Drexel UNIVERSITY

EXTREME PRECIPITATION STUDY

COURSE
CIVE T580: Stormwater Planning
in the Era of Climate Change

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FINAL REPORT

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ABSTRACT

This study is a collaboration between researchers at Drexel University and representatives of the Baltimore City Department of Public Works (BCPDW) to assess the vulnerability of Baltimore City to changes in future climate. The purpose of the analysis is to gain insight into any trends of future precipitation that can inform decision makers, to identify sources of variability in the methodology used to generate projections, and to discuss significance of design storm modifications and steps to mitigate risks due to changes in future climate.

The projections of future precipitation use a method of downscaling of existing, publicly available, gridded Global Climate Model (GCM) monthly precipitation datasets. Calculations of Delta Change Factors (DCF), which are based on a historical baseline period (1971-2000) and modeled projections of monthly precipitation for a future period (2010-2100), were developed for emission scenarios RCP 4.5 and RCP 8.5 with a dataset of 10 GCMs.

DCFs were then applied to a hydrologic model for two areas of interest to BCDPW with opportunities for BCDPW feedback and input on the selection of scenarios. Through the case study analysis, projections of future precipitation in BCDPW's service area indicate that there is a trend in future precipitation that exhibits seasonal tendencies, with the greatest average monthly precipitation change seen in the future winter periods. Based on the case study analysis, there may be 'low-regret' approaches, such as modifying drainage standards that could be relevant to mitigating future risks.

Additional detailed modeling analysis is a key area of future study that could apply the DCF results of this report as a future planning scenario. Selection of historical rain gauges can introduce a source of uncertainty where it was observed that historical datasets had significant variation in average rainfall that may reflect existing spatial variability. This also may be an area of future study at a regional level.

INTRODUCTION

This report is the product of partnership between representatives of the Baltimore City Department of Public Works (BCDPW) and a team of researchers at Drexel University. The partnership collaborated over the course of nine weeks to gain insight into the existing stormwater challenges that BCDPW currently face as a public utility. Through application of widely available projections of climate data, utilities within the Mid-Atlantic region can better understand how to develop a range of future precipitation patterns for evaluation in policy making and capital project planning decision making.

The objective of the report is to develop projections of future monthly precipitation for future time periods extending to the year 2100. The work of the course is structured within five assignments:

- Assignment 1 - Initial Interview Summary
- Assignment 2 - Review of Future Climate Projections
- Assignment 3 - Calculation of Delta Change Factors
- Assignment 4a - Selection of Historical and Future Design Storms
- Assignment 4b - Modeling of Future Design Storms for Case Study

As the work of the course progressed, the partnership with BCDPW worked to 'co-generate' the parameters of the analysis and refine the overall research questions. In the big picture, the feedback and discussion around the following research questions were used as a starting point:

- How do we illustrate uncertainty in the future projections?
- How do rainfall projections change as we move through three future time periods?
- And how can these projections be useful for identifying the local impacts on natural and built systems?

INFORMAL INTERVIEW

The team of researchers at Drexel University are participating in the course taught by Dr. Franco Montalto titled Stormwater Planning in the Era of Climate Change. Ryan Quinn works as an associate project manager at Pittsburgh Water and Sewer Authority (PWSA), Sean Flynn is a masters student at Drexel University and Professional Engineer at a private consulting firm in the City of Philadelphia, and Caroline Houlihan is an undergraduate environmental engineering student with experience in green stormwater infrastructure operations in the City of Philadelphia.

Representatives of BCDPW include Kimberly Grove and Jemil Yesuf. Kimberly Grove has over 12 years of experience working with BCDPW and has been their direct employee for 10 years. She has introduced a lot of structure to the city's stormwater program over that time, including the introduction of a stormwater utility fee. Kimberly has expressed particular interest in the precipitation forecasts for areas upstream of the City's drinking Water facilities. Jemil Yesuf has over six years of experience working with BCDPW, two of which as a direct employee, as a hydraulic modeler and technical lead for the flow and rainfall monitoring program. Jemil has recently completed an RFP for Stormwater Hydraulic Model Development and the City is expected to advertise it in the coming weeks. This project will allow the City to model its stormwater drainage system and understand better the impact of sea level rise in the Baltimore Harbor area.

ROLE OF LOCAL GOVERNMENT

Baltimore City Department of Public Works services an area within four interjurisdictional watersheds. Though it is organized as a local government agency BCDPW acts as a regional utility by providing drinking and wastewater services to areas outside the City. Drinking Water reservoirs (two of which are North of City limits) service 1.8 million customers in six counties. Baltimore and Anne Arundel Counties wastewater are managed at two of the biggest wastewater treatment plants in the state of Maryland under the control of BCDPW. **Figure 1** shows the 8-Digit Watersheds of Baltimore County and overlays the boundaries of Baltimore city in black.

Kimberly Grove states that stormwater tends to be the least funded and most forgotten utility until a flood occurs. Their stormwater management program boasts a Flood Alert System, extensive rain and stream gauge system which can be accessed remotely in real-time. DPW has 88 stream water quality monitoring locations checked on a weekly basis. Sanitary Sewer Overflows(SSO) exacerbated by an aging system are regulated by a consent decree instated by the US EPA, the DOJ, and the Maryland Department of Environment. The Watershed Implementation plan addresses the requirement to restore 20% of impervious surfaces and TMDL conditions of the City's MS4 permit. Efforts to Hydraulically model stormwater are under way with an RFP recently completed.

KEY STORMWATER ISSUES

In the big picture, Baltimore City (BC) has worked to address regulatory compliance within requirements of the USEPA's Chesapeake Bay Program and Baltimore City's Consent Decree. Compliance activities have included investment in MS4 pollution reduction projects, which have targeted 20% of impervious area managed with stormwater management practices. Specific Total Maximum Daily Load requirements have translated to monitoring programs and improvements for reductions of nutrient loading and other pollution sources, such as trash/floatables. These compliance efforts have been funded through a stormwater fee.

Baltimore City, as well as surrounding Baltimore County and other jurisdictions in the area, have experienced destructive microburst storms, which are without dedicated funding to address. Throughout the interview, impacts from these types of storm events were discussed, including: (1) flooding of local streams; (2) limited storm sewer infrastructure capacity; and (3) impact on road drainage and existing green infrastructure. BCDPW also identified that upsizing of the stormwater system is often not the best solution to addressing impacts of microburst storms. BC has also had to consider relocation of existing property users, identify opportunities for reduction of flows upstream of problem areas, as well as rely on a flood alert response system to mitigate impacts and risks of overland flooding.

According to BCDPW, USGS has expressed that the streams flowing through Baltimore City and the surrounding counties are some of the "flashiest" in their response to intense wet weather events. The Central Main stem of Jones and the Gwynn's Falls watershed are two areas that were identified to have repeated overland flooding. A recent storm demonstrated that intense events upstream (and outside of the City's boundaries) can result in flooding within the City, while little precipitation is experienced within the City itself.

In addition, Baltimore City is also vulnerable to the effects of both sea level rise and the impacts of coastal storms. One example cited by BCDPW expressed that flooding would have been severe if Hurricane Sandy's path had stalled over Baltimore for a "few more hours", instead of moving further north. Baltimore City's Inner Harbor waterfront, located at the mouth of Jones Falls, contains several regional landmarks, and so past flooding events have raised visibility of the risks faced to the waterfront.

EXTREME PRECIPITATION EVENTS

In 2016 and 2018, Ellicott City, MD - located 13 miles west of Baltimore City - made national headlines for the severe flooding of its historic commercial district. BCDPW noted that those same storms also impacted Baltimore City in a similar degree. The May 27, 2018 event created severe flooding conditions where a tributary of the Gwynns Falls enters a culvert. The tributary rose 8 feet in 45 minutes and overtopped. Evacuations of the area were needed within the next 45 minutes. BCDPW is partnered with the Silver Jackets (US Army Corps of Engineers), Maryland Department of Environment, and the Maryland Insurance Associations in the evaluation of feasible alternatives to reduce flooding risk in this area.

Most recently, in 2019, 2 notably intense storms required evacuations and road closures, and these events were notable examples of flooding with different spatial distribution of precipitation. In the first event, a short duration storm occurred north of the City, but resulted in flooding an hour later after reaching mid-city Baltimore.

A second event on August 22, 2019 was hyper localized to the downtown area that resulted in widespread flooding. Radar estimated 5 inches of rainfall in 1.5 hr and BCDPW measured 4.5 inches in 1.5 hr. Meanwhile, a location 2 miles north experienced less than 0.25 inches of rainfall in the same period.

From BCDPW, **Figure 2** shows the precipitation - duration response at several monitoring locations during the May 27, 2019 event and compares these responses with the 1-year through 100-year, 24 hour design storms. It can be seen that one of the locations exceeded the 100-year response over the first 3 hours of the rain event, though its total depth is consistent with the 10-year, 24 hour event.

Baltimore City has also experienced several long duration, lower intensity events, including Tropical Storm Cristobal (2020), Tropical Storm Tammy (2005), Hurricane Floyd (1999), Hurricane Isabel (2003), and Hurricane Sandy (2014). These storms are indicators of the long-term risk Baltimore City faces with the uncertainty associated with increasing frequency and intensity of coastal storms.

DATA COLLECTION & USE

Baltimore City DPW collects data from an array of rain gauges and water level sensors, including measurements taken at the Baltimore/Washington International Thurgood Marshall Airport (BWI) in partnership with the National Weather Service (NWS). Water level sensors inform their Flood Alert System and decades of data have been collected. The City has collected 63 years of rainfall data from the BWI station for use in the wet weather SSP MCD program. Peak intensity (in/hr) and total rainfall depth (inches) of the twenty year periods of representative rainfall data(1991-2010) and its comparison with 1-year through 10-year design storms are plotted on **Figure 3**.

Figure 3 shows that the design storms may not accurately represent the local, real-world conditions of Baltimore, especially during extreme precipitation events. As our climate changes, there are storms that fall outside of these events. Some of these events overwhelm infrastructure due to insufficient conveyance capacity or simply exceeding storage volumes. These types of events are labeled on Figure 3, including Hurricane Floyd (1999), Tropical Storm Tammy (2005), and Tropical Storm Cristobal (2008). These extreme events cause evacuations, devastate residents and businesses, and result in financial challenges for the City. However, it is not only single events that cause these extreme scenarios. Sometimes multiple storms occur back-to-back and overwhelm infrastructure with similar negative impacts. This back-to-back scenario, coupled with multiple factors that impede infrastructure (trash, debris, sedimentation, fats, oils, and grease) cause events like the June 2018 flooding of Frederick Avenue, which resulted in an overflow of approximately 28,600 gallons of stormwater mixed with sewer water.

BCDPW is pursuing improved design methods that do not rely upon single-event design storms, but instead are based on continuous-simulation modeling. BCDPW described their continuous-simulation modeling efforts as using historical data, the local hydrologic cycle, and land categories to develop accurate models to predict what happens before, during, and after rainfall events. This design approach can provide improved stormwater designs and be adjusted to adapt to future events. Baltimore County has a wealth of sensors within the Gwynns Falls watershed. BCDPW suggested this watershed for use in the Extreme Precipitation Study. Another source of information is the Baltimore Ecosystem Study (BES) Long Term Ecological Research (LTER) program funded by the National Science Foundation (NSF). The BES supports and conducts research in the Baltimore area, focusing on watershed biogeochemistry, ecological communities and sentinel species, and human environmental perceptions and behaviors. The BES has a large amount of publicly available data, including the 20 years of data mentioned previously, that may be helpful to the Extreme Precipitation Study.

CHALLENGES TO CHANGE

Baltimore City Department of Public Works faces several challenges to implement new stormwater management design methods, stormwater regulations, and integrated changes across multiple sectors to adapt for potential effects of climate change. Funding is a major issue. BCDPW identified that stormwater tends to be the least funded and most forgotten utility, until floods and other devastating issues occur. With aging infrastructure failing, BCDPW needs appropriate funding to handle repairs, while simultaneously developing new stormwater design methodologies to prepare for the future. Funding to conduct studies related to climate change impacts is a key element to communicate and justify additional funding for stormwater management improvements.

Coordination with other agencies is another major challenge identified by BCDPW. Specifically, the Baltimore Department of Transportation (BDOT). Baltimore City is a dense urban area of hardscapes and infrastructure. BDOT regulates the design of roadways and overall drainage requirements of transportation infrastructure within the City. BDOT’s control over drainage infrastructure in the public right-of-way will need to be closely coordinated with the stormwater department of BCDPW. Inlet capture, pipe conveyance capacity, and gutter spread impacts are specific examples of BDOT infrastructure and design requirements that require coordination with DPW. Without the support of other agencies like BDOT, localized improvements may not be realized if they rely on other agencies' infrastructure that is not adapted for climate change impacts.

PRELIMINARY ANALYSIS

As an initial ground truthing exercise, the U.S. Climate Resilience Toolkit's Climate Explorer is used to compare historical and projected precipitation for Baltimore, Maryland. This analysis is meant to be compared to the DCF products described later in this report. The Climate Explorer and the DCFs both use CMIP5 models, but are downscaled using different statistical methods. Comparing the outputs of these two processes is hypothesized to function as a crude indication of the sufficiency of the simple DCF method.

Using the Climate Explorer online data portal, projections of future climate conditions were estimated for the parameters shown in **Tables 1** and **2** for our study area of Baltimore, MD. The projections establish a range of outcomes for three future periods (2020s, 2050s, 2080s) and are compared with a baseline historical dataset (1961-1990). Values shown are based on RCP8.5, which assumes no reduction in future greenhouse gas emissions. Generally the source data are representative of downscaling of an ensemble of Global Climate Models and use of Localized Constructed Analogs. Climate Explorer utilizes CMIP5 models.

In **Table 1**, it is seen that average total precipitation increases over time from 45.0 inches of rainfall in the historical baseline period (1961-1990) up to 51.4 inches in the future 2080s scenario. The extremes of the future annual rainfall values also increase, with the 90th percentile value increasing from 50.5 inches in the 2020s scenario to 53.3 inches in the future 2080s scenario.

Total projected days with extreme rainfalls also increases. Values of the number of days in Baltimore with rainfalls greater than 2 inches approximately doubles. There are more moderate increases in the project values for days with rainfalls greater than 3 inches, which remain relatively stable in absolute value (90th percentile value does not increase across the future planning period).

A second table was produced, **Table 2**, which describes the historical and projected precipitation by season for Baltimore, MD. The baseline, historical data, shows the average monthly precipitation per season for the years 1961 - 1990. Projections for the average monthly precipitation by season are produced for 2025, 2050, and 2075. The average monthly precipitation increases from the baseline to each successive projection for all four seasons, with the greatest increase being in the season of Winter.

METHODS

Projections of monthly precipitation totals for the period of 1971 - 2099 for two areas within Baltimore City are produced using 20 Global Climate Models(GCM) of the Coupled Model

Intercomparison Project 5(CMIP5). The GCMs are statistically downscaled using the Multivariate Adaptive Constructed Analogs(MACA) method to remove biases and improve the spatial resolution. The two grid cells seen in **Figure 4** are 6km and 4km and called MACAv2-LINVEH and MACAv2-METDATA respectively, and contain the location of Baltimore City (39.286 N -76.626 E.) Model names and their assigned ID numbers can be seen in **Table 3**.

To determine which 10 of the 20 GCMs to use to project future precipitation, the accuracy of their ability to model a period for which historical records are available is determined. The historical period is defined as Baseline which includes the years 1971 to 2000. The annual precipitation for each of the years in the Baseline period are averaged together one time for the historical data derived from Climate Explorer, and 40 times for each gridcell and GCM in a future time slice. The percent difference of the MACAv2-METDATA and MACAv2-LINVEH precipitation projections for each model in the Baseline period from the historical observed precipitation are determined. These percent differences are averaged across both downscaling outputs for all 20 models, then ranked from smallest to greatest. This model bias is illustrated graphically in Figure 5. The ten models whose outputs had the smallest percent difference from the historical observed precipitation are chosen for continued analysis.

The percent change between projected and historical precipitation is called a delta change factor (DCF) and calculated for 1,440 Delta Change Factors (DCFs) for 10 models, 2 downscaling methods, 3 time slices with 12 months each, and for two Representative Concentration Pathways (RCP).

$$DCF = \frac{Future\ Projected\ Rainfall\ Depth - Baseline\ Model\ Rainfall\ Depth}{Baseline\ Model\ Rainfall\ Depth} \times 100$$

The future time slices are named the 2020's, 2050's, and 2080's and defined as the years 2010-2039, 2040-2069, and 2070-2099 respectively. RCPs 4.5 and 8.5 are used to consider future greenhouse gas emission scenarios of "some mitigation" and "business as usual".

DCF RESULTS

The 1,440 DCFs calculated can be represented in various ways and through isolation of a variety of variables. **Figure 6** visually represents all DCF values for each time slice and month across both RCPs as a box and whisker plot. Through observation of this figure, there is a high amount of uncertainty and noticeable trends related to seasonality. While the general trend shows an overall increase in precipitation depths, the Winter and Summer months exhibit the greatest increases in precipitation. **Figure 6** also suggests that the extremes are increasing.

Figure 6 includes DCFs across both RCP 4.5 and 8.5. If the DCFs are observed independently for RCPs 4.5 and 8.5, both show a general increase in precipitation, with those for RCP 8.5 showing a more prominent increase in precipitation. This can be seen in a representative sample calculation of delta change factors for a single model and single downscaling method summarized in **Table 4**. Each month has its own calculated DCF for a future time slice and RCP value. This was conducted for all 10 models selected across each downscaling method. A complete set of tabulated results may be made available upon request. These calculated DCF values were further processed for application in our case study.

CASE STUDY

A hydrologic case study illustrates the potential application of delta change factor analysis for two areas of interest to the Baltimore Department of Public Works. This case study utilizes representative delta change factors applied to historic storm event precipitation depths to produce future climate projected precipitation depths. Using these projected precipitation depths and hydrologic modeling, projections of peak rate and volume estimates are estimated for case study sites of specific interest to BCDPW.

The work of the case study includes the following components which reflect feedback from BCDPW to co-generate the modeling inputs:

- Delta Change Factor Selection
- Storm Event Selection
- Site Selection

DELTA CHANGE FACTOR (DCF) SELECTION

Processing of the DCF results was conducted to represent each meteorological season and simplify selection of DCFs for application to the case study. The process to simplify the DCFs included averaging each month's results across all ten GCMs for each of the two RCPs and three future time slices. The monthly DCFs were then averaged across each meteorological season (Winter: December, January, February; Spring: March, April, May; Summer: June July, August; Fall: September, October, November) for each RCP. This resulted in 24 seasonal DCF values for consideration:

$$3\, future\ time\ slices \times 4\, seasons\ \times 2\, RCPs = 24\, DCFs$$

There was not an apparent variability due to downscaled dataset (LIVNEH, METDATA) and the DCFs were not separated by dataset. The 24 DCFs, along with the average across each RCP, are recorded in **Table 5**. This table provides a simplified interpretation of the DCF results for each time slice by meteorological season and future climate trajectories (RCP 4.5, RCP 8.5).

Selection of specific delta change factors for the case study relied on seasonal variability and the intended service life of stormwater infrastructure. The Baltimore Department of Public Works expressed that design service for their proposed infrastructure is assumed to be 100 years. The 2080 future time slice fits within this range. As for seasonal variability, a trend of greater delta change factors was observed in the Winter and Summer, which is consistent with relation to the U.S. Climate Resilience Toolkit's Climate Explorer data led by the National Oceanic and Atmospheric Association. Based on the intended service life and seasonal observations, the Winter and Summer DCFs for each RCP were selected for the case study. This results in a total of four DCFs for consideration that represent two seasons across two future climate trajectories. This representation of DCFs allows for a range of model results for the Baltimore DPW case study. The DCFs chosen are highlighted in **Table 5.**

STORM SELECTION

Storm event selection for the case study was based on applicability to the locale. Baltimore City Design Standards include consideration of the 5, 10, and 50-year, 24-hour storm events. Historic precipitation depths for each return period and duration were collected from NOAA Atlas 14, Volume 2, Version 3 for Baltimore City, Maryland, USA. The precipitation depth for each of the three historic storm events were subjected to the four selected delta change factors. This resulted in 12 future precipitation depths. A summary of these historic and future precipitation depths are recorded in **Table 6**. These historic and future precipitation depths were used in the hydrologic model case study to produce a range of results.

SITE SELECTION

The Baltimore Department of Public Works provided two sites for the case study: Catchment O and Catchment F. Each catchment is approximately 40 acres and part of the Watershed 263 Stormwater Demonstration Project. The Watershed 263 is a Pilot Demonstration Project that consists of an approximately 930-acre stormwater drainage area in west and southwest Baltimore. The project's goal is to revitalize urban communities through urban forestry watershed projects to improve water quality and quality of life. Watershed 263 spans 12 neighborhoods of various use (industrial, institutional, and residential). This area has been specifically identified for the interest of mixed use land development and water quality improvements. Catchment O can be described as a densely developed urban residential area. Catchment F, located to the north of Catchment O, can be described as majority residential with less dense, and more various land uses in comparison to Catchment O. **Figure 7.1** and **7.2** illustrate the location of each catchment. Other relevant information to hydrologically represent the sites include that the hydraulic soil conductivity is class D (**Figure 8**), the roadways include frequent placement of inlets for stormwater capture.

MODELING & RESULTS

HydroCAD was utilized to hydrologically model the two catchments for each scenario. HydroCAD uses the National Resource Conservation Service (NRCS) Technical Release 20 (TR-20) unit hydrograph approach for calculations and hydrologic analysis. Based on the collected information and desktop analysis of sites, **Table 7** summarizes the hydrologic description for the case study model inputs.

Each design storm was defined in HydroCAD. Each storm was defined using the previously described historic and future precipitation depths and the NRCS Type-II rainfall distribution as recommended by the Baltimore City Design Standards.

The model results of consideration include peak rate (cubic feet per second) and volume (acre-feet). The results of the model are summarized in **Tables 8.1 through 8.4**. The results of the model demonstrate potential peak rate and volume increases for these catchments for future climate trajectories. Also, it is observed that the precipitation depth of the 5yr event for the 2080 Winter season exceeds the historic 10 year event precipitation depth. This is illustrated in **Figure 9.1 and 9.2**. These figures represent additional volume generated by future scenarios for the 5-year event in comparison to the historic 5-year event. The additional volume generated by the historic 10-year event in comparison to the historic 5-year event is included for reference. These observations may be helpful to consider when determining which design storms to utilize in the design of stormwater management practices and conveyance infrastructure.

DISCUSSION

The Case Study modeling is useful to bring to light the key decisions that were made to create projections. The modeling results, although presented as numerical values, should be reviewed with an intent to understand the trends in the numbers. There are also significant sources of uncertainty that are embodied in the analysis . Through a review of these trends, additional steps for additional study are identified and prioritized:

- Variability of the historical baseline period
- Planning impact of modified design storms
- Consideration of tropical storms and sea level rise

VARIABILITY OF THE HISTORICAL BASELINE PERIOD

The selection of historical rain gauge data influenced the selection of the 10 models included in the GCM ensemble. It can be expected that rain gauges within a single geographical region will exhibit year to year variability. For our study, we looked at the historical rainfall data of the Baltimore International Airport (BWI) and also the Climate Explorer historical dataset, which is based on interpolation of rain gauge data gridded to a County-wide value.

For this study, we elected to use the Climate Explorer historical dataset. This historical baseline averaged appx. 46.5 inches of precipitation per year annually during the baseline period (1971-2000) while the BWI gauge averaged 41 inches. This difference of values actually surrounded the range of the hindcast of the 20 GCM models for the baseline period which ranged from 42-45 inches per year.

The selection of 10 GCM models to minimize bias is based on minimizing the difference between the Climate Explorer historical dataset and the set of GCM models' hindcast datasets. This resulted in GCM's with higher annual precipitation baseline selected for development of the delta change factors.The historical average of the 10 GCM's selected is 44.2 inches, while the historical average of the 10 GCM's not selected is 42.9. This is only a difference of about 3%. It may be interesting in the future to look at the selection of models to determine to what extent they would impact the DCF values generated by the analysis if BWI had been selected as the historical rain gauge.

PLANNING IMPACT OF MODIFIED DESIGN STORMS

The application of the delta change factors reveals that runoff volumes and peak flows increase significantly within the case study areas as the time periods progress to the 2080's time period. Using RCP 4.5 and RCP 8.5 as the lower and upper bounds of the projection, it was observed that the future 5-year 24-hr storm produced runoff rates and volumes approaching the existing definition of the 10-year 24-hr storm. Where the 10-year 24-hr storm is a planning and policy criteria applied in BCDPW's service area, it is important to consider with additional analysis how infrastructure design criteria may need to be revised to account for this projected change. Even under a scenario such as RCP 4.5 that assumes reduction measures are implemented to reduce greenhouse gas emissions, this trend is observed.

BCDPW is currently working on planning for future capital stormwater improvements as well as coordination with the Baltimore City traffic department for drainage system standards. Where there are competing needs for funding, there is a need to further develop decision making tools to help utilities prioritize infrastructure investments. Policies that impact landuse and private development are also critical to improving stormwater management. BCDPW's planned implementation of continuous simulation H&H modeling will provide a framework for evaluation of future climate rainfall projections.

There may be opportunities for BCDPW to identify 'low-regret' policies that ensure infrastructure performs across a range of future climate conditions. Such possible recommendations could include modifications to green infrastructure inlets and curb cut construction details that would allow an increased interception capacity from local streets. Where street drainage is not performing, new standards for curbing and inlet sizing may be practical and cost effective. These modifications could be made as policy and then implemented over time as new projects are constructed and old infrastructure is renewed and replaced.

As discussed with BCDPW in the context of recent actual flooding events, there may be locations within the service area that may be particularly at risk, including a danger to public safety and property risks that may be more frequently experienced with increased future rainfall. In those cases, there may be justification to establish additional policy levers such as zoning code revisions and also funding for relocation of existing property owners. - items. Analysis of future climate projections may help prioritize and justify project funding partnerships. Just in the last few months, both the Bay Restoration Fund and the Federal Emergency Management Agency have increased their funding opportunities to prioritize investments that address flooding and future climate risks.

CONSIDERATION OF TROPICAL STORMS AND SEA LEVEL RISE

Through initial review of the Climate Explorer data, an increase in the frequency of flooding during high tide is also projected due to sea level rise. BCDPW also relayed the occurrence of historical flooding in Baltimore City due to storm surge. Recent research by others has indicated that the frequency of Atlantic tropical storms is expected to increase (reference). Where BCDPW has communicated that significant damage and risk has been demonstrated through microburst thunderstorm events, it’s also unknown how flooding impacts may be compounded due to the increase in precipitation due to Atlantic tropical storms and hurricanes.

The GCM data indicates that precipitation is projected to increase on average, but also that the range of rainfalls experienced are also expected to become more extreme, with dry years becoming more dry and wet years becoming wetter. With that projected trend in mind, there may be significant value in continuous simulation modeling where sufficient future scenarios can be developed that illustrate the impact of back to back storm events, influence of existing ground saturation and variation in groundwater influence.

CONCLUSION

Through the partnership with BCDPW, we have developed a range of projections for future rainfall patterns through the year 2100 for Baltimore City. It must be clearly understood that projections are not predictions. However, there is an observed trend of increasing precipitation as illustrated through the delta change factor methodology applied. The analysis relied on the use of publicly available global climate model datasets to provide downscaled estimates of impacts at a regional level. Through this specific study and the studies of other neighboring communities in the Mid-Atlantic region completed by other groups in the course, it may be possible to get a clearer picture of the uncertainties contained in these estimates.

The approach used for this set of delta change factor calculations is not the only approach to estimating these factors. Where research by others has looked at the sensitivity of DCF methodology applied to a cross section of urban cities across the United States, the reports for this course may be very helpful to better understand how these estimates may differ across areas within a smaller geographic region that was studied. For example, it may be reasonable to apply BCDPW's DCF analysis results for nearby municipalities such as Ellicott City, which was devastated two years in a row by extreme rain events.

The impact of future climate change is projected to have more frequent rainfall in part due to projected increase in temperatures. Urban areas like Baltimore City are especially at risk of the impacts of increased temperature due to the urban heat island effect, driven by large amount of developed impervious surfaces. It's possible that thoughtful implementation of stormwater management can provide co-benefits, such as mitigating the urban heat island effects.

Where BCDPW is interested in continuing evaluation of future climate conditions through application of downscaled GCM data, it would be interesting to consider the following areas of future additional study:

- Where this analysis relied on monthly precipitation data to estimate DCF values, daily precipitation data is available and may allow for more detailed adjustments. This approach could perhaps provide a more detailed resolution though it may not necessarily be more accurate. Being able to account for changes at a daily rainfall or individual rain event resolution could allow for continuous simulation modeling through generating annual daily time series data;

- This analysis used the 1971-2000 as the historical baseline period. Where future rainfall is projected to increase in this analysis, it may be helpful to evaluate the recent historical rainfall record (such as 2001-2020) to consider what trends are already becoming apparent and how they compare with the results of this study and the other studies completed in this course;

- There are existing studies that project changes in sea level rise which could be useful to consider in terms of evaluating flooding and potential disaster planning and response, beyond the scope of this analysis.

One of the most significant challenges that face utilities like BCDPW is the fragmentation in government jurisdictions and its impact on policy making and funding.   Where it takes multiple departments or multiple utilities to work together, it is much more likely that the status quo will be maintained. With the projected uncertainty in future climate and increases in future precipitation, it will be critical to not only develop decision making tools, but also to be willing to embrace partnership and innovation at a regional scale to implement programs most effectively and equitably.

APPENDIX

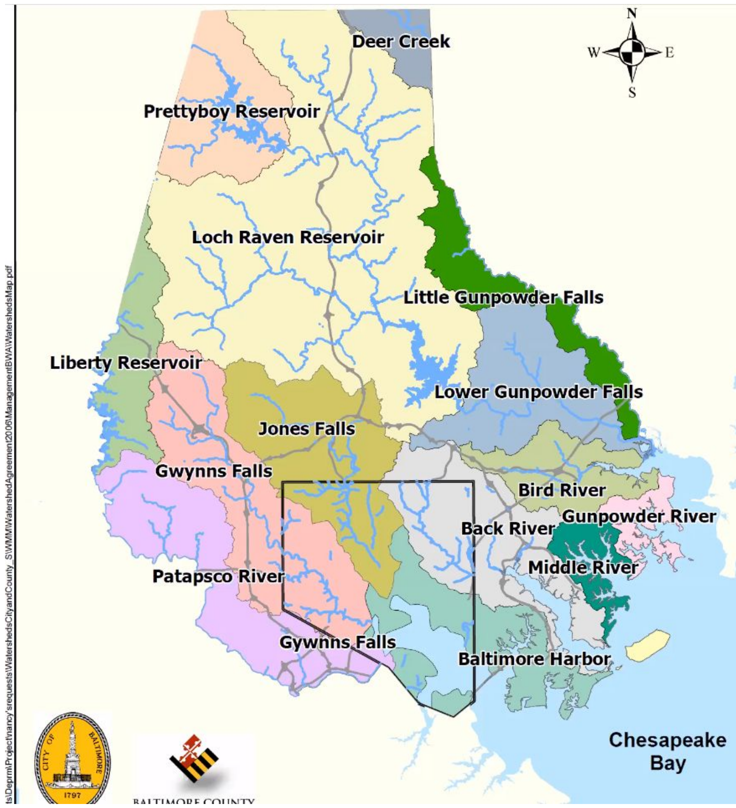

Figure 1: Watersheds of Baltimore County. Baltimore City Limits are shown in black.

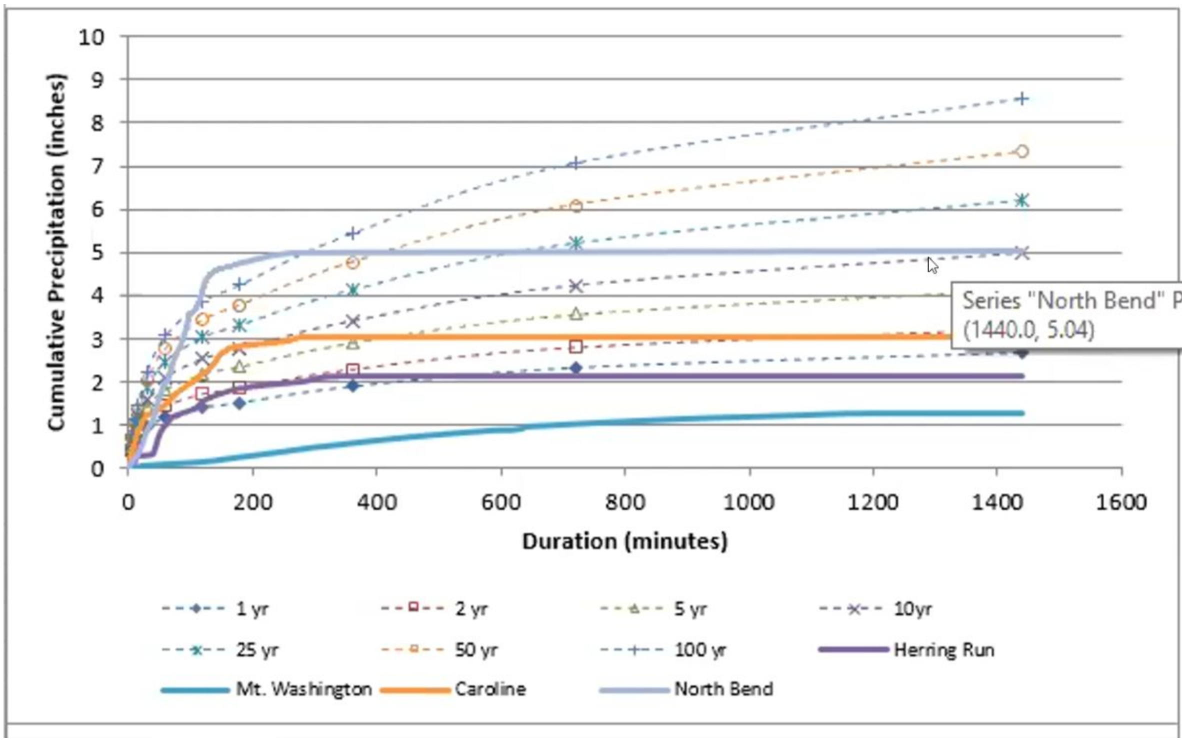

Figure 2: Precipitation - duration at several monitoring locations for the August 22, 2019 event compared with 24-hour Design Storms (BCDPW).

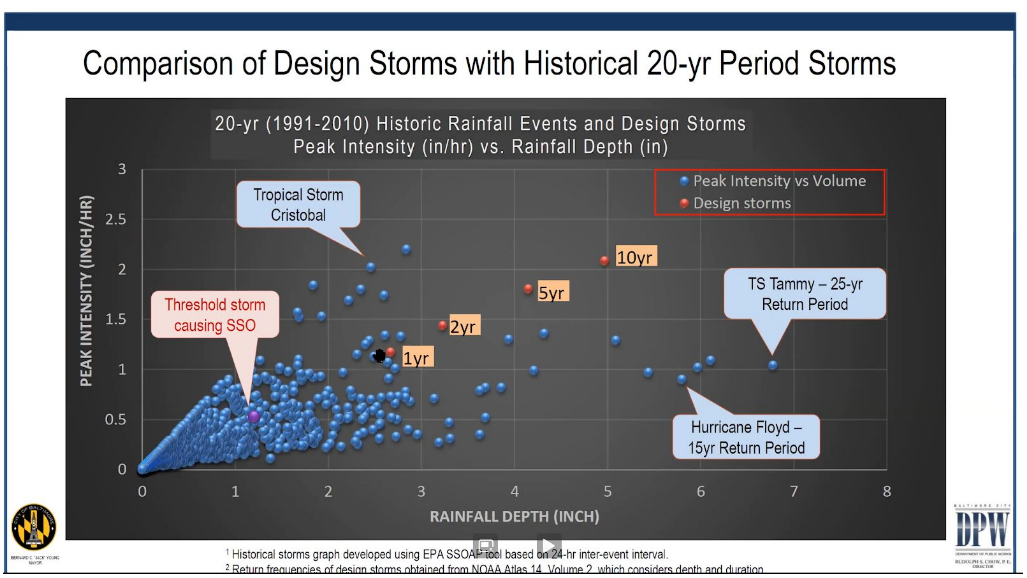

Figure 3: Comparison of design storms with Historical 20-yr Period Storms (BCDPW).

Projected Future Precipitation Values for Baltimore, MD						
2020s		**Low Estimate**	**Middle Range**			**High Estimate**
Data Category	**Baseline (1961-1990)**	**10th Perc.**	**25th Perc.**	**50th Perc.**	**75th Perc.**	**90th Perc.**
Total Annual Precipitation	45.0	45.9	46.5	47.6	48.8	50.5
Number of Days Per Year With:						
Rainfalls at or above 1 inch	8.40	9.20	9.60	9.95	10.50	10.98
Rainfalls at or above 2 inch	0.89	0.91	1.00	1.15	1.30	1.50
Rainfalls at or above 3 inch	0.17	0.11	0.20	0.20	0.30	0.40
2050s		**Low Estimate**	**Middle Range**			**High Estimate**
Data Category	**Baseline (1961-1990)**	**10th Perc.**	**25th Perc.**	**50th Perc.**	**75th Perc.**	**90th Perc.**
Total Annual Precipitation	45.0	46.6	47.5	49.1	50.2	52.1
Number of Days Per Year With:						
Rainfalls at or above 1 inch	8.40	9.80	10.20	10.80	11.60	11.79
Rainfalls at or above 2 inch	0.89	1.20	1.20	1.40	1.63	1.79
Rainfalls at or above 3 inch	0.17	0.20	0.20	0.25	0.30	0.39
2080s		**Low Estimate**	**Middle Range**			**High Estimate**
Data Category	**Baseline (1961-1990)**	**10th Perc.**	**25th Perc.**	**50th Perc.**	**75th Perc.**	**90th Perc.**
Total Annual Precipitation	45.0	48.1	49.6	51.4	52.4	53.3
Number of Days Per Year With:						
Rainfalls at or above 1 inch	8.40	10.41	11.15	12.00	12.33	12.50
Rainfalls at or above 2 inch	0.89	1.32	1.60	1.80	2.00	2.19
Rainfalls at or above 3 inch	0.17	0.20	0.30	0.30	0.40	0.40
Projections are based on data downloads from Climate Explorer, a part of the U.S. Climate Resilience Toolkit (managed by NOAA's Climate Program Office). Data shown reflect the RCP8.5 and CMIP5. Baseline data are for the observed historical 1961-1990 period. Values are the 10th, 25, 50th, 75th, and 90th percentiles for 30-year mean values from model-based outcomes. Decimal places are shown for values less than one, although this does not indicate higher precision. Sources of uncertainty include data and modeling constraints, the random nature of some parts of the climate system, and limited understanding of some physical processes. The projections are not true probabilities and the potential for error should be acknowledged.						

Table 1: Projected Future Precipitation Values for Baltimore, MD

Projected Seasonal Precipitation for Baltimore, MD				
	Average Monthly Precipitation [inches] by Season			
	Winter	Spring	Summer	Fall
Precipitation Baseline 1961 - 1990	3.40	3.97	3.87	3.77
2025	3.72	4.33	4.11	3.75
2050	3.93	4.39	4.12	3.84
2075	4.22	4.51	4.12	3.84

Winter = {December, January, February}, Spring = {March, April, May}, Summer = {June, July, August}, Fall = {September, October, November}. Historical and projected climate data herein are from The Climate Explorer Tool, a part of the U.S. Climate Resilience Toolkit. Projected data is generated by GCMs using RCP 8.5 for CMIP5 and downscaled using LOCA. Baseline data covers the period of 1961 - 1990. Uncertainties in projections can be attributed to data and modeling constraints and randomness and limited understanding of parts of the climate system. Decimal places are shown for values less than 1, but do not reflect that level of precision. Projections are not true probabilities and the potential for error should be acknowledged.

Table 2: Projected Seasonal Precipitation for Baltimore, MD

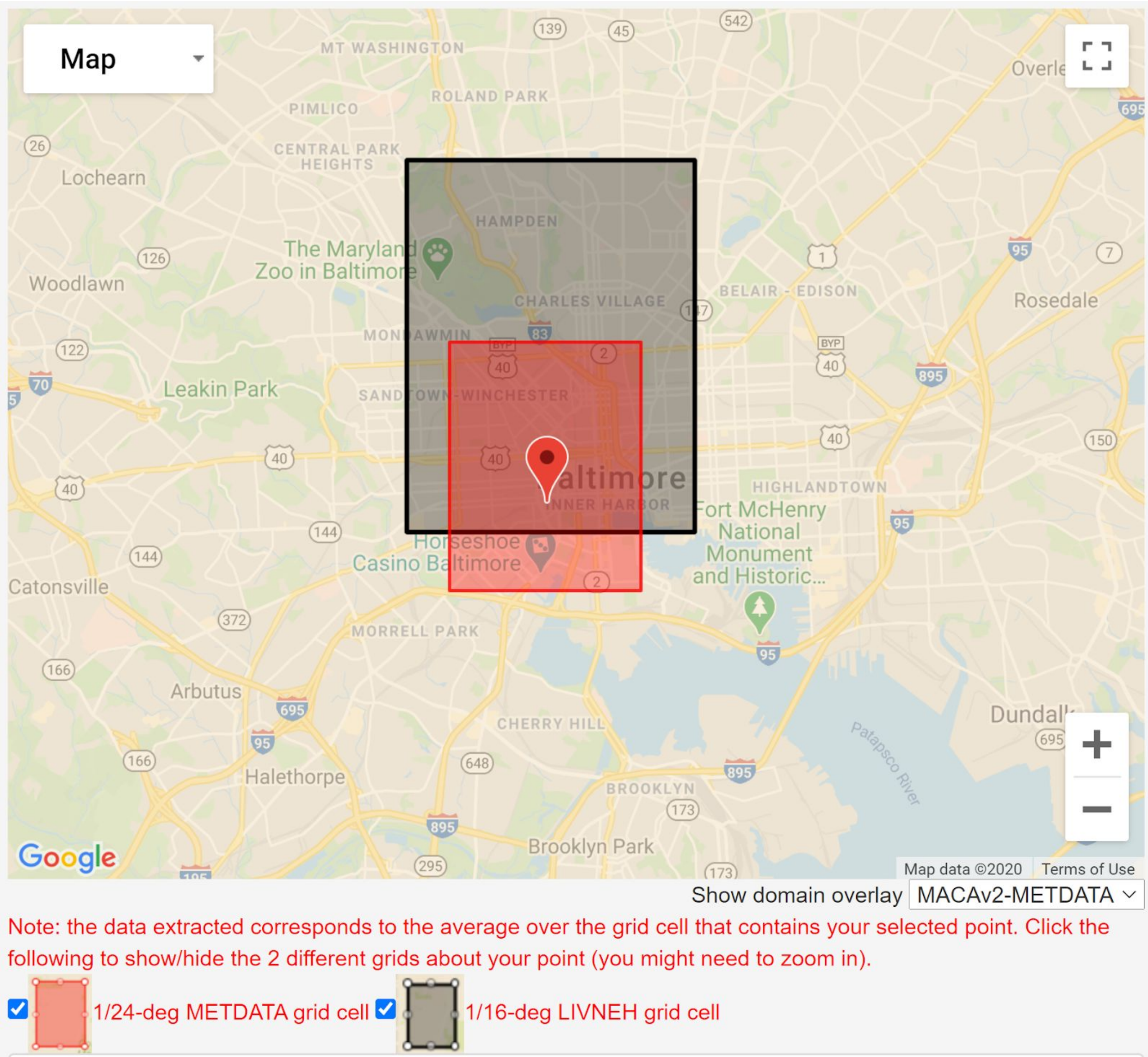

Figure 4: Domain geographic overlay of MACAv2-METDATA and MACAv2-LINVEH

Model	Model ID
pr_bcc-csm1-1	M1
pr_bcc-csm1-1-m	M2
pr_BNU-ESM	M3
pr_CanESM2	M4
pr_CCSM4	M5
pr_CNRM-CM5	M6
pr_CSIRO-Mk3-6-0	M7
pr_GFDL-ESM2M	M8
pr_GFDL-ESM2G	M9
pr_HadGEM2-CC365	M10
pr_HadGEM2-ES365	M11
pr_inmcm4	M12
pr_IPSL-CM5A-LR	M13
pr_IPSL-CM5A-MR	M14
pr_IPSL-CM5B-LR	M15
pr_MIROC5	M16
pr_MIROC-ESM	M17
pr_MIROC-ESM	M18
pr_MRI-CGCM3	M19
pr_NorESM1-M	M20

Table 3: Model names and their associated ID codes

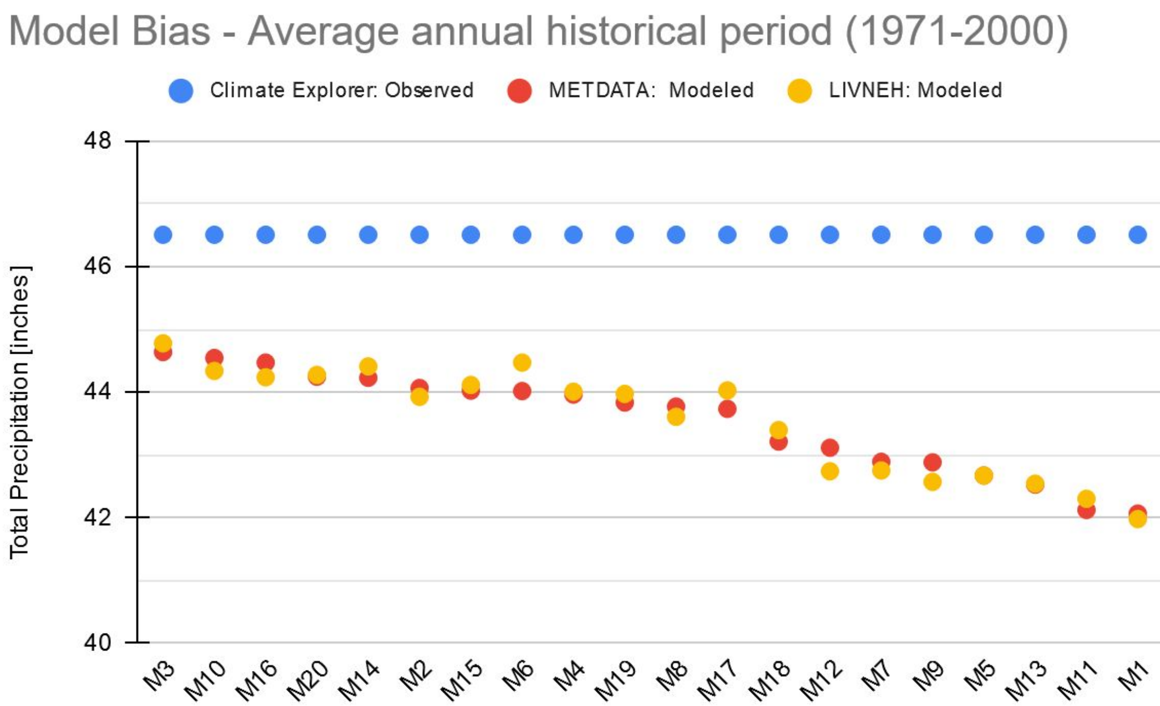

Figure 5: Models are compared with historic rainfall and selected to minimize model bias.

Note that GCM data downloaded is monthly covering the 1950-2005 (observed) future projections (2006-2099). Note the difference between Observed and modeled. Note that other baseline periods 61-90 for example has averages closer to 45 inches, which indicate that top 10 models are in agreement, and that outliers may influence the observed average.

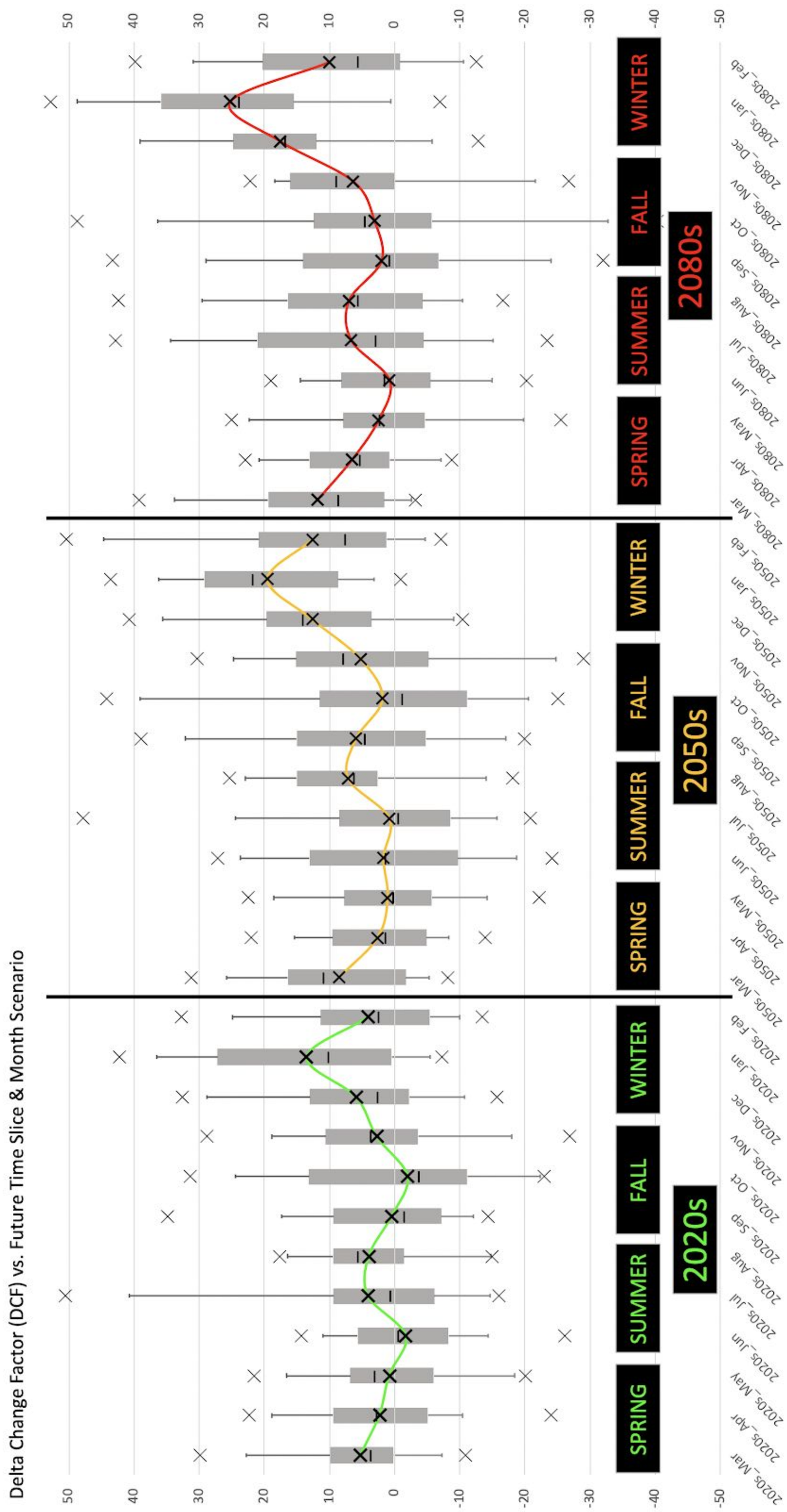

Figure 6: Box Plots for DCFs
(shown: min, 5th percentile, 1st quartile, mean, median, 3rd quartile, 95th percentile, max)

	Model:	pr_BNU-ESM				
	Downscaling:	MACAv2-LIVNEH				
	2020s		2050s		2080s	
RCP	Month	Delta Change Factor	Month	Delta Change Factor	Month	Delta Change Factor
2.5	January	-0.04%	January	-0.65%	January	13.52%
	February	-5.45%	February	-0.32%	February	-2.97%
	March	-2.22%	March	10.02%	March	-2.63%
	April	2.11%	April	6.33%	April	-7.69%
	May	-14.24%	May	-12.67%	May	-13.27%
	June	11.90%	June	-11.70%	June	-3.49%
	July	-10.05%	July	-13.78%	July	-3.69%
	August	-0.26%	August	-0.53%	August	10.17%
	September	-0.49%	September	26.53%	September	-18.60%
	October	9.80%	October	18.06%	October	8.49%
	November	4.53%	November	14.76%	November	12.29%
	December	-10.19%	December	18.63%	December	21.05%
8.5	January	4.72%	January	13.07%	January	21.28%
	February	18.72%	February	2.22%	February	0.83%
	March	0.54%	March	16.13%	March	0.26%
	April	-7.82%	April	0.10%	April	2.18%
	May	-0.53%	May	4.95%	May	-8.16%
	June	6.49%	June	7.85%	June	11.18%
	July	2.19%	July	-13.76%	July	20.74%
	August	27.86%	August	19.69%	August	10.08%
	September	-15.31%	September	34.08%	September	-24.74%
	October	-4.66%	October	11.29%	October	18.26%
	November	1.48%	November	14.60%	November	3.47%
	December	2.51%	December	9.43%	December	10.81%

Table 4: Monthly DCF results for one model and one downscaling method.

DELTA CHANGE FACTOR (DCF) SUMMARY				
Time Slice	**Season**	**RCP 4.5**	**RCP 8.5**	**Average**
2020	Winter	8%	7%	8%
	Spring	2%	4%	3%
	Summer	0%	4%	2%
	Fall	3%	-2%	1%
2050	Winter	13%	16%	15%
	Spring	4%	4%	4%
	Summer	3%	4%	3%
	Fall	3%	5%	4%
2080	Winter	**15%**	**21%**	17%
	Spring	3%	11%	6%
	Summer	**4%**	**6%**	5%
	Fall	2%	6%	3%

Table 5: Delta Change Factors chosen for use in the Case Study

PRECIPITATION DEPTH (INCHES)						
	5yr		10yr		50yr	
Scenario	**RCP 4.5**	**RCP 8.5**	**RCP 4.5**	**RCP 8.5**	**RCP 4.5**	**RCP 8.5**
Historic (Altas 14)	4.17		4.98		7.35	
2080 Winter	4.80	5.05	5.73	6.03	8.45	8.89
2080 Summer	4.34	4.42	5.18	5.28	7.64	7.79

Table 6: Historic and future time slice precipitation depths (in inches) by recurrence interval and RCP.

Figure 7.1: Case study sites (Catchment O, Catchment F)

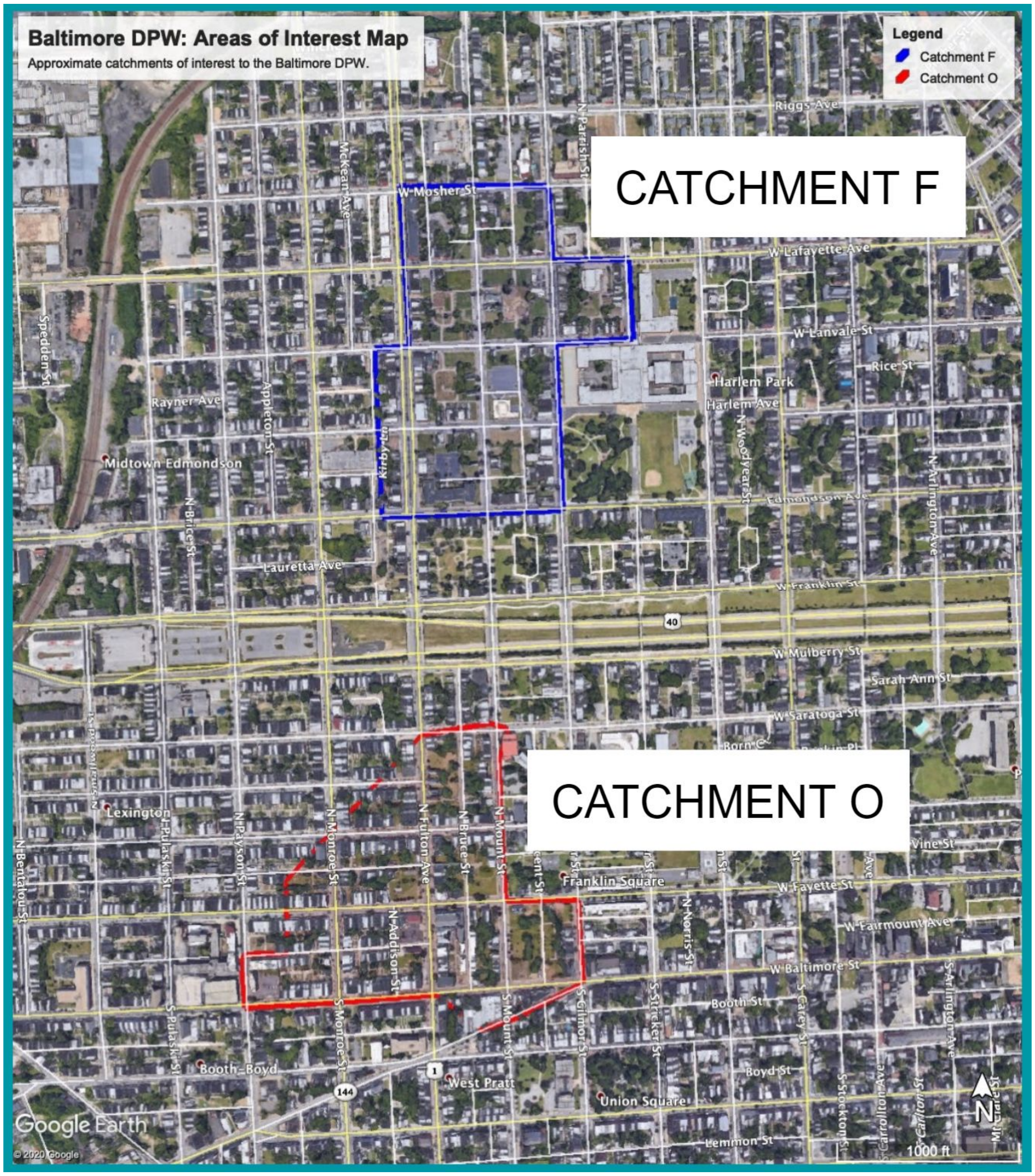

Figure 7.2: Case study sites (Catchment O, Catchment F)

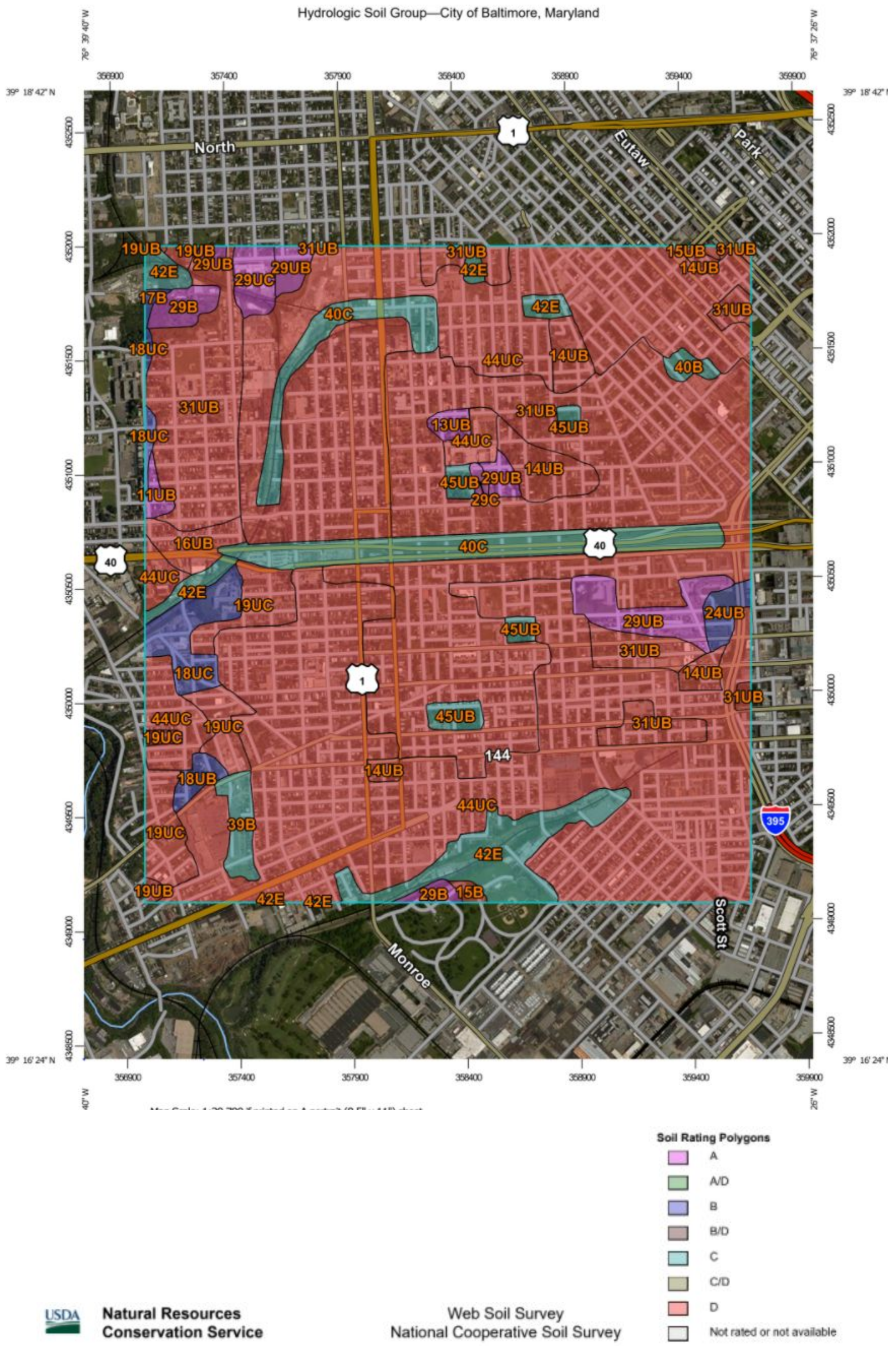

Figure 8: Natural Resource Conservation Service Web Soil Survey Map for hydraulic soil group.

DRAINAGE AREA SUMMARY					
Area ID	Area (acres)	Cover Description	Hydraulic Soil Group (HSG)	CN	Time of Concentration (min)
Catchment O	40	Residential 1/8 (town houses), 65% imp	D	92	5
Catchment F	40	Residential 1/4, 38% imp	D	87	5

Table 7: Catchment O & F drainage area summary of hydrologic parameters.

CATCHMENT F: PEAK RATE RESULTS (CFS)					
		RCP 4.5		RCP 8.5	
Storm Event	Historic (Atlas 14)	2080 Summer	2080 Winter	2080 Summer	2080 Winter
5YR	195	205	233	210	249
10YR	244	257	290	263	308
50YR	388	406	455	415	481

Table 8.1: Catchment F peak rate model results

CATCHMENT F: VOLUME RESULTS (ACRE-FEET)					
		RCP 4.5		RCP 8.5	
Storm Event	Historic (Atlas 14)	2080 Summer	2080 Winter	2080 Summer	2080 Winter
5YR	9.3	9.8	11.3	10.1	12.0
10YR	11.8	12.4	14.2	12.8	15.1
50YR	19.4	20.3	22.9	20.8	24.4

Table 8.2: Catchment F volume model results

CATCHMENT O: PEAK RATE RESULTS (CFS)					
		RCP 4.5		RCP 8.5	
Storm Event	Historic (Atlas 14)	2080 Summer	2080 Winter	2080 Summer	2080 Winter
5YR	220	230	258	235	273
10YR	268	280	313	286	331
50YR	410	427	475	436	501

Table 8.3: Catchment O peak rate model results

CATCHMENT O: VOLUME RESULTS (ACRE-FEET)					
		RCP 4.5		RCP 8.5	
Storm Event	Historic (Atlas 14)	2080 Summer	2080 Winter	2080 Summer	2080 Winter
5YR	10.9	11.5	13.0	11.7	13.8
10YR	13.6	14.2	16.0	14.5	17.0
50YR	21.3	22.3	24.9	22.8	26.4

Table 8.4: Catchment O volume model results

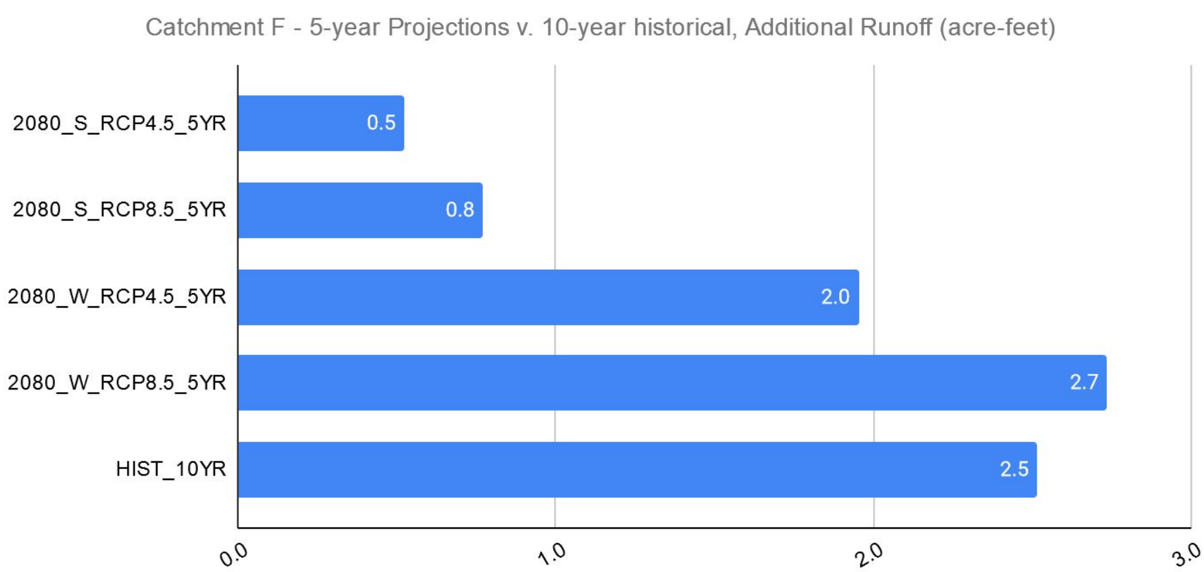

Figure 9.1: Additional runoff volume generated by 5yr scenario projections and 10yr historical in comparison to 5yr historical (Catchment F)

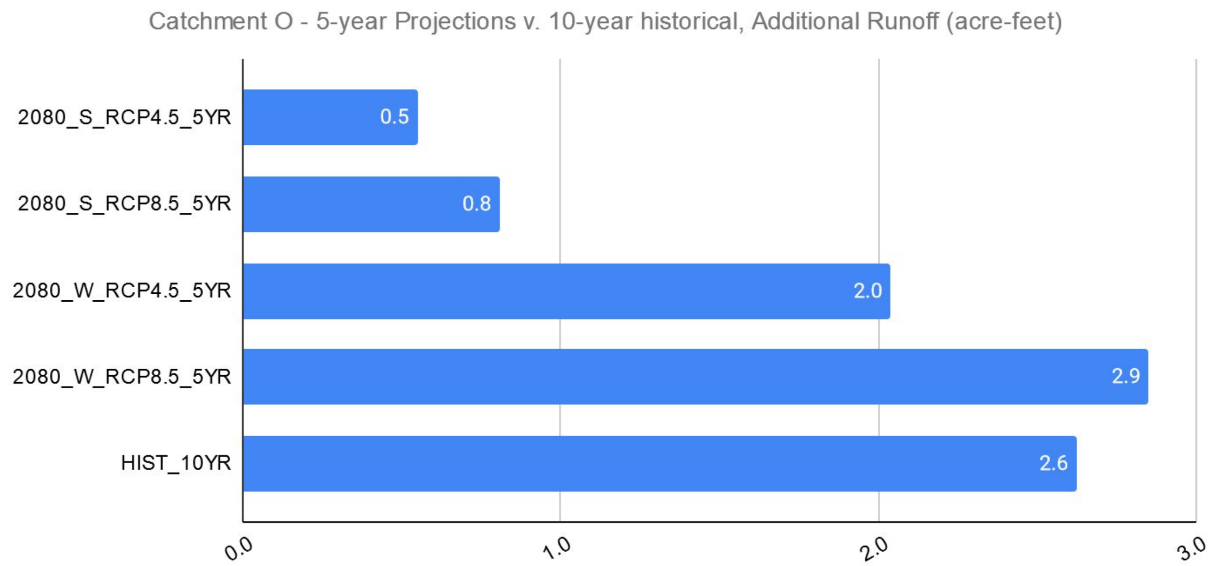

Figure 9.2: Additional runoff volume generated by 5yr scenario projections and 10yr historical in comparison to 5yr historical (Catchment O)