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Final Report

Background & Introduction

Climate change has been a largely discussed topic by academics and researchers for the last several decades (Andrew Revkin, 2018). This complex topic now leaves engineers and planners to determine how to practically plan and design for the likely future we are headed to. The scale of climate change has been, and will continue to be debated, but local municipalities are looking for answers now. In the case of this report, they are looking for answers specifically regarding rainfall and on what scale it will increase in the future due to the effects of climate change. This report gives background on data sources, methods of analysis, and results of a case study completed by a group of students at Drexel University (DU), specifically prepared for the Washington D.C. Department of Energy and the Environment (DOEE) as part of a community-based learning partnership between the two entities.

Data Sources

Global Climate Models (GCMs) are created by various groups of scientists all over the world and provide data about the changing climate on a global scale (NOAA, n.d.). This data is useful for a variety of applications; however, to utilize these models in specific geographic locations, various calculations and methods need to be employed to scale the data down. During this analysis, the Multivariate Adaptive Constructed Analogs (MACA) method was used. This statistical method downscaled GCMs to a higher spatial resolution such that daily and monthly meteorology can be simulated, while factoring in the changes seen in GCMs (Climatology Lab). The MACA tool was used to plot historical rain patterns for 3 twenty year time slices: 2020s, 2050s, and 2080s for the Washington D.C. area.

To gather the needed MACA data, the MACA Home online resource was used. This source allows the user to select from 20 different GCMs that have been compiled from a variety of authors.

The tool also allows for different emission scenario analysis. To model the changing climate, varying levels of emissions must be considered and the tool provides two options for Representative Concentration Pathways (RCPs). These RCPs represent a lower emission scenario, RCP 4.5, and a higher emission scenario, RCP 8.5. The numerical value represents an emissions scenario in which the radiative forcing level stabilizes at 4.5 or 8.5 Watts per square meter by 2100.

Another option that the tool provides is two different resolutions of data over the geographic area observed. LIVNEH provides a resolution of 1/16-deg (~6 km) and the METDATA offers a resolution of 1/24-deg (~4 km). These resolutions can be seen in Figure 1. Note the METDATA is the overlaid red rectangle and the LIVNEH data is the overlaid grey rectangle.

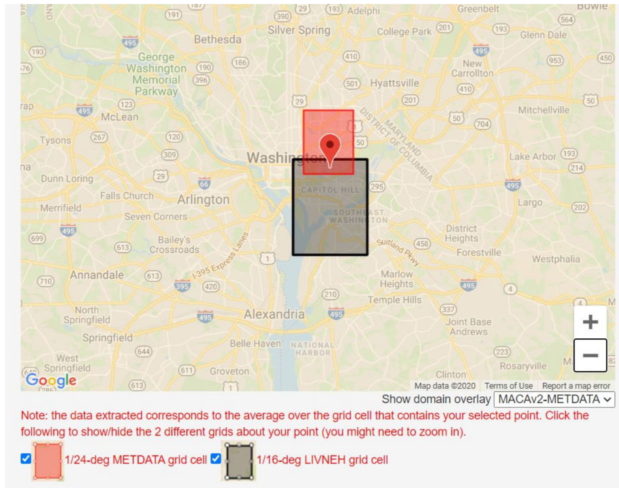

Figure 1: METDATA (1/24-deg; red rectangle) and LIVNEH (1/16-deg; grey rectangle) resolutions

Methodology

There were several steps taken to gather the data from MACA Home. The first step of the analysis was to determine whether daily or monthly data should be used; In this report, monthly data was used. The latitude and longitude used for the Washington D.C. area were (38.9, -77.0) and the data for the 20 GCMs was downloaded. Next, the 20 GCM's were narrowed down to 10 GCM's for ease of analysis, while still keeping an amount that would yield valid results. This was performed by comparing the 20 GCM's yearly modeled historical data to the actual observed historical data of Washington D.C. at the Reagan International Airport, collected by NOAA. The 10 GCMs were chosen by calculating the annual yearly precipitation over the 20 year period 1986-2005 and graphing it alongside observed annual yearly precipitation data from the same time slice. This 20 year time slice was chosen as it was the most recent data available. Although a different time slice was used to graph projected data it was decided amongst the group that because this time slice was only used to choose the 10 GCMs and did not affect the projected data it was appropriate to keep for this portion of the project. Once the data was graphed, the three members of the team used an observational method to choose the 10 GCM's that most closely matched the observed data and did not include any extreme outliers. The ten GCM's that were chosen to use for this analysis were as follows:

bcc-csm1-1	bcc-csm1-1-m	GFDL-ESM2G	IPSL-CM5A-LR	MIROC5
CNRM-CM5	GFDL-ESM2M	NorESM1-M	IPSL-CM5B-LR	BNU-ESM

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Once the 10 GCMs were chosen the projected data could then be collected. The scenarios chosen to observe are monthly precipitation data for LIVNEH and METDATA at both RCP 4.5 and RCP 8.5 for the projected time slices of 2020s (2010-2039), 2050s (2040-2069), and 2080s (2070-2099). Once all of the projected data was collected, the average monthly precipitation was calculated for all 10 GCMs in all scenarios. Using this data the delta change factors (DCF's) were calculated. DCF's relate the change in future projections to historical data, allowing the stake holder to apply these change factors to different design storms as applicable to the municipality, in this case specifically to Washington D.C. This relationship can be seen below in Equation 1.

$$DCF = 100\% * [(Future - Historical)/Historical] \qquad \text{Equation 1}$$

The historical data used in the calculation of the DCF's was the modeled precipitation data for all 10 GCMs over the period 1971-2000. This 30 year time slice was chosen to stay consistent with the rest of the class. This information was used to calculate the monthly average data for all 10 GCMs. DCF values were found for each month of each of the 10 GCM's, for each of the two climate emissions scenarios, and for each of the two geographically gridded sets resulting in 120 data points for each scenario. Monthly average DCF values were combined for each projected time slice and were summarized by 5th, 25th, 75th, and 95th percentiles and the median.

Box plots of the data were created to further illustrate the results. The figures below contain the same data as explained above, which depicts values of the combination of each scenario (RCP 4.5 and 8.5), each gridded set (MET and Livneh), and what term the data is modeling (near, mid, and far term). The figures are split by the term and have synthesized the combinations mentioned. The box plots for near, mid, and far term can be seen in Figure 2-4 below.

To apply these DCF values, NOAA Atlas 14 and the Washington DC DOEE Stormwater Guidance Manual were used to choose historical design storms. According to Washington DC regulations, the 2-year/24-hour, 15-year/24-hour, and 100-year/24-hour NRCS Type II storm durations and distributions are required to be analyzed. Using NOAA Atlas 14, the 24-hour storm depths were determined for the storms above. The chosen DCF values were then applied to each of these storms to determine the effects of climate change on the site chosen for the case study.

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DCF results

The range of DCF values is shown in Figures 2-4 and it was decided to use the highest monthly median, lowest monthly median, and average monthly median DCF for use in the case study. The 2050's and 2080's time period were selected due to the 2030's period including the time we are in now. The numerical values chosen are shown in Table 1. Although these values do not contain the greatest possible event predicted by the various GCM's, it is more likely that these events will occur and it is feasible for utilities to prepare for these storms.

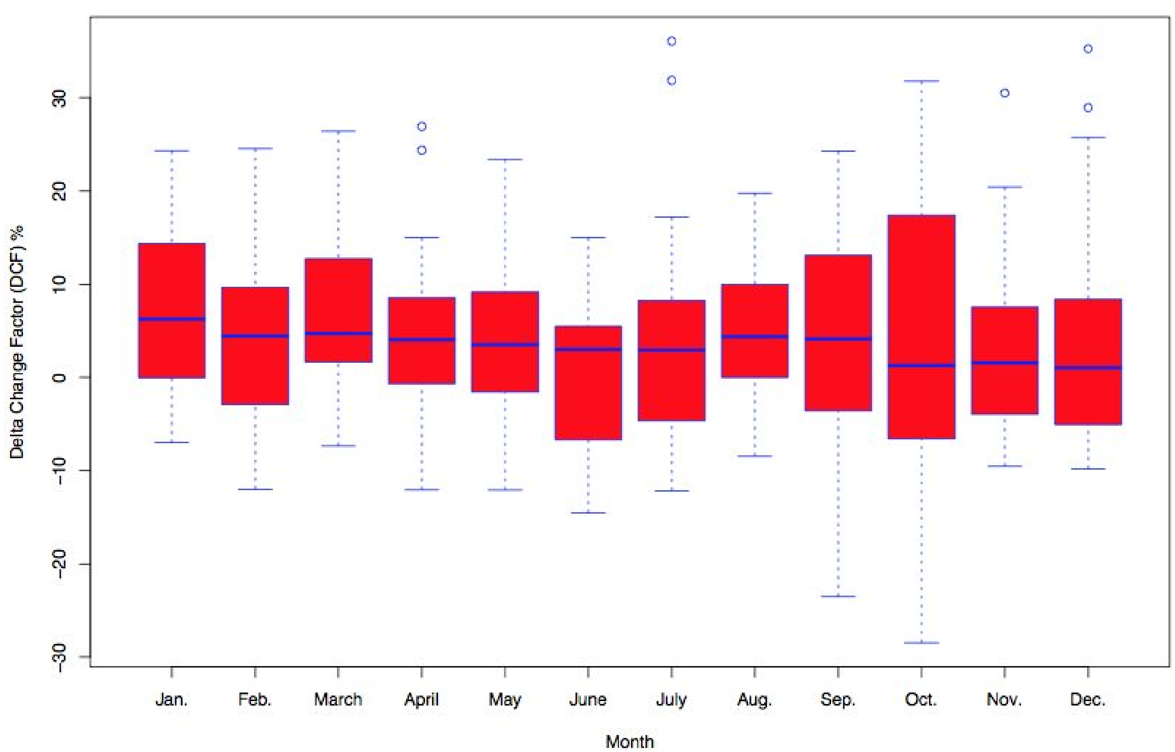

Figure 2: Boxplots of Delta Change Factors for the Near Term (2010-2039)

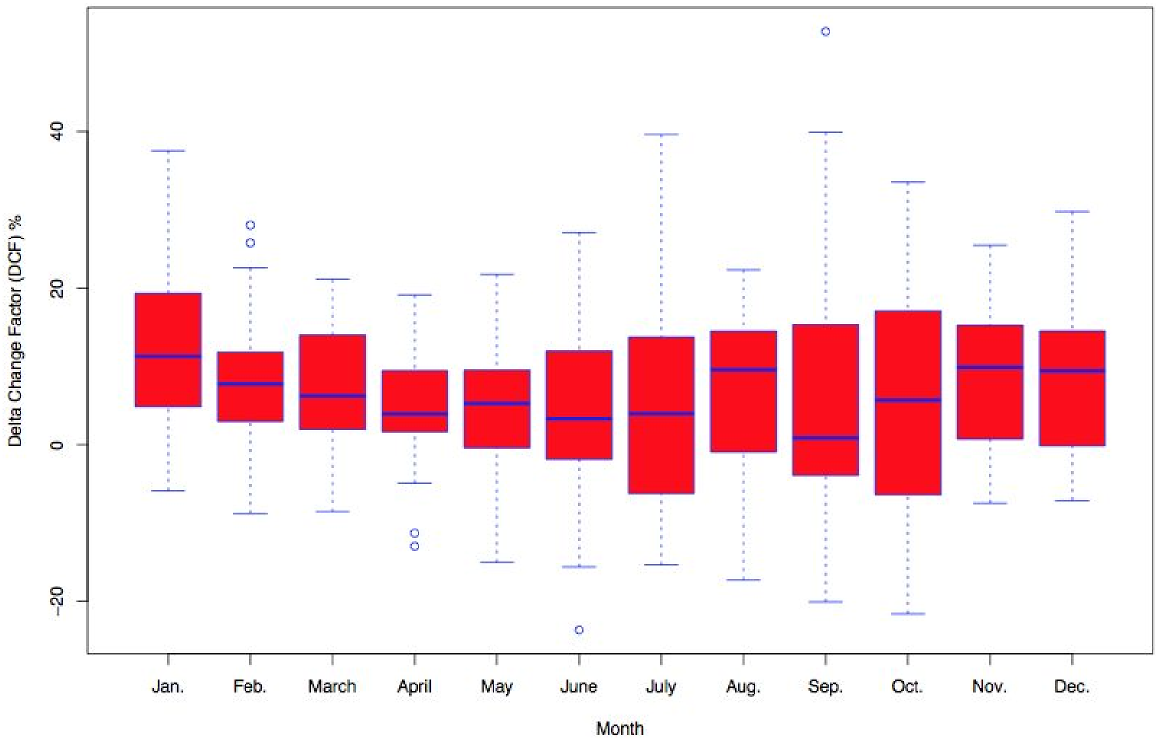

Figure 3: Boxplots of Delta Change Factors for the Mid Term (2040-2069)

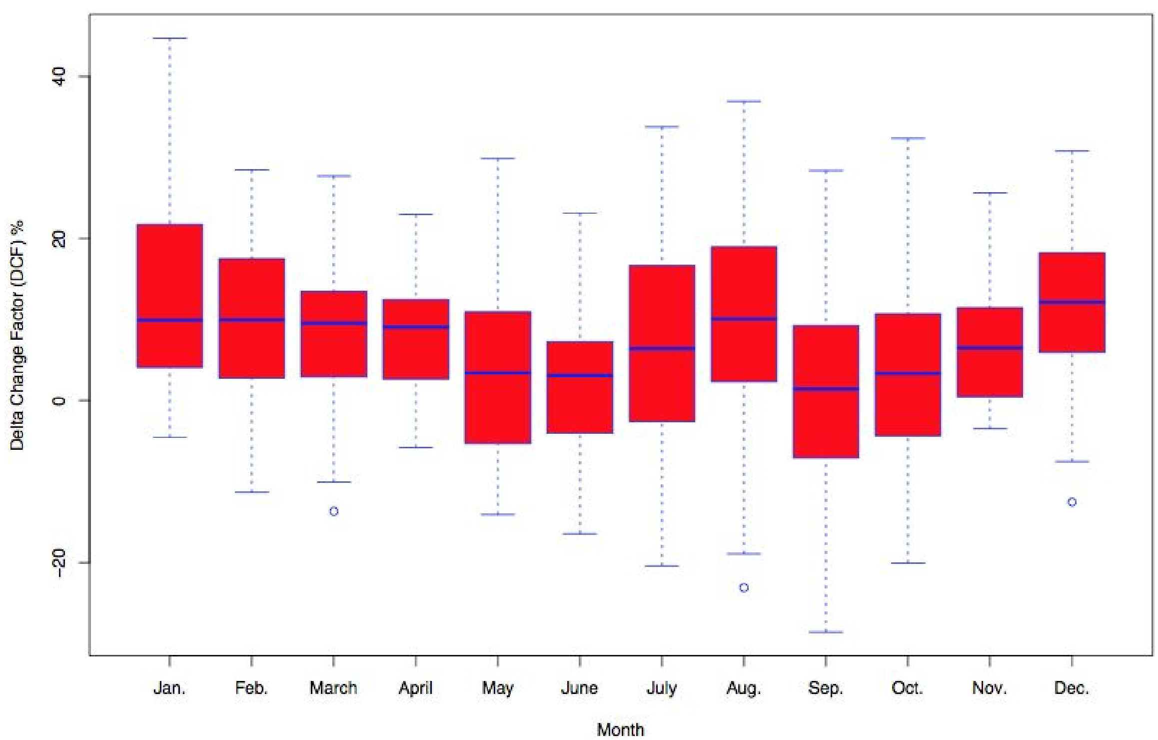

Figure 4: Boxplots of Delta Change Factors for the Far Term (2070-2099)

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Table 1: Projected DCF values for 2050s and 2080s to be used in modeling of projected rainfall

2050s Projected DCF (%)		2080s Projected DCF (%)	
Min	1.62	Min	0.11
Max	10.79	Max	12.62
Average	5.52	Average	5.91

The following Table 2 shows the numerical rainfall values for the historical storms, and the future predicted storms based on the DCF values in the table above.

Table 2: Historical and Projected Rainfall Amounts for 2050s and 2080s to be used in modeling of projected rainfall

Storm & DCF	Rainfall (in.)
2-yr 2050s avg	3.31
2-yr 2050s max	3.48
2-yr 2050s min	3.19
2-yr 2080s avg	3.33
2-yr 2080s max	3.54
2-yr 2080s min	3.14
2-yr Historical	3.14
15-yr 2050s avg	5.52
15-yr 2050s max	5.79
15-yr 2050s min	5.31
15-yr 2080s avg	5.54
15-yr 2080s max	5.89
15-yr 2080s min	5.24
15-yr Historical	5.23
100-yr 2050s avg	8.76
100-yr 2050s max	9.2
100-yr 2050s min	8.43
100-yr 2080s avg	8.79
100-yr 2080s max	9.35
100-yr 2080s min	8.31
100-yr Historical	8.3

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Description of Case Study

The DOEE provided the group from Drexel with a residential site that is in Northwest Washington, D.C. The goal of the given site development was to raze the existing two story home and build it into a three story single family home. Site plans can be seen in Appendix I. Figure 5 shows an aerial view of the location site in relation to the downtown area of Washington, D.C.

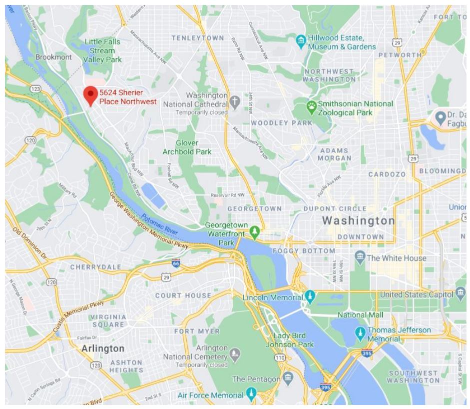

Figure 5: Aerial view of site.

Figure 6 provides a closer, satellite view of the site.

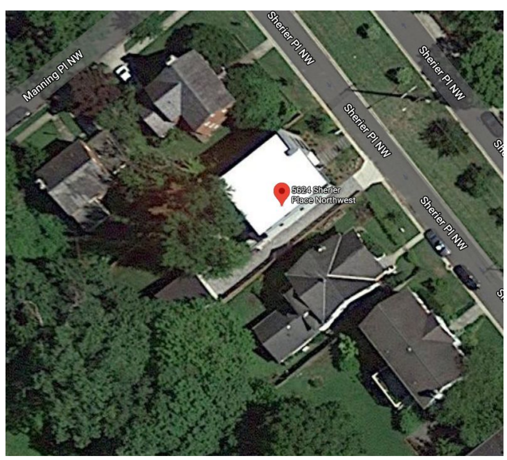

Figure 6: Satellite aerial view of Sherier Place site.

The following figure, Figure 7, shows the Hydraulic and Hydraulic model (H&H) that was created to show how the site performed under the current design, and how the site performed under the projected changes. A subsurface infiltration facility was constructed for compliance with DOEE and D.C. water stormwater regulations.The model built shows the subcatchment area, the stormwater facility, and the point of interest (POI).

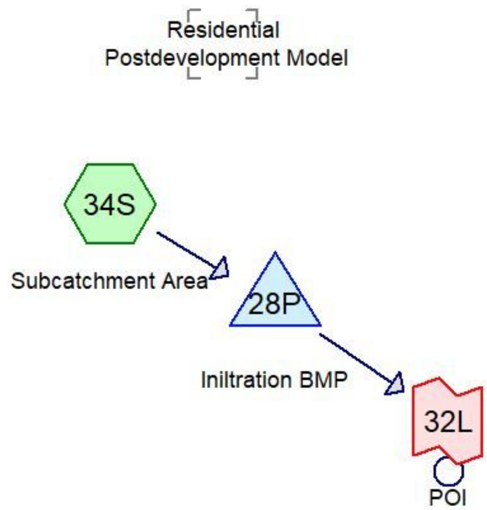

Figure 7: Model of stormwater flow at design site

The chosen return periods to evaluate using this model are the 2-yr, 15-yr, and 100-yr. These were all evaluated over a duration of 24-hours as a NRCS Type II distribution for the projected periods of the 2050s and 2080s. Along with the projected storms are the historical 2-yr, 15-yr, and 100-yr storm for comparison. The final results from the model are listed in table 3 below.

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Results

Table 3: Final results of HydroCAD model

Storm & DCF	Rainfall (in.)	Site Runoff (in.)	BMP Outflow (in.)	Peak BMP outflow (CFS)
2-yr 2050s avg	3.31	1.63	0	0
2-yr 2050s max	3.48	1.77	0	0
2-yr 2050s min	3.19	1.53	0	0
2-yr 2080s avg	3.33	1.64	0	0
2-yr 2080s max	3.54	1.82	0	0
2-yr 2080s min	3.14	1.49	0	0
2-yr Historical	3.14	1.49	0	0
15-yr 2050s avg	5.52	3.55	1.1904	0.78
15-yr 2050s max	5.79	3.79	1.3888	0.79
15-yr 2050s min	5.31	3.36	1.0368	0.72
15-yr 2080s avg	5.54	3.57	1.2064	0.78
15-yr 2080s max	5.89	3.89	1.4752	0.9
15-yr 2080s min	5.24	3.29	0.9888	0.65
15-yr Historical	5.23	3.29	0.9792	0.64
100-yr 2050s avg	8.76	6.58	3.8848	1.64
100-yr 2050s max	9.2	7.01	4.2688	1.74
100-yr 2050s min	8.43	6.27	3.584	1.57
100-yr 2080s avg	8.79	6.61	3.9072	1.65
100-yr 2080s max	9.35	7.15	4.4032	1.77
100-yr 2080s min	8.31	6.15	3.4848	1.54
100-yr Historical	8.3	6.15	3.4784	1.54

The important variables in table 3 are the BMP outflow (inches) and the peak BMP outflow (CFS). The percent changes were calculated for the BMP outflow by comparing the projected storms to the same historical storm. These values were separated by time period and storm type and compiled into table 3 below. The percent changes were also calculated for the peak BMP outflow using the same method. The results of these calculations are listed in table 4 and 5 below.

Table 4: Percent change in the BMP outflow(inches) for the 15-yr and 100-year storms.

Percent Change in BMP Outflow			
	DCF	2050s	2080s
15-yr Storm	mean	22%	23%
	max	42%	51%
	min	6%	1%
100-yr Storm	mean	12%	12%
	max	23%	27%
	min	3%	0.2%

Note: The 2-yr storm was not included in the table as all percent changes equal zero.

Table 5: Percent change in peak BMP outflow(CFS) for the 15-yr and 100-year storms.

Percent Change in BMP Storage			
	DCF	2050s	2080s
15-yr Storm	mean	22%	22%
	max	23%	41%
	min	13%	2%
100-yr Storm	mean	7%	7%
	max	13%	15%
	min	2%	0%

Interpretation of Results

Overall, the chosen DCF values align with other research that has been done on the topic. In a paper written by Maimone et. al. the range of DCF values found are -4.6% to 17.8% which can be seen in Table 6. Table 7 shows values from the EPA Stormwater Management Model Climate Adjustment Tool (SWMM-CAT) ranging from -7.30% to 25.30%. While both sources have a slightly higher range of values, the values found in this analysis are on the same magnitude, and within the ranges found by other researchers. This proves that this method could be a valid process for choosing DCF values for any municipality, without directly using complex models or statistics.

*Table 6: DCF Values Published by Maimone et al.**

Percentage Change	
	Daily Mean
GCM Ensemble Average	10.2
Individual GCMs (maximum)	17.8
Individual GCMs (minimum)	-4.6

*Values are for Philadelphia

*Table 7: DCF Values Published by EPA Via SWMM CAT Tool**

Near Term Projected DCF(2020-2049, %)		Far Term Projected DCF (2050-2079, %)	
Min	-4.00	Min	-7.30
Max	13.90	Max	25.30
Average	2.79	Average	5.09

* EPA Stormwater Management Model (SWMM) Climate Adjuster Tool (CAT) published by EPA and is available here. Values based on CMIP3 projections.

The case study and model show that the implications of applying DCF values can be extremely important.The model shows that the BMP was designed to manage the full volume from the 2-yr storm and even with the new DCF applied the BMP still manages the 2-year storm. The 2050s show an increase in BMP outflow of 6%-42% for the 15-yr storm and 3%-23% for the 100-yr storm. The 2080s shows an increase in BMP outflow of 1%-51% for the 15-yr storm and 0.2%-27% for the 100-yr storm. The variability in BMP outflow is greater for the 2080s possibly due to uncertainty in model predictions as the models move further in time.

The 2050s and 2080s also show an increase in peak BMP outflow (CFS) for the 15-year and 100-year storms. The 2050s see a percent increase of 13%-23% for the 15-year storms and a percent increase of 2%-13% for the 100-year storm. The 2080s shows a percent increase of 2%-41% for the 15-year storm and 0%-15% for the 100-year storm.

It is important to note that in the case study shows that the increase in percentage of rainfall does not exactly equal the change in volume of runoff or peak runoff rates. In all cases there is a higher percentage change in runoff volume and rates than there was in precipitation. This means that while there may only be a +12.62% increase in rainfall compared to the historical condition, there may be a +51% increase in runoff when compared to historical runoff. Planners and engineers should account for this as downstream flooding may become more prevalent due to the changing rainfall.

Planners and designers in Washington D.C. should use the maximum, monthly, median value for each of the time periods described in the report, 10.79% for anything with a design life in the 2050s time period, and 12.62% for anything in the 2080s time period. This allows for a conservative, likely analysis based on the GCM's chosen and the process completed to ensure that the effects of climate change on extreme precipitation are taken into account for new and future stormwater designs.

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Resources

Design your Own CSV File of MACA Point Data (n.d.). Retrieved July 2020, from https://climate.northwestknowledge.net/MACA/data_csv.php

MACA. (n.d.). Retrieved July 2020, from http://www.climatologylab.org/maca.html

NOAA National Centers for Environmental Information. (n.d.) Retrieved July 2020, from https://www.ncdc.noaa.gov/cdo-web/datasets/GHCND/stations/GHCND:USW00013743/detail

NOAA. (n.d.). Climate Models. Retrieved August 2020 from https://www.climate.gov/maps-data/primer/climate-models

Revkin, A. (Sept 2017). "Climate Change First Became News 30 Years Ago. Why Haven't We Fixed It?" National Geographic. Retrieved August 2020 from https://www.nationalgeographic.com/magazine/2018/07/embark-essay-climate-change-pollution-revkin/

US EPA SWMM-CAT from https://www.epa.gov/water-research/storm-water-management-model-swmm#:~:text=The%20SWMM%20Climate%20Adjustment%20Tool,impact%20of%20future%20climate%20changes.

Maimone et. al (2019) "Transforming Global Climate Model Precipitation Output for Use in Urban Stormwater Applications" American Society of Civil Engineers

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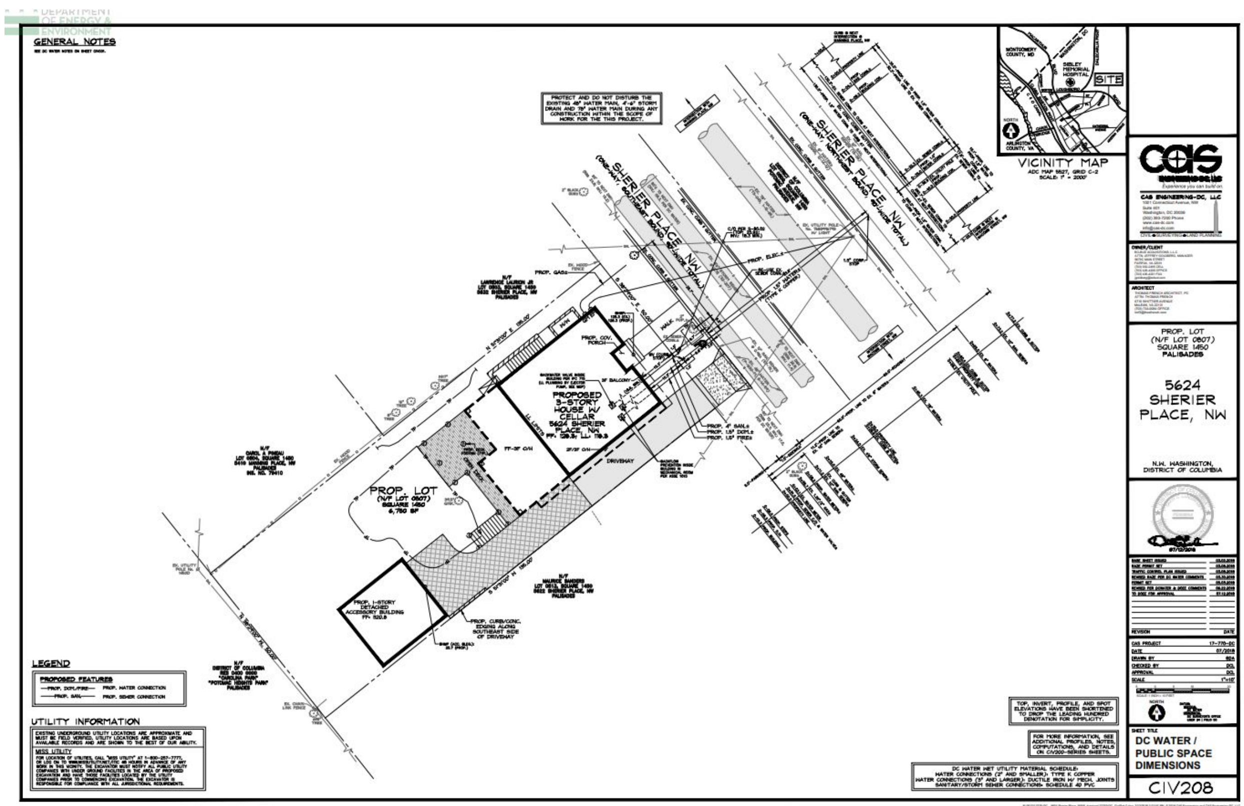
Appendix I



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Appendix II

Table 1: PDS-based point precipitation frequency estimates with 90% confidence intervals (in.)

PF tabular

PDS-based point precipitation frequency estimates with 90% confidence intervals (in inches)[1]

Duration	Average recurrence interval (years)									
	1	**2**	**5**	**10**	**25**	**50**	**100**	**200**	**500**	**1000**
5-min	**0.355** (0.322-0.391)	**0.426** (0.387-0.469)	**0.506** (0.459-0.559)	**0.566** (0.511-0.624)	**0.641** (0.575-0.707)	**0.697** (0.622-0.770)	**0.753** (0.667-0.833)	**0.807** (0.710-0.896)	**0.876** (0.762-0.980)	**0.930** (0.803-1.05)
10-min	**0.567** (0.515-0.624)	**0.681** (0.618-0.750)	**0.811** (0.735-0.894)	**0.905** (0.817-0.997)	**1.02** (0.916-1.13)	**1.11** (0.991-1.23)	**1.20** (1.06-1.32)	**1.28** (1.13-1.42)	**1.39** (1.21-1.55)	**1.47** (1.26-1.65)
15-min	**0.709** (0.644-0.780)	**0.856** (0.777-0.942)	**1.03** (0.929-1.13)	**1.14** (1.03-1.26)	**1.30** (1.16-1.43)	**1.41** (1.25-1.55)	**1.51** (1.34-1.67)	**1.61** (1.42-1.79)	**1.74** (1.52-1.95)	**1.84** (1.59-2.07)
30-min	**0.972** (0.882-1.07)	**1.18** (1.07-1.30)	**1.46** (1.32-1.61)	**1.66** (1.50-1.83)	**1.92** (1.72-2.12)	**2.12** (1.89-2.34)	**2.32** (2.05-2.56)	**2.51** (2.21-2.79)	**2.77** (2.42-3.10)	**2.98** (2.57-3.35)
60-min	**1.21** (1.10-1.33)	**1.48** (1.35-1.63)	**1.87** (1.69-2.06)	**2.16** (1.95-2.38)	**2.56** (2.29-2.82)	**2.87** (2.56-3.17)	**3.19** (2.83-3.53)	**3.52** (3.10-3.91)	**3.98** (3.47-4.45)	**4.35** (3.75-4.89)
2-hr	**1.42** (1.29-1.56)	**1.73** (1.57-1.91)	**2.19** (1.99-2.41)	**2.55** (2.31-2.80)	**3.06** (2.75-3.36)	**3.47** (3.10-3.82)	**3.91** (3.46-4.31)	**4.36** (3.84-4.83)	**5.01** (4.36-5.59)	**5.55** (4.77-6.23)
3-hr	**1.52** (1.38-1.68)	**1.85** (1.68-2.04)	**2.34** (2.12-2.59)	**2.74** (2.47-3.02)	**3.30** (2.95-3.64)	**3.77** (3.35-4.16)	**4.26** (3.76-4.71)	**4.79** (4.18-5.31)	**5.55** (4.78-6.19)	**6.18** (5.25-6.93)
6-hr	**1.87** (1.70-2.07)	**2.26** (2.05-2.50)	**2.86** (2.58-3.16)	**3.34** (3.01-3.69)	**4.07** (3.63-4.49)	**4.68** (4.14-5.18)	**5.35** (4.69-5.93)	**6.07** (5.26-6.76)	**7.15** (6.09-8.02)	**8.05** (6.76-9.09)
12-hr	**2.26** (2.04-2.54)	**2.73** (2.46-3.06)	**3.47** (3.12-3.89)	**4.11** (3.67-4.59)	**5.07** (4.48-5.66)	**5.92** (5.17-6.61)	**6.86** (5.92-7.69)	**7.91** (6.73-8.90)	**9.52** (7.93-10.8)	**10.9** (8.93-12.4)
24-hr	**2.62** (2.39-2.92)	**3.18** (2.89-3.53)	**4.08** (3.71-4.53)	**4.88** (4.42-5.40)	**6.10** (5.48-6.72)	**7.19** (6.41-7.88)	**8.42** (7.44-9.20)	**9.83** (8.58-10.7)	**12.0** (10.3-13.0)	**13.9** (11.8-15.1)
2-day	**3.04** (2.77-3.37)	**3.68** (3.35-4.08)	**4.71** (4.29-5.22)	**5.60** (5.08-6.19)	**6.94** (6.25-7.64)	**8.11** (7.26-8.90)	**9.41** (8.35-10.3)	**10.9** (9.55-11.9)	**13.1** (11.3-14.3)	**15.0** (12.8-16.4)
3-day	**3.22** (2.93-3.56)	**3.89** (3.55-4.31)	**4.97** (4.53-5.50)	**5.91** (5.36-6.53)	**7.31** (6.60-8.05)	**8.54** (7.65-9.38)	**9.90** (8.79-10.9)	**11.4** (10.1-12.5)	**13.7** (11.9-15.0)	**15.7** (13.4-17.2)
4-day	**3.39** (3.10-3.75)	**4.10** (3.75-4.54)	**5.23** (4.77-5.79)	**6.21** (5.65-6.86)	**7.69** (6.94-8.46)	**8.97** (8.05-9.85)	**10.4** (9.24-11.4)	**12.0** (10.6-13.1)	**14.4** (12.5-15.8)	**16.4** (14.1-18.1)
7-day	**3.93** (3.61-4.32)	**4.73** (4.35-5.21)	**5.98** (5.48-6.58)	**7.05** (6.45-7.75)	**8.65** (7.86-9.48)	**10.0** (9.06-11.0)	**11.6** (10.3-12.6)	**13.3** (11.8-14.5)	**15.8** (13.8-17.3)	**17.9** (15.5-19.7)
10-day	**4.49** (4.13-4.92)	**5.39** (4.96-5.91)	**6.74** (6.19-7.38)	**7.86** (7.20-8.61)	**9.50** (8.66-10.4)	**10.9** (9.85-11.9)	**12.4** (11.1-13.5)	**14.0** (12.5-15.2)	**16.3** (14.4-17.8)	**18.3** (16.1-20.0)
20-day	**6.07** (5.64-6.55)	**7.22** (6.70-7.79)	**8.72** (8.09-9.41)	**9.94** (9.21-10.7)	**11.6** (10.7-12.5)	**13.0** (12.0-14.0)	**14.4** (13.2-15.6)	**15.9** (14.5-17.2)	**18.0** (16.3-19.4)	**19.6** (17.6-21.2)
30-day	**7.47** (6.97-8.03)	**8.84** (8.25-9.50)	**10.5** (9.80-11.3)	**11.9** (11.0-12.7)	**13.7** (12.7-14.7)	**15.2** (14.0-16.3)	**16.7** (15.4-17.9)	**18.3** (16.8-19.6)	**20.4** (18.6-21.9)	**22.1** (20.0-23.7)
45-day	**9.39** (8.81-9.99)	**11.1** (10.4-11.8)	**12.9** (12.1-13.8)	**14.4** (13.5-15.3)	**16.3** (15.2-17.3)	**17.7** (16.6-18.8)	**19.1** (17.8-20.4)	**20.5** (19.1-21.9)	**22.3** (20.7-23.8)	**23.7** (21.9-25.3)
60-day	**11.2** (10.5-11.9)	**13.1** (12.4-13.9)	**15.2** (14.3-16.1)	**16.7** (15.8-17.7)	**18.7** (17.6-19.9)	**20.2** (19.0-21.4)	**21.7** (20.3-23.0)	**23.0** (21.5-24.4)	**24.8** (23.0-26.3)	**26.0** (24.1-27.7)

[1] Precipitation frequency (PF) estimates in this table are based on frequency analysis of partial duration series (PDS).
Numbers in parenthesis are PF estimates at lower and upper bounds of the 90% confidence interval. The probability that precipitation frequency estimates (for a given duration and average recurrence interval) will be greater than the upper bound (or less than the lower bound) is 5%. Estimates at upper bounds are not checked against probable maximum precipitation (PMP) estimates and may be higher than currently valid PMP values.
Please refer to NOAA Atlas 14 document for more information.

Note that the numbers in parentheses represent the upper and lower bounds of the 90% confidence interval and the bold number above that is the median of those bounds.