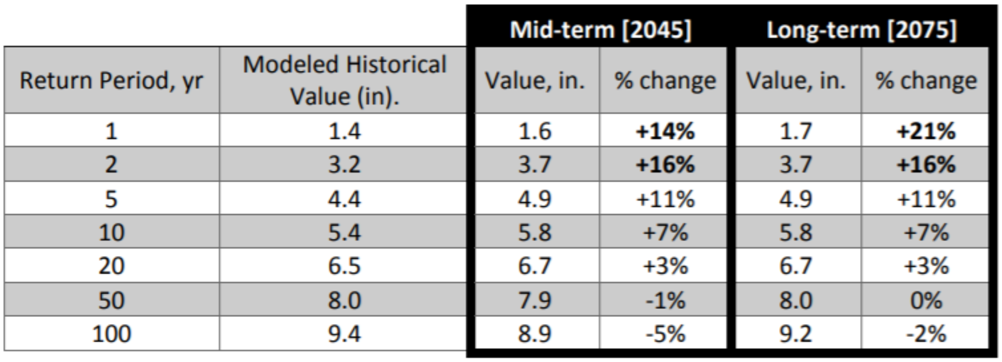
Using RCP8.5, increases of 17-24% are expected across all return periods (except the 1-year) by 2045. For the long-term projection, much more significant changes in the range of 21-41% are expected.

Table 7. Summary of Virginia Beach precipitation-frequency changes under RCP8.5 between modeled historical climate, and mid-term and long-term model projections. Bold values indicate statistically significant at 90% confidence interval.

		Mid-term [2045]		Long-term [2075]	
Return Period (yr)	Modeled Historical Value (in)	Value (in)	% change	Value (in)	% change
1	1.4	1.3	-8%	1.7	+21%
2	3.2	3.7	**+17%**	3.9	**+22%**
5	4.4	5.4	**+21%**	5.6	**+25%**
10	5.4	6.6	**+22%**	7.0	**+28%**
20	6.5	8.0	+23%	8.5	**+32%**
50	8.0	10.0	+24%	11.0	+37%
100	9.4	11.7	+24%	13.3	+41%

Although there is a statistically significant 14-21% increase in the 1-year and 2-year rainfall amounts under the RCP4.5 scenario, there is little change for less frequent events such as the 10-year event. The higher resolution available for RCP8.5 simulations suggest a stronger increase for the less frequent events like the 100-year, which is projected to increase by 41% using the 11 km simulations but only 26% in the 44 km simulations.

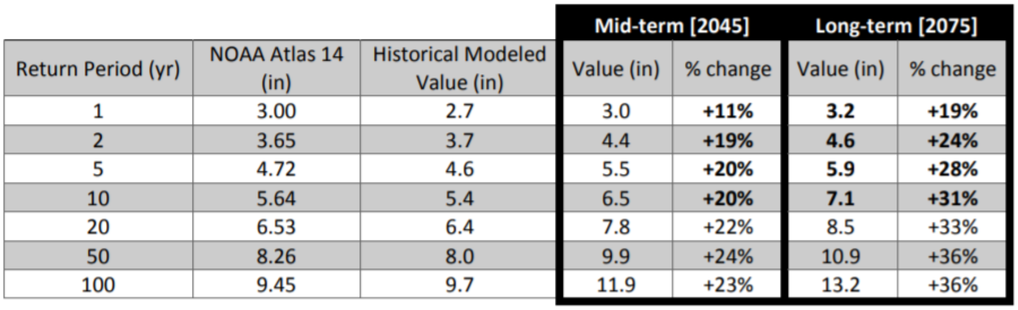
Table 8. Summary of Virginia Beach precipitation-frequency changes under RCP4.5 between modeled historical climate, and mid-term and long-term model projections. Bold values indicate statistically significant at 90% confidence interval.



		Mid-term [2045]		Long-term [2075]	
Return Period, yr	Modeled Historical Value (in).	Value, in.	% change	Value, in.	% change
1	1.4	1.6	**+14%**	1.7	**+21%**
2	3.2	3.7	**+16%**	3.7	**+16%**
5	4.4	4.9	+11%	4.9	+11%
10	5.4	5.8	+7%	5.8	+7%
20	6.5	6.7	+3%	6.7	+3%
50	8.0	7.9	-1%	8.0	0%
100	9.4	8.9	-5%	9.2	-2%

It was hypothesized that the underestimates for the 1 and 2 year return periods are due to the use of Annual Maximum Series (AMS) to develop the precipitation-frequency estimates. The AMS is used in Atlas 14 IDF curves, but a drawback to the method for future projections is that the AMS dismisses potentially high rainfall amounts that were the second or third highest in its actual year, but may have qualified as the annual maximum during many other years. It was further hypothesized that the underestimate issue could be improved or resolved using a different approach, called the Partial Duration Series (PDS), as seen in the Table 9.

Table 9. Summary of Virginia Beach precipitation-frequency changes using the PDS method. Bold values indicate statistically significant at 90% confidence interval.



			Mid-term [2045]		Long-term [2075]	
Return Period (yr)	NOAA Atlas 14 (in)	Historical Modeled Value (in)	Value (in)	% change	Value (in)	% change
1	3.00	2.7	3.0	**+11%**	**3.2**	**+19%**
2	3.65	3.7	4.4	**+19%**	**4.6**	**+24%**
5	4.72	4.6	5.5	**+20%**	**5.9**	**+28%**
10	5.64	5.4	6.5	**+20%**	**7.1**	**+31%**
20	6.53	6.4	7.8	+22%	8.5	+33%
50	8.26	8.0	9.9	+24%	10.9	+36%
100	9.45	9.7	11.9	+23%	13.2	+36%

Application of Projections

The City of Virginia Beach is currently the only example in the Chesapeake Bay Watershed of a jurisdiction formally requesting a revision of their stormwater design criteria to account for increased precipitation caused by climate change. Virginia Beach has revised their stormwater regulations to increase in their design storm by 20%, and the request is currently under review by VA DEQ.

While not directly linked to these findings, the Virginia Department of Transportation (VDOT) has also revised its bridge design manual to account for climate change. VDOT has implemented a 20% increase in rainfall intensity and a 25% increase in discharge in design of bridges (VDOT, 2020).

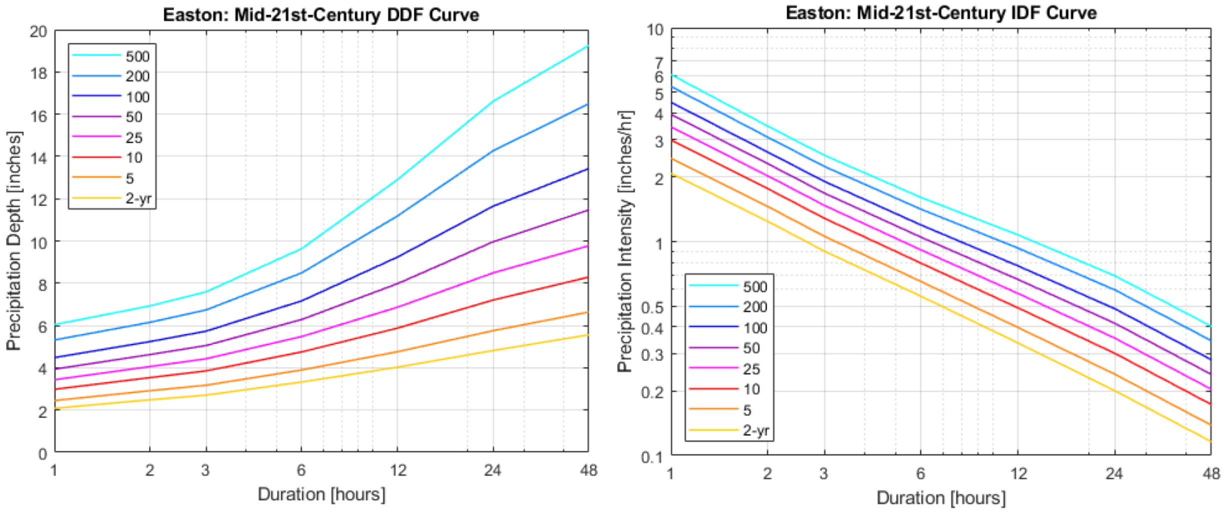
Maryland's Eastern Shore (Charochak and Bass, 2019)

Full Report: https://www.eslc.org/wp-content/uploads/2020/01/ExtremePrecipitationReport.pdf

Summary of Projections

Mid-century precipitation frequency from the average of five dynamically downscaled model pairs show increases in precipitation depth and intensity over the entire study region for all durations and average return periods. Relative increases are greater for short, more intense precipitation events (e.g., 1-hour). Depth-duration-frequency (DDF) and IDF curves were calculated from each modeled grid point and interloped to a finer grid to match gridded data retrieved from NOAA Atlas 14 online. An example of a DDF and IDF curve are shown in Figure 3.

Figure 3. Mid-Century DDF and IDF curves for Easton, MD.



Application of Projections

Along with the projected IDF and DDF curves, the Eastern Shore Land Conservancy (ESLC) produced a series of "Extreme Precipitation Policy Recommendations" for counties and cities on Maryland's Eastern Shore. Among the recommendations are:

- Upsizing pipe and storm drain infrastructure (no specific values were recommended)
- Utilize more hybrid green/gray infrastructure
- Implement a stormwater utility fee
- Adopt enhanced floodplain design criteria into local development standards

Virginia (Wang, 2019)

Full Report: https://serdp-estcp.org/content/download/49905/491754/file/RC18-1569%20Final%20Report.pdf

Summary of Projections

The results showed that in most locations, storm intensity increased. Long-term storm intensity tended to increase more than shorter duration events. This indicates that structures designed based on historic IDF curves and set to a design runoff volume will be more likely to be undersized. Probabilistic IDF curves were developed for eight gauge stations in Virginia. As examples, two of those projections are presented in Figures 4 and 5 for the 1hr and 24hr duration.

Figure 4. Mid-Century probabilistic IDF curves for Staunton, VA gauge station.

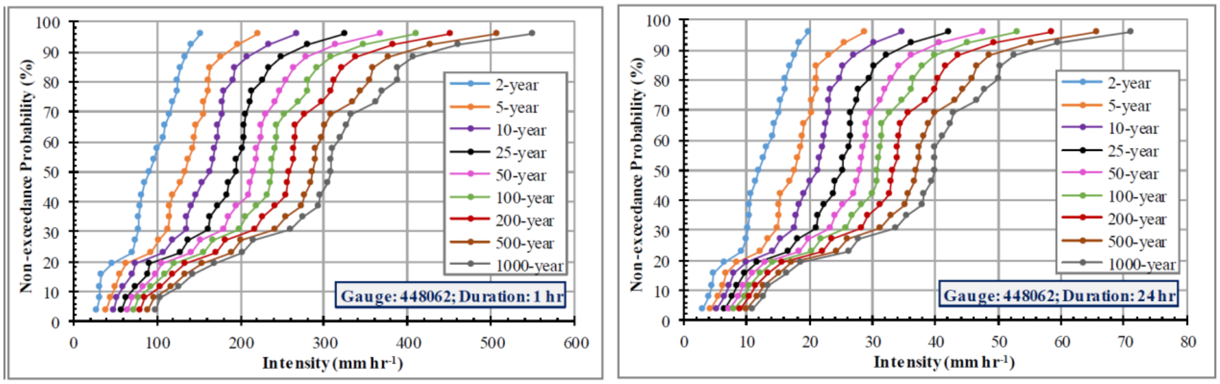
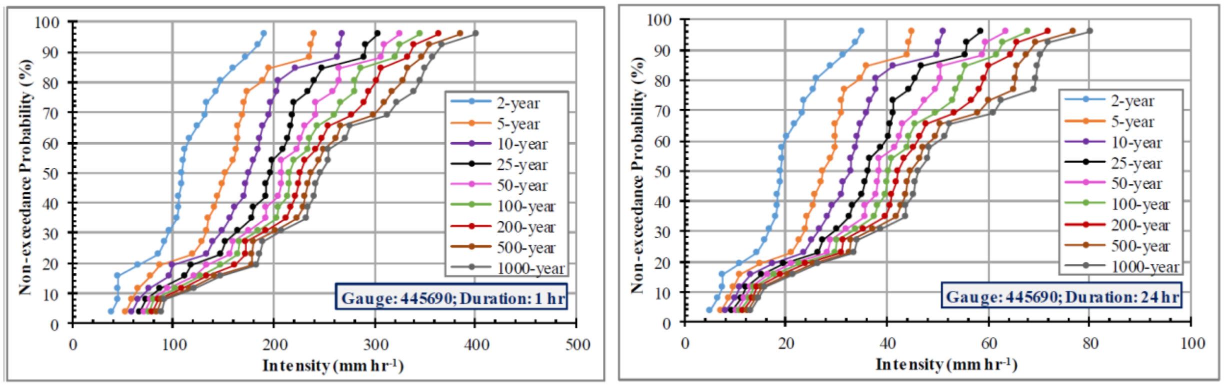


Figure 5. Mid-century probabilistic IDF curves for the Montebello Fish Hatchery gauge station.



Application of Projections

To date, these projections have not been applied. The project was funded by the Department of Defense, but additional study would likely be needed before the projections could be used to inform revised design guidelines.

To apply this style of curves, a locality or practitioner would need to set a desired level of risk – represented by the percent non-exceedance probability. For a given duration and return-frequency, the practitioner can select the non-exceedance probability (80% was used in Table 7) to determine the rainfall intensity.

Maryland (Butcher, 2020)

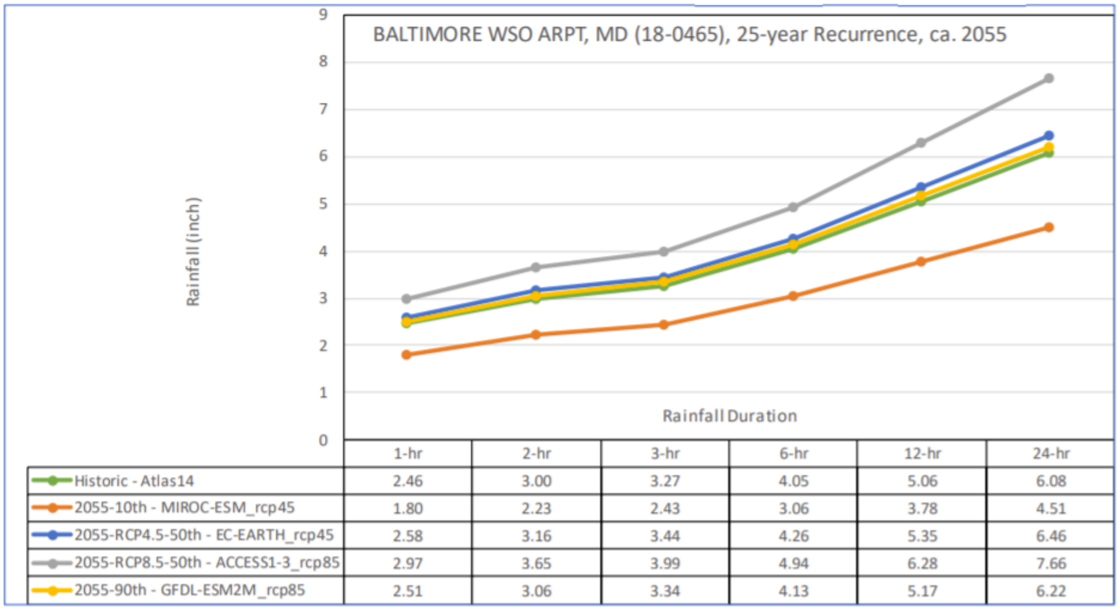
Full Report: https://cbtrust.org/wp-content/uploads/Grant16928-Deliverable11-FinalProjectReport.pdf

Summary of Projections

Results suggest a widespread risk of increased precipitation intensity under future conditions in Maryland. However, the increase is not uniform across the model simulations and at many stations, the results suggest more of an increase in the cone of uncertainty than a unimodal increase in intensity. For some GCM simulations the predicted intensity of low-recurrence events decreases, presumably due to drier conditions predicted during the convective storm season.

The predicted intensity of the 90th percentile, 24-hour event (the “water quality” storm) does not show a consistent increase at most stations under future conditions. This is in line with studies that suggest total annual precipitation volume will most likely increase under future climate, but that much of this increase will be associated with more extreme, low-recurrence events.

Figure 6. Projected 25-year IDF Curves for Baltimore WSO Airport ca. 2055



	1-hr	2-hr	3-hr	6-hr	12-hr	24-hr
Historic - Atlas14	2.46	3.00	3.27	4.05	5.06	6.08
2055-10th - MIROC-ESM_rcp45	1.80	2.23	2.43	3.06	3.78	4.51
2055-RCP4.5-50th - EC-EARTH_rcp45	2.58	3.16	3.44	4.26	5.35	6.46
2055-RCP8.5-50th - ACCESS1-3_rcp85	2.97	3.65	3.99	4.94	6.28	7.66
2055-90th - GFDL-ESM2M_rcp85	2.51	3.06	3.34	4.13	5.17	6.22

Application of Projections

To date, these projections have not been applied. The results were published during development of this report, and more time will be needed to determine if and how the findings will inform future management decisions.

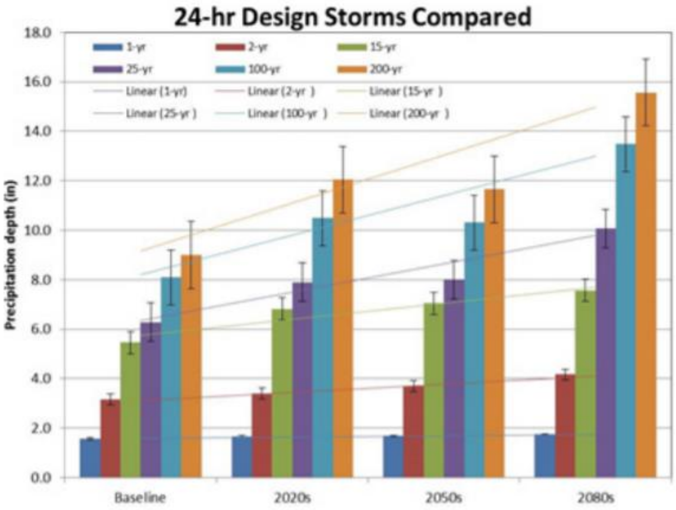
District of Columbia (DOEE, 2015)

Full Report:
https://doee.dc.gov/sites/default/files/dc/sites/ddoe/publication/attachments/150828_AREA_Research_Report_Small.pdf

Summary of Projections

The frequency and intensity of extreme precipitation events are projected to increase during the studied time horizons. The rainfall depths associated with the 24-hour and 6-hour duration design storms for the are projected to steadily increase from the present through 2080s for all recurrence intervals. For example, the present 15-year 24-hour storm, which is the typical design capacity of the District's sewer system, is projected to increase from the Atlas 14 value of 5.3 inches to 7.1 inches by the 2050s and 7.6 inches by the 2080s. The results also indicate that extreme rainfall events will become more frequent. For example, the Atlas 14 100-year 24-hour storm will be the 25-year 24-hour storm by mid-century (2050s) and the 15-year 24-hour storm by end of the century (2080s).

Figure 7. Projected 24 hour design storms for the the averages of the Dalecarlia and the National Arboretum stations.



Application of Projections

Because complete, projected IDF curves were not a product of this analysis, the results have not been directly incorporated into stormwater sizing guidance as of this report. However, these results have been used to inform a number of climate resilience and adaptation strategies in the District, as summarized in the second memo of this series (Wood, 2020).

Conclusion

As outlined, it is well-understood that climate change is contributing to rising sea levels, changing streamflow, increases in temperature and more intense precipitation events. The critical decision is how to adapt stormwater management to account for these projected changes. Multiple approaches have been developed to downscale global and regional climate projections to better inform local stormwater design. However, policy decisions are needed to establish acceptable levels of risk and uncertainty. Each downscaling method has strengths and weaknesses, as do different approaches to adapting those projections to new design standards.

In addition to decisions about sizing criteria, it is also important to consider how other policy options may compliment decisions about infrastructure sizing. Green infrastructure implementation and maintenance, combining green and gray infrastructure improvements, floodplain development regulations, and funding mechanisms are all part of the equation. The fourth and final memo in this series will provide more information on the impacts of climate change on stormwater BMPs and potential interventions to improve resilient siting, design and maintenance practices.

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Appendix A. Glossary of Key Terms

Table 1. Glossary of Terms[1]

General Circulation Model (GCM)	Complex, global climate models that numerically solve the equations of physics (e.g., dynamics, thermodynamics, radiative transfer, etc.) and chemistry applied to the atmosphere and its constituent components, including the greenhouse gases.
Coupled Model Intercomparison Project (CMIP5)	The latest IPCC Model. CMIP5 provides output from over 50 GCMs with spatial resolutions ranging from about 30 to 200 miles per horizontal size and variable vertical resolution.
Representative Concentration Pathway (RCP)	A range of plausible pathways, scenarios, or targets that capture the relationships between human choices, emissions, concentrations, and temperature change.
RCP8.5	Represents the baseline scenario without additional efforts to reduce GHG emissions beyond those in place today. In the RCP 8.5 emissions scenario the radiative forcing level reaches 8.5 W/m^2 characterized by increasing greenhouse gas emissions over time representative for scenarios in the literature leading to high greenhouse gas concentration levels.
RCP4.5	An intermediate mitigation scenario. The RCP 4.5 scenario is a stabilization scenario, which means the radiative forcing level stabilizes at 4.5 W/m^2 before 2100 by employment of a range of technologies and strategies for reducing greenhouse gas emissions.
Stationarity	The idea that natural systems fluctuate within an unchanging envelope of variability. In other words, the climate variability observed in the past will not change in the future.
Partial Duration Series (PDS)	A series of data composed of all events during the period of record that exceed some set criterion, for example, all daily rainfalls greater than a specified amount.
Annual Maximum Series (AMS)	A series of data that include only the highest values that occur within each year of the period of record.
Intensity Duration Frequency (IDF) Curve	A mathematical function that relates the rainfall intensity with its duration and frequency of occurrence. These curves are commonly used in stormwater management for floodplain mapping, hydrologic and hydraulic modeling and infrastructure design.

[1] Definitions summarized from Bader (2020), IPCC (2019) and Milly et al (2008).

Appendix B. Summary of Precipitation Downscaling Studies

New York

Future projections of extreme precipitation intensity-duration-frequency curves for climate adaptation planning in New York State

Source: Degaetano and Castellano (2017)

Objective:

This study was conducted to 1) evaluate downscaling method–climate model combinations to assess their ability to replicate historical precipitation extremes, 2) downscale projected precipitation extremes for future periods, 3) quantify methodological and climate model uncertainties.

Methods:

For the extreme value analysis, partial duration series (PDS) of the largest independent daily precipitation events were obtained for each station during the 1970–1999 period. While other studies have relied on annual maximum series (AMS) to calculate recurrence interval precipitation amounts, PDS was chosen because two or more of a station’s largest daily precipitation events may occur during the same calendar year.

After PDS were constructed for each station, precipitation amounts corresponding to 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals were computed using two statistical fitting approaches: maximum likelihood Beta-P distribution fitting, and regional L-moments general extreme value (GEV) fitting.

For the downscaling analysis, the study used three different downscaling approaches (delta, analogue, dynamical) to project precipitation intensity, duration and frequency for 157 stations across New York State. The delta approach took the difference between future and historic simulated precipitation extremes from CMIP5 (GCM scale) and applied those ratios to gauge-station data to produce downscaled projections. The dynamical approach used a bias-correction technique to adjust the Coordinated Regional Climate Downscaling Experiment (CORDEX; Jones et al. 2011), results. The analogue approach selected historical weather patterns commonly associated with heavy precipitation and paired them with simulated precipitation estimates. Based on the observed precipitation pattern corresponding to the selected analog, the historical values were reassigned to obtain a future rainfall projection.

From the different downscaling method–climate model combinations, a set of 49 extreme precipitation projections (25 quantile method + 4 CORDEX + 20 analog method) was created at each station for each of the two climate scenarios (RCP4.5 and RCP8.5) and three time periods. For each set, the mean and 10th, 25th, 50th, 75th, and 90th percentiles were computed.

Model Performance Results:

For analyzing extreme values, the Beta-P and L-moments approaches produced similar values at shorter recurrence intervals, but the GEV-based L-moments values are typically lower than the Beta-P values at longer recurrence intervals.

Regarding the downscaling methods, while each method produced realistic 100-year recurrence interval precipitation amounts at most stations, on average, the dynamical downscaling method overestimated recurrence interval precipitation amounts by approximately 5–10%, whereas the analog downscaling underestimated the precipitation extremes by a similar amount. The dynamically downscaled CORDEX simulations exhibit the largest station-to-station variability. This is likely an artifact of the limited number of available CORDEX simulations, but may also be influenced by the higher resolution of the CORDEX data.

City of Virginia Beach

Analysis of Historical and Future Heavy Precipitation

Source: (Smirnov et al. 2018)

Objectives:

The study was conducted for the City of Virginia Beach Department of Public Works to 1) summarize changes in heavy rainfall frequency and intensity using historical observations and bias-corrected future projections. 2) Evaluate three heavy rainfall events that were responsible for flooding in the City of Virginia Beach during 2016, and 3) compare the three events to regional Probable Maximum Precipitation estimates.

Methods:

To evaluate the stationarity of historical precipitation data, analysis was conducted at gage, local, and regional scales. Annual Maximum Series (AMS) of daily rainfall was gathered and analyzed for trends in intensity (AMS), frequency (peak over threshold), and changes in the 99th percentile rainfall event volume.

To project future precipitation, the study used bias-corrected dynamical downscaling. The study used the output from the North American Coordinated Regional Modeling Experiment (NA-CORDEX; Castro et al. 2015). NA-CORDEX is a set of medium- to high-resolution regional climate model (RCM) simulations that use boundary conditions from the CMIP5 GCMs. NA-CORDEX simulations were accessed for both RCP4.5 (medium emission) and RCP8.5 (high emission) scenarios. The model resolution for RCP8.5 (11km) was higher than that for RCP4.5 (44km), due to data availability.

Daily model outputs from 1950-2005 were termed a “historical hindcast” where observed greenhouse gas forcing was used, whereas the 2006-2100 period was forced by RCP8.5 emissions. After bias-correcting the model data, the study investigated two properties of model-simulated heavy rainfall: its frequency using the Peaks-Over-Threshold approach, and its intensity using the AMS.

Stationarity Analysis Results:

AMS values are increasing across the region, indicating non-stationarity well beyond a level allowed simply by chance. Peak-Over-Threshold results are similar to the AMS trends, though with an even stronger signal indicating the presence of non-stationarity. Of 175 qualifying gages, 44 (25%) show a statistically significant trend with 43 showing a positive trend, which is higher than can be expected by chance alone.

Of the 175 qualifying gages, 73 (42%) show an increase in the 99th percentile intensity with 52 showing substantial increases of 15% of greater (only 15% show decreases). For the 70th percentile intensity, there are about as many gages seeing increases as decreases. Similar results are found when using the 50th, 60th and 80th percentiles. Collectively, the results imply that while the higher end rainfall events are getting wetter, this does not apply for the rest of the distribution.

Maryland’s Eastern Shore

Preparing for Increases in Extreme Precipitation Events in Local Planning and Policy on Maryland’s Eastern Shore

Source: (Charochak and Bass, 2019)

Objective:

Identify and illustrate risk associated with the increasing frequency of extreme precipitation events on Maryland’s Eastern Shore and provide guidance to local governments seeking to incorporate evolving flood and stormwater risk into local plans and decision-making.

Methods:

The study used a delta, statistical downscaling method. Precipitation estimates used in the research are the average of values derived by frequency analysis of 30-year (2040-2070) model outputs of five regional-global model pairs in the North American Regional Climate Change Assessment Project (NARCCAP) (Mearns et al. 2007, updated 2014). For each model location, AMS were developed for a 1971—2000 hindcast and for 2041-2070 projection. For each location, a series of change factors were created by comparing the two time periods.

Virginia

Next-Generation Rainfall IDF Curves for the Virginian Drainage Area of Chesapeake Bay

Source: (Wang 2019)

Objectives:

The objectives of this project were to: 1) develop an innovative approach for creating next-generation IDF curves that consider nonstationary rainfall, and 2) use this approach to create probability-based IDF curves for the state of Virginia, most of which is located within the Chesapeake Bay Watershed.

Method:

The predicted historic (i.e., pre-2013) and future (i.e., 2038 ~ 2070) data on regional precipitation at a 3-h time interval and a 50-km spatial resolution were downloaded from the North American Regional Climate Change Assessment Program (NARCCAP). Statistical methods were developed and used to downscale the 3-h predictions of the RCM-GCM models to the gauges using an average of the four gridded precipitation values around each gauge. Regression was done for the record period of the gauge and the best fit was selected to create a delta comparison to the future projections.

For instances where trends indicated non-stationarity at a gauge, the data were split into subsets to satisfy the stationarity requirement of the analysis.

Maryland

Source: (Butcher, personal comm)

Report (published after completion of this memo): https://cbtrust.org/wp-content/uploads/Grant16928-Deliverable11-FinalProjectReport.pdf

Objective:

Develop projected IDF curves and 90th percentile rainfall events for the state of Maryland for use in future stormwater design and planning.

Method:

A modified delta statistical downscaling approach was applied, where the change from historic to projected future conditions was used to develop future IDF curves, but using the shape of the entire rainfall distribution, not just the change in annual maximums. Equidistant quantile mapping was then used to further downscale to the gauge level. This is consistent with the approach NOAA used in Atlas 14.

The study used the LOCA dataset, and screened the 32 GCMs in CMIP5. From that set, they selected a drier model (10th percentile of combined RCP4.5 and RCP8.5), a median model (GCM median of each RCP4.5 and RCP8.5) and a wetter model (90th percentile of combined RCP4.5 and RCP8.5).

The study used annual maximum series (AMS) values to maintain consistency with NOAA methods, and produced mid-century and end of century projections with 30-year ranges, centered on 2055 and 2075.