Planning Climate Resilient Stormwater Infrastructure for a Growing Region

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Introduction

Heavy, short-duration rainfall events remain the leading cause of flash floods in urban areas, leading to traffic disruptions, infrastructure damage, and, in the worst cases, deaths. In a warming climate, these types of events are expected to become both more intense and frequent. This is due to the increased water holding capacity of the atmosphere, and consequently, more favorable conditions to generate rainfall. Previous studies have shown that heavy, short-duration rainfall is becoming more severe in recent decades, and that these trends will continue during the 21st century. Flood management infrastructure such as channels, roadway culverts, and stormwater systems, as well as other critical infrastructure including airports, roadways, bridges, and dams, are mostly designed by utilizing historical observations or 'retrospective' data. Hence, anticipating and quantifying expected changes in short-duration precipitation is key to evaluating the level of protection provided by current infrastructure and to inform future adaptation.

The design value in hydrologic engineering for a particular piece of infrastructure is commonly obtained from statistical analyses of hydrological data and associated with a risk. This is expressed as a probability of occurrence, such as the average recurrence interval (ARI) or return period. For example, an event with an ARI of 100 years has an annual probability of occurrence of 1% and is expected to be equaled or overcame once in 100 years. However, it has been seen that events of these magnitudes do not always follow the historical statistics and can occur multiple times within a single year or decade. When focused on precipitation-driven events, the design value is commonly defined from hydrologic studies using intensity-duration-frequency (IDF) curves, which provide extreme rainfall intensity (i.e., inches/hour) or depth (inches) values for various durations (minutes to days) and return periods (years). In long term planning, climate change may lead to considerable underestimation of precipitation design values based on retrospective analyses alone. Thus, the use of state-of-the-art climate models becomes critical for updating IDF curves regarding anticipated changes.

Global climate models enable simulations of Earth's complex physical, chemical, and biological processes and allow for the characterization of future climate, including extreme precipitation changes. Although many uncertainties are associated with global climate modeling and urban flooding, such as data processing methods, the translation of outputs to hydrologic models, and natural climate variability, global models have shown marked improvement and the ability to capture changes in the Earth system. As a result, they provide high-quality and physically based information for exploring the impacts of future climate changes. Thus, providing valuable inputs to inform decision making and urban planning. The proposed method provides an alternative approach which can leverage valuable information from climate models while overcoming their associated uncertainties and limitations. This includes a flexible plan prepared to commit to short-term actions, guide future actions, and allow updates as the knowledge improves (e.g., newer data, advances in climate models, more recent projections).

To put this promising framework into action, Northern Virginia provides an exceptional candidate region as one of the most rapidly growing urban centers of the United States. However, the region's ability to sustainably manage this dynamic growth are increasingly challenged by the effects of multiple environmental stressors – particularly the intensification of extreme precipitation events from climate warming. The Northern Virginia Regional Commission (NVRC) - a council of governments for 13 local authorities - has developed a "Resilient Critical Infrastructure Roadmap" to help the region absorb, recover from, and more successfully adapt to adverse events emanating from extreme weather events and climate-related hazards. NVRC has partnered with the American Geophysical Union and its membership at George Mason University to investigate regional extreme precipitation changes and incorporate climate change in flood engineering design. With a priority to support the action items that were recommended in NVRC's "Resilient Critical Infrastructure Roadmap."

Objectives

The objectives of this project were to provide a comprehensive analysis of spatial-temporal variability of average and extreme historical precipitation trends and to assess future extreme precipitation changes for multiple planning horizons in the 21st century, i.e., 2040, 2060, 2080, and 2100, by considering the effects of a changing climate. Specifically, the project aims to use climate model projections to enable analysis of precipitation related risks to infrastructure and for identifying the need for additional investments in flood resilient landscapes. A broader understanding of past precipitation patterns is necessary for optimizing future demands on stormwater infrastructure, particularly when combined with a warming climate and regional population growth.

The main project outcomes were as follows:

1) ***Analysis of historical precipitation patterns and changes.***

2) ***Incorporation of future precipitation changes in flood engineering design standards across Northern Virginia.***

3) ***Development of an adaptive framework/strategy for the application/replication of these changes by local watershed planners and engineers.***

4) ***Recommendations for how the information can be used to create flood resilient landscapes and infrastructure.***

Data and Methods

Northern Virginia Region

This study was conducted in the Northern Virginia Region encompassing the jurisdiction of the NVRC and located in the Potomac River Watershed (**Figure 1**.) According to the 2020 census, the region has a population of over 2.5 million residents, up from approximately 2.2 million in 2010.

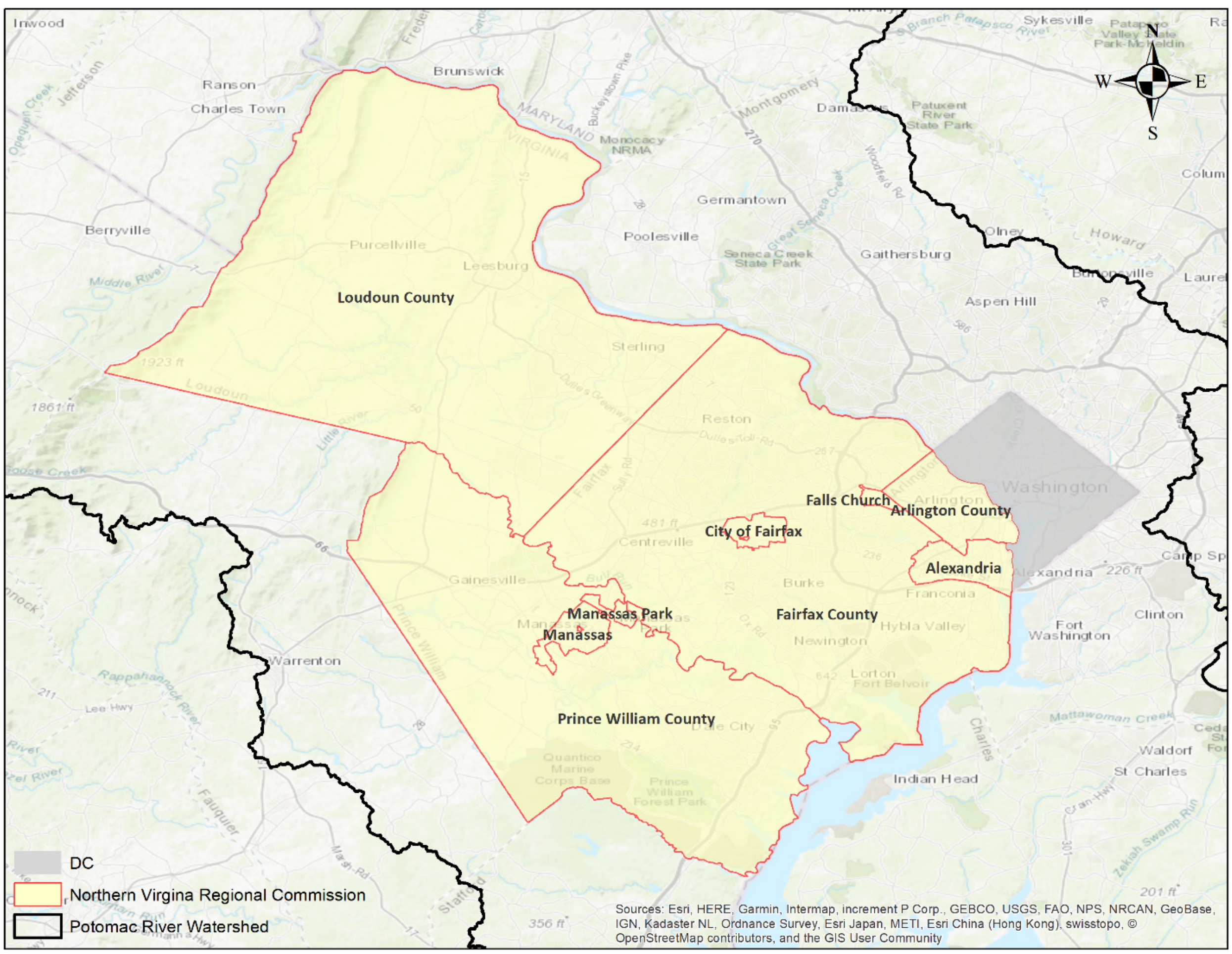


Figure 1. *Study region Northern Virginia Region Commission counties and jurisdictions.*

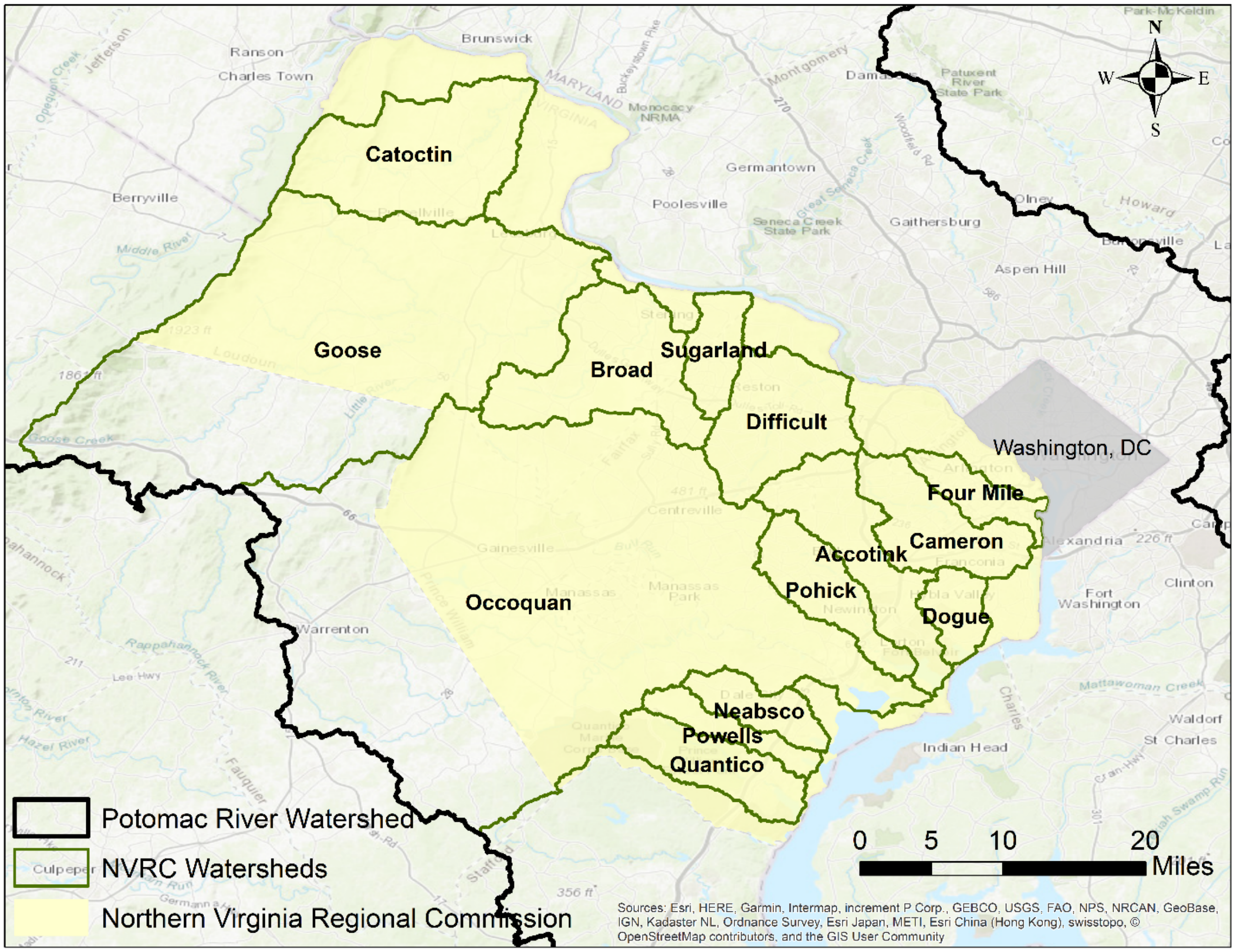


Figure 2. *Watersheds within the NVRC jurisdiction.*

Historical Precipitation Analysis

To assess the average and extreme spatiotemporal trends in precipitation, we used historical precipitation data from the North American Land Data Assimilation, version 2 (NLDAS-2). This dataset combines observational data with high-end modeling capabilities to derive an accurate record of precipitation in North America. Specifically for the period spanning 1980 to 2018, hourly data and with an approximate spatial resolution of 1/8th degree (approximately 7 miles or 50 mi^2) was collected and used for analyses. We performed a trend analysis of the annual maximum and seasonal precipitation extremes to identify and quantify changes over the historical period.

Current Hydrologic Engineering Design

The National Oceanic and Atmospheric Administration (NOAA) Atlas 14 is the primary source of IDF curves in the United States and was used in this study as a reference for current hydrologic engineering design standards [https://hdsc.nws.noaa.gov/hdsc/pfds/]. However, design standards vary between counties and jurisdictions, which may or may not be based on Atlas 14. Furthermore, the Mid-Atlantic Regional Integrated Sciences and Assessments (MARISA) provides climate-change informed intensity-duration-frequency (IDF) curves for counties across the Chesapeake Bay Watershed and the Commonwealth of Virginia that have been integrated in the climate adaptation plans of some jurisdictions. The IDF curves for the Northern Virginia Region that are presented in Volume 2 of Atlas 14 and were developed based on precipitation data from in-situ stations available until 2000. Note that NOAA periodically updates these volumes. The IDF curves in Atlas 14 are provided as a mean value and the respective lower and upper bounds at the 90% confidence interval. This represents the range of uncertainty in the statistical distribution fitting. Point frequency estimates from Atlas 14 are available in a uniformly spaced grid allowing us to both analyze the spatial precipitation distributions and to update estimates considering future changes across Northern Virginia. The results of this study are based on these gridded data.

Climate Model Data

In this study we used the latest climate model data following the Coupled Model Intercomparison Project Phase 6 (CMIP6, https://esgf-node.llnl.gov/projects/cmip6/) that defines the protocols for designing and distributing global climate model simulations. The historical simulations following the CMIP6 protocols comprise the period 1850-2014, and projected simulations 2015-2100. Projections can be developed considering different socioeconomic and forcing pathways, namely Shared Socioeconomic Pathways (SSPs) in CMIP6. The SSPs describe alternative evolutions of future society ranging from aggressive climate action (SSP1-2.6) to the absence of climate policy and continued unregulated growth of fossil fuel consumption (SSP5-8.5). The projected simulations are referred to as SSPx-y, where x is the specific SSP and y is the forcing pathway, defined by its long-term global average radiative forcing level as given in the Representative Concentration Pathways (RCP).

We assessed the total daily precipitation obtained from the historical and the SSP3-7.0 scenario from 70 members of the large ensemble (LE) prepared with Community Earth System Model version 2 (CESM2). This model was developed at the National Center for Atmospheric Research (NCAR) and is considered among the most advanced in the world. Ensembles provide an effective method to capture climate uncertainty by producing many slightly varied simulations and achieve enhanced performance relative to any single model realization. The SSP3-7.0 is a new scenario in CMIP6 that represents the medium to high end of the range of future pathways, filling a gap between the previous medium- and high-end emission scenarios (former RCP4.5 and RCP8.5). The CESM2-LE is the largest and newest available large ensemble following the CMIP6 protocols, which motivated our choice for using it to develop and implement our methodology. This model, and others similar to it, provide the backbone of analyses into climate variability and future projections as discussed in recent Intergovernmental Panel on Climate Change (IPCC) reports [https://www.ipcc.ch/assessment-report/ar6/].

Data Processing

Processing steps were as follows:

1) Extracting the extreme precipitation values from the climate model for each ensemble member and period.

2) Grouping the data from all members in the same period to create a long time series.

3) Computing the cumulative distribution function (CDF).

4) Computing the relative change between the reference and projected periods for each ARI.

5) Incorporating the change factor into Atlas 14 IDF curves.

We defined a reference period (1941-2000) for the modeled historical data to closely match the data period used to develop Atlas 14, and five 20-yr projected periods (i.e., 2000-2020, 2021-2040, 2041-2060, 2061-2080, and 2081-2100) for supporting a multi-temporal assessment. The extreme precipitation values were extracted from each ensemble member and period using the partial duration series method, which takes the highest *N* daily values in the period of record, where *N* is equivalent to the total number of years. The data series extracted from all 70 ensemble members were polled for reference and each project period producing a larger data set (e.g., 1400 years for projected periods), statistically enabling the estimation of longer return periods (>20 years). For each pooled data set, after computing the CDF, we calculated the relative change in precipitation between the reference and projected periods for multiple ARIs up to 100 years. Then, the relative change value was incorporated to the current Atlas 14 values to obtain projected IDF curves for different periods.

Scientific Outcomes

Historical Precipitation Changes

The analysis of domain averaged annual maximum precipitation using NLDAS-2 presented a significant positive trend having a 0.06 inch/year average rate of increase (**Figure 3**). This suggests a notable increase in extreme precipitation events at the daily timescale within recent decades.

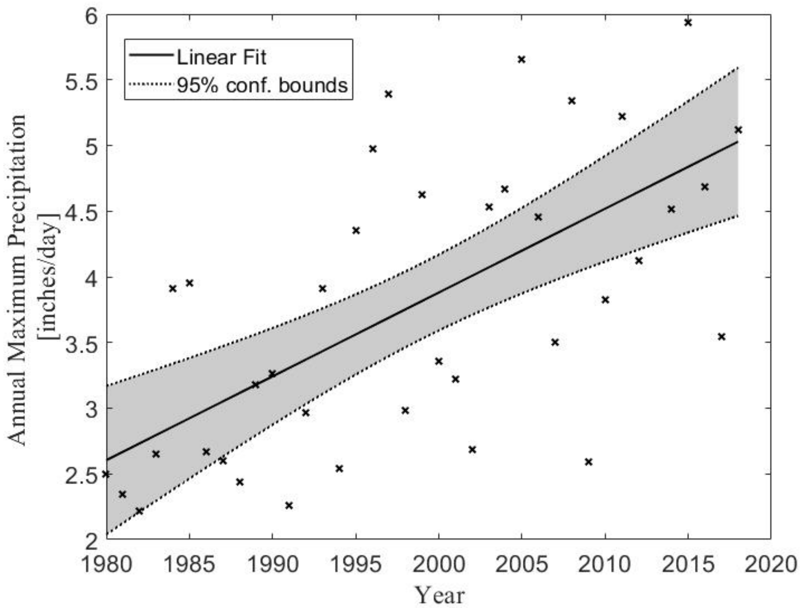


***Figure 3.** Linear trends during 1980–2018 period of NLDAS-2 observation-based records in annual maximum precipitation in inches/day. Cross markers represent the observed precipitation annual maximum daily values for each year and the fitted least square regression line is shown as a solid red line.*

Increases in summertime precipitation are prevalent in the central and northeastern parts of the domain, which including most counties in Northern Virginia (**Figure 4 b**). While positive trends are also observed in other seasons, they are markedly smaller than those observed in summer (June, July, and August) and were in most cases not found to be statistically significant. Region wide, summer shows large variability in trends with clear wetting trends in the northeastern counties of Northern Virginia along the southern side of Potomac River, north of DC, and through central Maryland, and even some drying trends in the southwestern region near the Shenandoah Valley. About 30% of the area was found to have significant trends of increasing precipitation extremes (with 95% confidence), with many of these areas concentrated in the Washington D.C. Metropolitan region.

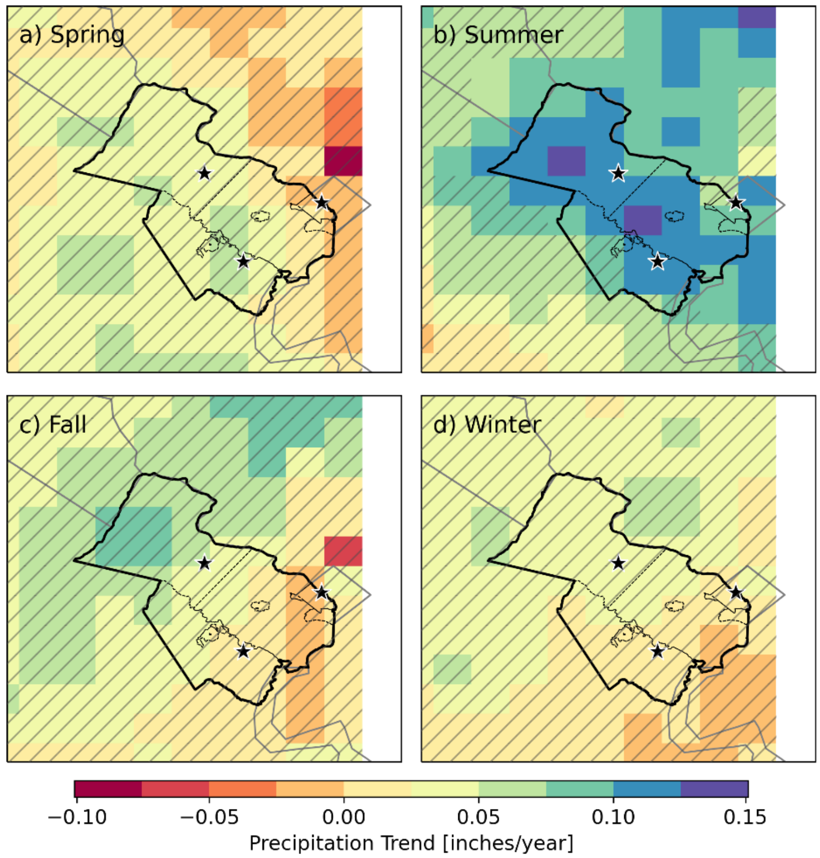


Figure 4. *Trends of seasonal precipitation totals (1980–2018) for (a) Spring (March–April–May), (b) Summer (June–July–August), (c) Fall (September–October–November), and (d) Winter (December–January—February). Cold colors indicate a wetting trend, whereas warm colors refer to drying trends. The size of the cross markers shows the three significance levels used to perform a trend test. Hatching indicates grid cells with non-significant trends at 95% confidence level.*

Fall precipitation trends in the region are primarily positive (**Figure 4 c**), with most of the Northern Virginia Region showing significant positive trends larger than 0.075 inches/year (with 95% confidence). These are clustered in northern Maryland and southern Pennsylvania. Precipitation trends in the immediate Washington D.C. metro region are markedly lower in fall as compared to summer and were not found to have significant wetting trends. In both winter and spring (**Figure 4 a**, **d**), trend magnitudes remain fairly small across the region, suggesting less significant historical changes in extreme events in these seasons over the previous four decades.

The average 1-day maximum precipitation (annual) for the 39-year period of record is shown in **Figure 4 a**, ranging from 2.0 to 2.6 inches/day across the Northern Virginia Region. Higher 1-day rainfall totals can be seen along a southwest to northeast gradient due to terrain effects. In regard to daily maximum annual trends, **Figure 5 b** shows that the entire Northern Virginia Region have statistically significant increasing trends with 95% confidence level. An increasing precipitation trend of 0.03-0.04 inches/year is present in part of Fairfax County extending to Eastern Loundon County, while the remaining of Northern Virginia Region is in the 0.01-0.03 inches/year range. While seemingly small, this rate equates to the expectation of over 0.75 inches (>1.5 inches in areas with the highest trends) of additional rainfall from the largest annual 1-day precipitation event today, as compared to 1980. This is more than enough to stress urban stormwater management systems and is only expected to worsen as we move further into the

21st century. In short, our analysis of historical reanalysis precipitation records suggests that both the severity of extreme precipitation events at the daily scale, and their contribution to regional rainfall totals, is growing. Thus, the historical record shows increasing intensity of short duration rainfall across much of the region, especially focused in the summer months.

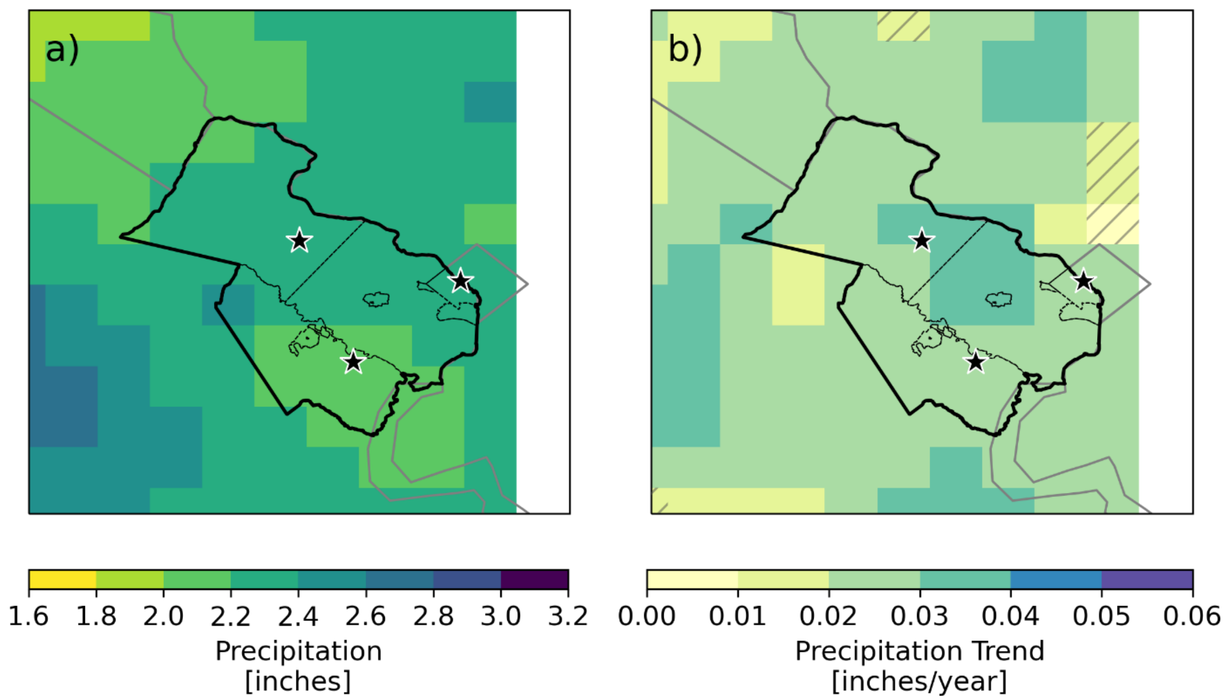


Figure 5. *Spatial distribution of extremes and associated trends in extremes (1980–2018) for (a) average 1-day maximum annual precipitation with a histogram in the right corner showing the right skewed distribution of 1-day maximum precipitation for all grids; and (b) 1-day maximum annual precipitation trend. Hatching indicates grid cells with non-significant trends at 95% confidence level.*

Future Precipitation Changes and Potential Impact on Engineering Design

Based on the percentage increases presented in **Figure 6**, the spatial precipitation distribution of the 24 hour duration event from Atlas 14 and projected periods is shown in **Figure 7** for the Northern Virginia Region. The maps for the period 2001-2020 demonstrate how the current precipitation references could change by updating the IDF curves with the past two decades of data. Although no significant changes are observed, an increase in the order of 0.5 inches is present in some areas.

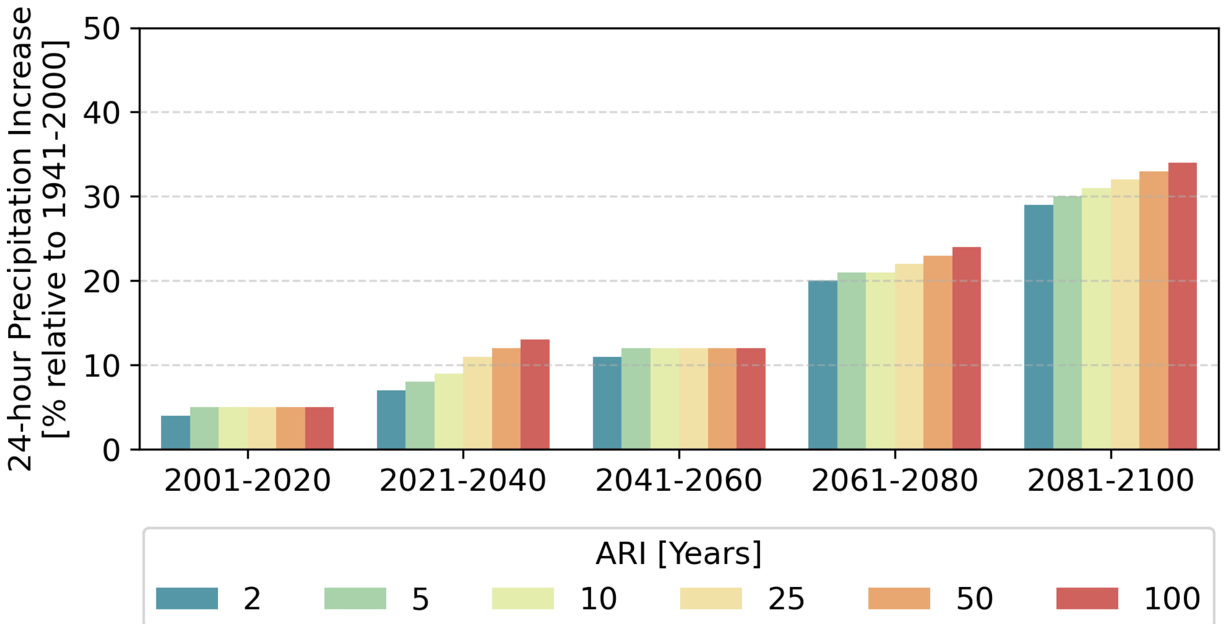
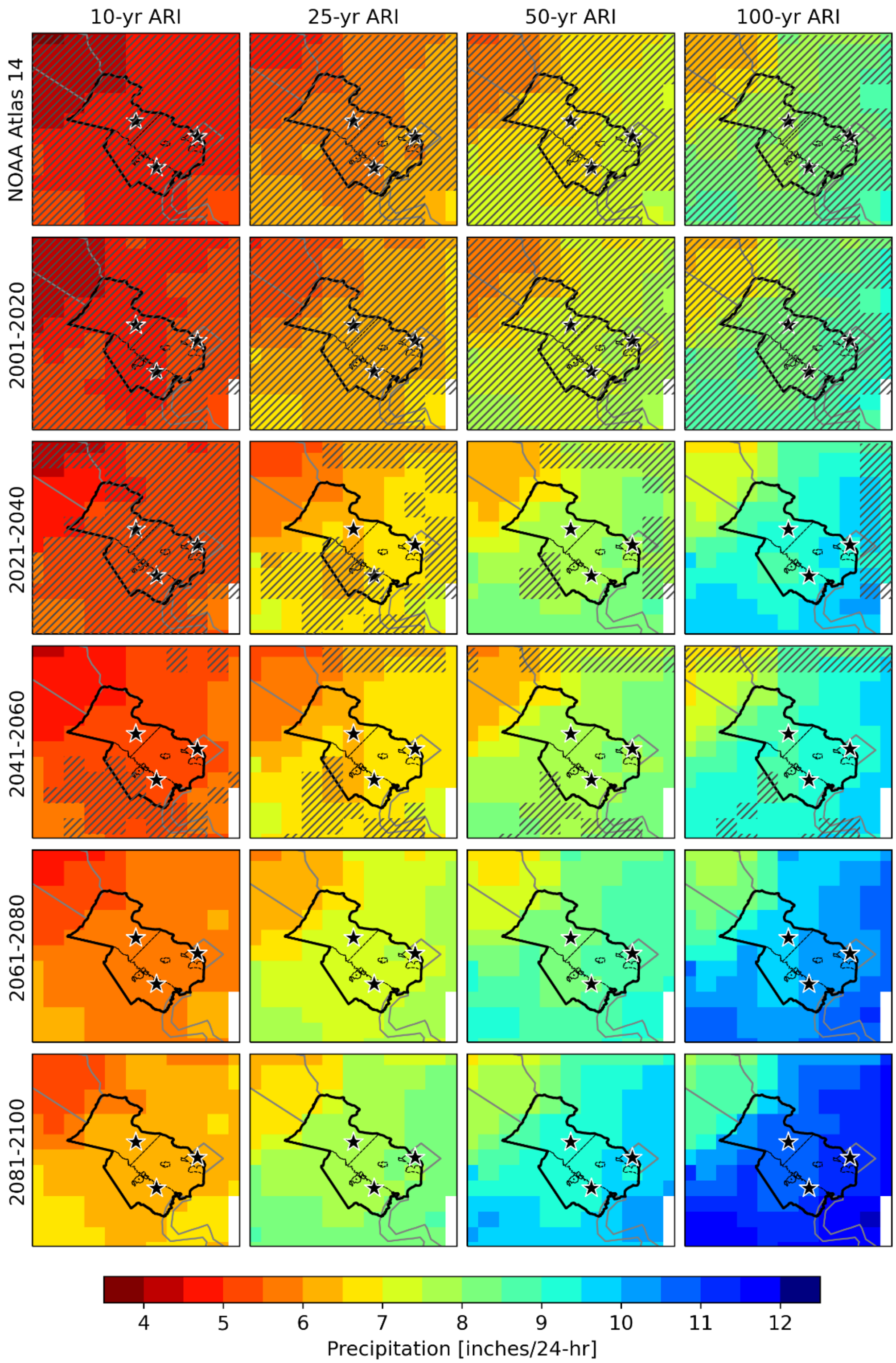


Figure 6. *Expected percentage increase in 24-hour precipitation relative to the reference period (1941-2000) for various average recurrence intervals (ARIs).*

The projected maps for 2021-2040 indicate that most of the values in the Northern Virginia Region for 25-yr and 50-yr ARI, and all for 100-yr ARI will be obsolete. Precipitation extremes are shown to progressively increases towards the end of the century, and the current IDF values are expected to be fully obsolete beyond 2060. By the 2081-2100 period, relative to today, increases of approximately 2 and 4 inches for 10-yr and 100-yr ARI daily events are expected.

The projected IDF curves at three selected locations are presented in **Figure 8**. The IDF curve for 2001-2020 (green) shows a slight increase in relation to Atlas 14 (blue) at the three locations. The projected IDF curves for the periods 2021-2040 (pink) and 2041-2060 (purple) are very similar and located at the upper bound of the 90% confidence interval (grey) of Atlas 14. Lastly, the projected IDF curves for 2061-2080 (yellow) and 2081-2100 (red) are much above the 90% confidence interval upper bound of Atlas 14. This illustrates the expected acceleration of increases in extreme precipitation considering the SSP-3.70 pathway. A scenario that remains a realistic middle of the road expectation based on current trends.



10-yr ARI
25-yr ARI
50-yr ARI
100-yr ARI
NOAA Atlas 14
2001-2020
2021-2040
2041-2060
2061-2080
2081-2100
4
5
6
7
8
9
10
11
12
Precipitation [inches/24-hr]

__Figure 7.__ Precipitation estimates in 24-hour duration for 10-yr, 25-yr, 50-yr, and 100-yr ARI (columns) from NOAA Atlas 14 (row 1), and for projected periods (rows 2-6). Hatching indicates grid cells where the projected precipitation is inside NOAA Atlas 14 90% confidence interval.

The point estimates of precipitation provided by Atlas 14 serve as a widely used baseline to estimate extreme rainfall events at the local scale. These estimates are frequently used for developing design storms, which is a key component of hydrologic and hydraulic (H&H) studies required in runoff estimation for sizing stormwater management facilities and estimating stream stage for flood plain analyses. This study showed that the extreme precipitation increases facilitate a need for adjusting the current IDF standards, and H&H studies should incorporate these changes to assess the current level of protection and required needs to sustain the expected level of infrastructure protection into the future. We also highlight additional variables such as soil moisture, land use, and land cover also remain important inputs for interpreting and updating flood resilience in the context of design.

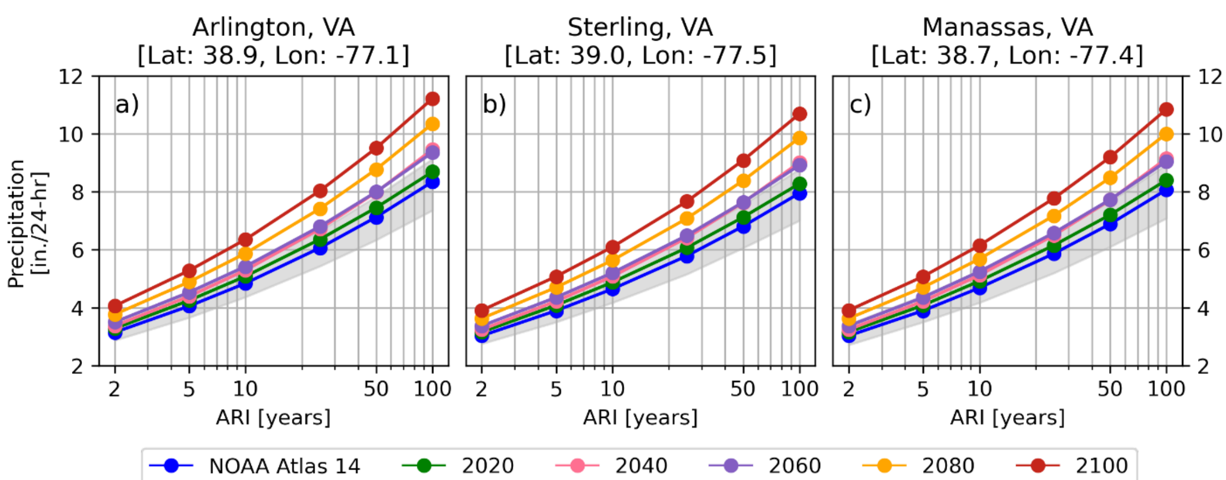


__Figure 8.__ Current and projected IDF curves at selected locations: a) Arlington, VA; b) Sterling, VA; c) Manassas, VA, as indicated by stars in __Figure 4__, __Figure 5__, and __Figure 7__.

Community Outcomes

The Community Outcomes discuss the implications of the anticipated changes in precipitation for stormwater infrastructure planning and management based on the research conducted in this project. Although the uncertainty associated with climate projections can lead to a broad range in the magnitude of the projected changes, we identified the recommendations that can be drawn from this study as follows:

1) ***Daily precipitation amounts used for infrastructure design are expected to increase by between 7-13% in 2040 and 29-34% by 2100 considering a middle-of-the-road climate pathway.***

2) ***Existing infrastructure in flood-prone areas could be at greater risk of flooding than estimated based on the Atlas 14 IDF curves.***

3) ***New infrastructure projects (e.g.., drainage networks) should consider the impacts of future precipitation conditions (changes in IDF curves) based on the expected project life.***

4) ***Utilization of additional climate data and other Shared Socioeconomic Pathways (SSPs) simulations should be explored to better represent the full range of possible precipitation futures and their regional implications.***

An indirect outcome of this project was to motivate a Congressionally mandated Community Project to create the Virginia Climate Center. The new Center will receive funding from NOAA in FY2022 to conduct a pilot project to investigate feasibility. The Virginia Climate Center will function as an extension service based at George Mason University to help municipalities in the Commonwealth understand and cope with the impacts of climate change, including the increase in intensity of precipitation events in northern Virginia that was determined in this study. Partners in the pilot project include the Northern Virginia Regional Commission as well as the city and county of Fairfax.