JUNE 2015

CLIMATE PROJECTIONS & SCENARIO DEVELOPMENT

CLIMATE CHANGE ADAPTATION PLAN FOR THE DISTRICT OF COLUMBIA

RFA: 2013-9-OPS

PREPARED FOR

WE ARE WASHINGTON DC

DEPARTMENT OF ENERGY & ENVIRONMENT

PREPARED BY

PERKINS +WILL

KLEINFELDER

ACKNOWLEDGMENTS

This research was funded by the District of Columbia Sustainable DC Innovation Fund (DOEE ID# 2013-9-OPS).

DEPARTMENT OF ENERGY & ENVIRONMENT
Tommy Wells, Director
Kate Johnson, Climate Program Analyst
Phetmano Phannavong, Environmental Engineer

Produced in collaboration with

PERKINS+WILL
Amy Thompson, Project Manager
Janice Barnes, Principal
Douglas Pierce, Principal

KLEINFELDER
Lisa Dickson, Principal in Charge
Nathalie Beauvais, Project Manager
Indrani Ghosh, Lead Modeler
Dennis Greene, Senior Modeler
Nasser Brahim, Vulnerability Assessment
Andrew Nunnery, Climate data analysis
Karin Hagan, GIS Lead

ATMOS RESEARCH AND CONSULTING
Katharine Hayhoe, PhD, Senior Scientist
Anne Stoner, PhD, Senior Scientist
Downscaled climate projections (precipitation and temperature)

UNIVERSITY OF NEW HAMPSHIRE
Paul Kirshen, Lead Scientific Reviewer; hydrology and sea level rise

UNIVERSITY OF MASSACHUSETTS IN BOSTON
Ellen Douglas, Lead Scientific Reviewer; design storms

JUNE 2015

CLIMATE PROJECTIONS & SCENARIO DEVELOPMENT

CLIMATE CHANGE ADAPTATION PLAN FOR THE DISTRICT OF COLUMBIA

RFA: 2013-9-OPS

PREPARED FOR

PREPARED BY

PHOTO CREDIT: VICTORIA PICKERING. SUSTAINABLE DC, CLIMATE CHANGE PHOTO CONTEST

CONTENTS

LIST OF TABLES AND FIGURES

FIGURES

TABLES

EXECUTIVE SUMMARY

Cities throughout the United States and the world have come to realize that climate change presents significant new risks to their communities. Using the records and knowledge of past climatic events are no longer reasonable proxies for planning for current or future conditions or events. This presents significant challenges for cities in their infrastructure and disaster preparedness planning. What will be the impacts of this "new normal"? How should cities build today in order to prepared for tomorrow? There is significant uncertainty as to possible futures, however a community can assess its overall risk with respect to climate change and plan for and later take actions to prepare for the possibilities. The District Department of Energy and Environment (DOEE) has taken a proactive stance on climate change and committed to identifying, prioritizing, and addressing the critical needs associated with this "new normal." This report is the first step of a multi-phase project led by DOEE to develop a citywide climate adaptation and preparedness plan for the District of Columbia (the District). The climate change projections provided here will allow the District to assess its vulnerabilities and risks in the face of a changing climate and to identify strategies that will help the city adapt and prepare.

The Climate Change Adaptation Plan will provide an integrated analysis of existing climate change data, an assessment of the District's vulnerable assets, and a risk-based, prioritized plan for adaptation and resiliency. This report defines climate projections and scenario development for the District and serves as the first step toward a comprehensive climate change adaptation plan. A key step in assessing climate change vulnerability is identifying relevant climate information for future projections. Since climate change projections are specific to geographic location, it is important to establish a set of climatic parameters describing the phenomena most relevant to DC.

For this study, the team, along with DOEE decided to compare three planning horizons – the 2020s, 2050s, and 2080s – against the baseline conditions of 1981-2000. High and low greenhouse gas emission scenarios were also used. As expected, the higher emission scenario yielded more significant increases in temperatures and precipitation-driven flooding than was observed with the lower emission scenarios, which accounts for the range of results in the following trends:

- Annual average and summer temperatures are expected to increase in future years. Heat waves will become more intense and have a longer duration. In the past, there has been an average of 11 days per year exceeding 95°F. Projections indicate an average of 18-20 days per year by 2020, 30-45 days the 2050, and as much as 40-70 days per year by 2080.

- The frequency and intensity of extreme precipitation events are expected to increase in future years. This change in precipitation patterns with more intense storms of shorter duration will add stress to infrastructure and increase the likelihood of flooding.

- Sea level rise is expected to continue, and even accelerate in the future due to climate change. Relative sea level rise projections range from 0.6 to 1.9 feet by 2050 and 0.9 to 3.8 feet by 2080.

Key Findings for Changes in Temperature

Heat has been the largest single weather-related cause of death in the US since the National Oceanic and Atmospheric Administration (NOAA) began reporting data for heat in 1988. Due to climate change, the annual average, as well as summer, temperatures are expected to increase in future years in the District. Heat waves, defined by the District as three or more consecutive days with daily maximum heat index values exceeding 95°F, will also become more intense and have longer durations; meaning the heat waves will continue for more consecutive days and will be hotter and more humid. In this study, baseline or historic conditions (1981-2000) for summer daytime maximum temperatures currently average 87°F with nighttime minimum temperatures averaging around 66°F. These values are projected to increase 2.5-3°F by the 2020s, 5-7°F by the 2050s, and as much as 6-10°F by the 2080s.

Extreme heat events are also projected to increase. A threshold of 95oF was chosen as the indicator of extreme temperature based on the District's Heat Emergency Plan. In the past, as documented from 1991-2010, there has been an average of 11 days per year when air temperatures exceeded 95oF. Projections indicate an average of 18-20 days with temperature exceeding 95oF by the 2020s, 30-45 days by the 2050s, and 40-70 days per year by the 2080s.

Another critical measure for temperature is the heat index, which combines ambient air temperature and relative humidity to determine what the temperature feels like to the human body. For the baseline period (1981-2000), there are 29 days per year with a heat index over 95oF. By the 2020s, an increase is expected to around 50 such days. By the 2050s, there may be 70 to 80 such days and by the 2080s, the number of days with heat index at or exceeding 95oF could average around 70 under the lower scenario and 105 under the higher.

Key Findings for Changes for Precipitation

The frequency and intensity of extreme precipitation events are projected to increase during the studied time horizons. The District currently receives an average of 10 days per year with greater than 1 inch of rain in a given 24-hour period, and an average of 1 day per year with greater than 2 inches of rain in a 24-hour period. By the 2020s, the number of days per year with more than 1 inch of rainfall per 24-hour period is expected to be 11 days. That number is projected to increase to 12 days by the 2050s and 13 days by the 2080s. The number of days per year with more than 2 inches of rainfall per 24-hour period is expected to increase to 3 days per year by the 2020s, an average of 3.5 days per year by the 2050s, and between 3.5 to 4.5 days per year by the 2080s.

Changes in rainfall volumes have a significant impact on drainage infrastructure. Engineers use design storms as baselines to inform their calculations for drainage structures like culverts and sewer pipes. Until recently, engineers could rely on past storm events to determine what amount of precipitation a "typical" storm event would produce and how that might affect the local infrastructure, but climate change has produced new types of storms that behave differently than those of the past. This means that new design storms must be calculated to allow engineers to adequately size drainage structures, including not only pipes but features such as rain gardens and bioswales.

For the purposes of this study, a large number of extreme precipitation indicators were calculated. These included the number of days with rainfall above 1 to 2 inches, 24-hour design storms for 1-, 2-, 15-, 25-, 100-, and 200-year recurrence intervals, 6-hour design storms for 2-, 15-, 100-, and 200-year recurrence intervals, and the precipitation amounts associated with the historical and projected future 80th, 90th, and 95th percentile of wet days. DOEE gathered input on the extreme precipitation parameters from DC Water, the District Department of Transportation (DDOT), and DOEE's Stormwater Management Division as informed by their current use and applicability in informing design standards for stormwater, wastewater, and transportation infrastructure.

Overall, precipitation events in DC are projected to increase both in intensity and frequency. The rainfall depths associated with the 24-hour and 6-hour duration design storms for the aforementioned recurrence intervals are all projected to steadily increase from the present through 2080s. For example, the present 15-year 24-hour storm, which is the typical design capacity of the District's sewer system, is projected to increase from the present value of 5.3 inches to 6.8 inches by the 2020s, 7.1 inches by the 2050s and 7.6 inches by the 2080s. Similarly, the present 100-year 6-hour storm, which is used for interior drainage modeling and design, is projected to increase from the present value of 5.1 inches to 6.7 inches by 2020s, and to 8.6 inches by 2080s. The results also indicate that these extreme rainfall events will become more frequent. For example, the present 100-year 24-hour storm will be the 25-year 24-hour storm by mid-century (2050s) and the 15-year 24-hour storm by end of the century (2080s).

Key Findings for Sea Level Rise and Storm Surge

Over the past century, sea levels have been rising as a result of climate change. Locally, sea levels on the District waterfront have risen 11 inches since 1924, and are expected to continue to rise in the future. There are various projections of sea level rise based on the emission scenario that is used. For this study, we relied on the data published by the United States Army Corps of Engineers (USACE) North Atlantic Coast Comprehensive Study (NACCS) released in January 2015. The NACCS estimated relative sea level rise (SLR) of 0.4 to 1.4 feet by 2050 and 0.7 to 3.4 ft. by 2080, depending on the SLR scenario (USACE low, medium, or high SLR scenario from 2014).

Storm surge was also analyzed as part of this study. Storm surge is a measure of how high water rises over and above normal tide levels during storms. It is influenced by several factors including wind speed, direction, and duration, barometric pressure (the lower pressure allows the water to expand), and tidal elevations. The USACE modeled typical flooding associated with Category 1, 2, and 3 hurricanes and used huricane intensity to determine the maximum probable extent of flooding during each event.

Next Steps for the District Adaptation Plan

The purpose of this report is to identify probable and plausible futures for the District with respect to climate change. This is the first step towards defining a framework for informing policies and actions to best address this “new normal.” The scenarios recommended will be used to assess the District’s vulnerabilities to climate change, which will inform priority adaptation strategies.

2020 SCENARIO

SLR/ STORM SURGE
100-year flood = base flood elevation

PRECIPITATION
Higher scenario: 10.5 inches for the 100-year 24-hour storm
Lower scenario: 4.6 inches for the 15-year 6-hour storm

HEAT
Increase of daytime maximum by 2.5 ° - 3°F
Possible heat wave of 6 days

2050 SCENARIO

SLR/ STORM SURGE
100-year flood + 3 feet = base flood elevation + 3 feet

PRECIPITATION
Higher scenario: 10.5 inches for the 100-year 24-hour storm
Lower scenario: 4.7 inches for the 15-year 6-hour storm

(According to the model results there were no significant changes in the design storm depths between 2020s and 2050s. Hence the precipitation scenarios are similar between these two planning horizons).

HEAT
Increase of daytime maximum by 5 ° - 7°F
Possible heat wave of 8 - 9.5 days

2080 SCENARIO

SLR/ STORM SURGE
FEMA 500-year flood = base flood elevation + 4 ft.

PRECIPITATION
Higher scenario: 13.5 inches for the 100-year – 24 hour storm
Lower scenario: 5.1 inches for the 15-year – 6 hour storm

HEAT
Increase of daytime maximum by 6 ° - 10°F
Possible heat wave of 9.5 - 12 days

PHOTO CREDIT: PATRICK BENKO . SUSTAINABLE DC, CLIMATE CHANGE PHOTO CONTEST


PHOTO CREDIT: ALEXANDRA HAY . SUSTAINABLE DC, CLIMATE CHANGE PHOTO CONTEST

01

INTRODUCTION:
WHY PREPARE FOR CLIMATE CHANGE?

WHY PREPARE FOR CLIMATE CHANGE?

Climate change is no longer a distant threat. Its effects are evident today in changes in both yearly averages and extreme events. Temperature and precipitation patterns are changing, in addition to rising sea level and extreme weather events.

The District has experienced a 2oF increase in annual average temperature from 1947 to the present day. Summers are warming faster, at a rate of 0.4oF per decade, while winters are warming more slowly, at 0.2oF per decade (NOAA, 2015). Dangerous extreme heat events are also becoming more frequent. Compared to 1950, there are now an average of 9 more days per year with maximum temperature greater than 95oF. ,

Precipitation patterns have also changed. While the annual volume of precipitation has not changed much, there are strong seasonal trends. Fall and winter average annual precipitation has been increasing at a rate of 0.4 and 0.1 inches per decade, respectively. There has been little change in spring precipitation, and a decrease in summer precipitation of 0.3 inches per year per decade (NOAA, 2014). Meanwhile, more rain is falling in extreme events as the average amount of precipitation in the wettest day of the year has increased by one-fifth of an inch since the 1950s.

Sea level has been increasing steadily in the District area during the past century (11 inches from 1924 to 2013). Sea level rise is of particular concern for the East Coast of the United States since empirical data indicates that sea level is rising nearly three times faster in this region than the global average.

Storm surge, the extreme wind-driven flooding caused by coatal storms, is also of concern. While there are questions regarding how extreme future coastal storms may be – both in terms of intensity and frequency – any increase in sea level rise would have obvious implications for overall flooding during any event – even if storm surge were to remain at current levels.

These trends are consistent with those documented across the greater mid-Atlantic region and the US as a whole. However, the District occupies an interesting position with respect to the geographic boundaries that were developed as part of the 2014 National Climate Assessment (NCA) (Wash et al. 2014). For the NCA, the District straddles the dividing line between the Northeast and the Southeast regions. Across the Northeast, the frequency of heavy precipitation, including both rain and snow events, has increased by 71% from 1958 to 2012, accompanied by an increase in the magnitude of floods (Figure 1; Walsh et al., 2014a). Smaller but consistent increases of +27% have been observed over the same time period throughout the Southeast region. Across the entire US, extreme heat days are becoming more frequent while extreme cold days become less frequent (Walsh et al., 2014a).

Given that the District is located between two regions, DOEE performed detailed downscaling of precipitation and temperature projections for the District. Dr. Katharine Hayhoe of ATMOS Research performed this work as part of the project team. The analysis was developed using a combination of historical observations, global climate model simulations, and high-resolution empirical statistical downscaling models. This downscaling analysis outlines the direction of future trends and, for some indicators, the likely magnitude of the expected changes in temperature and precipitation within a range of scientific and human uncertainty.

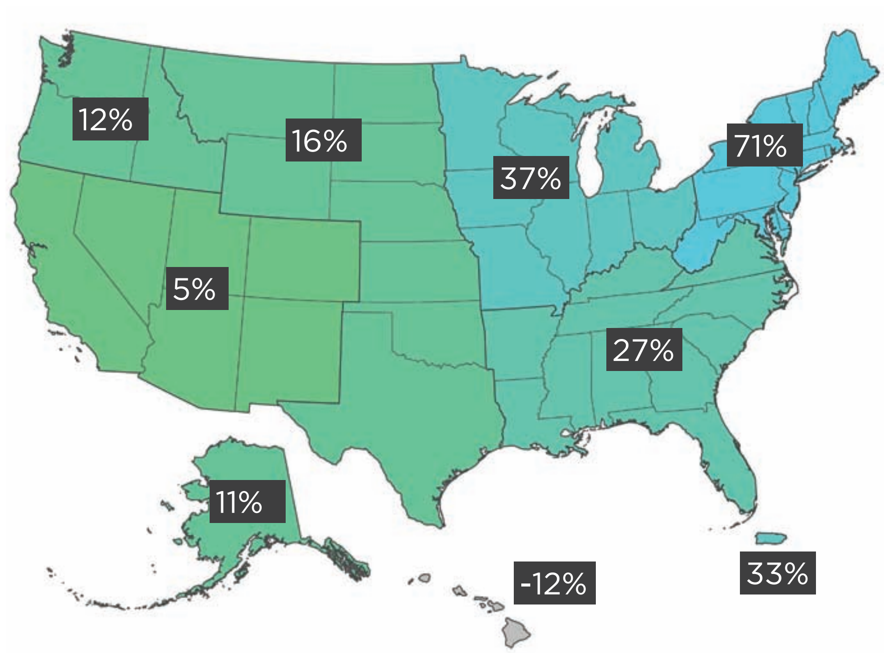


FIGURE 1: Observed change in very heavy precipitation events (defined as the heaviest 1% of all daily events) from 1958 to 2012. The District lies on the divide between the Northeast and the Southeast regions. Source: Walsh et al. 2014a

PLANNING HORIZONS

In order for the Team to develop climate scenarios, it was necessary choose planning horizons.. The planning horizons are the span of years over which the climate change projections will be analyzed. For the District study, three 20-year planning horizons were selected, centered on the decades 2020 (covering 2015-2034), 2050 (covering 2045-2064), and 2080 (covering 2075-2094). For percentile storm projections, a 31-year planning horizon was used to match the methodology used by the District. All future changes are calculated relative to a matching historical reference period centered on 1990 (1981-2000), except for the extreme heat projections, which used a different set of time horizons.

Due to the fact that the observation data sourced from the weather station at Reagan National Airport did not begin to track humidity until 1990, not all of the most extreme heat indicators include humidity. For that reason, the historical reference period used for extreme heat indicators is centered on 2000 (1991-2010).

This 20-year averaging period was carefully selected to balance two competing needs. The first is the need for a shorter period to accurately capture the rate of climate change (too long an averaging period could result in important differences between conditions at the beginning versus the end of the same period). The second is the need for a longer period to reduce the influence of interannual and decadal variability on the long-term mean (too short an averaging period means that projected values could be strongly affected by the variability that arises naturally from the climate system and its cycles, such as El Niño/La Niña and North Atlantic Oscillation.

The 2020s provides a nearer-term target that can be easily incorporated into existing planning horizons, while the 2050s and 2080s provide a longer-term vantage that aligns well with the life expectancy of built infrastructure and a longer-range forecast on shifts in climate. Together, they represent the near-term, mid-term, and longer-term planning horizons most relevant for conducting both the vulnerability assessment and developing the adaptation plan for these time frames.

METHODOLOGY FOR DEVELOPMENT OF FUTURE PROJECTIONS

The second parameter to be determined is the source of the future climate projections used in the assessment. The results of the NACCS report were used to analyze sea level rise and storm surge. Temperature and precipitation projections were derived from Dr. Hayhoe's work and are based on simulations from the most recent generation of Global Climate Models (GCMs) that were used in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment report and the 2014 Third National Climate Assessment. Future projections correspond to the IPCC Representative Concentration Pathways (RCPs) higher (RCP 8.5) and lower (RCP 4.5) scenarios (Figure 2). Under the RCP 8.5 scenario, carbon emissions continue to increase throughout the century, and atmospheric carbon dioxide levels more than triple compared to pre-industrial levels by 2100. Under the RCP 4.5 scenario, carbon emissions peak around mid-century and then decline, while atmospheric carbon dioxide levels approximately double relative to pre-industrial levels by 2100. Global mean temperature changes resulting from these two scenarios range from +4oF (under the lower RCP 4.5 scenario) to +9oF (under the higher RCP 8.5 scenario) by 2100.

Since GCM output cannot resolve fine-scale topography and physical processes that determine the absolute values of temperature and precipitation at the local scale, the GCM output was downscaled using three individual long-term weather stations in the District: Dalecarlia Reservoir, the National Arboretum, and Reagan National Airport (Table 1). This incorporation of local data allows for the translation of the model

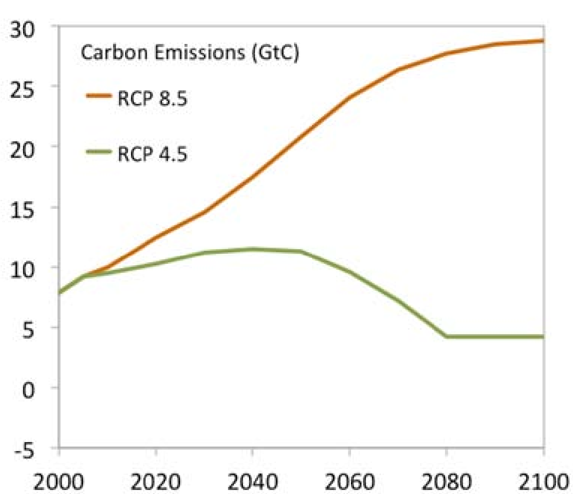


FIGURE 2: Climate change projections for the District corresponding to two scenarios for this study: the higher RCP 8.5 scenario, where human emissions of carbon dioxide and other heat-trapping gases continue to rise, and the lower RCP 4.5 scenario, where emissions peak and then begin to decline by mid-century. This figure compares the carbon emissions corresponding to each scenario.

from a global perspective, to a more local one. Data reported are daily maximum (Tmax) and minmum (Tmin) temperature, 24 hour cumulative precipitation (Pr) and daly maximum and minimum relative humidity (RH). It is important to note that observations and projections of relative humidity and its derived products, such as heat index, were only available for the Reagan Airport location.

For this study, the Team developed projections based on nine GCMs and the RCP 8.5 and 4.5 scenarios, downscaled to three weather stations, for each planning horizon (2020s, 2050s, and 2080s). Together these estimates provide a range of plausible changes in temperature and precipitation that might be expected during the coming century. A detailed description of the climate models, future scenarios, and downscaling methodology is provided in the report, Climate Change Projections for the District of Columbia, included as Appendix 1.

STATION NAME	ID	LOCATION		VARIABLE	LENGTH OF RECORD
DALECARIA RESERVOIR	USC00182325	38.94	-77.11	Tmax, Tmin, Pr	1950-2012
NATIONAL ARBORETUM	USC00186350	38.91	-76.97	Tmax, Tmin, Pr	1950-2012
REAGAN NATIONAL AIRPORT	USW00013743	38.85	-77.03	Tmax, Tmin, Pr, RH	1950-2012

TABLE 1: Weather stations used in this analysis to generate high-resolution climate projections

UNCERTAINTY AND LIKELIHOOD IN CLIMATE CHANGE PROJECTIONS

There is strong scientific consensus that climate change, caused by human activities, is occurring and will accelerate if GHG emissions continue to increase. There is still uncertainty, however in projecting the magnitude of future climate change. The primary drivers of these uncertainties at the global scale can be attributed to: (1) uncertainties in future greenhouse gas levels and other climate drivers which alter the global energy balance, such as aerosols and land-use changes, and (2) uncertainties in how sensitive the climate system, as reflected in the global climate models, will be to greenhouse gas concentrations and other climate drivers. In this assessment, we address these uncertainties by relying on projections corresponding to a higher (RCP 8.5) and lower (RCP 4.5) scenario, based on simulations from nine different GCMs with different levels of sensitivity to carbon dioxide and other climate drivers. However, we acknowledge that actual emissions, and hence atmospheric carbon dioxide levels and global temperature, could rise above the higher scenario (if carbon emissions continue to increase at the rate they have since 2000, for example) or be cut to below the lower scenario (if carbon-free energy solutions are implemented rapidly at the global scale, for example).

For the 2020s, there is no statistically significant difference between the magnitude of climate change projected under a higher scenario as compared to a lower one. This is due to the unlikelihood that a change in human behavior will have a noticeable impact on present trends in climate, due to the inertia of both the climate system and effects of historical human impacts. Climate projections for the 2050s and 2080s, on the other hand, are scenario-dependent. Therefore, projections must be considered separately for the higher and the lower scenarios. Therefore, the vulnerability assessment will depend on the scenarios used for future projections, and the eventual proposed adaptation plan strategies will be preliminary for the 2080s.

At the local to regional scale, climate projections are additionally uncertain due to natural variability (which is much greater at smaller temporal and spatial scales than for national or global averages), selection of weather stations (whether they adequately capture the range of climate variability over the region), and the downscaling method used (since statistical methods will not be able to capture changes in local physical processes that operate at finer scales than the GCMs can simulate, such as the intensification of land/sea breezes during hot summer days).

To address the uncertainty due to natural variability, climate projections have been averaged over 20-year time frames, as described previously, and for individual simulations from nine different GCMs. For the model simulations, this gives a mean value that is similar to averaging over the natural variability of 180 years. This mean value is indicated by the colored lines in the time series plots, while the shaded areas show the range of year-to-year variability in the individual simulations.

For observations, however, we only have one outcome. For certain variables, observations over a 20-year period are still subject to significant natural variability. For example, for the indicator of days with more than 2 inches of rain in 24 hours, the observations include large swings that are evident in the range, but not the average, of nine climate model simulations over the same time period.

To further reduce the uncertainties, projections from three weather stations in the District and one in Virginia were used. Within the scope of this project, however, it is not possible to reduce the uncertainty in downscaling that is associated with a change from relatively stable climate conditions (stationarity) to more fluctuating conditions that are outside the historically observed ranges (non-stationarity). To reduce the stationarity/non-stationarity issue would require the use of an ultra-high-resolution regional climate model. This model and associated simulations, corresponding to multiple scenarios and GCMs, are not currently available at adequate resolution for the latest generation of RCP scenarios and GCMs.

In general, there is greater uncertainty associated with extreme events (e.g. the 1-in-20 year precipitation event or the recurrence of the 2012 heat wave that occurred in the District) than for those events that occur more frequently (e.g. average summer maximum temperature, or days per year with more than 1 inch of precipitation in 24 hours). Uncertainty is also usually greater for precipitation than temperature - particularly at the tails of the distribution. In contrast to temperature, there are few significant differences between the extreme precipitation changes projected under higher as compared to lower future scenarios. In general, however, changes projected by 2080s are usually larger than those projected by 2020s.

Despite the uncertainty inherent in predicting future climate change, these model- and scenario-based projections of future climate can inform long-term planning by providing information on possible future conditions. In some cases that information is qualitative (identifying the existence and/or direction of a trend), while in others it can be quantitative, estimating the difference between a near-term vs. longer-term planning horizon or between the changes expected under a higher vs. a lower future emissions scenario. These scenarios provide baselines of possible future scenarios that can be used to inform preparedness actions including planning and investment decisions.

PHOTO CREDIT: JOHN SONDERMAN . SUSTAINABLE DC, CLIMATE CHANGE PHOTO CONTEST

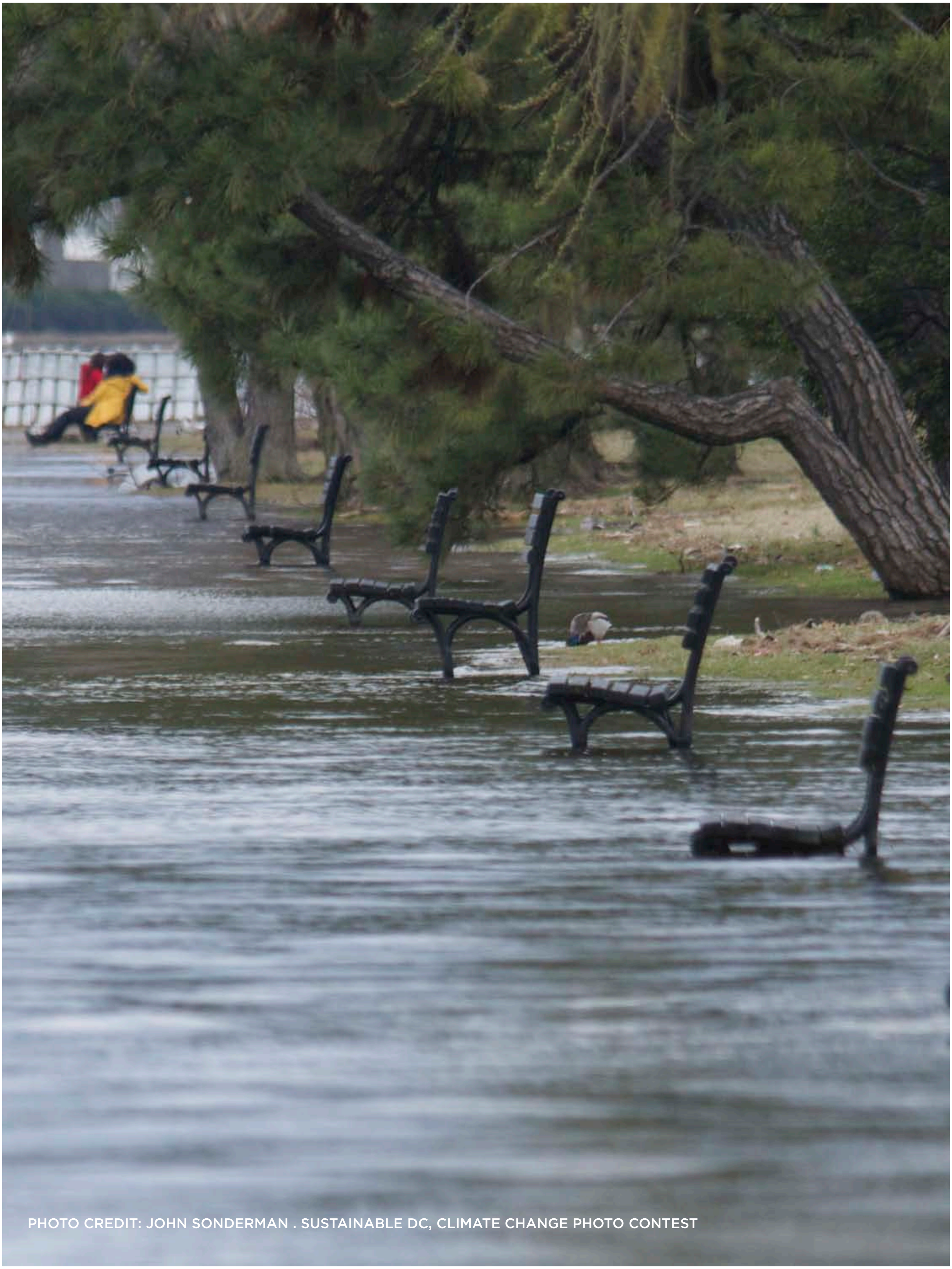


PHOTO CREDIT: JOHN SONDERMAN . SUSTAINABLE DC, CLIMATE CHANGE PHOTO CONTEST

02

CLIMATE CHANGE PROJECTIONS FOR THE DISTRICT

The sections below present key findings from the evaluation of each climate parameter, including temperature, precipitation, storm surge, sea level rise, and extreme weather events. In many cases, especially for temperature, the projections include a range that covers the plausible future scenarios that may occur in the District under predicted climate change conditions. These scenarios provide a sort of stress test for assessing possible impacts to the built environment and social fabric of the District.

TEMPERATURE PROJECTIONS FOR THE 2020s, 2050s, AND 2080s

Over the coming century, average and seasonal temperatures in the District are expected to increase. The District is vulnerable to the adverse health impacts of heat, and will face challenges in the years to come as a result. Both mortality (deaths) and morbidity (e.g., hospital visits or reported illnesses) can be exacerbated by extreme heat. The elderly and those with underlying health conditions such as obesity and diabetes are at greater risk for heat-related illness. (Basu and Samet, 2002). Populations with respiratory or circulatory disease also face greater physiological challenges during extreme or prolonged heatwaves (Anderson and Bell, 2009).

Mean summer temperature projections are based on simulations for all three weather stations described in Table 1. For baseline conditions (1981-2000), summer daytime maximum temperatures average around 87°F and nighttime minimum temperatures average around 66oF. The magnitude of projected change is similar for both daytime and nighttime temperatures with values increasing 2.5-3°F by the 2020s, 5-7°F by the 2050s, and as much as 6-10oF by the 2080s, depending on which scenario is used (Figure 3). Lower nighttime temperatures are important during a heatwave from a public health perspective because of the relative relief from high daytime temperatures. As minimum nighttime temperatures increase, there is less relief and higher likelihood of heat-related illnesses.

A threshold of 95°F was chosen as the indicator of extreme temperature as the District's Heat Emergency Plan is activated and cooling centers are opened when either the actual temperature or the heat index reaches 95°F. The number of days per year with maximum air temperature greater than 95°F historically averages 11 days per year. Projections indicate an increase to 18-21 days by the 2020s. By the 2050s, the number of days is expected to increase to between 30 and 45, depending on whether projections correspond to the lower or higher scenario. By the 2080s, the number of days above 95°F could average around 40 days under the lower and 70 days per year under the higher scenario, respectively (Figure 4).

A critical measure for temperature is the heat index, which combines ambient air temperature and relative humidity to determine what the temperature feels like to the human body. For the baseline period (1981-2000), there are 29 days per year with a heat index over 95°F. By the 2020s, there are expected to be around 50 such days. By the 2050s, there may be 70 to 80 such days and by the 2080s, the number of days with heat index at or exceeding 95°F could average around 70 under the lower scenario and 105 under the higher.

Heat waves, defined as three or more consecutive days with a daily maximum heat index value above 95°F, are also likely to be more frequent and last longer. According to this definition, historically there has been anywhere from 0 to 8 heat waves per year, averaging 4 heat waves per year over the period 1991-2010. The average number of heat waves per year is expected to rise to 6 events by the 2020s, 7 events per year by the 2050s, and 8 events by the 2080s. The

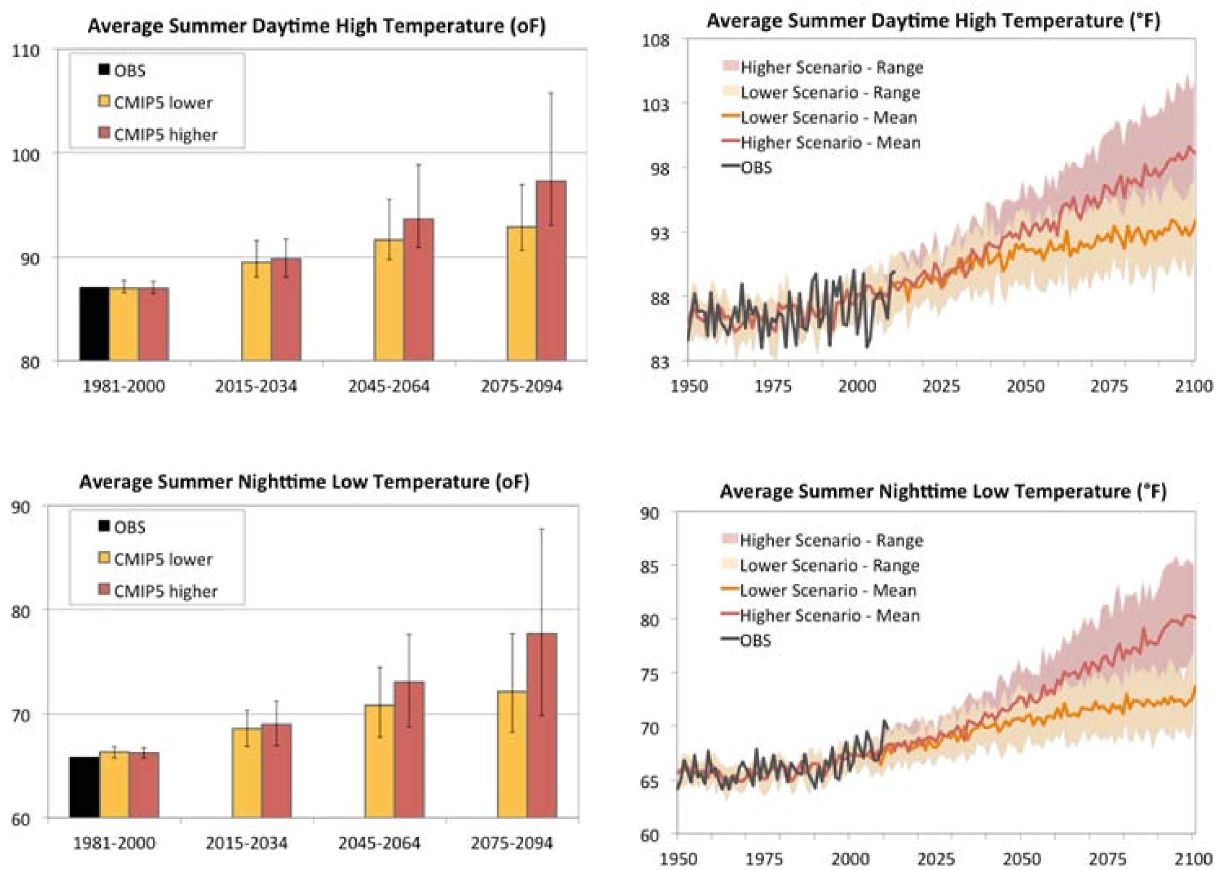


FIGURE 3: Historical and projected summer (Jun-Jul-Aug) (a) average daytime maximum or high and (b) average nighttime minimum or low temperature averaged across the three weather stations used in this analysis under higher (red) and lower (orange) future emission scenarios.

For the bar charts, the uncertainty range, indicated by the thin vertical lines above and below each bar, encompasses the range of projections from the nine different global climate models used in this analysis.

For the time series plots, the solid line indicates the multi-model average for each year while the shaded range encompasses the range of projections from the nine different global climate models.

In each plot, the black bar or line indicates observed values.
(Source: ATMOS, May 2015. See Attachment 1)

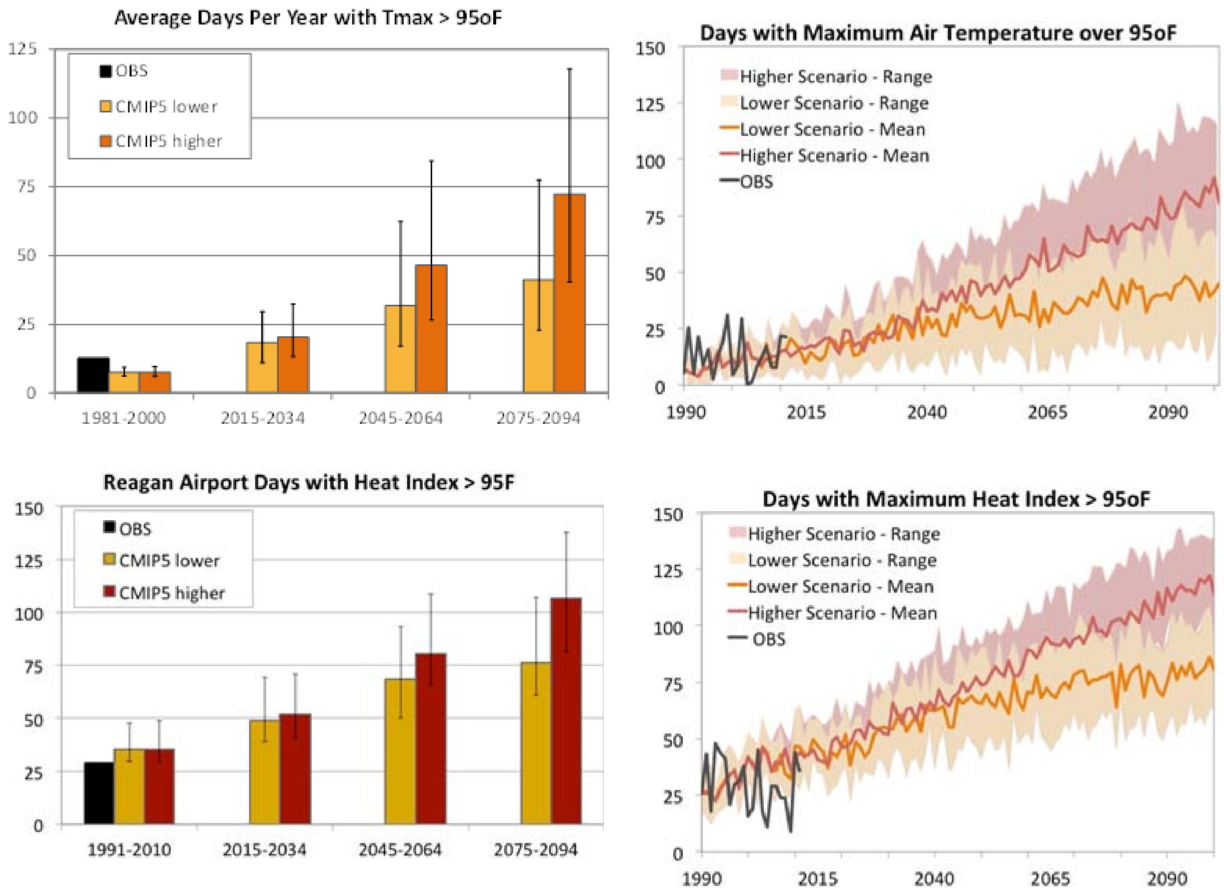


FIGURE 4: Observed (black) and projected future days per year with (a) daytime maximum air temperature (averaged over all three weather stations) and (b) daytime maximum heat index over 95oF (for the Washington Reagan National Airport station only, since the other weather stations do not have the relative humidity observations required to calculate heat index) under higher (orange) and lower (yellow) future scenarios. 1990 is the first date of relative humidity observations at Washington Reagan National Airport.

For the bar charts, the uncertainty range, indicated by the thin vertical lines above and below each bar, encompasses the range of projections from the nine different global climate models used in this analysis. Each coloured bar represents the average of 180 years of simulations, while each black bar represents the average of 20 years of observations.

For the time series plots, the solid coloured lines indicates the multi-model average for each year while the shaded range encompasses the range of projections from the nine different global climate models. The solid black line indicates the single annual value for observations that year. As such, the black line is much more similar to the shaded range (which shows year to year values) rather than the coloured lines (which average across 9 model-years).

The primary reason for differences between the observed and multi-model mean values for the historical period is the lack of data in the historical observed record (beginning at 1990 only).
(Source: ATMOS, May 2015. See Attachment 1)

duration of these heat waves is also expected to increase. Historically, the average heat wave has lasted between 4 and 10 days, with the average a little less than 5 days. Future projections suggest heat waves will average around 6 days by the 2020s, between 8 and 9.5 days by the 2050s, and between 9.5 and 12 days by the 2080s, depending on the scenario used. Although the number of events is slightly greater under the higher as compared to the lower scenario, in contrast to projected changes in the days per year exceeding a heat index of 95°F, there is not a large difference between scenarios for this indicator. In contrast, there is a noticeable difference in the length of the heat waves between the higher and the lower scenario. This suggests that the frequency of the weather patterns that bring heat waves to the region is not likely to differ much between the scenarios (i.e., although extreme heat days may become more common under the higher as compared to the lower scenario, the frequency of such multi-day events may not differ much), but these weather patterns may last longer, bringing more extended heat waves, under the higher as compared to the lower scenario.

In 2012, the District experienced a record-breaking heat wave event lasting more than 11 days. Temperatures met or exceeded 95°F for 11 straight days, topping 100°F on 5 of those days. Based on historical data, which included daytime maximum and nighttime minimum temperatures (see Appendix 1 for more detail), there is a 66% chance of a similar heat wave to the one that occurred in 2012 occurring every 10 years by the 2020s. By the 2050s, there could be between 0.4 (under lower) and 1 (under higher) events each year (with a high degree of uncertainty, since this is such a rare event), and by the 2080s, the number of these events is

Years	Average Summer Offensive Days	% of Total Summer Days
1942 to 1951	7.6	8.30%
1952 to 1961	9.7	10.50%
1962 to 1971	7.4	8.00%
1972 to 1981	13.9	15.10%
1982 to 1991	14.4	15.70%
1992 to 2001	15.6	17.00%
2002 to 2011	16.2	17.60%

TABLE 2: Summer days in the District with offensive, dangerous air masses present. (Source: DOEE/Global Cool Cities Alliance, Urban Heat Island Mitigation Study. 2013)

projected to be average between 0.8 and 2.8 events per year, depending on the scenario used. A more detailed explanation of the method used to determine this probability is included in Appendix 2.

Another measure of extreme temperature can be assessed through the overall mortality aspects associated with these types of events. Offensive summer days (days when the District experiences air mass types that impact daily mortality; Kalkstein et al. 2013) have also increased significantly from the 1940s to present day (Table 2). Increasing temperatures will likely contribute to a further increase in offensive summer days, with serious public health implications.

All of these challenges become exacerbated in urban areas because of the urban heat island (UHI) effect. The UHI effect occurs in areas where the building materials are more prone to absorb and retain heat (e.g., black pavement, dark-colored roofs) as opposed to areas that are covered by vegetation, shaded beneath tree canopies or comprised of lighter-colored materials. Land use and carefully considered design criteria play important roles in mitigating these impacts.

PRECIPITATION PROJECTIONS FOR THE 2020s, 2050s, AND 2080s

The District currently receives an average of 10 days per year with greater than 1 inch of rain in a given 24-hour period, and an average of 1 day per year with greater than 2 inches of rain in a given 24-hour period. By the 2020s, the number of days per year with more than 1 inch of rainfall per 24-hour period is expected to be 11 days. That number is projected to increase to 12 days by the 2050s and 13 days by the 2080s. The number of days per year with more than 2 inches of rainfall per 24-hour period is expected to increase to 3 days per year by the 2020s, an average of 3.5 days per year by the 2050s, and between 3.5 to 4.5 days per year by the 2080s.(See Figure 5).

Changes in rainfall volumes have a significant impact on drainage infrastructure. Design storms are the selected events that engineers use as baselines to inform their calculations for drainage structures such as sewer pipes and culverts. Up until recently, engineers could rely on past events to determine what a "typical" 10-year 24-hour storm event would look like. Climate change has produced new and different types of storms that behave differently than those of the past. This means that new design storms have to be calculated to allow engineers to adequately size the drainage structures, including not only pipes but features such as rain gardens and bioswales.

Design storms are estimated based on specified exceedance probabilities, i.e., the likelihood that a particular rainfall depth will be equalled or exceeded in any given year (over the long term). The recurrence interval for a design storm is the reciprocal of its exceedance probability. For instance, the definition of a "10-year storm" is a storm that has a 10% probability of its rainfall amount being equaled or exceeded in any given year, the definition of a "25-year storm" is one that has a 4% exceedance probability and the definition of a "100-year storm" is one that has a 1% exceedance probability.

Estimating rainfall depths associated with design storms for future planning horizons is important since historical precipitation patterns are already changing, and projected to further change in terms of both intensity and frequency. Therefore, new construction projects designed to alleviate flooding and/or upgrades to existing stormwater and wastewater infrastructure to mitigate flooding impacts need to be evaluated in terms of future projected rainfall trends.

One objective of this project was to identify needed changes to infrastructure in the District as a response to climate change. DOEE gathered input on the extreme precipitation parameters from DC Water, the District Department of Transportation, and DOEE's Stormwater Management Division as informed by their current use and applicability in informing design standards for stormwater, wastewater, and transportation infrastructure. The projected rainfall depths associated with the chosen design storm are summarized in Table 3.

The 80th, 90th, and 95th percentile events are also projected to increase in each of the time horizons evaluated. These percentile events are used to determine the amount of stormwater that development projects

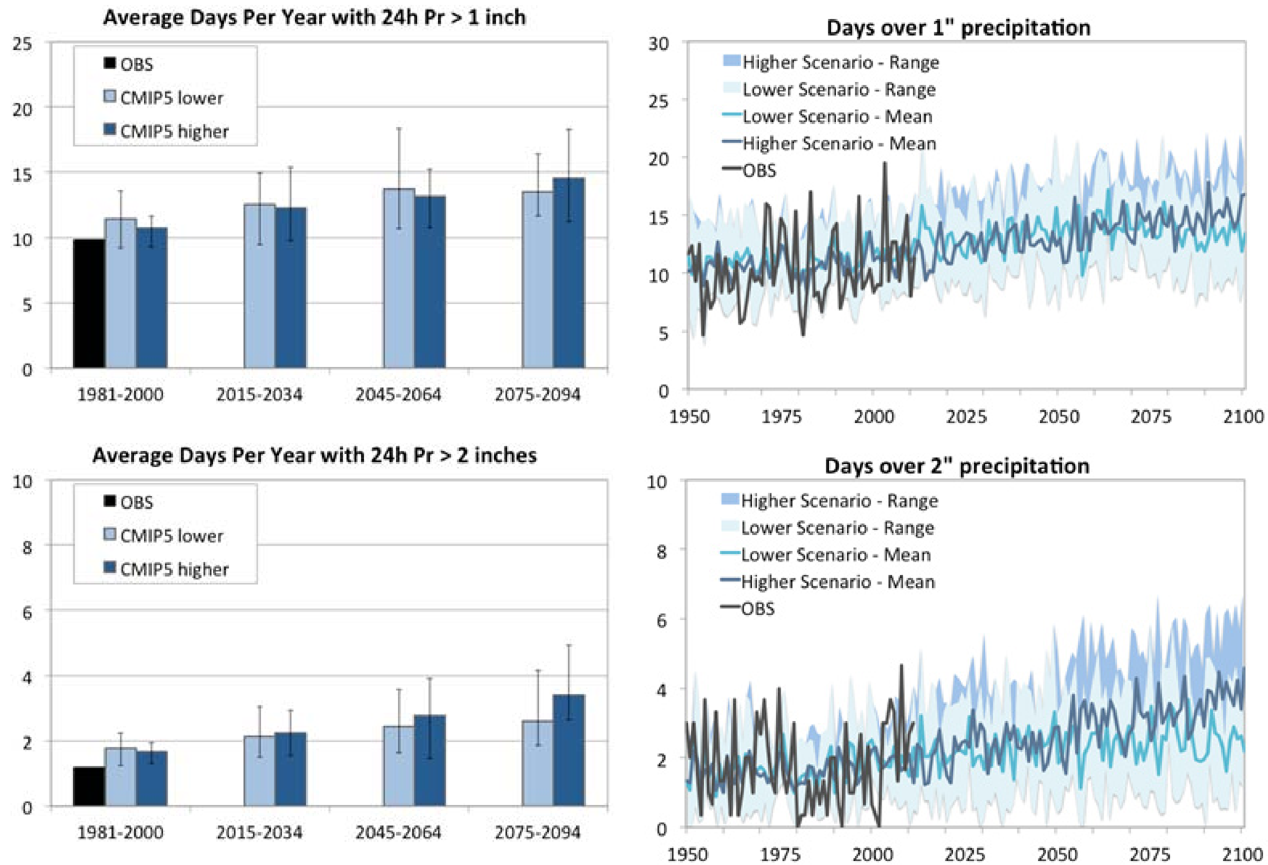


FIGURE 5: Number of days per year with more than 1" (top) and 2" (bottom) of precipitation in 24h. Values are averaged across the three weather stations used in this analysis under higher (dark blue) and lower (light blue) future scenarios.

For the bar charts, the uncertainty range, indicated by the thin vertical lines above and below each bar, encompasses the range of projections from the nine different global climate models used in this analysis. Each coloured bar represents the average of 180 years of simulations, while each black bar represents the average of 20 years of observations.

For the time series plots, the solid coloured lines indicates the multi-model average for each year while the shaded range encompasses the range of projections from the nine different global climate models. The solid black line indicates the single annual value for observations that year. As such, the black line is much more similar to the shaded range (which shows year to year values) rather than the coloured lines (which average across 9 model-years).

It is important to note in this figure that, by chance, the historical period 1981-2000 encompasses the lowest part of the historical range of days per year with more than 2 inches of precipitation in 24 hours. This is reflected by the fact that the model observations, downscaled using the full 60-year record, are higher than observed for the historical period.
(Source: ATMOS, May 2015. See Attachment 1)

Serial No.	Precipitation Indicator	Baseline 1981-2000	2015-2034 (2020s)	2045-2064 (2050s)	2080s
1	# of days/year with rainfall at or above 1 in	10	12 (10 – 15)	13 (11 – 18)	14 (12 – 18)
2	# of days/year with rainfall at or above 2 in	1	1.5 (1 – 2)	2 (1 – 3)	3 (2 -5)
3	1-yr 24 hr. storm (in)	1.6	1.7 (1.5 - 1.8)	1.7 (1.5 - 1.8)	2 (±<1)
4	2-yr 24 hr. storm (in)	3.2	3.4 (3.2 - 3.7)	3.7 (3.5 - 3.9)	4 (4 - 5)
5	15-yr 24 hr. storm (in)	5.5	6.8 (6.0 - 7.3)	7.1 (6.7 - 7.6)	8 (4 - 9)
6	25-yr 24 hr. storm (in)	6.3	7.9 (6.8 - 8.6)	8 (7.5 - 8.8)	10 (8 - 12)
7	100-yr 24 hr. storm (in)	8.1	10.5 (8.9 - 12.4)	10.3 (9.0 - 11.9)	14 (10 - 16)
8	200-yr 24 hr. storm (in)	9	12 (10.1 - 14.7)	11.7 (9.8 - 13.6)	16 (11 - 19)
9	2-yr 6 hr. storm (in)	2.3	2.4 (±<0.1)	2.6 (2.6 - 2.7)	3 (±<1)
10	15-yr 6 hr. storm (in)	3.6	4.6 (4.3 - 4.8)	4.7 (4.6 - 4.8)	5 (4 - 6)
11	100-yr 6 hr. storm (in)	5.1	6.7 (6.5 - 6.8)	6.5 (6.4 - 6.7)	9 (7 - 10)
12	200-yr 6 hr. storm (in)	5.6	7.5 (7.2 - 7.7)	7.2 (±<0.1)	10 (8 - 11)
13	80th Percentile storm (in)	0.8	0.9 (0.1)	0.9 (0.1)	0.95 (0.1-0.15)
14	90th Percentile storm (in)	1.14	1.24 (0.1)	1.24 – 1.34 (0.1-0.2)	1.24 – 1.39 (0.1-0.25)
15	95th Percentile storm (in)	1.5	1.6 – 1.65 (0.1-0.15)	1.6 – 1.75 (0.1-0.25)	1.75 – 1.85 (0.15-0.35)

TABLE 3: Table of precipitation indicators. Ranges of indicators are shown in parentheses. Results in Serial Numbers 3 through 12 are averages of projections for Dalecarlia and the National Arboretum weather stations (Reagan excluded), and ranges shown are representative of the median for upper (RCP 8.5) and lower (RCP 4.5) projections. (Source: ATMOS study- Appendix 1-- and Kleinfelder analysis; please refer to Appendix 2 for methodology for design storms.)

must retain under the District's 2013 Rule on Stormwater Management and Soil Erosion and Sediment Control.

The 80th, 90th, and 95th percentile values were calculated based on 31-year periods to match the methodology currently in use by the District to define historical thresholds. The minor differences between existing values used by the District and the ones calculated for the baseline in Table 4 can be attributed to slight differences in data screening and calculation methods and are considered reasonably close in value for the purposes of this study. Small but consistent increases are projected in the amount of precipitation falling in the 80th, 90th, and 95th percentile of events in each future 20-year period. For the 80th percentile event, increases of only a tenth of an inch are projected by end of century. For the 90th percentile, increases of 0.1 inch are expected by the 2020s, 0.1-0.2 inch by the 2050s and 0.1-0.25 inch by the 2080s, with slightly greater increases under the higher scenario. Slightly greater increases (from +0.05 to +0.1 inch more) are projected for the 95th percentile event.

Calculations of design storms based on "present" model output (1981 to 2000) were compared to NOAA Atlas 14 point precipitation frequency estimates for each of the stations used. The Atlas is produced by the National Weather Service and provides precipitation frequency estimates per region. Based on that comparison, it was determined that only two stations out of the three (Dalecarlia Reservoir and National Arboretum) were suitable to calculate design storms for future projections. The omission of design storm data from one station (Reagan National Airport) provides a better fit to current design storm criteria. With the exception of 1-year 24-hour design storms for both the National Arboretum and Dalecarlia, our design storm calculations for "present" (1981-2000) modeled precipitation are within the expected range of Atlas 14 values (Table 4).

Table 4 shows that for the 24-hour duration storms, the design storm depths by the end of the century are expected to increase by approximately 11% for the 1-year events, 32% for the 2-year events, 39% for the 15-year events, 60% for the 25-year events, 66% for the 100-year events, and 72% for the 200-year events. For the 6-hour duration storms, those numbers are expected to increase by approximately 32% for the 2-year event, 39% for the 15-year event, 67% for the 100-year event, and 73% for the 200-year event by the end of the century. Bar charts showing comparisons of 24-hour and 6-hour design storms for each planning horizon are provided in Figure 6 (below).

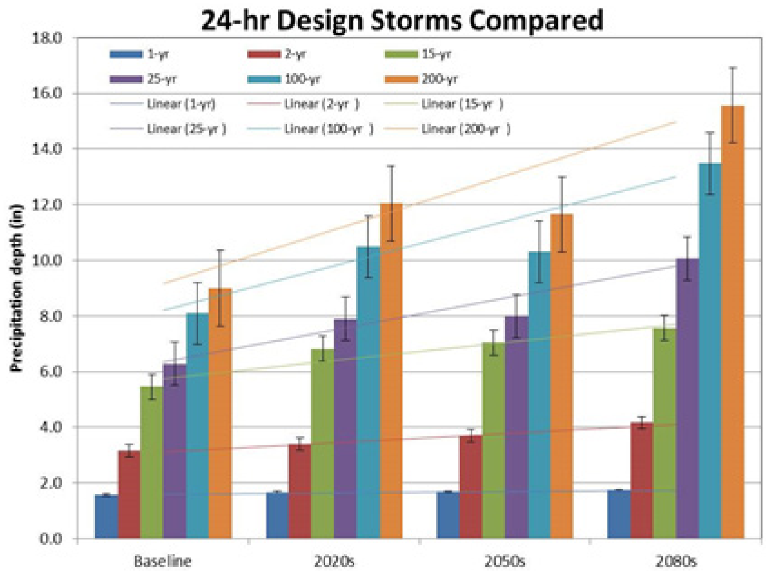
DALECARLIA RESERVOIR

	Atlas 14	Atlas 14 Bounds	Present (1981-2000)	2020s (2015-2034)	2050s (2045-2064)	2080s (2065-2094)
1 yr.	2.63	2.40-2.92	1.66	1.68	1.73	1.73
2 yr.	3.18	2.90-3.53	3.23	3.42	3.73	4.15
15 yr.	5.27	unavailable	5.40	6.49	6.95	6.17
25 yr.	6.11	5.49-6.72	6.10	7.62	7.85	9.00
100 yr.	8.43	7.44-9.20	7.77	10.27	10.15	11.69
200 yr.	9.83	8.59-10.70	8.66	11.68	11.62	12.96

NATIONAL ARBORETUM

	Atlas 14	Atlas 14 Bounds	Present (1981-2000)	2020s (2015-2034)	2050s (2045-2064)	2080s (2065-2094)
1 yr.	2.61	2.37-2.90	1.48	1.65	1.63	1.75
2 yr.	3.15	2.87-3.50	3.10	3.38	3.66	4.19
15 yr.	5.23	unavailable	5.50	7.16	7.15	8.97
25 yr.	6.06	5.43-6.67	6.45	8.17	8.17	11.14
100 yr.	8.36	7.37-9.13	8.43	10.69	10.47	15.26
200 yr.	9.75	8.50-10.60	9.33	12.41	11.68	18.16

TABLE 4: Table of calculated 24-hour design storms for present, 2020s, 2050s, and 2080s compared to NOAA Atlas 14.



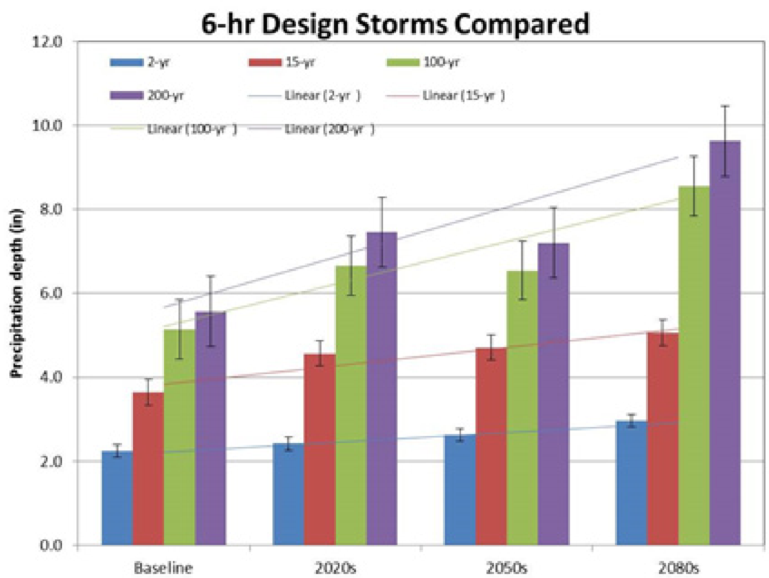


FIGURE 6: Bar charts compare 24-hour (left) and 6-hour (right) design storms for each of the planning horizons (Baseline [1981-2000], 2020s, 2050s, and 2080s). Values shown on the bar charts are the averages of the Dalecarlia and the National Arboretum stations. Trend lines are displayed for each planning horizon to show. (Source: Kleinfelder, 2015)

INTERIOR FLOODING HAZARDS

Due to its location at the confluence of two tidally influenced rivers, the District is influenced by three primary types of flooding: interior (inland drainage), riverine and coastal. Different storm events will result in various combinations of flooding – some resulting in more inland impacts, while others may be more coastally influenced. It is interesting to note that storm surge has the potential to turn drainage outlets into inlets with the potential for causing flooding miles away from the coast as it travels through the piped infrastructure and surfaces in remote, interior sections. Table 5 summarizes major historical flooding events in the District dating back to 1889.

The Federal Emergency Management Agency (FEMA) updated its Flood Insurance Rate Maps (FIRMs) for Washington, DC in 2010. FIRMs were issued for 100-year (1%) and 500-year (0.2%) recurrence intervals. FIRMs are based on historical data (up to 2003) and account for both riverine and tidal flooding (Figure 8). Flood inundation estimates were developed with the Hydrologic Engineering Center-River Analysis System (HEC-RAS) computational model to obtain backwater elevations using flood frequency inputs, and created as follows:

- Flood frequencies for nontidal river segments were based upon frequency analysis at nontidal gauges.
- Flood frequencies for tidal river segments were based upon gauges in the tidal portions.
- Flood frequencies for ungauged river segments and watersheds were based upon rainfall-runoff relationships or regression equations. It was not reported how flood frequencies were determined in the tidal portions of ungauged streams.

NOAA tidal gauge 8594900 is an important data source due to its location near the confluence with the Potomac and Anacostia Rivers. Data from this gauge was used to correlate flood frequencies and tidal elevation for both rivers (FEMA, 2010). Tidal gauge 8594900 data was also used for sea level rise projections in this study.

Current FEMA flood mapping is based on riverine modeling with historical flood frequency inputs, and does not account for potential future effects of climate change. For example, if FEMA riverine modeling inputs were revised to account for 100-year, 24-hour precipitation projections, then projected 100-year flood depths and extents would increase relative to current estimates.

There are historic precedents for similar events. In June 2006, 6 inches of rain fell in a 6 hour period, which is comparable to the 200-year, 6-hour storm event as shown in Table 3. The event caused extensive flooding in the Federal Triangle Area. As captured in Figure 7, several Federal buildings were damaged and businesses were interrupted as a result of inundation of two DC Metro train stations that were inaccessible for several hours.

EVENT DATE	TYPE OF EVENT	DESCRIPTION
February 18, 1889	Ice Jam, Potomac River	$55,000 damages.
June 1-2, 1889	Flood, Potomac RiverBasin	--
March 28-30, 1924	Snowmelt and intense rainfall runoff, Potomac, River Basin	5 Deaths, $4 million in damage. .
May 12-14, 1924	Rainfall	Greatest damage since flood of 1889.
23-Aug-33	Tidal Surge	Chesapeake-Potomac Hurricane of 1933.
March 17-19, 1936	Thick Ice, Snowmelt and intense rainfall runoff, Potomac River Basin	Greatest flood since 1889. Exceeded flood of May 1924.
April 25-28, 1937	Rainfall	Third Largest flood after 1936 and 1889. Comparable to May 1924.
October 13-17, 1942	Flood from extended rainfall	Potomac River Stage at Washington 0.3 ft. higher than in 1936.
August 12-13, 1955	Flood, Rock Creek, Potomac, Anacostia River Basins	Hurricanes Connie and Diane.
June 21-23, 1972	Flood, Rock Creek	Hurricane Agnes
September 5-6, 1979	Flood Rock Creek	Hurricane David, $374,000 in damage
November 4-7, 1985	Flood, Potomac River Basin	Hurricane Juan combined with stationary front. $9 million damage along C&O canal and $113 million along Potomac.
5-May-89	Flood	Three people killed, hundreds of homes and businesses destroyed.
January 19-21, 1996	Snowmelt Flood	Fifth highest flood on official record.
September 6-8, 1996	Flood, Potomac River	Hurricane Fran, flooding similar to Hurricane Juan.
11-Aug-01	Flash Flood, Rock Creek	Rock Creek discharge at Sherrill Drive gauge about 1.5 times the 100-year discharge.
September 18-19, 2003	Flood, Potomac, Anacostia River Basins	Hurricane Isabel. Caused a system malfunction in the 14th Street pumping station. The incident closed 395 in both directions for 48 hours. $125 million in property damages.
June 22-23, 2006	Rainfall	Localized flooding throughout region damaged major Federal buildings. $10 million in damages.

TABLE 5: Major historical flooding events in the District (Source: District of Columbia Multi-Hazard Mitigation Plan, December 2007)

Figure 9 shows known vulnerable flooding areas identified by key stakeholders for this study. These include vulnerable Washington Metro Area Transit Authority (WMATA) assets (WMATA stations with flooding issues), repetitive loss properties (i.e. areas of recurrent flooding) in the National Flood Insurance Program (NFIP) database as well as neighborhoods with historic flooding—such as Palisades. The map also documents high-risk storm drain sites according to the 2010 DC Multi-Hazard Mitigation Plan. There are other known flood risks indicated on the map including the Federal Triangle area of downtown (Greeley and Hansen, 2011) and the low capacity storm/sewer system identified by the Bloomingdale LeDroit Park study (Mayor's Task Force, DC, 2012). Further analyses and modeling of the flood risk in these areas would translate the projected extreme rain into flooding impacts (i.e. expected depth and extent of flooding).

FIGURE 7: Flooding of Federal Triangle Area from the June 24-26, 2006 storm (Federal Triangle Stormwater Drainage Study, Greeley and Hansen, 2011)

FEMA FLOOD AREAS

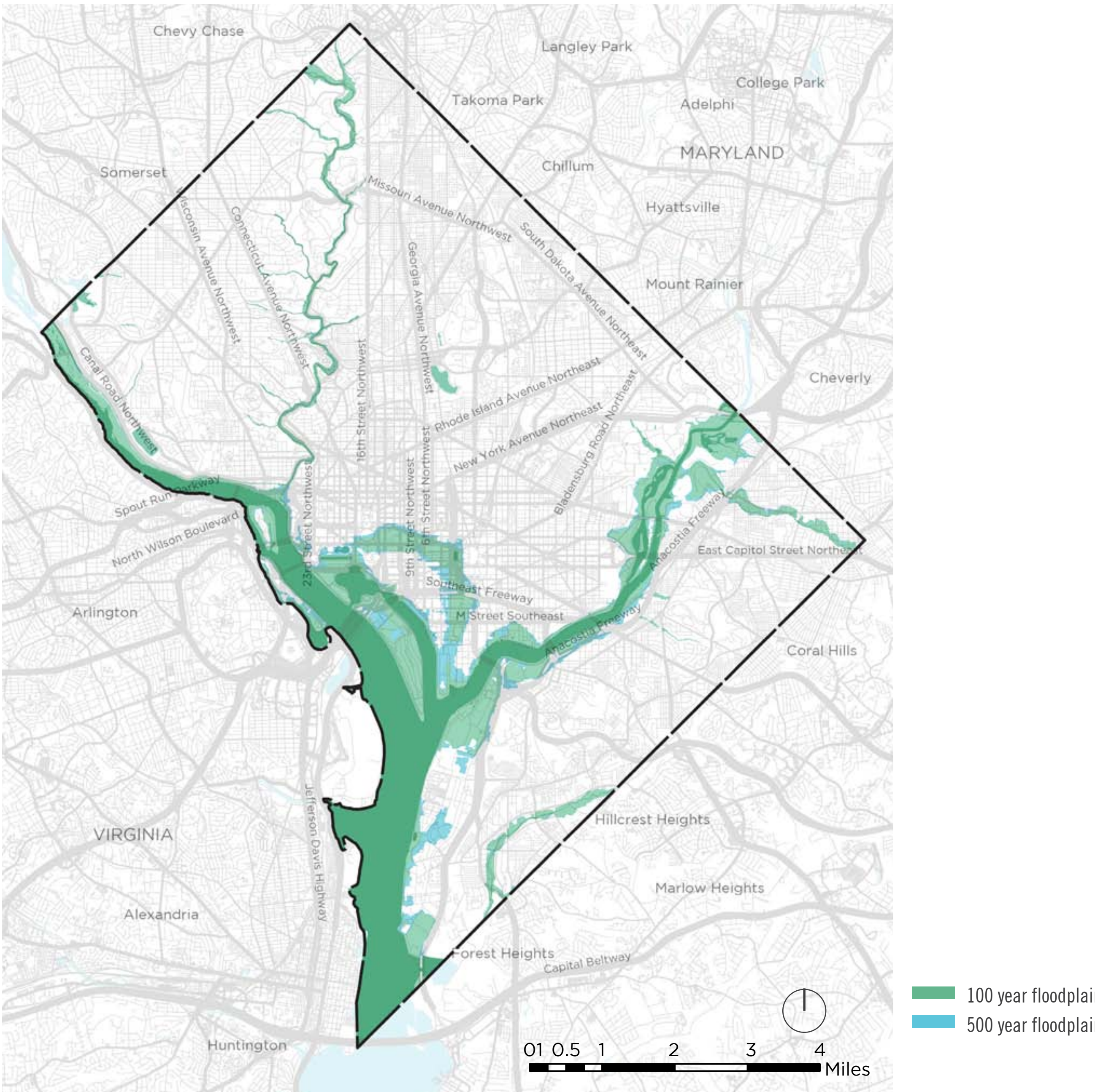


FIGURE 8: FEMA flood insurance rate maps, 100-yr and 500-yr Floods (FEMA map overlaid on GIS map base, Kleinfelder, 2015)

HISTORIC FLOOD AREAS

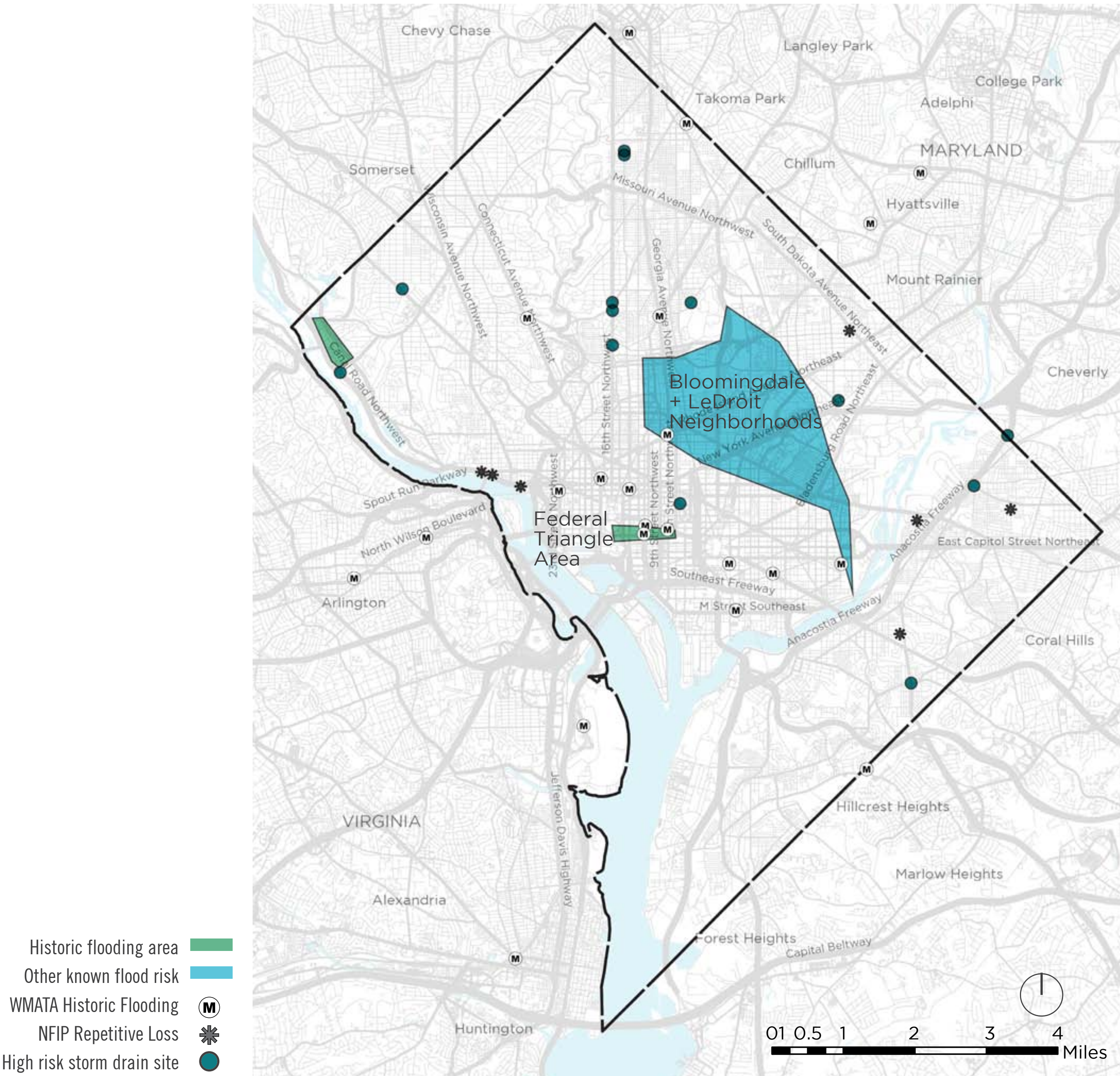


FIGURE 9: Historical flooding areas in Washington, DC (Source: Kleinfleder as indentified by stakeholders, November 2014)

SEA LEVEL RISE PROJECTIONS FOR THE DISTRICT

Over the past century, sea levels have been rising as a result of climate change. Oceans have warmed causing their volumes to expand, and glaciers and land-based ice have melted contributing additional fresh water to the oceans' volumes, resulting in global sea level rise (GSLR). The estimated long-term rate of GSLR is 1.7 mm/year (0.065 in/year) (USACE, 2013). Relative sea level rise (RSLR) in the District area has been higher than GSLR because the local landmass in the region has been sinking as the result of long-term geological processes, known as land subsidence. Sea level rise is expected to continue, and even accelerate in the future due to climate change. In fact, there may be some evidence of this as Church et al (2013) reports that the average annual rate from 1993 to 2012 is 3.2 mm/year, nearly double the long-term rate. Figure 10 shows historical RSLR observed on the District waterfront (NOAA gauge 8594900 in Washington Channel, source: NOAA, http://tidesandcurrents.noaa.gov). Average RSLR at this location from 1924 to 2013 is 3.2 mm/year (0.125 in/year), with a total RSLR of 11 inches during this period. Local land subsidence in Washington is estimated as the difference between local RSLR and long-term GSLR, or 1.5 mm/year (0.060 in/year). This has resulted in a more than 300% increase in the incidence of nuisance flooding in the District in the last 90 years (NOAA, 2014).

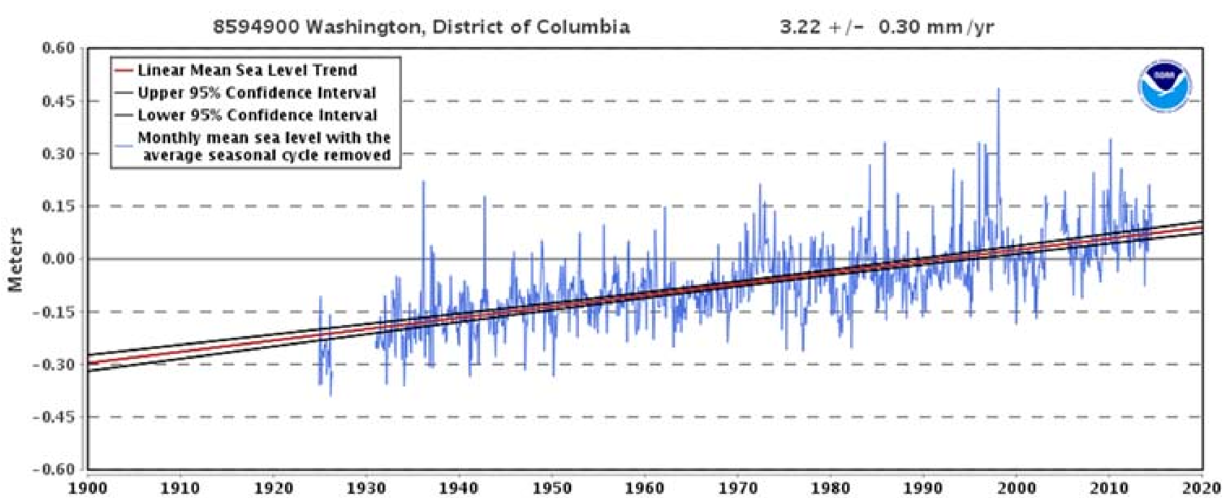


FIGURE 10: Relative Sea Level Rise (RSLR) at Washington, DC waterfront. NOAA gauge 8594900 in Washington Channel. (Source: http://tidesandcurrents.noaa.gov)

RSLR has been projected up to the year 2100 from the baseline years of 1992 and 2014. The projections are based on the high, intermediate, and low scenarios for RSLR estimated by the USACE (USACE, 2014). The USACE RSLR projections were presented in the recent USACE North Atlantic Coast Comprehensive Study (NACCS, 2015). USACE RSLR scenarios are based on the following:

- High – sea level rise projections due to polar and glacial ice loss, and ocean warming
- Intermediate – sea level rise projections due to ocean warming only
- Low – sea level rise projections based on linear extrapolation of historical rates

Estimates of RSLR on the District waterfront from 2018 through 2100 are listed in Table 6 for base year 1992 and Table 7 for base year 2014. RSLR projections for base year 2014 are also presented graphically in Figure 11. The RSLR is projected to increase by 0.2 feet by 2020, 1.4 ft. by 2050 and by 3.4 ft. by 2080 according to the USACE high scenario and base year 2014. Figure 12 shows RSLR inundation mapping for the high scenario for years 2018, 2068, and 2100.

The NACSS also presented the US National Oceanic and Atmospheric Administration (NOAA) high scenario from an earlier study for comparison purposes (NOAA, 2012). This scenario projects higher RSLR than the USACE high scenario. For the purpose of this study, the NACCS /USACE projections have been adopted as providing the most recent and comprehensive projections.

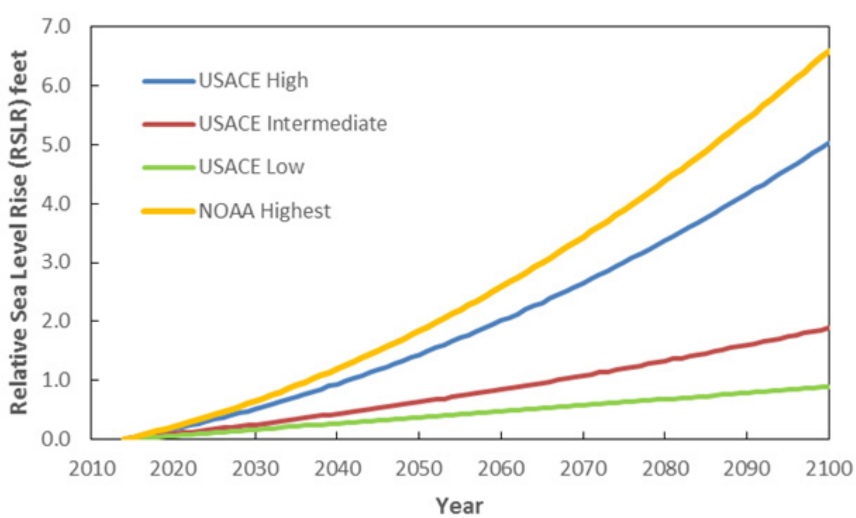


FIGURE 11: USACE “High”, “Intermediate,” and “Low” scenario projections for relative SLR in Washington, DC (2018-2100) from base year of 2014 (Source: USACE 2014)

Total Relative Sea Level Rise (RSLR) – feet from 1992	2018	2020	2050	2068	2080	2100
USACE High Scenario	0.5	0.6	1.9	2.9	3.8	5.4
USACE Intermediate Scenario	0.3	0.4	0.9	1.3	1.6	2.2
USACE Low Scenario	0.3	0.3	0.6	0.8	0.9	1.1

TABLE 6: USACE High, Intermediate, and Low scenario projections for relative SLR in Washington, DC (2018-2100) from base year of 1992[1]

Total Relative Sea Level Rise (RSLR) – feet from 2014	2018	2020	2050	2068	2080	2100
USACE High Scenario	0.1	0.2	1.4	2.5	3.4	5.0
USACE Intermediate Scenario	0.1	0.1	0.6	1.0	1.3	1.9
USACE Low Scenario	0.0	0.1	0.4	0.6	0.7	0.9

TABLE 7: USACE High, Intermediate and Low scenario projections for relative SLR in Washington, DC (2018-2100) from base year of 2014[2] (Source: USACE, 2014)

1. According to USACE (www.corpsclimate.us/ccaceslcurves.cfm)
2. According to USACE (www.corpsclimate.us/ccaceslcurves.cfm)

PROJECTED SEA-LEVEL-RISE

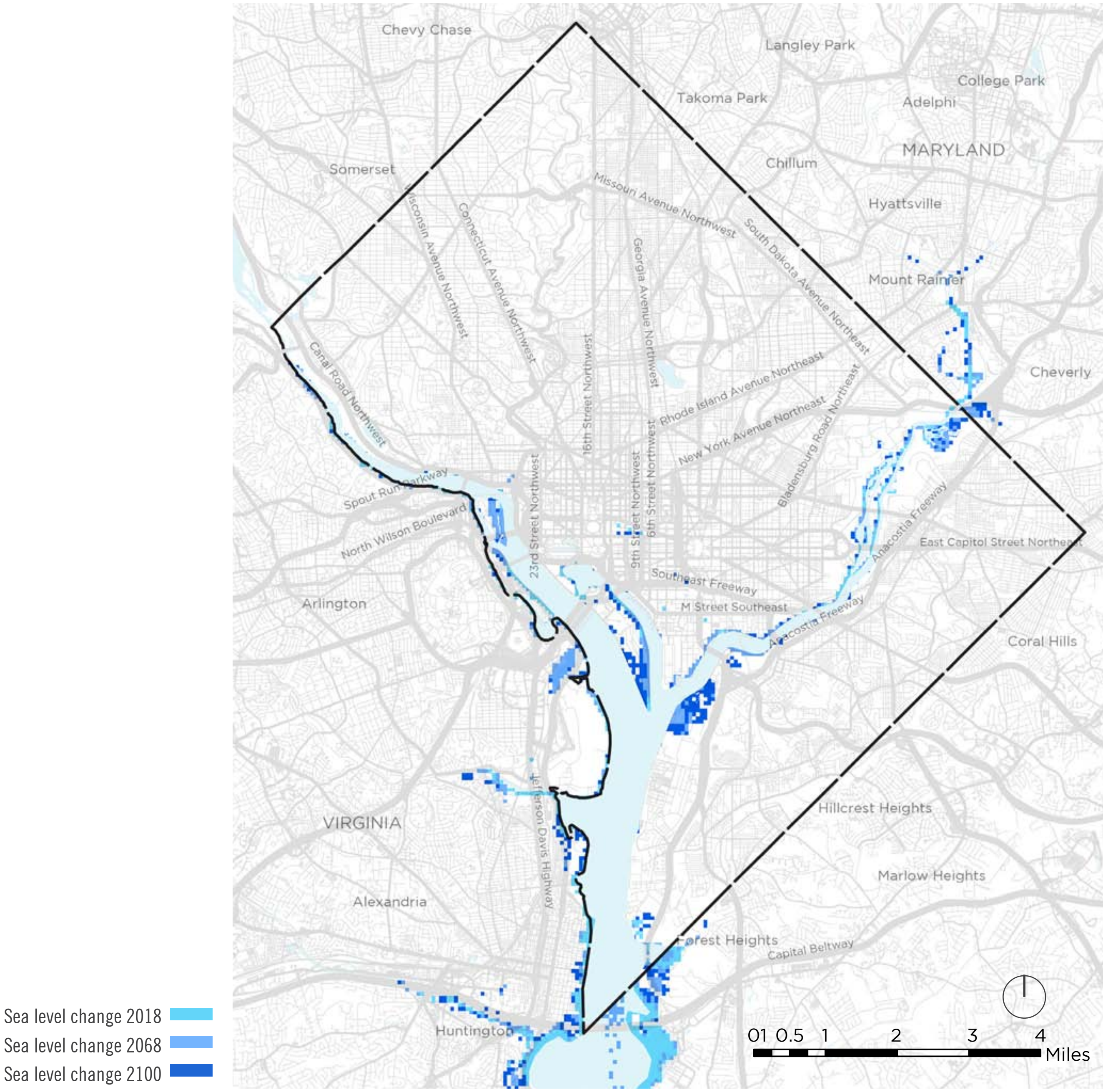


FIGURE 12. Relative sea level rise (RSLR) inundation mapping in Washington, DC for USACE “High” scenario, for years 2018, 2068, and 2100 (NACCS map overlaid on GIS map base, Kleinfelder, 2015)

STORM SURGE PROJECTIONS FOR THE DISTRICT

Storm surge from hurricanes and nor'easters can have significant impacts on the District region, and will be exacerbated in the future by climate change due to sea level rise and storm intensification. A review of historical hurricane data for the District region was conducted to assess hurricane occurrence by Saffir-Simpson category. This study was performed using the NOAA Hurricane Database (http://coast.noaa.gov/hurricanes/#), which enables tabulation of hurricane occurrence from 1851 to present (163 years) for a specified radius around the District. For the period of record, eight Category 1 storms and two Category 2 storms have tracked within 150 miles. No Category 3 or higher storms have been recorded. Table 8 lists historical hurricanes that have tracked within 150 miles of the District, and includes a qualitative description of storm impacts (if available).

The potential impacts of storm surge for the District were estimated from existing flood mapping from the NACCS (2015). The NAACS includes estimates of extreme flooding from:

- Hurricane events based on modeling conducted by NOAA using the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) numerical model,
- Estimate of the 10-year flood from the USACE Engineer Research and Development Center (ERDC) extreme water level analysis,
- FEMA 100-year flood plus 3 feet.

Figure 13 shows maximum of maximum (MOM) storm surge extents predicted by SLOSH for Category 1, 2, and 3 hurricanes. As shown, the predicted aerial extent of flooding increases significantly from Category 1 to 2, and from Category 2 to 3.

Although SLOSH modeling provides a preliminary baseline against which to estimate impacts, there are some notable limitations that should be addressed before relying too heavily on these for significant planning decisions. These limitations include:

- The storm surge predictions do not account for sea level rise, and therefore may underestimate the maximum flood extent under the most extreme events.
- SLOSH model results are not indexed to a specific probability of occurrence; it is an event-based model that focuses on consequences of significant storm events.
- The NACCS results only depict maximum extent of flooding and do not include depth of flooding.
- SLOSH yields relatively coarse estimates of flooding extent because it does not resolve near shorewave dynamics.
- Flood mitigation structures (e.g., levees, sea walls) are not automatically included in SLOSH modeling.

As an alternative to SLOSH modeling projections, storm surge inundation can also be estimated using the existing FEMA flood inundation mapping, which include depth of flooding. There are two possible approaches.

The first is to use the FEMA 100-year flood elevations in conjunction with RSLR estimates as a proxy for storm surge. For example, the maps created for the NACCS (Figure 15) correspond to the current FEMA 100-year (1%) flood plus 3 feet. This map aligns closely with the Category 3 SLOSH inundation map (Figure 13). The second is to adopt the FEMA 500-year elevations for planning purposes.

One strength of the FEMA flood mapping compared to SLOSH modeling is that it accounts for both riverine and tidal flooding based on historical gauge data. Therefore, FEMA mapping may be most suitable for near-term planning efforts. As sea level rise is only expected to be 0.1 to 0.2 feet higher in 2020 than today, the current FEMA 100-year flood (2010) is expected to be similar to the 100-year flood in 2020. On this basis, it is recommended that the 2010 FEMA 100-year flood map be used for the 2020 vulnerability assessment, and it is assumed that the 500-year flood is likely too conservative for

Date	Category	Name	Documented Storm Impacts(1)
August 2011	1	Irene	Storm surge of 1 to 2.5 ft. in the northern Chesapeake Bay region.(2)
September 2003	2	Isabel	Very large field of tropical storm force winds which caused unusually high storm surge in the Chesapeake Bay and the Potomac River Basin. Moderate to major river flooding occurred in the Potomac.
September 1999	1	Floyd	A 2 to 3 feet surge occurred along the Chesapeake Bay due to strong southerly winds blowing ahead of the storm.
August 1933	1	Unnamed	This storm caused record high tides up the entire west side of the Chesapeake Bay and in Washington, DC, with damages the highest ever recorded from a storm surge. In Washington DC, the surge reached 11 feet.
September 1903	1	Unnamed	Not available
September 1896	1	Unnamed	Not available
October 1894	1	Unnamed	Not available
September 1893	1	Unnamed	Not available
October 1878	2	Unnamed	Not available
September 1876	1	Unnamed	Not available

TABLE 8: Historical hurricanes with tracks within 150 miles of the District.

(1) http://www.erh.noaa.gov/lwx/Historic_Events/hurricane_history/

(2) NOAA Hurricane Irene Service Assessment, 2012.

near-term planning for most of the District's infrastructure with the exception of critical facilities. Critical facilities may include those that are vital to flood response activities or critical to the health and safety of the public before, during, and after a flood, such as a hospitals, emergency operations centers, electric substations, police stations, fire stations, nursing homes, schools, vehicles and equipment storage facilities, or shelters.

For future planning periods, current FEMA flood inundation mapping can be projected using RSLR projections as a proxy for time. Considering the available FEMA 100-year flood plus 3 feet mapping (NACCS, 2015), a 3-foot RSLR roughly corresponds to the year 2072 based on the USACE high scenario, as shown in Figure 14. Thus, the present day 100-year flood + 3 feet roughly translates to the 100-year flood in 2072 using under the high sea level rise scenario. Therefore, it is recommended that the FEMA 100 year plus 3 feet inundation map be used for vulnerability and risk assessment analysis for the 2050 planning period. Figure 15 shows the present day 100-year flood + 3 feet.

For the 2080 planning period, the present day 500-year flood should be used for vulnerability and risk assessment. The present day 500-year flood is approximately 4 feet higher than the present day 100 year flood at NOAA gauge 8594900 (FEMA, 2010). Projecting a 4-foot sea level rise using the USACE high scenario (Figure 14), the present day 500-year flood roughly translates to the 100-year flood of 2085.

The sea level rise and storm surge scenarios discussed above rely on current inundation mapping from the NACCS which only delineate extent of flooding, not depth of flooding. Although, it should be noted that USACE is currently conducting higher resolution storm surge modeling for the region accounting for near-shore wind and wave dynamics, using the Coastal Storm Modeling System (CSTORM-MS). The NACCS states that CSTORM-MS for the North Atlantic coast may be updated for future climatology, including sea level rise.

However, the frequency, duration, extent and depth of flooding will be influenced by more than sea level rise and storm surge. Precipitation, riverine flooding, and over capacitated drainage infrastructure will also contribute – and often during the same event. It is therefore recommended that an integrated hydrology and hydraulics model be developed to understand the true impact of flooding during both current and future conditions. This modeling effort would involve developing a dynamic coastal model which incorporates sea level rise, storm surge and wave dynamics. The model would be able to account for joint probabilities associated with different coastal storm types and tidal elevations, as well as determining both the extent and depth of flooding and how the probability of those flooding events will change under the future climate. Similar models would need to be developed for inland flooding related to riverine flow, as well as flooding related to over capacitated drainage infrastructure. All three models would need to be dynamically linked so that they behaved as an integrated system and

SLOSH HURRICANE STORM SURGE

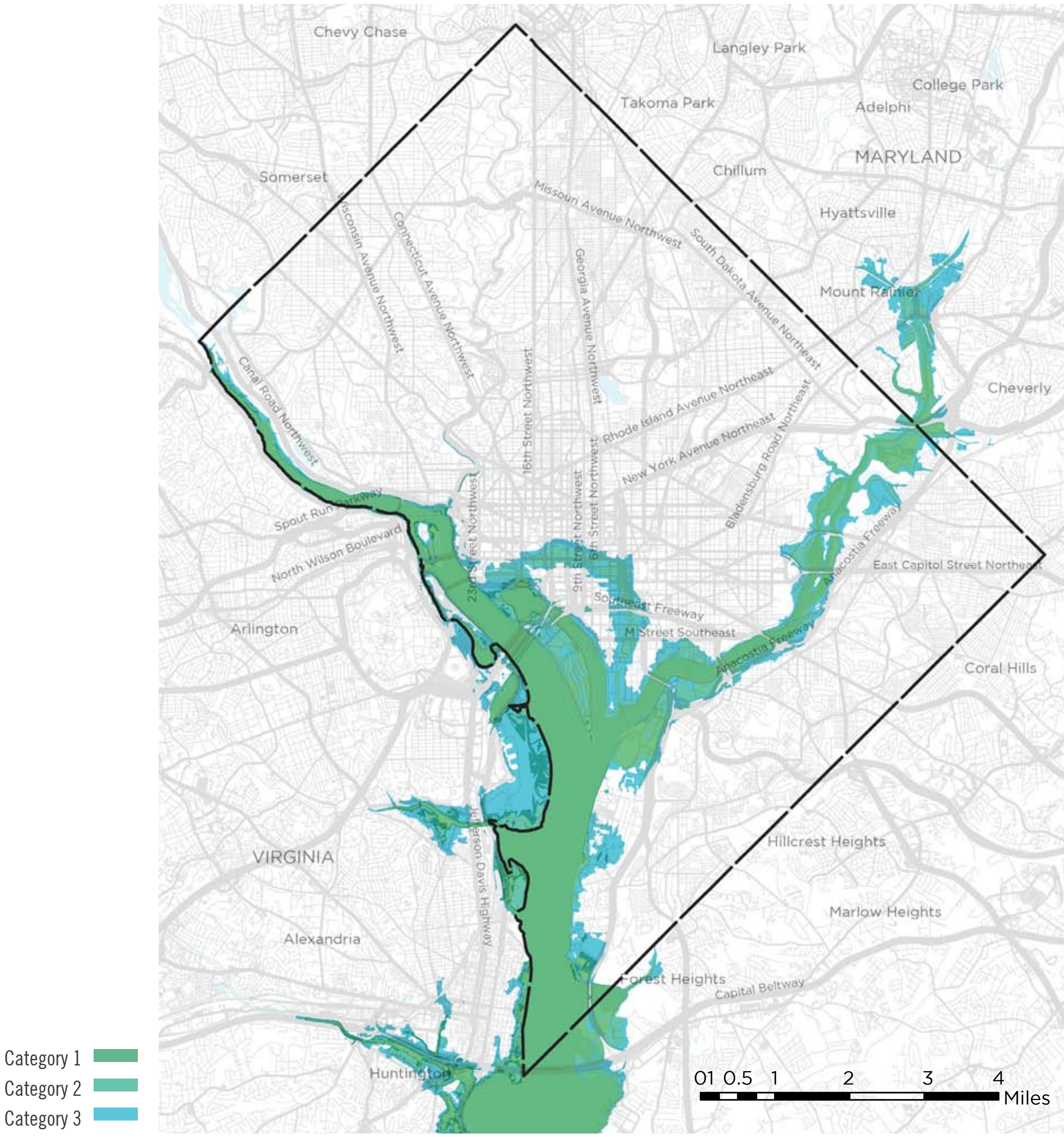


FIGURE 13: SLOSH hurricane storm surge inundation mapping for Washington DC, for present day Category 1, 2, and 3 storms (NACCS map overlaid on GIS map base, Kleinfelder, 2015)

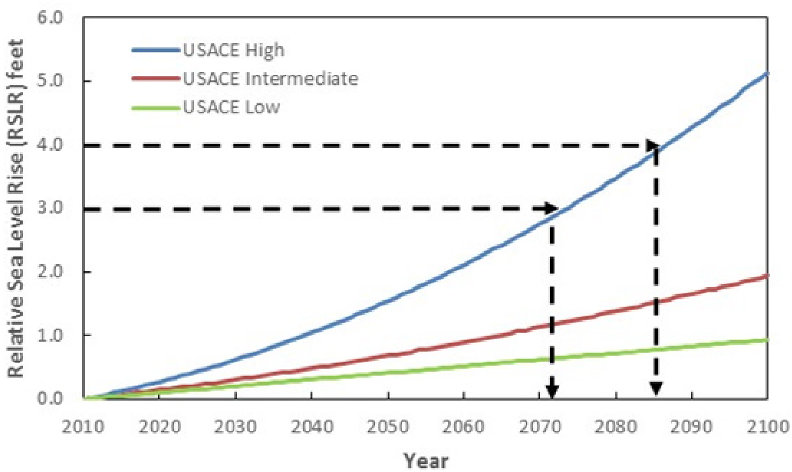


FIGURE 14: Three- and four-foot relative sea level rise compared with USACE RSLR projections for Washington, DC, from base year 2010. (Source: Kleinfelder, 2015)

actual flooding extent and depths could be generated both from a probability-based perspective (the flooding associated with a 100-year 24 hour storm in 2050) as well as an event-based perspective (i.e., the maximum level of flooding that could be expected from a Category 1 hurricane in 2080). This type of modeling is quite complex and very new. Kleinfelder and its teaming partners are developing one for the metro-Boston area that will be released soon. It is anticipated that a similar modeling methodology could be used for the District.

The National Climate Assessment (NCA) and other peer-reviewed literature have cited an increase in the intensity, frequency and duration of hurricanes in the North Atlantic in the last 30 years. The general assumption is that as temperatures continue to rise, this trend will continue as there is greater energy (heat) in the atmosphere and oceans to fuel the development and duration of these storms. However, hurricane formation is dependent on several contributing factors in addition to just increased temperature. Since North Atlantic hurricanes are spawned from the Sahara, localized conditions there play a role as well. Likewise, other changes in ocean currents, upwelling events and regionalized weather systems (e.g., it appears that there needs to be a localized weather disturbance such as a thunderstorm, to spawn a hurricane) also effect whether or not a hurricane is formed. So, while an increase in temperature will increase the potential for severe weather events, the joint probability of that occurring with the range of other factors necessary to form a hurricane must also be considered.

FEMA 100-YEAR PLUS 3FT

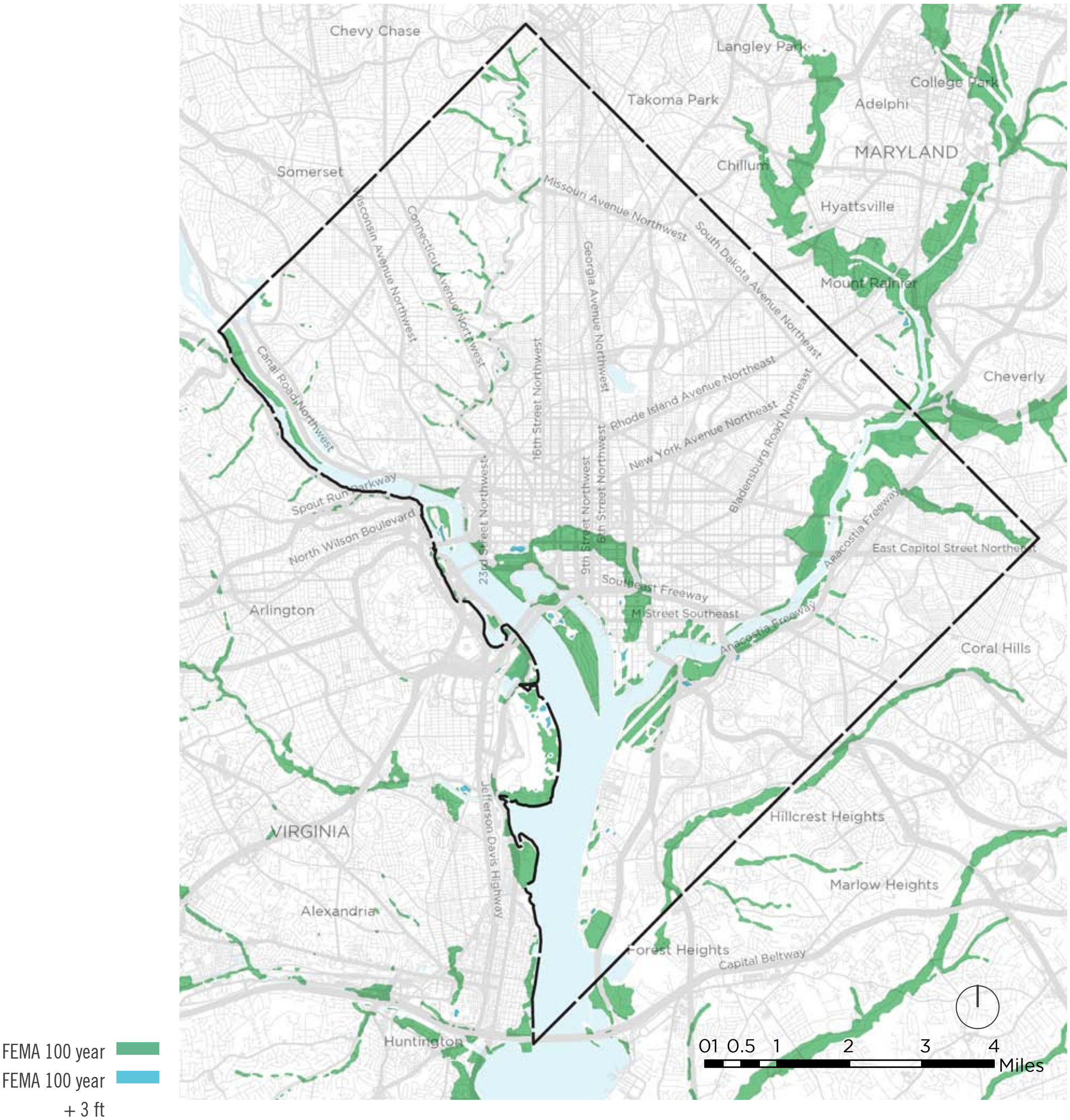


FIGURE 15: FEMA 100-year plus 3 feet inundation map for Washington, DC (NACCS, 2015).

EXTREME WIND EVENTS

Extreme surface winds at Washington Reagan National Airport (DCA) are chiefly associated with structured storm systems such as hurricanes, nor'easters, and thunderstorms (of which derechos are one class). For the purpose of this study, wind data from DCA were compiled.

The historical record of daily peak wind gust speeds covers approximately 50 years from 1948 to 1998. The highest peak wind gust speed (98 mph) ever recorded at this location occurred on October 15, 1954, when Hurricane Hazel passed within 50 miles of the District as an extra-tropical storm, after transitioning from a Category 4 hurricane earlier in the day. Hurricane Bret (1981), Hurricane Connie (1955), and an unnamed tropical storm in 1949 all produced peak wind gust speeds of >50 mph at DCA. An analysis of the occurrence of peak wind gust speeds >50 mph reveals that approximately half of the days occur in the winter months (Nov-Mar = 53%; Dec-Mar = 47%), and a third occurred in the summer (May-Sep = 36%; Jun-Sep = 30%).

The historical record of daily fastest 5-second wind speeds covers approximately 50 years from 1998 to present. Data up to May 2014 were included in this analysis. The fastest 5-second wind speed (74 mph) recorded at DCA accompanied a rainstorm on March 5, 2008. The second fastest 5-second wind speed (70 mph) recorded at DCA was on June 29, 2012, during the Derecho event that caused widespread power outages and cascading impacts on water and telecommunications services in the District.[3] Hurricane Sandy (2012) and Hurricane Isabel (2003) also produced 5-second wind speeds >50 mph (61 mph and 58 mph, respectively). An analysis of the occurrence of 5-second speeds >50 mph reveals that such days approximately occur at a similar frequency in the winter months (Nov-Mar = 43%; Dec-Mar = 38%) as in the summer (May-Sep = 43%; Jun-Sep = 38%).

Pryor et al. (2007, 2009, 2010) reported a declining trend in average and extreme (90th percentile) wind speeds over large portions of the United States from 1973 to 2005, including the Mid-Atlantic.

However, IPCC (2012, 2013) reported having low confidence in historical wind trends and their causes due to various shortcomings associated with data collection (e.g., changing locations and heights of wind measurement instruments over time), among other reasons.

IPCC (2012, 2013) also reported having low confidence in future projections of changes in extreme winds because of the scarcity of studies, shortcomings in the simulation of these events, and a lack of coherence in terms of models and methods used and regions studied. For these reasons, this study has not attempted to develop quantitative projections of future wind speeds, and does not recommend that this be pursued further at this time.

3. Information on the Derecho's power, telecommunications, and water service impacts was retrieved from a presentation "Case Studies: Extreme Events and Water Utilities in Six Local Watersheds" by Karen Metchis, EPA Office of Water on February 26, 2013.

NORTHEASTERS

Cold season extratropical storms, known as nor'easters, are large, closed (i.e. circular or oval-shaped), low pressure systems that form in the Atlantic and move up the coast, typically in winter months. The tracks of these types of storms have reportedly been shifting poleward (IPCC 2012) and may continue to move poleward under projected climate change (moderate certainty). However, there is limited certainty about whether these events will become more or less frequent and intense in the future due to climate change.

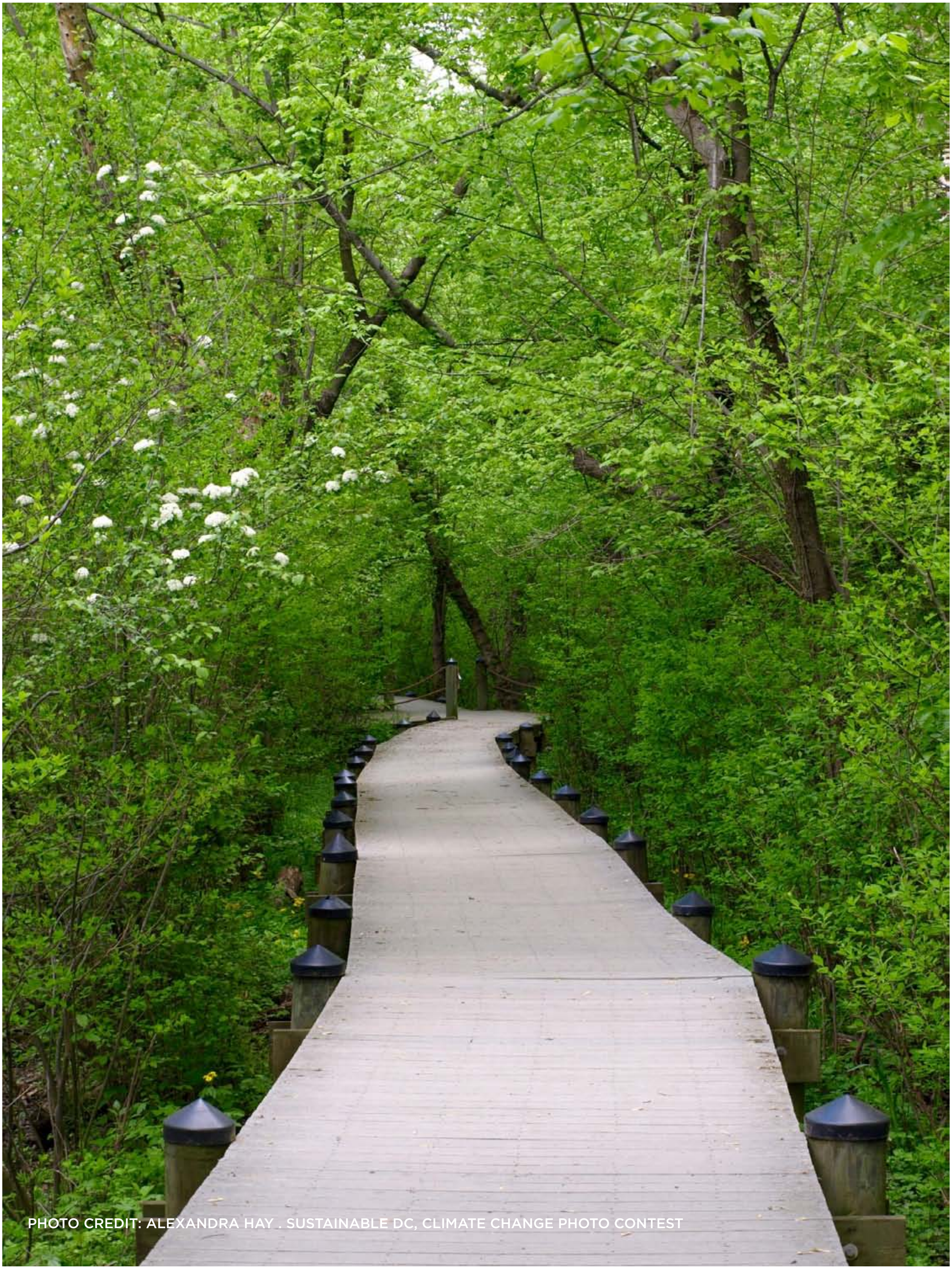


PHOTO CREDIT: ALEXANDRA HAY . SUSTAINABLE DC, CLIMATE CHANGE PHOTO CONTEST

03

RECOMMENDED SCENARIOS

It is important to emphasize that the proposed climate scenarios present a permutation of possible flood and heat events illustrating "probable futures" as guidance for preparedness planning. These projections are meant to be reviewed and updated as the science of climate change evolves, with new tools and revised observed trends.

The next step of this project will be to perform a vulnerability and risk assessment of the District's critical assets and resources. This assessment will be based on the projected increase in temperature, precipitation, and sea level rise and storm surge for each of the planning horizons.

As this report relies on different sources for defining climate projections for different parameters (temperature, precipitation, SLR, and storm surge), distinct scenarios, will be used for conducting the risk and vulnerability assessment separately for each climate parameter.

SEA LEVEL RISE/STORM SURGE

Storm surge projections incorporating sea level rise are currently not available for the District region; current FEMA flood mapping with flood depth addition were used as a proxy for future storm surge inundation (e.g., FEMA 100-year flood plus 3 feet).

2020
current 100-year flood = baseline elevation

2050
current 100-year flood + 3 feet = baseline elevation + 3 feet

2080
current 500-year flood = baseline elevation + 4 feet

PRECIPITATION

The following design storms are intermediate options of scenarios to be vetted by DOEE and stakeholders but are recommended as options.

2050s

- High scenario: 7.1 inches for the 15-year – 24-hour storm (high scenario for higher probability)
- Low scenario: 6.5 inches for the 100-year 6-hour storm (low scenario for lower probability)

2080s

- High scenario: 8 inches for the 15-year – 24-hour storm (high scenario for higher probability)
- Low scenario: 9 inches for the 100-year 6 hour storm (low scenario for lower probability)

The precipitation scenario will be addressed qualitatively as there are no available comprehensive models for the District to map potential flooding that could be caused by future projections. Future modeling work should involve translating the precipitation volumes into actual flooding extents and depths. Existing hydrologic and hydraulic models can be run using the precipitation projections developed in this study to determine the flooding implications. However, those models would need to be linked to one another, as well as to the larger sea level rise and storm surge model to fully capture the extent of flooding vulnerability – both for existing and future conditions.

TEMPERATURE

Due to climate change, temperatures are projected to increase in the District. Summer daytime maximum temperatures currently average 87°F with nighttime minimum temperatures averaging around 66°F. These values are projected to increase 2.5-3oF by the 2020s, 5-7oF by the 2050s, and as much as 6-10°F by the 2080s. Another critical measure for temperature is the heat index. By the 2020s, there are expected to be around 50 such days with heat index over 95 oF. By the 2050s, there may be 70 to 80 such days and by the 2080s, the number of days with heat index at or exceeding 95°F could average around 70 under the lower scenario and 105 under the higher.

As the duration of heat waves is expected to increase, the scenarios for heat wave are based on the higher projections translating into 8-9.5 days with a daily maximum heat index value above 95°F by the 2050s, and 9.5-12 days by the 2080s. Heat scenarios will be addressed for the District as a whole as increased stress on infrastructure and for public health.

2020 SCENARIO

Increase of daytime maximum by 2.5 - 3°F

Possible heat wave of 6 days

2050 SCENARIO

Increase of daytime maximum by 5 - 7°F

Possible heat wave of 8 - 9.5 days

2080 SCENARIO

Increase of daytime maximum by 6 - 10°F

Possible heat wave of 9.5 - 12 days


PHOTO CREDIT: MISTY BROWN . SUSTAINABLE DC, CLIMATE CHANGE PHOTO CONTEST

04

NEXT STEPS

While this report provides valuable new information on projected changes in temperature and precipitation, additional studies would further enhance the understanding of climate change impact for the District.

MAINTAIN A COMPLETE RECORDING OF WEATHER STATIONS IN THE DC AREA

It is important to report that design storms have been projected using best practices; however, some anomalies remain in the projections. For example, the values for 100-year and 200-year 24-hour design storms for 2050s and 2080s are less than those projected for the 2020s. These are likely due to the short historic record limiting the analysis of the baseline. More data are needed for a robust downscaling analysis of temperature and precipitation. The weather report for the District for critical parameters is as recent as 1991, for example for relative humidity. To provide a more robust analysis will require a longer record period. Therefore, it is recommended that the District establish an approach for recording key weather indicators to allow more robust analyses in the future.

LINKING COASTAL FLOODING WITH INLAND OR INTERIOR FLOODING

The NACCS report provides a useful baseline to estimate for potential flooding extents, but additional modeling could provide more detailed information such as depth of flooding as well as to more fully incorporate future climate change. The USACE is currently conducting higher resolution storm surge modeling (CSTORM-MS) for the region to account for near-shore wind and wave dynamics, as well as updating that model to include future climatology (e.g. potential intensification of storms) and sea level rise. This will be important in making the work more relevant for site-specific concerns and actions.

Also informing DC are FEMA maps accounting for surface flooding that is associated with riverine and tidal influences. However, FEMA maps do not consider flooding that is the result of overflowing storm pipes and other types of drainage structures. Examples of these types of flooding events include the 2006 Federal Triangle flooding, as well as the recurrent flooding in neighborhoods such as Bloomingdale and LeDroit Park. While the precipitation projections developed for this project give information on the types of storms that may become more prevalent in the future, additional modeling could translate those precipitation volumes into flooding – not only with respect to river flooding, but also for the piped drainage and green infrastructure (e.g., rain gardens, bioswales) that helps to mitigate stormwater flows. It is likely that future events will overwhelm the capacity of many of the existing systems resulting in further exacerbation of existing vulnerabilities and/or flooding in areas that have not been vulnerable up to this point.

One important aspect is the need to link the inland or interior flooding (both surface water flows and piped flow) with the coastal flooding. This is essential to understand the true extent of flooding during these events and to develop meaningful design and preparedness criteria. It is especially important to the District since neither of the rivers have dams and therefore minimal adaptive capacity with respect to sea level rise and storm surge. Comprehensive modeling of sea level rise, storm surge, riverine flooding, and piped drainage would provide the District (and abutting region) a more realistic assessment of joint probability events and possible implications.

REFERENCES

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S.Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Dunn, A.J. Payne, W.T. Pfeffer, D. Stammer, and A.S. Unnikrishnan, 2013: Sea Level Change In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, U.K. and New York, NY, USA.

IPCC Scenario Process For AR5 – Representative Concentration Pathways page, http://sedac.ipcc-data.org/ddc/ar5_scenario_process/RCPs.html, accessed March 5, 2015.

Federal Emergency Management Agency (FEMA) Flood Insurance Study, District of Columbia, 2010.

Grelley and Hansen, 2011. Federal Triangle Drainage Study.

Kalkstein, L. S., Sailor, D., Shickman, K., Sheridan, S., Vanos, J., 2013, Assessing Health Impacts of Urban Heat Island Reduction Strategies in the District of Columbia, Global Cool Cities Alliance.

Mayor's Task Force, District of Columbia, 2012. Report on Prevention of Flooding in Bloomindale and LeDroit.

National Oceanic and Atmospheric Administration, Center for Operational Oceanographic Products and Services, http://tidesandcurrents.noaa.gov/.

National Oceanic and Atmospheric Administration, Historical Hurricane Tracks, http://coast.noaa.gov/hurricanes/.

National Oceanic and Atmospheric Administration. 2012. Global Sea Level Rise Scenarios for the US National Climate Assessment. NOAA Tech Memo OAR CPO-1. Silver Spring, MD: Climate Program Office.

National Oceanic and Atmospheric Administration. 2012. Hurricane Irene Service Assessment.

National Oceanic and Atmospheric Administration, Sea Level Rise and Nuisance Flood Frequency Changes around the United States, July 2014, http://www.noaanews.noaa.gov/stories2014/20140728_nuisanceflooding.html

NOAA Climate at a Glance, http://www.ncdc.noaa.gov/cag/. Accessed March 5, 2015

Stoner, A., K. Hayhoe, X. Yang and D. Wuebbles. 2011. An Asynchronous Regional Regression Model to Downscale Daily Temperature and Precipitation Climate Projections. Intl. J. Climatology, 33, 11, 2473–2494.

Taylor, K. E., R. J. Stouffer, G. A. Meehl. 2012. An Overview of CMIP5 and the Experiment Design. Bulletin of the American Meteorological Society, 93, 485–498.

US Army Corps of Engineers (USACE) ER 1100-2-8162, Incorporating Sea Level Change in Civil Works Programs, 2013

US Army Corps of Engineers (USACE) North Atlantic Coast Comprehensive Study, 2015.

US Army Corps of Engineers (USACE), Climate Change Adaptation, Comprehensive Evaluation of Projects with Respect to Sea-Level Change, http://www.corpsclimate.us/ccaceslcurves.cfm.

Walsh, J., D. Wuebbles, K. Hayhoe, K. Kunkel, R. Somerville, G. Stephens, P. Thorne, R. Vose, M. Wehner and J. Willis. 2014a. Chapter 2: Our Changing Climate. In: USGCRP, The Third National Climate Assessment (in press).

Walsh, J., D. Wuebbles, K. Hayhoe, K. Kunkel, R. Somerville, G. Stephens, P. Thorne, R. Vose, M. Wehner and J. Willis. 2014b. Appendix: NCA Climate Science – Addressing Commonly Asked Questions from A to Z. In: USGCRP, The Third National Climate Assessment (in press).

AREA RESEARCH

arearesearch.org