City of Richmond

CIVE T580: Stormwater in an Era of Climate Change

August 26, 2020

Drexel University
Team Members

Julia Coleman
Elise Eggert-Crowe, PE
Jake Simmet

1. Introduction

1.1. Project Overview

CIVE T580: Stormwater in an Era of Climate Change sought to connect the analyzation aspects of climate change model development to the real-world aspect of climate change as observed by seven municipalities across the East Coast of the United States. Students in the class were split into groups of two or three people and partnered with a government agency that sought to better understand how to prepare for the changes the world's changing climate would be bringing. The municipalities faced challenges such as flooding, extreme precipitation, and an uphill battle involving educating those ignorant of the changes the changing climate wrought on local neighborhoods and entire cities.

In many instances, the municipalities simply did not have the funds required of a full-time climate scientist, so participation in this class as a government partner served to dip their toes in the water of climate change and to get a feel for how large in magnitude these changes would be on their area of interest. Over the course of ten weeks, students worked to develop a representative table of values to be applied to known design storms to approximate the changes to be seen in the 2020s, 2050s, and 2080s. While the values themselves were merely "multiplicative," meaning there was no overarching equation to approximate the amount of water other than multiplying these Delta Change Factors (DCFs) with the design storm values, it was a step in the right direction for municipalities who had never before consulted a third party in the ways of climate change.

1.2. City of Richmond: Background

Our interview with the City of Richmond took place over Zoom on July 1, 2020 with participants Brianne Mullen, the two-year Sustainability Coordinator in the Office of Sustainability and Jenn Clarke, the year and-a-half-long Public Education and Outreach Coordinator, part of the Stormwater Utility, one of five departments of public utilities within the city. Brianne's focus is with the City Climate Action Plan, monitoring the climate resilience of Richmond. Jenn's work focuses on public outreach and education of stormwater, particularly the water quality and the impacts of climate change. She also runs RVA H2O, which is the City of Richmond's Clean Water Plan.

The City of Richmond Department of Public Utilities, including both the Stormwater Utility and the Wastewater Utility are responsible for stormwater management locally. Approximately two-thirds of the city is served by separate storm sewer (MS4), covered by the Stormwater Utility, while the remaining third of the city is a combined sewer. Cooperation between both Stormwater and Wastewater occurs frequently, allowing for a mutual partnership. Richmond also has the first “Integrated Permit” in Virginia, with wastewater, CSO, and MS4 all under one permit. This is a new step for the state, although VA is not the first.

Geographically, the City of Richmond is split on two sides of the James River, which contributes to the Chesapeake Bay Watershed. Topographically, there are a few low sections of the city, and these areas have longstanding issues attributed to their elevation, most notably: Shockoe Bottom. Most of the north side of the city drains through Shockoe Bottom as well. Compositionally, Richmond’s South Side is very impervious and flows downhill toward the river, so there is generally less infrastructure given the overland flow ability. A final notable feature of the city is the flood wall, built to withstand a 280-year storm. Frequent testing allows all employees hands-on experience and knowledge necessary for closing the gates if flooding is predicted. The wall is located mostly on the south side of Richmond, although a portion of the north side is more inland. The flood wall was built mostly to protect the built environment.

1.3. City of Richmond: Current Data and Methods

The current method of design stormwater infrastructure is to utilize the 10-year design storm. This design storm was chosen 15 years ago and has not gone through any modifications based on current climate data. The 10-year design storm has a 24-hour rainfall depth of 5.08 inches. The design storm data currently used from the 2008 design manual is provided below.

Table 1: City of Richmond, VA Design Strom Information

City of Richmond Storm Data						
24 hour rainfall depths, inches From VDTO Hydraulic Design Advisory 05-04.2 revised 2/1/08						
1-year	2-year	5-year	10-year	25-year	50-year	100-year
2.76	3.34	4.28	5.08	6.27	7.29	8.42

The Richmond International Airport has a rain gauge that provides data going back one hundred years. The rain gauge data has allowed time steps to be created. Brianne noted that these time series data have been utilized in her work to analyze the rainfall history to use for both planning and communication to the community. Jenn noted that the time series data from the airport gauge is used by the city in their CSO notification system. A 100-year floodplain is used to delineate an area in which the construction of buildings is restricted.

Over the past two years, a climate and risk assessment was performed. This involved finding and studying what data and information other cities already performed and made available. A broad understanding of what the climate issues are and who or what are vulnerable to these climate impacts. This information is currently being used to better understand how to assess the risks associated with climate impacts. Gaining a better understanding of the precipitation is an important technical issue to assess the risk on the built environment, existing and future.

There has been public outreach for the past ten years. During this period, the pushback has decreased as the public begins to accept the reality and acknowledge that something should be done to help remedy future issues. Part of this outreach involves explaining the risk to the existing infrastructure and ways to be preventative. The rain events of 2018 may have aided in the public understanding of risks associated with climate change. In 2018, there was a day with seven inches of rain, another day with five inches and three hurricanes. This year stands out as an especially high rain event year. During one of these hurricanes, the floodwall along the James River was closed as a preemptive measure. The location of the storm changed, and the rain covered the city not the river. Unfortunately, the floodwall did not contain any openings or channels to allow water to enter the river from the town side. This caused the rainfall to pond within the city and major flooding of buildings.

At the governmental level, Jenn noted that department budgets, policy, programs, and limited staff are potential barriers to implementing climate change policy and methods. The represented municipal departments do not have dedicated funding to support the development of a robust and reliable model or precipitation forecast. There also appears to be anticipated resistance from developers and engineering consultants around new methodologies or more stringent design criteria.

1.4. City of Richmond: Stormwater Issues

The most pressing stormwater issues presented include combined sewer overflow (CSO) events, infrequent maintenance on public storm infrastructure, and nuisance flooding. Additional areas of stormwater concern include the appropriate sizing of infrastructure from the past, present and into the future.

Approximately one-third of the city contributes to a combined sewer system, which experiences CSO events during large storm events when the infrastructure is overwhelmed by runoff. In March 2020, Virginia lawmakers passed a bill to require interim planning, annual reporting, and a hopeful elimination of CSO events by 2035. The bill is pending the Governor's signature.

City representatives frequently cited maintenance issues as contributing to the city's stormwater problems. A team of workers employed with the Public Utility do scheduled maintenance at least once a year, however the sheer number of structures and pipes present a challenge. Despite best efforts, it is difficult to stay proactively ahead of issues and often the obstructions are cleared only once flooding has occurred.

Nuisance flooding appears to be a secondary issue to CSO and maintenance. Nuisance flooding was attributed not to the amount or intensity of rainfall events, but deferred maintenance or areas of low elevation or downstream areas with historical issues of flooding, such as the Shockoe Bottom neighborhood. The south side of the city also has flooding issues, given the high amount of impervious surfaces and less stormwater infrastructure. Both Brianne and Jenn spoke to the possibility of unreported flooding issues, particularly on the south side of the City of Richmond, which is also a recognized equity issue. The south portion of the city ends to have higher rates of poverty and communities of color, which may not report flooding at the same occurrence as other areas of the city.

City representatives raised general concerns on appropriate infrastructure sizing for the past, present, and future conditions. Design criteria set by the city requires sizing infrastructure to the 10-year, 24- hour design storm, as dictated in the 2008 manual. The concern is that the 10-year design storm from 2008 is no longer accurate, which leads to undersized infrastructure from past and present designs. Looking toward a future with climate change, the City anticipates increased intensity, volume, and frequency of precipitation events, and it is unclear if the current design standard is robust enough to safely convey runoff from these events.

While not a stated issue during the interview, city representatives noted that the James River is tidal up to the "locks" or "falls", located approximately mid-city along the James River. This is a similar, related issue in water resources planning under climate change, and this tidal influence may indicate that the City of Richmond is susceptible to sea-level rise. Sea-level rise and tidal influences directly affect stormwater infrastructure outflow conditions.

1.5. City of Richmond: Stormwater Goals

In her work on the Virginia Climate Vulnerability & Risk Assessment, Brianne is specifically noted two goals: (1) understanding potential climate impacts and (2) who/what is vulnerable to these climate impacts. Changing precipitation is just one of many impacts that the City of Richmond faces under climate change.

Gaining an understanding of anticipated precipitation events with a changing climate is critical in order to plan for the future of the city. Precipitation data is a direct input into stormwater and sewer conveyance design, CSO modeling, site development design, and stormwater/green infrastructure design. Precipitation data is technical in nature, and the city currently lacks technical resources to develop predictions for precipitation under climate change scenarios. Without a reliable prediction of changing precipitation information, the city is unable to plan and is unable to codify design storm information that may lead to better designs.

Once there is an understanding of future precipitation information, the city can also embark on identifying who and what is vulnerable to these precipitation predictions and allocate available resources to mitigate these risks. For example, it may be possible to identify that a geographic location is susceptible to flooding and mitigate that risk using green infrastructure, elevating structures, increasing infrastructure conveyance capacity, or even recede from those areas all-together. Assessing risk and defining mitigation strategies are often very complex from economic, social, political perspectives, which can only come after an understanding of the scientific and statistical understanding of the climate phenomenon.

2. Understanding Past & Projected Precipitation

2.1. Data Source and Methods

The Climate Explorer (https://crt-climate-explorer.nemac.org/) is a web application containing data and maps available for decision making and planning efforts. In order to assist with municipal-level planning and decision making for the City of Richmond.

Precipitation is expected to change dramatically in the face of climate change. Both historical and projected precipitation data are analyzed in this report. Projected data is included for two representatives carbon pathways, RCP 4.5 and RCP 8.5. RCP 4.5 is a climate change scenario with radiative forcing of 4.5 W/m^2 in 2100, and it uses 19 climate models to make projections. RCP 8.5 is a climate change scenario with radiative forcing of 8.5 W/m^2 in 2100, and it uses 20 climate models to make projections. Representative carbon pathways are not emissions-based scenarios, but rather represent a warming scenario and one would work backwards to derive a range of emissions trajectories that would correspond to that warming. Note that RCP 8.5 corresponds to a scenario with more warming.

2.2. Annual Precipitation

Current drainage systems within cities, especially Richmond, do not take into account the ever-changing nature of the climate. For yearly precipitation, a general trend to increase is observed in the data collected, but current guidelines for utilities within Richmond do not evaluate these changes in a way to mitigate the slow, but sure, requirements in drainage capacity. Undersized drainage pathways can result in flooding, undue roadway wear due to flooding, increased maintenance on existing catch basins, and unpredictability in their efficacy.

Properly sizing systems is the first step to preventing the potential problems with standing water due to slow drainage. The second step to prevention is to adequately increase the size of currently undersized systems, to foresee increases in annual rainfall and to mitigate the strain on the system. From Table 2, patterns in both the minimum and maximum extremes show a general increase in precipitation over the next century.

Table 2: Historical and Projected Annual Precipitation

a. 2020s	Baseline (1971-2000)			RCP 4.5			RCP 8.5		
	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
	44.67	35.20	59.70	46.58	24.10	79.50	46.55	23.20	75.90
b. 2050s	**Baseline (1971-2000)**			**RCP 4.5**			**RCP 8.5**		
	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
	44.67	35.20	59.70	47.71	22.90	83.50	48.17	24.20	80.00
c. 2080s	**Baseline (1971-2000)**			**RCP 4.5**			**RCP 8.5**		
	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
	44.67	35.20	59.70	48.06	23.20	80.00	49.79	24.80	87.40

Note: All data downloaded from The Climate Explorer (https://crt-climate-explorer.nemac.org/), accessed July 26, 2020, for the City of Richmond, VA (FIPS Code 51760). Baseline data are from yearly observed rainfall over the period of 1971-2000. Decadal data was averaged from the yearly projected RCP 4.5 and 8.5 data. For example, the RCP 8.5 Average for 2050s is the average of yearly projected rainfall data using the RCP 8.5 projections for the period 2040-2069. While both RCP methods approximate from 19 and 20 models, respectively, it is important to note the remaining uncertainty in this data.

2.3. Seasonal Precipitation

Seasonal precipitation events can provide planners with a best guess of when the worse rain events may occur, either frequency or intensity. The time period for each season are as follows: winter is December to February, spring is March to May, summer is June to August, and fall is September to November. The baseline data is the observed historical data from the years 1950 to 2006. The amount of precipitation increases for each season, spring has the greatest rate of increase. Summer and fall both contain maximums above 10 inches. The data seems to suggest that fall will experience dry spells followed by high intensity rain events.

Table 3: Historical and Projected Seasonal Precipitation

a. 2025	Baseline (1961-1990)	RCP 4.5			RCP 8.5		
	Avg.	Avg.	Min.	Max.	Avg.	Min.	Max.
Winter	3.20	3.44	0.66	8.20	3.43	0.70	8.61
Spring	3.60	3.90	0.84	9.41	3.85	0.77	9.33
Summer	4.30	4.50	0.91	12.53	4.53	0.89	12.09
Fall	3.60	3.69	0.43	12.22	3.71	0.39	11.76
b. 2050	Baseline (1971-2000)	RCP 4.5			RCP 8.5		
	Avg.	Avg.	Min.	Max.	Avg.	Min.	Max.
Winter	3.20	3.51	0.71	8.95	3.59	0.73	8.77
Spring	3.60	4.02	0.87	10.07	3.99	0.73	10
Summer	4.30	4.57	0.81	12.58	4.58	0.84	13.3
Fall	3.60	3.71	0.38	11.16	3.74	0.35	12.36
c. 2075	Baseline (1971-2000)	RCP 4.5			RCP 8.5		
	Avg.	Avg.	Min.	Max.	Avg.	Min.	Max.
Winter	3.20	3.67	0.73	8.91	3.8	0.71	9.37
Spring	3.60	4.02	0.84	10.08	4.08	0.71	10.19
Summer	4.30	4.67	0.78	12.94	4.68	0.71	13.5
Fall	3.60	3.84	0.35	12.64	3.79	0.34	13.02

Note: All data downloaded from The Climate Explorer (https://crt-climate-explorer.nemac.org/), accessed July 12, 2020, for the City of Richmond, VA (FIPS Code 51760). Baseline data are from monthly data over the period of 1961-1990. Seasonal data was averaged from monthly RCP 4.5 and RCP 8.5 projection data. For example, the RCP 4.5 Average for Winter 2025 is the average of monthly projected data using the RCP 4.5 scenario over the months of December to February. The minimum and maximum values correspond to the lowest or highest value within the season. Climate models are projections with inherent uncertainties and the associated potential for uncertainty or error in data derived from climate models should be acknowledged.

2.4. Extreme Precipitation

Extreme precipitation events can be particularly concerning for municipal-level planners. Precipitation data is used for a variety of applications, including, sizing of sewer conveyance systems, sizing of culverts, inlet placement to avoid road flooding, sizing of stormwater detention systems, riverine flood-stage models, dam operation, and countless others. Critical infrastructure must maintain conditions for public health and safety in all events, but particularly must be able to handle extreme precipitation events.

Planning decisions made today must be made with an understanding of potential extreme precipitation of the future. Extreme precipitation events are defined here as the number of days per year with rainfall above 1 inch, 2 inches, and 3 inches. Over the baseline period, Richmond experiences approximately 8 days per year with rainfall above 1 inch, which is expected to remain steady through 2020, and increase to approximately 9 days by 2050, and 10 days by 2080. Considering maximum future projections, Richmond could see up to 19 days per year with precipitation over 1 inch. In analyzing more extreme events of 2-inches and 3-inches, the projections show the averages are to remain somewhat steady, but the variability increases significantly. For example, the historical analysis shows a range of 0 to 2.7 days per year with rainfall over 2-inches, which will grow to a range of 0 to 5.4 days per year under the RCP8.5 2080 projection (Table 4).

Table 4: Historical and Projected Extreme Precipitation

a. 2020s	Baseline (1971-2000)			RCP 4.5			RCP 8.5		
	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
No. of days per year with rainfall above 1 inch	8.3	3.3	15.6	8.0	0.2	24.8	8.1	0.8	23.5
No. of days per year with rainfall above 2 inches	1.0	0.0	2.7	1.1	0.0	7.7	1.1	0.0	5.6
No. of days per year with rainfall above 3 inches	0.2	0.0	1.0	0.2	0.0	2.3	0.2	0.0	2.7
b. 2050s	**Baseline (1971-2000)**			**RCP 4.5**			**RCP 8.5**		
	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
No. of days per year with rainfall above 1 inch	8.3	3.3	15.6	8.5	0.9	24.8	9.0	1.0	22.4
No. of days per year with rainfall above 2 inches	1.0	0.0	2.7	1.1	0.0	7.5	1.2	0.0	8.9
No. of days per year with rainfall above 3 inches	0.2	0.0	1.0	0.2	0.0	3.0	0.3	0.0	3.1
c. 2080s	**Baseline (1971-2000)**			**RCP 4.5**			**RCP 8.5**		
	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.
No. of days per year with rainfall above 1 inch	8.3	3.3	15.6	8.8	1.2	23.5	9.8	1.0	25.3
No. of days per year with rainfall above 2 inches	1.0	0.0	2.7	1.3	0.0	6.7	1.6	0.0	7.7
No. of days per year with rainfall above 3 inches	0.2	0.0	1.0	0.3	0.0	4.1	0.4	0.0	3.4

Note: All data downloaded from The Climate Explorer (https://crt-climate-explorer.nemac.org/), accessed July 12, 2020, for the City of Richmond, VA (FIPS Code 51760). Baseline data are from yearly data over the period of 1971-2000. Projected data was averaged from yearly RCP 4.5 and RCP 8.5 projection data for a 30-year range surrounding the target projection. For example, the RCP 4.5 Average for 2020s is the average of yearly projected data using the RCP 4.5 scenario over the years 2010-2039. While fractions of less than one day per year are not realistic, the information has been presented following uniform methodology to enable comparisons. Climate models are projections with inherent uncertainties, and the associated potential for uncertainty or error in the data derived from climate models should be acknowledged.

3. Projected Delta Change Factors (DCF)

3.1. Data Source and Methods

The Multivariate Adaptive Constructed Analogs (MACA) Datasets contain readily available, bias corrected, climate model outputs (https://climate.northwestknowledge.net/MACA/index.php). The MACA method is a statistical downscaling method applied to 20 global climate models (GCMs). The MACA tool contains historical data from the Coupled Model Inter-Comparison Project 5 (CMIP5) and future projections from Representative Concentration Pathways (RCPs) RCP4.5 and RCP8.5.

Within the MACA tool there are two data products: MACAv2-METDATA and MACAv2-LIVNEH. These will be referred to as METDATA and LIVNEH throughout this report. These two data products differ in two main aspects including training dataset and resolution (Table 5).

Table 5: Key Parameters in MACA Datasets

	MAVAv2-METDATA	MACAv2-LIVNEH
Training Dataset	Abatzoglou et. al., 2012 (1979-2012)	Livneh et. al., 2013 (1950-2011)
Resolution	~6-km (1/16 deg)	4-km (1/24 deg)

For all datasets downloaded using the MACA web tool, monthly data was exported for a point of interest over the Richmond International Airport, with approximate coordinates of 37.5068 N, -77.3208 E. Precipitation was the only variable extracted in this analysis, though the MACA tool contains additional climate variables.

Historical monthly data was exported for all 20 GCMs and both datasets (METDATA and LIVNEH) for the period January 1971 to December 2000. This was compared to historical observed annual precipitation from The Climate Explorer. Model selection is discussed in Section 3.3.

Projected monthly data was exported for selected models. Projected monthly data was analyzed for both RCP4.5 and RCP8.5 in 30-year timeslices, centered around the namesake decade: 2020s (2010-2039); 2050s (2040-2069); 2080s (2070-2099). This was completed for both the 10 selected METDATA models and 10 selected LIVNEH models.

3.2. Map of Data Sources

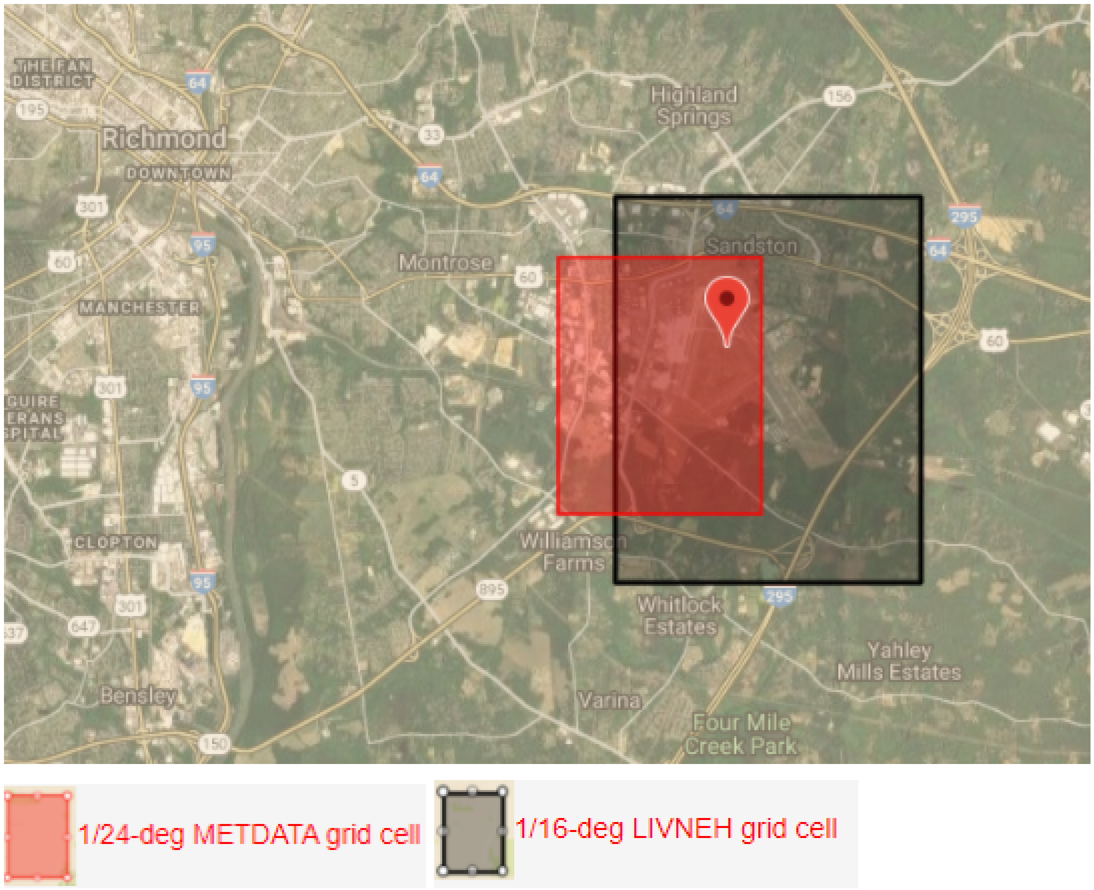

Figure 1: MACA tool dataset grids

3.3. Model Selection

The MACA tool contains downscaled bias-corrected of 20 GCMs. Only 10 of these models were selected for continued analysis. In order to select the 10 models, historical observed annual precipitation from The Climate Explorer was compared to historical modeled annualized (from monthly data) precipitation from all 20 MACA models (METDATA and LIVNEH) for the period 1971-2000. The sum of precipitation (1971-2000) was taken for the observed historical dataset and for each modeled historical (METDATA and LIVNEH) dataset. A difference was calculated between the historical observed and historical modeled precipitation sums, and the 10 METDATA and 10 LIVNEH models with the least value of difference were selected. Note that since the METDATA and LIVNEH datasets are different, model selection was not identical across the two datasets. Additionally, it should be noted that identical model selection would hold with an analysis of the difference in average (instead of sums) of precipitation. Selected models are highlighted in blue in Table 6.

Table 6: Model Section (blue highlighted models used)

METDATA Models	LIVNEH Models
bcc-csm1-1 (China)	bcc-csm1-1 (China)
bcc-csm1-m (China)	bcc-csm1-m (China)
BNU-ESM (China)	BNU-ESM (China)
CanESM2 (Canada)	CanESM2 (Canada)
CCSM4 (USA)	CCSM4 (USA)
CNRM-CM5 (France)	CNRM-CM5 (France)
CSIRO-Mk3-6-0 (Australia)	CSIRO-Mk3-6-0 (Australia)
GFDL-ESM2M (USA)	GFDL-ESM2M (USA)
GFDL-ESM2G (USA)	GFDL-ESM2G (USA)
HadGEM2-CC365 (United Kingdom)	HadGEM2-CC365 (United Kingdom)
HadGEM2-ES365 (United Kingdom)	HadGEM2-ES365 (United Kingdom)
imncm4 (Russia)	imncm4 (Russia)
IPSL-CM5A-LR (France)	IPSL-CM5A-LR (France)
IPSL-CM5A-MR (France)	IPSL-CM5A-MR (France)
IPSL-CM5B-LR (France)	IPSL-CM5B-LR (France)
MIROC5 (Japan)	MIROC5 (Japan)
MIROC-ESM (Japan)	MIROC-ESM (Japan)
MIROC-ESM-CHEM (Japan)	MIROC-ESM-CHEM (Japan)
MRI-CGCM3 (Japan)	MRI-CGCM3 (Japan)
NorESM1-M (Norway)	NorESM1-M (Norway)

3.4. DCF Values

The Delta Change Factor (DCF) approach compares historical and future values. For the purposes of this analysis, DCF was calculated as follows:
*DCF = 100 * [(future - historical) / historical]*

This particular form results in a DCF that represents a percent increase over baseline condition. DCF values were calculated on a monthly basis for all months of the year. For example, a DCF value of 5.5 represents a 5.5% increase in precipitation for the given timeframe, month, RCP, and GCM. Note that a DCF of 0 (0%) would indicate no change from historical precipitation. Also note, it is possible to obtain a negative DCF, which would indicate a decline in precipitation for a future value.

Historical monthly data was averaged from 1971-2000 for the selected models (10 METDATA, 10 LIVNEH). For example, the historical value for January was obtained by averaging 600 January values (30 January values x 10 models x 2 datasets). This results in 12 values, one average for each month of the year.

Projected monthly data was averaged for the both RCP4.5 and RCP8.5 in 30-year timeslices, centered around the namesake decade: 2020s (2010-2039); 2050s (2040-2069); 2080s (2070-2099). This was completed for both the 10 selected METDATA models and 10 selected LIVNEH models. This results in 1440 values (20 GCMs x 2 RCPs x 12 months x 3 timeslices).

The DCF calculation compares the historical modeled and projected modeled precipitation. This was completed for both RCP4.5 and RCP8.5 in 30-year timeslices, centered around the namesake decade: 2020s (2010-2039); 2050s (2040-2069); 2080s (2070-2099). Additional items were selected by the utility, including 2030s (2020-2049) and 2070s (2060-2089). This was completed for both the 10 selected METDATA models and 10 selected LIVNEH models. This results in 1440 values (20 GCMs x 2 RCPs x 12 months x 3 timeslices). Note there are 40 DCFs per month per timeslice (20 GCMs x 2 RCPs). Results are shown in Figures 2-4.

Additional items were subsequently requested by the utility partner, including 2030s (2020-2049) and 2070s (2060-2089, which are included for reference in Figures 5-7. Note that the discussion pertains to results from the 2020s, 2050s, and 2080s in keeping with the course-wide analysis framework.

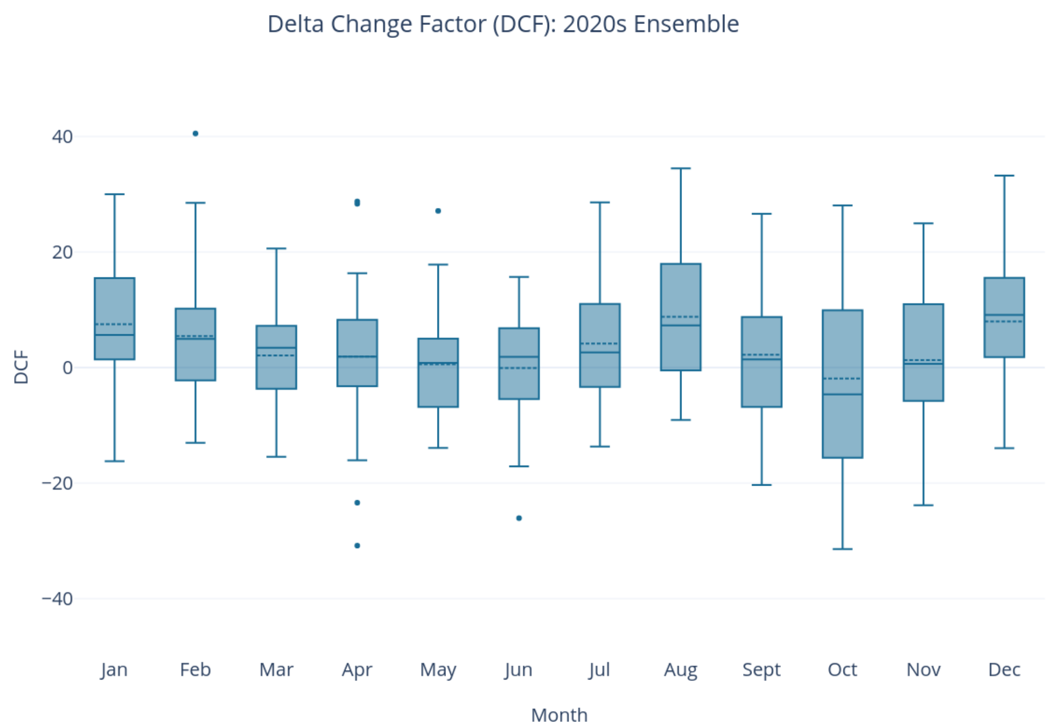

Figure 2: Monthly DCF (% increase) for 2020s

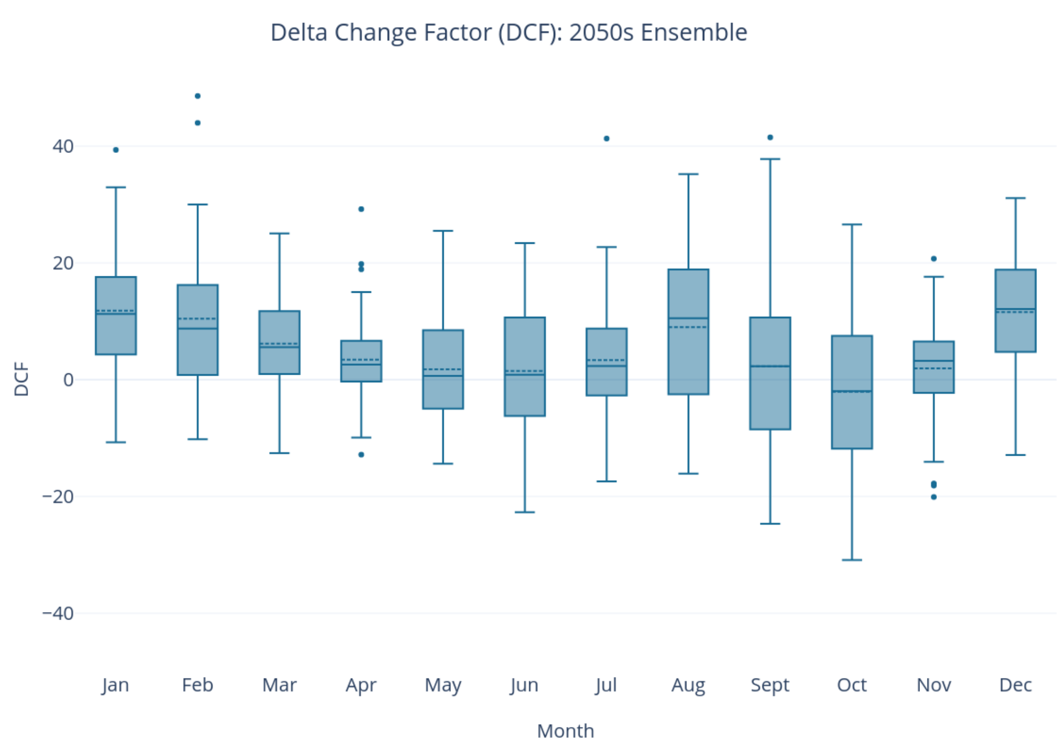

Figure 3: Monthly DCF (% increase) for 2050s

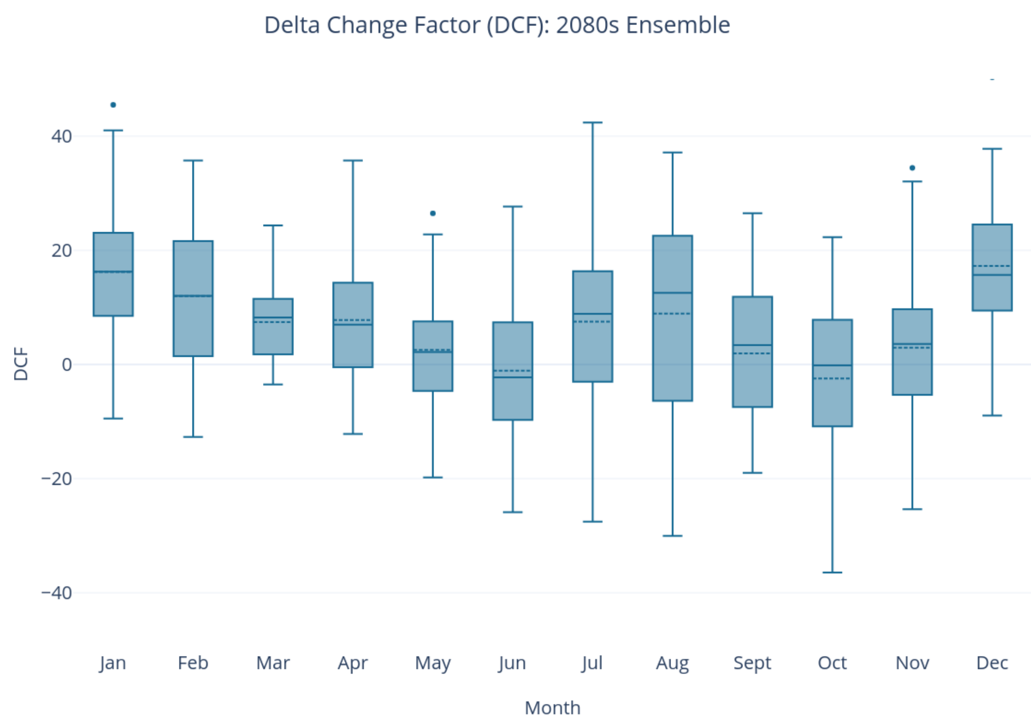

Figure 4: Monthly (% increase) for 2080s

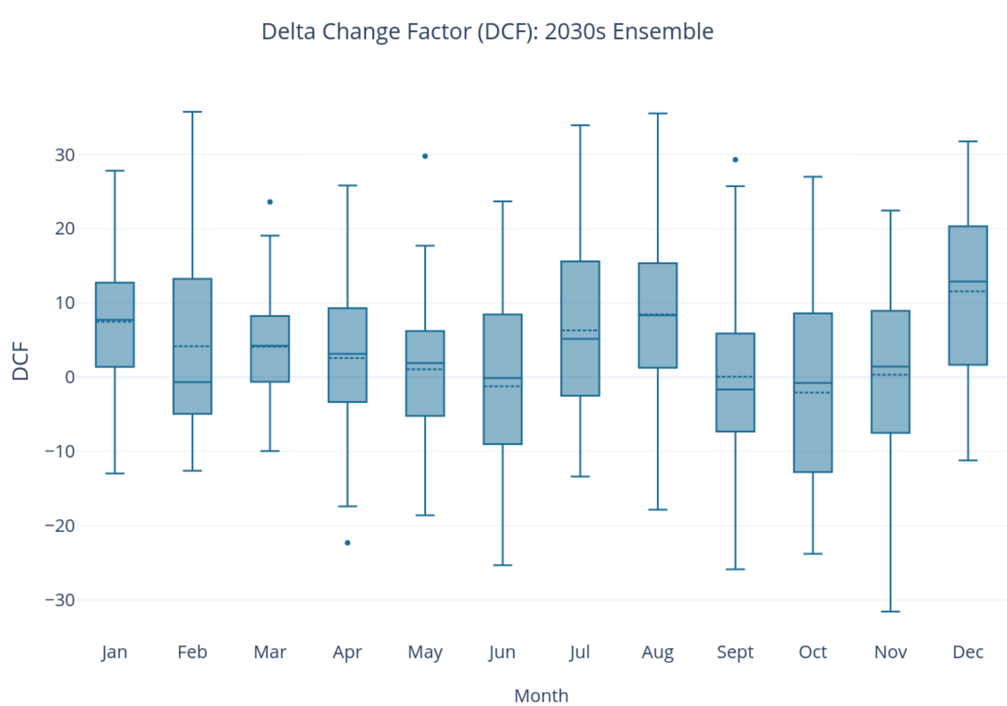

Figure 5: Monthly DCF (% increase) for 2030s

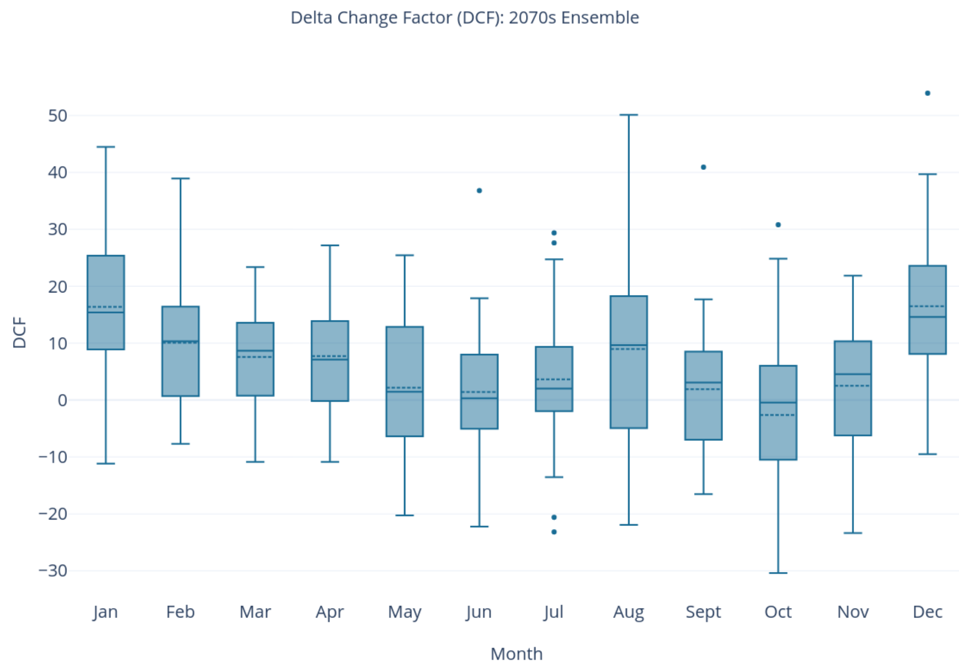

Figure 6: Monthly DCF (% increase) for 2070s

3.5. DCF Discussion

There is considerable variability in DCF values within individual months and across months of the year. This is somewhat expected, especially given that the DCF values represent both RCP4.5 and RCP8.5 scenarios and that each time slice is representative of 30-years of data.

The median values generally increase with increasing time, which is consistent with scientific consensus of increased precipitation for the eastern United States. The 2020s has expected monthly medians ranging from -4.92 (Oct.) to +9.10 (Dec.). The 2050s has expected monthly medians ranging from -1.97 (Oct.) to +12.09 (Dec.) The 2080s has expected monthly medians ranging from -2.25 (Jun.) to +16.25 (Jan). This suggests a somewhat seasonal response, resulting in dryer summer/fall and wetter winters.

The extreme values (minimum and maximum) of each time slice are also variable. In the 2020s, the minimum DCF value is -30.82 (Apr), and the maximum DCF value is 40.52 (Feb). In the 2050s, the minimum DCF value is -24.67 (Sept), and the maximum DCF value is 48.58 (Feb). In the 2080s, the minimum DCF value is -30.04 (Aug), and the maximum DCF value is 50.30 (Dec). While the highest value tends to fall consistently in the winter, the lowest value falls in different seasons altogether for each time slice. This information also appears to suggest that winters will experience increased precipitation in the future. The seasonal variation in the lowest extreme value may be indicative of periods of drought throughout the spring, summer, and fall.

4. Past and Projected Design Storm

4.1. City of Richmond: Current Design Storms

The CIty of Richmond, VA uses the Stormwater Management Design and Construction Standards manual, dated July 1, 2012 for stormwater management design in the city. The manual prescribes the use of 24-hour design storms, for the 1-year, 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year return periods. The Type II distribution is applicable to Virginia per the guidance in the National Engineering Handbook, Chapter 4. The Richmond manual provides design storm depths, which are close in comparison to recently obtained NOAA Atlas 14, Version 2, Volume 3 Depths (Table 7). The more recent values obtained through NOAA Atlas 14 are used in this analysis.

Table 7: Historical Design Storm Depths for Richmond, VA

City of Richmond 24-Hour Design Storm Depth (inches)							
Return Period→ Source↓	1-year	2-year	5-year	10-year	25-year	50-year	100-year
Richmond Manual (2008)	2.76	3.34	4.28	5.08	6.27	7.29	8.42
NOAA Atlas 14 Version 2, Volume 3 Accessed 8/9/2020	2.74	3.32	4.25	5.04	6.22	7.23	8.35

4.2. Design Storm Selection

The 2-year, 10-year, and 100-year return periods, using a 24-hour duration are selected for the analysis. The 2-year storm represents smaller, frequent storms. The 10-year storm is the basis for minor arterial, collector, local roads and streets within the Richmond design manual. Finally, the 100-year storm represents a large, infrequent storm. All design storms are distributed with a Type II distribution.

4.3. DCF Selection

To exemplify the effect of a changing climate, three DCF values were selected from the 2050s ensemble and three DCF values were selected from the 2080s ensemble. Given seasonal indications in the data discussed previously, a seasonal approach was executed for DCF selection. The seasonal average DCF values were computed for the 2050s and 2080s (Table 8).

Table 8: Average Seasonal DCF

Season	2050s DCF (%)	2080s DCF (%)
Winter (Dec, Jan, Feb)	11.3	15.2
Spring (Mar, Apr, May)	3.8	5.9
Summer (Jun, Jul, Aug)	4.6	5.1
Fall (Sept, Oct, Nov)	0.7	0.8

Note that all seasons represent a projected increase in precipitation (DCF>0) in the future time slices. Winter and fall were selected for the relative maximum and minimum values, respectively. Spring was selected to illustrate a wider range of DCF outcomes.

4.4. Projected Design Storm

Projected design storm depths are calculated by applying the DCF (% increase) relative to historical design storm depth with the following equation:

*Future Depth = Historical Depth * [(1 + DCF) / 100]*

The projected design storm depths for 2020s and 2080s are presented below in Table 9 and Table 10, respectively.

Table 9: Projected Rainfall Depths 2050s

Return Period (24-hour duration)	2-year	10-year	100-year
Historical Depth (inches)	3.32	5.04	8.35
2050.1 Depth (inches) DCF = 11.3%	3.70	5.61	9.29
2050.2 Depth (inches) DCF = 3.8%)	3.45	5.23	8.67
2050.3 Depth (inches) DCF=0.7%	3.34	5.08	8.41

Table 10: Projected Rainfall Depths 2080s

Return Period (24-hour duration)	2-year	10-year	100-year
Historical Depth (inches)	3.32	5.04	8.35
2080.1 Depth (inches) DCF = 15.2%	3.82	5.81	9.62
2080.2 Depth (inches) DCF = 5.9%)	3.52	5.34	8.84
2080.3 Depth (inches) DCF=0.8%	3.35	5.08	8.42

5. Case Study: Modeling a site in the City of Richmond

5.1. Site Description

The site selected by the government partners was a single block bound by 25th Street to the west, Cary Street to the south, Main Street to the north, and 26th

Street to the east. It contained two large apartment buildings with a vegetated corridor between them. In addition, the site was located upgradient of the Richmond City Canal, which connects to the James River. No known information was given about underwater piping or overall drainage on the site, so approximations were made based on the impervious and pervious area. An aerial image of the site was used to approximate the site area, in addition to the pervious and impervious area breakdowns. Overall the site was approximately 104,878 square feet (2.41 acres) in size, with 90,117 square feet (2.07 acres) being impervious and 14,761 square feet (0.34 acres) being pervious.

5.2. Modeling Methods

HydroCAD Version 10.00 was used to model stormwater runoff from the selected site, using the following parameters::

Table 11: Modeling Parameters

Parameter	Value
Runoff Method	SCS TR-20
Storm Type	Type II, 24-hour
Storm Duration	24-hour
Back-to-Back Storms	1 (single event)
Antecedent Moisture Condition	2 (normal condition)
Rainfall Depth	See Table 9 and Table 10
Time Span	0.00 to 48.00 hours
Time Increment	0.01 hours
Curve Number (CN) Weighting Method	SBUH (Separate pervious/impervious runoff)
CN Pervious Cover	74 (Lawn, grass >75%, HSG C)
CN Impervious Cover	98
Time of Concentration (Tc)	6 minutes (minimum)

5.3. Site Stormwater: NOAA Atlas 14 and Projected Stormwater

Table 12a-c: Model Results for Selected 2050s DCFs

a) Stormwater Runoff Scenarios for 2050s (2-Year)				
Scenario	DCF (% Increase)	2-Year		
		Depth (inches)	Runoff Volume (CF)	Peak Rate (CF)
NOAA Atlas 14	-	3.32	24,557	10.38
2050.1 (11.3%)	11.3	3.7	27,725	11.68
2050.2 (3.8%)	3.8	3.45	25,639	10.82
2050.3 (0.7%)	0.7	3.34	24,724	10.45

b) Stormwater Runoff Scenarios for 2050s (10-year)				
Scenario	DCF (% Increase)	10-Year		
		Depth (inches)	Runoff Volume (CF)	Peak Rate (CF)
NOAA Atlas 14	-	5.04	39,018	16.29
2050.1 (11.3%)	11.3	5.61	43,863	18.26
2050.2 (3.8%)	3.8	5.23	40,630	16.94
2050.3 (0.7%)	0.7	5.08	39,357	16.43

c) Stormwater Runoff Scenarios for 2050s (100-Year)				
Scenario	DCF (% Increase)	100-Year		
		Depth (inches)	Runoff Volume (CF)	Peak Rate (CF)
NOAA Atlas 14	-	8.35	67,350	27.77
2050.1 (11.3%)	11.3	9.29	75,456	31.04
2050.2 (3.8%)	3.8	8.67	70,107	28.88
2050.3 (0.7%)	0.7	8.41	67,866	27.98

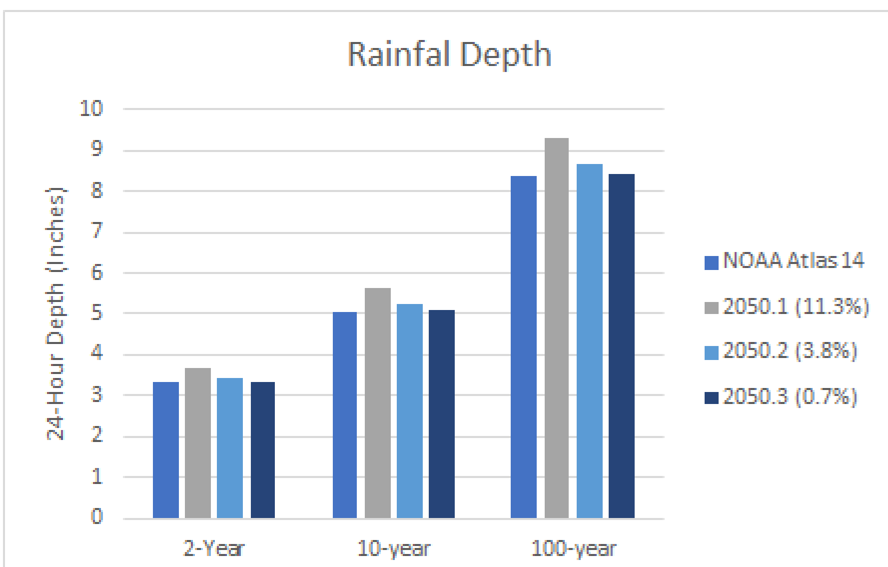

Figure 7: Comparison of rainfall depths across selected 2050s DCFs

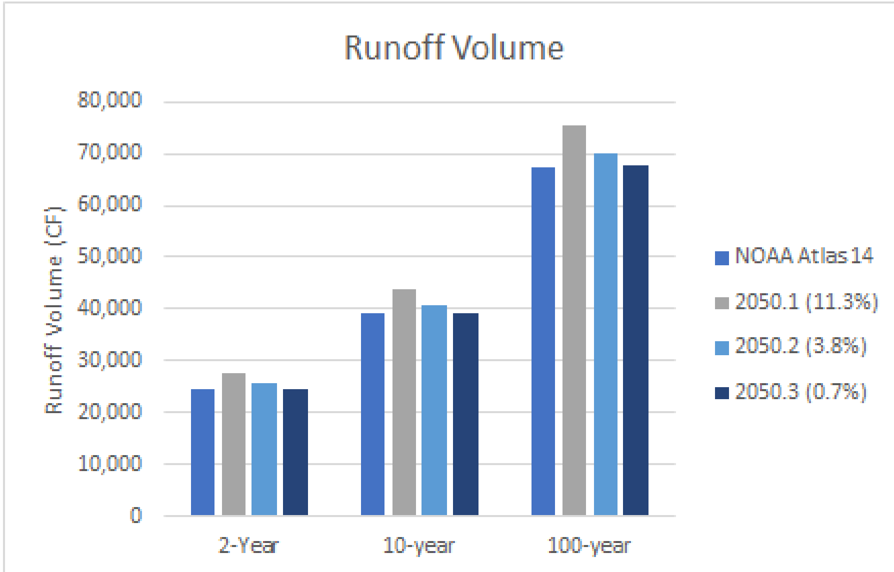

Figure 8: Comparison of rainfall volume across selected 2050s DCFs

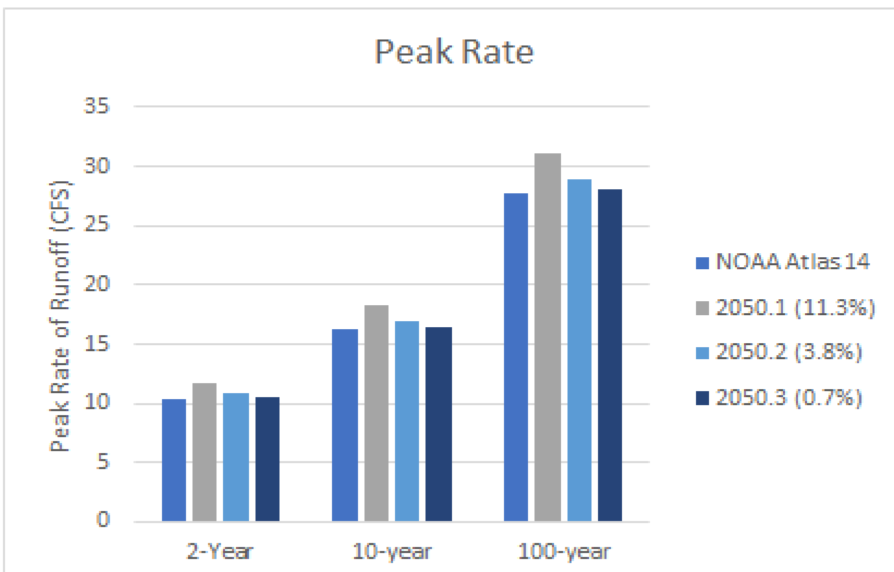

Figure 9: Comparison of peak rate of runoff across selected 2050s DCFs

Table 13a-c: Model Results for Selected 2080s DCFs

a) Stormwater Runoff Scenarios for 2080s (2-Year)				
Scenario	DCF (% Increase)	2-Year		
		Depth (inches)	Runoff Volume (CF)	Peak Rate (CF)
NOAA Atlas 14	-	3.32	24,557	10.38
2080.1 (15.2%)	15.2	3.82	28,729	12.09
2080.2 (5.9%)	5.9	3.52	26,222	11.06
2080.3 (0.8%)	0.8	3.35	24,807	10.48

b) Stormwater Runoff Scenarios for 2080s (10-Year)				
Scenario	DCF (% Increase)	10-Year		
NOAA Atlas 14	-	5.04	39,018	16.29
2080.1 (15.2%)	15.2	5.81	45,567	18.95
2080.2 (5.9%)	5.9	5.34	41,565	17.32
2080.3 (0.8%)	0.8	5.08	39,357	16.43

c) Stormwater Runoff Scenarios for 2080s (100-Year)				
Scenario	DCF (% Increase)	100-Year		
		Depth (inches)	Runoff Volume (CF)	Peak Rate (CF)
NOAA Atlas 14	-	8.35	67,350	27.77
2080.1 (15.2%)	15.2	9.62	78,305	32.18
2080.2 (5.9%)	5.9	8.84	71,573	29.47
2080.3 (0.8%)	0.8	8.42	67,953	28.01

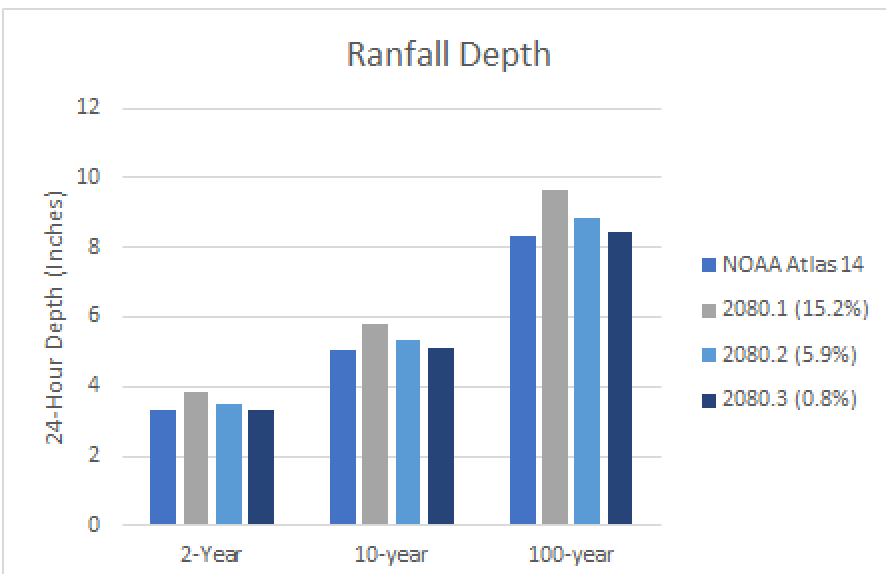

Figure 10: Comparison of rainfall depths across selected 2080s DCFs

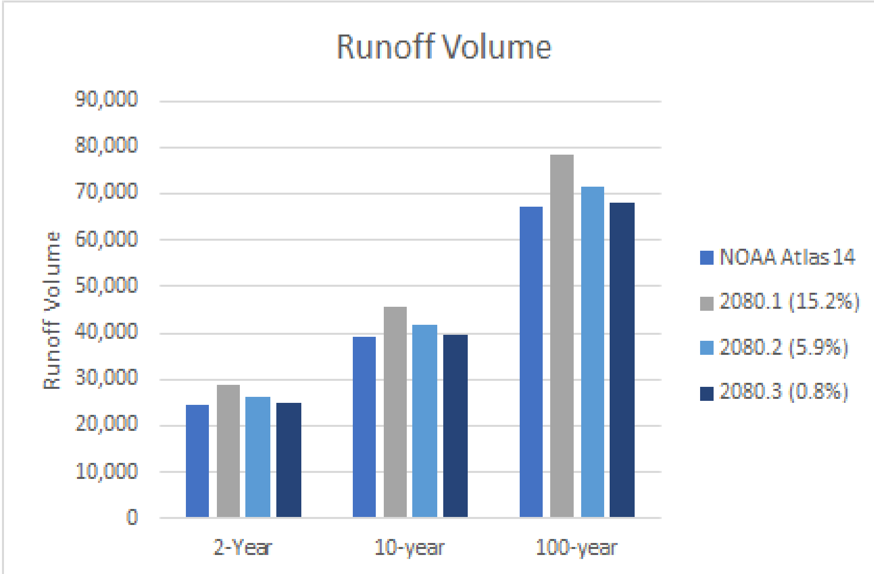

Figure 11: Comparison of runoff volumes across selected 2080s DCFs

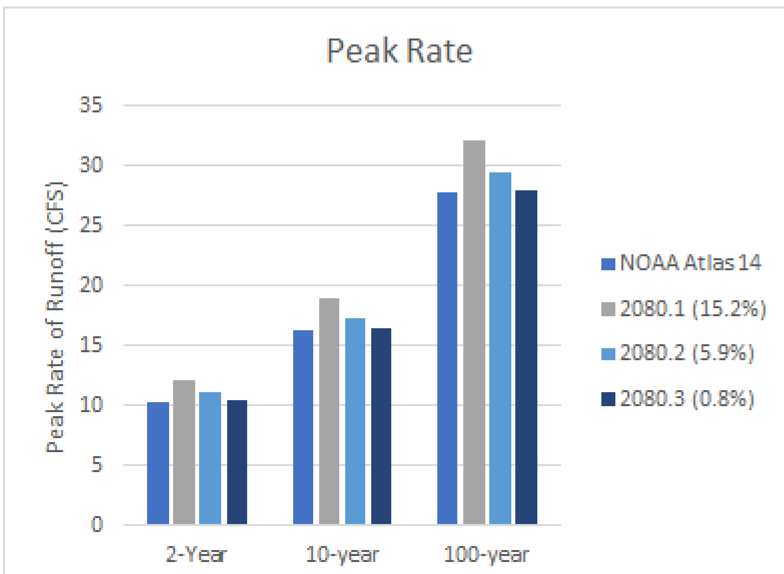

Figure 11: Comparison of peak rate of runoff across selected 2080s DCFs

5.4. Discussion of Modeling Results

An immediate take away from the case study modeling results indicate that with projected increase in precipitation, there will be associated increases in both stormwater runoff volume and peak rate of runoff. While this result may seem intuitive at first, it is important to note that this observation is limited to the model used, which is based solely on the SCS / TR-20 Curve Number Method. This model does not replicate physical processes of infiltration or evaporation.

The results exhibit neither a proportional nor a linear relationship between precipitation increase. For example, a projected increase in precipitation of 11.3% does not result in 11.3% increase in runoff volume or 11.3% increase in peak rate of runoff. Also notable is the observation that the lower the return period, the higher the variance in percent change, regardless of DCF. For example, the % changes for runoff and peak rate for the 2-year storm are further from the depth % change, than compared to the same results of the 10-year storm. (Figure 12a-b and Figure 13a-b).

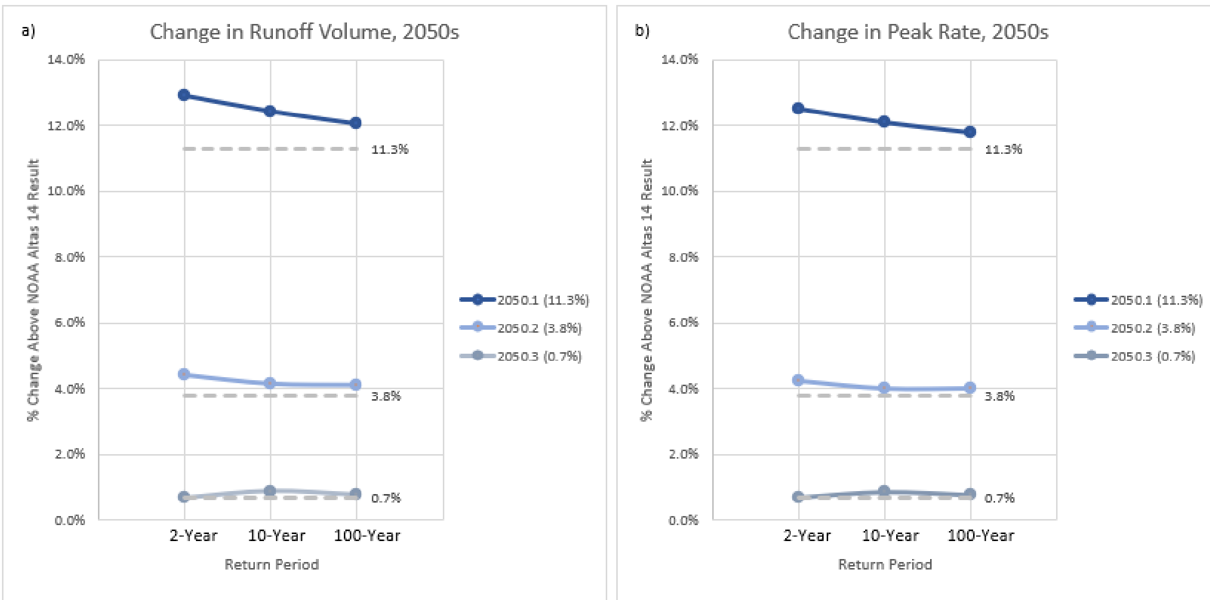

Figure 12 (a-b): Comparison of % changes in depth, volume, and peak rate for 2050s.

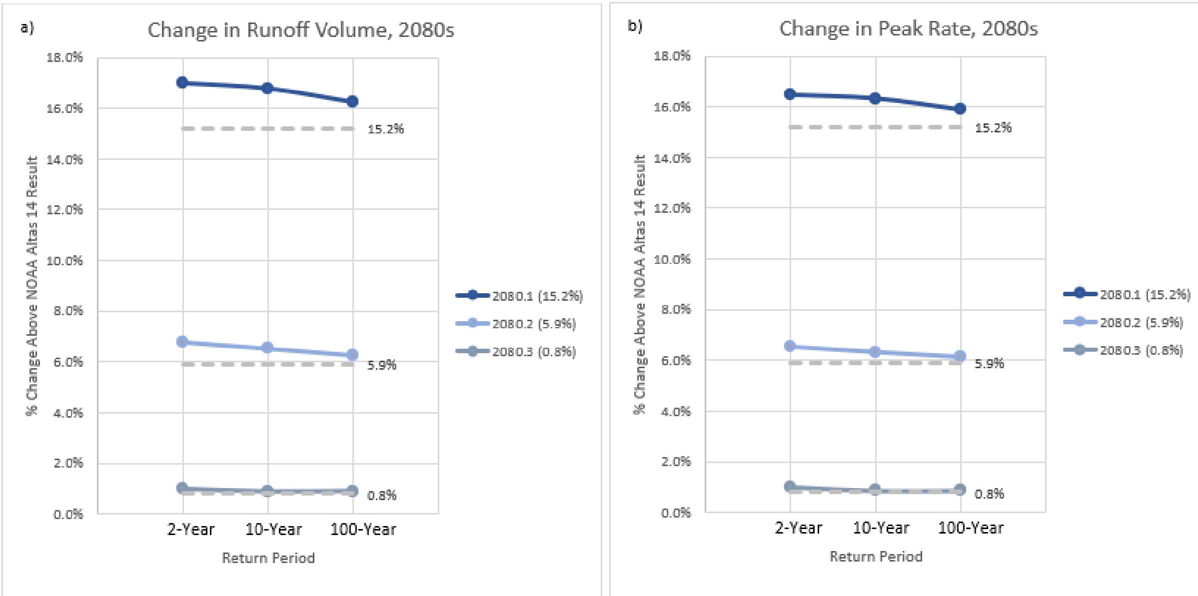

Figure 13 (a-b): Comparison of % changes in depth, volume, and peak rate for 2080s.

6. Summary and Recommendations

6.1. Summary

Through the analyzation of the collected data, a trend towards a future increase in precipitation was observed. Widely accepted climate science corroborates this trend. There was a large range of DCF values for each month, however most of the median values were positive. October in both the 2050 and 2080 time slices and June 2080 were the only negative medians. October consistently had a wide variability; this could be caused by the unknowns created by hurricane season. Overall, late summer and early fall have highly variable projections. Spring and early summer tended to have a narrower range of projected values. Due to the high median DCF values observed for the winter months, it is reasonable to anticipate the winter months to be wetter than the current. The increased precipitation affected the predicted runoff volumes and peak runoff rates calculated in the model of the chosen site in Richmond, Virginia. There was an increase in runoff volumes and peak runoff rates when applying the DCFs generated for both the 2050 and 2080 time slices.

6.2. Acknowledgement of Limitations

Many limitations were found as a direct consequence of the ten short weeks given for such an analysis. From selecting data to the final report, groups were essentially given eight weeks to develop a reasonable value for an approximate storm for a representative area for a selected time frame. Many assumptions were made, and consequently, these limitations present problems to perhaps be changed in future analyses.

The first major limitation, other than time, was the scope of the course. In an attempt to synchronize data with the other seven groups, it was not always feasible to tailor these analyses to one particular municipality. In addition, the findings in this course could have also had higher meaning in terms of academia, for those interested in such analyses based off of papers such as Maimone, whose process was generally followed in this project to develop such DCFs. As a result, the groups were reigned in to follow a generally similar pattern of analysis and discussion often lead to reanalyzing data to fit with the overall group, rather than just specifically one's municipality.

Another limitation encountered was the variety of data available to the student groups for analysis. Many instances of data were missing a crucial parameter or year, and many datasets were missing data smaller than an annual scale. Processes had to be modified to the available data, so analysis was often reworked after groups determined the available data was insufficient for certain tasks. Related to the issue of data availability, this is one case study out of many more that could have been done, simply based on how many assumptions were made in this project. Changing the time slices, the area of interest, the data that was analyzed would all have different outcomes on the results of the study. While the choices made in this project were justified and discussed with the class as a whole, it is important to note that some approximations might need adjustment in future analyses, primarily ensuring that the site selected was approximated correctly in terms of pervious and impervious land cover.

It is important to note the gross simplification of the modeled case study. The model implemented was a very basic curve number runoff model and several estimates and approximations were made given the limited information provided on the site in terms of conveyance pipes and structures, existing stormwater management, cover conditions, soil conditions, etc. The curve number method does not account for soil infiltration, evaporation, and other physical processes that occur between water, air, and soil, and further it does not account for hydraulic interactions within conveyance networks. A more complex model is outside the scope of this course, and the results provided are for example purposes only.

While it appears in countless municipal design manuals, there is often criticism of the Type II, 24-hour storm distribution for its lack of correlation with actual storm events. Real-world storm events rarely, if ever, occur following the distribution embedded in the Type II storm, and storms are rarely, if ever, 24-hours in duration. These design storms are exactly that - design events for design purposes.

Given the computational and time limitations, the full range of DCF values were not analyzed. The results are limited to those six DCF values that were chosen, and the results therefore do not span the entire range of projected precipitation events, which one will recall is extremely variable. It is critical to understand that the selected DCFs do not indicate predictions, rather they are simply six scenarios out of thousands calculated as part of this course.

The group acknowledges the simplicity of the delta change factor method. While the method is fairly simple to calculate making it ideal for widespread use, it is possible that the method does not capture the true complexity of projected precipitation events under climate change scenarios. To understand the potential differences or over-simplifications, one might explore another method on the same data set or same data sources and compare results.

6.3. Recommendations

Increased precipitation is expected in the coming decades; however the extent of the increase is variable. Even though there is variable in the amount of predicted precipitation quantity, planning should still consider utilizing an increased value when sizing and implementing stormwater infrastructure. Richmond may be more inclined to incorporate higher regulations, since they have previously constructed a flood wall that withstands a current 280-year storm. There are multiple methods where the implementation of any DCFs provided within this report will be beneficial. Additional funding can be allocated to the appropriate departments that are currently studying sustainability and Richmond’s infrastructure in order to identify problematic areas that should become locations of interest. Design standards can be adjusted to reflect the predicted increase in precipitation. This will minimize future issues due to the infrastructure having adequate capacity. The government itself can draft and pass policy initiatives that will incentivize actions towards counteracting the effects of climate change on an existing and developmental property-based level. These include but are not limited to reducing impervious cover, greater stormwater management regulations, and various structural components, such as green roofs. A major component that is ongoing and should remain consistent if not increase, is public outreach on current and future climate change issues. This educates the public on how to help reduce the impact of current climate related issues, the consequences of the do-nothing option, and provide information in a way that will relate and not alienate a non-technical audience. There are a good number of options to help curb the effects of climate change and it will be on the municipality to decide what is worth implementing.

Appendices

Appendix	Data File Name	Description of Data
A	1.0 TCE Historical Observed Annual	The Climate Explorer Historical (1950-2013) Total Observed Annual Precipitation
B	1.1 TCE Projected Annual	The Climate Explorer Projected (2006-2099) Total Projected (RCP4.5, RCP8.5) Annual Precipitation
C	2.0 TCE Historical Observed Monthly	The Climate Explorer Historical (1961-1990) Monthly Observed Precipitation
D	2.1 TCE Projected Monthly	The Climate Explorer Projected (2025, 2050, 2075) Monthly Projected (RCP4.5, RCP8.5) Precipitation *Note 2025 is average from 2010-2040; 2050 is average from 2035 to 2065; 2075 is average from 2060-2090)
E	3.0 TCE Observed 1-inch	The Climate Explorer Historical (1950-2013) Observed days per year with rainfall above 1-inch
F	3.1 TCE Projected 1-inch	The Climate Explorer Projected (2006-2099) RCP4.5, RCP8.5 Days per year with rainfall above 1-inch
G	4.0 TCE Observed 2-inch	The Climate Explorer Historical (1950-2013) Observed days per year with rainfall above 2-inches
H	4.1 TCE Projected 2-inch	The Climate Explorer Projected (2006-2099) RCP4.5, RCP8.5 Days per year with rainfall above 2-inches
I	5.0 TCE Observed 3-inch	The Climate Explorer Historical (1950-2013) Observed days per year with rainfall above 3-inches
J	5.1 TCE Projected 3-inch	The Climate Explorer Projected (2006-2099) RCP4.5, RCP8.5 Days per year with rainfall above 3-inches
K	6.0 Historical METDATA	Historical Monthly Precipitation (1971-2000) METDATA Models 1-10
L	6.1 Historical METDATA	Historical Monthly Precipitation (1971-2000) METDATA Models 11-20
M	7.0 Historical LIVNEH	Historical Monthly Precipitation (1971-2000) LIVNEH Models 1-10
N	7.1 Historical LIVNEH	Historical Monthly Precipitation (1971-2000) LIVNEH Models 11-20
O	8.0 Projected 4.5 METDATA	Projected Monthly Precipitation (2020-2099) RCP4.5 METDATA Selected 10 Models
P	8.1 Projected 8.5 METDATA	Projected Monthly Precipitation (2020-2099) RCP8.5 METDATA Selected 10 Models
Q	9.0 Projected 4.5 LIVNEH	Projected Monthly Precipitation (2020-2099) RCP4.5 LIVNEH Selected 10 Models
R	9.1 Projected 8.5 LIVNEH	Projected Monthly Precipitation (2020-2099) RCP8.5 LIVNEH Selected 10 Models
S	10.0 DCF Tables	Calculated DCF for 2020s, 2050s, 2080s
T	10.1 DCF Tables - Additional	Calculated DCF for 2030s, 2070s per utility request
U	11.0 Case Study Model Results	Tabulated Stormwater Runoff Volume and Peak Rate from Model for 2050s, 2080s