# Evaluation of Potential Climate Change Impacts on Rainfall Volume, Stormwater Facility Size and Stream Flashiness

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King County

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# EXECUTIVE SUMMARY

King County was awarded a Puget Sound Watershed Management Assistance Program Fiscal Year 2009 grant by Region 10 of the U.S. Environmental Protection Agency (U.S. EPA) to develop a stormwater retrofit plan for Water Resources Inventory Area (WRIA) 9. The primary goal of this grant-funded study is to develop a plan and associated costs to implement stormwater Best Management Practices (BMPs) in developed areas of WRIA 9, that were built primarily without stormwater controls. Another overall goal of the study is to extrapolate stormwater retrofit costs to all of the developed area draining to Puget Sound. This report is one of the interim project reports needed to complete the overall study goals. This report evaluates possible effects of climate change on rainfall volumes, stormwater facility designs and stream flashiness.

The majority of the climate change research on precipitation and runoff in the Pacific Northwest to date has focused on increases in air temperature and effects on snowpack accumulation and melt timing and associated effects on seasonal mountain river runoff. Limited research to date has been conducted on future changes in precipitation in the Puget lowlands at a daily or sub-daily scale needed to inform stormwater management.

To partially address the paucity of research on potential climate change implications for stormwater management, projected rainfall from 20 different global climate models statistically downscaled to represent local conditions were obtained from University of Washington Climate Impacts Group. The models were run using the A1B greenhouse gas emission scenario, which assumes global energy production in the future is balanced between fossil fuels and non-fossil energy sources. This relatively optimistic emission scenario projects annual carbon dioxide emissions to increase to a peak in year 2050, then decline from that peak over the next 50 years, at which point emissions in 2100 are approximately 30 percent greater than in the year 2000. The downscaled model output represents daily rainfall amounts from 1916-2006 and from 2001-2097.

Dynamically downscaled global climate model output was also obtained from the University of Washington Climate Impacts Group from two global climate models. Dynamic downscaling means that the global climate model was downscaled using a dynamic regional climate model. One of the dynamically downscaled sets of output was intended to represent an optimist future scenario and was generated using a global climate model that shows smaller climate impacts in the Pacific Northwest and used the A1B greenhouse gas emission scenario which presumes substantial substitution of energy sources away from fossil fuels before 2100. The other set of dynamically downscaled output was intended to represent a pessimistic future scenario. The pessimistic scenario was based on a global climate model that shows larger changes in Pacific Northwest climate and the generated A2 greenhouse gas emission scenario. The A2 scenario is more pessimistic than the A1B scenario and assumes a slow progress in the transition from fossil fuel based energy to cleaner emission technologies with carbon dioxide emissions increasing through the end of the twenty-first century. The dynamically downscaled data represented two 30-year time periods (1970 to 2000 and 2020 to 2050).

Three approaches were used to evaluate possible climate change impacts on stormwater management: (1) changes in daily rainfall volume, (2) changes in the volume of stormwater ponds designed to treat runoff from a theoretical watershed, and (3) changes in stream flashiness determined from a watershed model forced by historical and future projections of rainfall.

An evaluation of the statistically downscaled precipitation output from the 20 global climate models for the A1B emission scenario showed a modest increase (15 percent) in the average of the annual daily maximum rainfall total. The analysis also indicated that larger storms were generally predicted to become larger and smaller storms would generally become smaller.

Stormwater ponds sized for hypothetical drainages showed that the optimistic scenario resulted in less than a 1 percent increase in necessary stormwater pond volume. The more pessimistic scenario required stormwater pond volumes that were approximately 11 percent greater than under current rainfall conditions. Stream flow flashiness was projected to range from a decrease of 8 percent to an increase of 27 percent, depending on scenario and modeled land use.

Modeling changes in future precipitation patterns and their impacts on stormwater infrastructure design is very challenging. Some key uncertainties are associated with: estimating future greenhouse gas emissions; the ability of global climate models to accurately represent average precipitation patterns in the Pacific Northwest; the use of different approaches to downscale output from global climate models to obtain daily or subdaily rainfall totals for different locations; and the difficulty projecting changes to rainfall patterns that currently show a high degree of year-to-year variability. To account for this uncertainty and the variability in model output, a conservative approach is used to evaluate the degree that climate change will increase needed stormwater facility sizes (and associated costs) in the future. Based on the results of the analyses done for this report, a conservative, planning-level estimate of 10 percent increase in stormwater facility sizing is recommended to account for potential climate change conditions. Additional research is recommended on the sensitivity of stormwater facility design to climate change that uses dynamically downscaled precipitation patterns from multiple global climate models before implementing any changes in stormwater design requirements. Future research would also investigate the timing of projected changes in precipitation patterns, which would inform when to best modify stormwater infrastructure design requirements.

# 1.0. INTRODUCTION

King County was awarded a Puget Sound Watershed Management Assistance Program Fiscal Year 2009 grant by Region 10 of the U.S. Environmental Protection Agency (U.S. EPA) to develop a stormwater retrofit plan for Water Resources Inventory Area (WRIA) 9 (King County 2010a). The goal of this grant-funded study was to develop a plan and associated costs for implementing stormwater Best Management Practices (BMPs) in WRIA 9 sufficient to improve stream flow and water quality. This report is one of the interim project reports needed to complete the overall study goals. This report evaluates possible effects of climate change on rainfall volumes, stormwater facility designs and stream flashiness.

## 1.1 Historical Precipitation Trends

Historical weather monitoring allows for detailed statistical analyses of how precipitation patterns and amounts have or have not changed over time. Changes can be assessed over multiple timescales, including annual, seasonal, monthly, weekly, daily, hourly, and subhourly. Increases in precipitation frequency and magnitude are anticipated by projected warming of air temperatures in the lower atmosphere which results in increased evapotranspiration and atmospheric moisture levels (Trenberth et al. 2003; NRC 2011).

Research on historical trends in precipitation has generally focused on metrics more relevant to river basins that characterize monthly, seasonal and annual precipitation characteristics (e.g., King County 2010a; Ecology 2012a; Dalton et al. 2013). Ecology (2012a) concluded that annual precipitation in the Pacific Northwest has increased 13 percent since 1920. However, Dalton et al. (2013) concluded that there is no trend in Pacific Northwest annual precipitation, although there is greater interannual variability since 1970. With the possible exception of Rosenberg et al. (2010), the majority of existing research has not evaluated the rainfall characteristics that drive lowland stormwater runoff and associated stormwater facility design (e.g., King County 2009; Ecology 2012b).

Stormwater management design requirements are driven by rainfall characteristics, including storm intensity and frequency. In Western Washington, stormwater flow control involves sizing a facility such that outflow would be similar to the runoff that would be expected from an undeveloped forested site. Changes in storm intensity and frequency would therefore be expected to influence stormwater design requirements. Research evaluating historical precipitation trends across the continental United States showed increases in frequency and magnitude of storms over the last century (e.g., Karl and Knight 1998, Kunkel 2008; Walsh et al. 2014). However, there are differences in direction and magnitude among regions. For example, along the west coast, most parts of western Washington State and California experienced increases in extreme rainfall events, while Oregon experienced a decreasing trend (Mass et al. 2011; Dulière et al. 2013). These results are consistent with findings by Madsen and Figdor (2007), Warner et al. (2012), and King County (2010a).

Along the Pacific Northwest coast, the majority of largest observed rainfall events are caused by narrow bands of high moisture content, commonly referred to as *atmospheric*

*rivers* (aka Pineapple Express) (Warner et al. 2012). These atmospheric rivers originate from the tropic (and subtropics) region in the middle of the Pacific Ocean (e.g., Neiman et al. 2008) and make landfall on the United States west coast. These types of large storm events generally last one to three days (e.g., Warner et al. 2012) and can result in five to ten inches of precipitation in the Puget lowlands, and twice that amount in the Cascade Mountains.

Rosenberg et al. (2010) investigated historical rainfall distributions in Washington State specifically attempting to characterize trends more relevant to stormwater. The Rosenberg et al. (2010) study is of particular interest since the dynamically downscaled climate model precipitation output from that study was also used in analyses conducted for this report. Rosenberg et al. (2010) analyzed hourly observed rainfall data spanning several decades using three different methods to evaluate historical rainfall trends in the Puget Sound region, southwest Washington State, and eastern Washington State. Three data analysis techniques used are described below.

A Regional Frequency Analysis. The regional frequency analysis looked at annual maximum rainfall events ranging in duration from 1 hour to 10 days. These metrics were normalized within each of the three regions to calculate regional L-moment parameters to define regional growth curves based on Generalized Extreme Value distributions. The regional growth curves were then used to define magnitudes of design storms within each region (e.g., 2-, 5-, 10, 25-, and 50-year). Segmenting rainfall into two periods (1956-1980 and 1981-2005), differences in distributions were evaluated using Kolmogorov-Smirnov and Wilcoxon rank-sum techniques. Rosenberg et al. (2010) found statistically significant increases over time for the 2-day duration storm event for the Seattle-Tacoma station. This increase in storm intensity is consistent with findings by Mass et al. (2011) and Dulière et al. (2013). For the Seattle-Tacoma station, the 2-day duration storms increased 23 percent 1981-2005 relative to 1956-1980. No other statistically significant precipitation changes were identified in duration among the three stations.

A Precipitation Event Analysis. The precipitation event analysis assessed whether changes annual precipitation were due to changes in event frequency or intensity. Trends in precipitation frequency and magnitude were evaluated using a non-parametric Mann-Kendall test. Trends were evaluated for one well maintained rainfall station within each region (i.e., Seattle-Tacoma, Spokane, and Portland international airport stations). For the Seattle-Tacoma station, an 8.9 percent declining trend in annual precipitation was observed over the 1949-2007 time period, although this trend was not statistically significant. Most of this decrease was associated with a decrease in event frequency.

An Exceedance-Over-Threshold Analysis. The exceedance-over-threshold analysis further evaluated changes in storm event frequency. The change in the annual exceedance frequency of five 24-hour storm volume thresholds (0.1, 0.2, 0.3, 0.4, and 0.5 inches) was evaluated using a non-parametric Mann-Kendall test. At the Seattle-Tacoma station, there was a 10 to 15 percent decrease in the frequency of exceedances across all five thresholds evaluated, although these decreases were significant ($p<0.05$) only for the 0.2 and 0.3 inches per day thresholds.

## 1.2 Projected Future Precipitation

Resolution of global climate models (GCMs) is generally measured in 100's of kilometers. Each of these GCMs has errors and biases (e.g., Mass et al. 2002; Sun et al. 2006; Tebaldi et al. 2006). Researchers have worked over the decades to reduce errors and biases and improve model accuracy (Dulière et al. 2010). However, these GCMs are still limited by their relatively coarse representation of local topography which influence regional and local climate conditions, and by the course temporal output, typically monthly, which limits their ability to track storm events (Salathé et al., 2010; Dulière et al. 2010; Dulière et al. 2013).

To account for the course spatial and temporal scale of the GCM output, methods have been developed to downscale the GCM results to hourly or daily results at the regional or local scale. Two basic approaches to downscale GCM output have been developed. First, a statistical method can be used that is based on the historical statistical relationship between daily averages at specific locations and monthly averages over larger geographic areas. Second, dynamic downscaling methods can be implemented that use the GCM output to force regional climate models to generate hourly or daily output for different locations. GCMs downscaled using regional climate models (e.g., Weather Research and Forecasting - WRF and Hadley Center Regional Model- HadRM) compared to observations over the same time period adequately characterize distributions of rainfall, but not the sequence that occurs over time (Salathé et al. 2010; Dulière et al. 2010).

Relative to the 1970 to 1999 time period, annual average precipitation in the Pacific Northwest is projected to be within a range of an 11 percent decrease to a 12 percent increase for years between 2030 and 2059 and within a range from a 10 percent decrease to an 18 percent increase between 2070 to 2099 (Mote and Salathé 2010). Reviewing results from multiple GCMs, Snover et al. (2013) concluded that the projected change in annual average precipitation by the 2050s (ranging from a decrease of 4 percent to an increase of 14 percent) is smaller than currently observed annual variability of plus/minus 15 percent.

Snover et al. (2013) also concluded that there will be a seasonal shift in precipitation patterns in the Pacific Northwest, with slightly (6 percent to 8 percent decrease) drier summers by the 2050s and slightly wetter (2 percent to 7 percent increase) winters. These findings are consistent with the findings of Mote and Salathé (2010), who found that a large majority of the 20 GCMs evaluated projected a decline in summer precipitation by the 2080s relative to 1970 to 1999, with an average decrease of 14 percent across all models. Mote and Salathé (2010) also found that most models projected a similarly sized increase in winter precipitation by the 2080s.

Regarding large storm events, Snover et al. (2013) concluded that heavy rainfall events in the Pacific Northwest are projected to become more severe by the 2050s. Specifically, Snover et al. (2013) found that the number of days with greater than 1 inch of rain is projected to increase by 13 percent by the 2050s relative to 1970 to 1999, and the number of days with greater than 3 inches of rain is projected to increase by 22 percent. Warner et al. (2014) found that precipitation on extreme atmospheric river days is projected to increase by 15 to 39 percent by 2070 to 2099 relative to 1970 to 1999, suggesting a

substantial increase in the size of large storm events. Rosenberg et al. (2010) bias corrected and analyzed hourly rainfall data for two future climate scenarios dynamically downscaled by Salathé et al. (2010) using the Weather Research and Forecasting model. Salathé et al. (2010) evaluated an "optimistic" scenario based on a modest increase in greenhouse gas emissions and a GCM that is less sensitive to greenhouse gas emissions, and a "pessimistic" scenario based on higher greenhouse gas emissions and a GCM that is more sensitive to greenhouse gas emissions. For the bias corrected pessimistic scenario, Rosenberg et al. (2010) found that statistically significant increases in the annual maxima 1-hour, 2-hour, 3-hour, 6-hour, 12-hour, 24-hour, 2-day, and 10-day precipitation at SeaTac airport for 2020 to 2050 relative to 1970 to 2000. Under the optimistic scenario, Rosenberg et al. (2010) found statistically significant increases only for the annual maxima 24-hour and 2-day precipitation at SeaTac airport for the same time periods. Rosenberg et al. (2010) concluded that "Projections from two regional climate model (RCM) simulations generally indicate increases in extreme magnitudes throughout the state over the next half-century, but their projections vary substantially by both model and region, and actual changes may be difficult to distinguish from natural variability."

## 1.3 Projected Impacts on Urban Streams and Stormwater Management

The impact of changing precipitation patterns on urban streams and stormwater systems in the Pacific Northwest has received little attention. Stormwater design standards in King County and Washington State (King County 2009; Ecology 2012b) use multi-decade hourly rainfall data to generate variable runoff rates reflective of fast responding stormwater and stream systems. In addition, urban hydrologic modeling is typically conducted using 15-minute or 1-hour rainfall data and continuous hydrologic models such as Hydrologic Simulation Program – Fortran (HSPF). Rosenberg et al. (2010) used the bias corrected dynamically downscaled data from Salathé et al. (2010) as input to an urban hydrology model to simulate stream flows in two urban watersheds. Rosenberg et al (2010) found that the more pessimistic scenario resulted in statistically significant increases in 2-year, 5-year, 10-year, 25-year, and 50-year peak flows for both streams evaluated, with peak flows projected to increase from 26 percent to 59 percent. The more optimistic scenario showed non-statistically significant increases in peak flows ranging from 3 percent to 30 percent.

## 1.4 Study Area

The project study area includes drainages starting a short distance downstream of the Howard Hanson Dam on the Green River down to approximately 4.3 miles upstream from the mouth of the Duwamish River in Elliot Bay as well as the Puget Sound shoreline drainages totaling approximately 278 square miles in drainage area (Figure 1).

## 1.5 Goals and Objectives

The goal of the overall WRIA 9 project is to estimate as rigorously as possible the potential public cost of implementing stormwater Best Management Practices (BMPs) and Low

Impact Development (LID) techniques in existing and future (2040) developed areas of WRIA 9 to improve stream flow and water quality to near-pre-development conditions (King County 2010b). The scope of the study called for consideration of how climate change is likely to affect stormwater management, facility design and stream flashiness. The goal of this report is to provide an indication of the potential impact of climate change on the size of stormwater flow control and water quality treatment facilities.

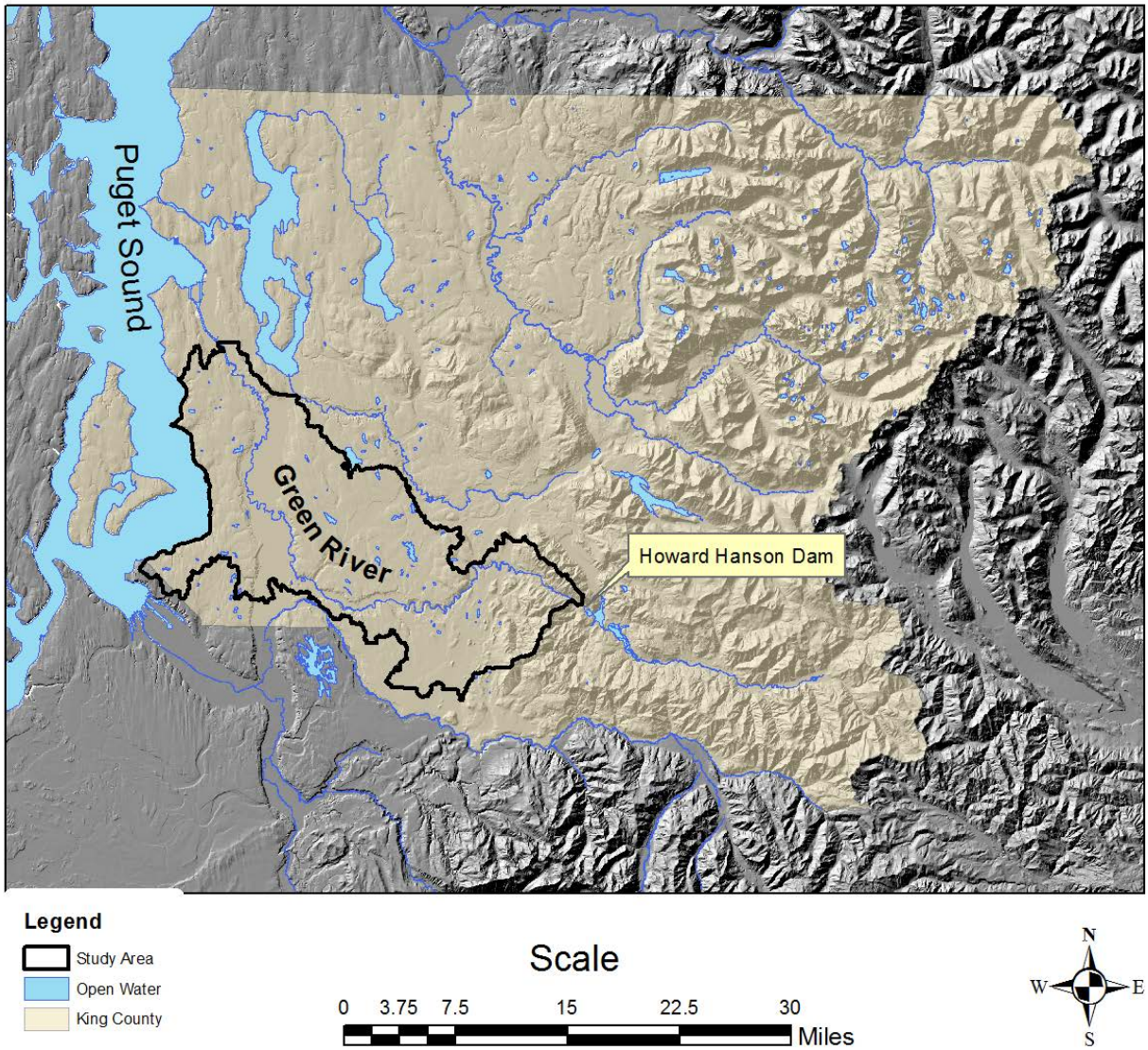


**Figure 1. Map of project study area.**

# 2.0. METHODS

The potential for climate change to impact stormwater facility needs is driven by potential changes in precipitation patterns. Stormwater facility sizes and designs are influenced by the timing and magnitude of precipitation. Stormwater facility designs in Western Washington are developed using continuous time series of rainfall at sub-daily time increments (typically hourly) to generate variable runoff rates reflective of fast responding stormwater conveyance systems. Ideally, this data would be available for multiple future climate projections, allowing for an ensemble modeling assessment of stormwater facility needs. However, most of the projected precipitation data from the University of Washington Climate Impacts Group (CIG) are only available in daily time increments, which are not ideal for use in modeling stormwater facility needs which can be strongly influenced by hourly and subhourly rainfall patterns. Therefore, three different methods were used to characterize the effects of climate change on rainfall and potential impacts to stormwater infrastructure, including:

1) A comparison between historical and future daily rainfall volume output from 20 different GCMs statistically downscaled to daily time increments at the watershed scale,
2) A comparison between modeled stormwater facility storage volumes for historical precipitation and projected future precipitation using output from two GCMs dynamically downscaled to hourly time intervals at the watershed scale , and
3) A comparison between modeled rainfall runoff generated stream flashiness for historical precipitation and projected future precipitation for output from two GCMs dynamically downscaled to hourly time intervals at the watershed scale.

Given that Rosenberg et al. (2010) found the largest increases in historical extreme precipitation events were between the 1-day and 2-day annual maximum event, and several studies previously mentioned also concluded significant rainfall durations were in the range of 1 to 3 days, comparing precipitation events among the scenarios using 1-day rainfall totals was deemed appropriate.

## 2.1 GCM Data

Four families of emissions scenarios were developed by the Intergovernmental Panel on Climate Change (IPCC)—the A1, A2, B1, and B2 families (IPCC 2000). Each theme of a family represents variations in economic growth and the consumption of fossil fuels, and levels of response mitigating environmental impacts from economic growth. This study focuses on the A1B and A2 emissions scenarios. The A1B scenario is part of the A1 family and is considered a moderate emission scenario, while the A2 scenario is part of the A2 family and is consider to be a more pessimistic emission scenario.

> *"A1B is a future world of very rapid economic growth, global population that peaks mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. Major underlying themes are economic and cultural*

*convergence and capacity building, with a substantial reduction in regional differences in per capita income. Energy production is balanced between fossil fuels and non-fossil energy sources"* (IPCC 2000).

*"The A2 scenario family represents a differentiated world. Compared to the A1 storyline it is characterized by lower trade flows, relatively slow capital stock turnover, and slower technological change. The A2 world "consolidates" into a series of economic regions. Self-reliance in terms of resources and less emphasis on economic, social, and cultural interactions between regions are characteristic for this future. Economic growth is uneven and the income gap between now-industrialized and developing parts of the world does not narrow, unlike in the A1 and B1 scenario families"* (IPCC 2000).

Figure 2 illustrates the global total carbon dioxide emissions from all energy sources. In the A1B scenario, global carbon dioxide emissions increase to about 16 GtC/yr by 2050. Then slowly decreases to an amount of 13 GtC/yr by 2100. In the A2 scenario, global carbon dioxide emissions steadily increase throughout the century to about 29 GtC/yr by 2100.

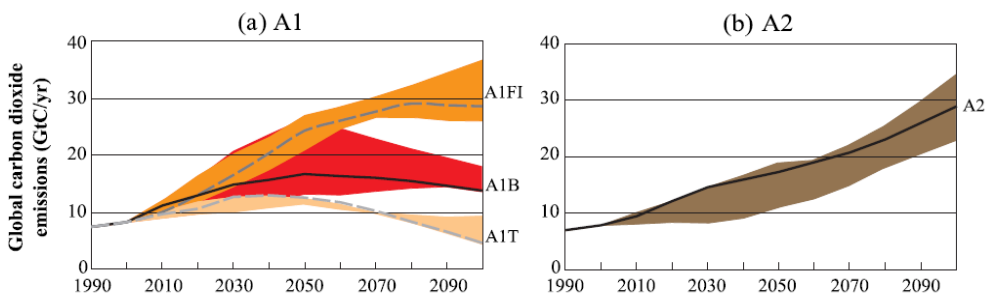


**Figure 2. Total global annual CO2 emissions from all sources (energy, industry, and land-use change) from 1990 to 2100 (in gigatonnes of carbon (GtC/yr)) for two of the four families (A1 and A2) and four of six scenario groups (A1FI, A1B, A1T, and A2). Each colored emission band shows the range of emissions within each group (IPCC 2000).**

Bias corrected and spatially and temporally downscaled output from 20 GCMs (Table 1) for the A1B emission scenario were obtained from the CIG. These projected future scenarios for daily rainfall totals generally spanned January 2001 through December 2098. Output from each of the 20 GCMs representing a historical time series (1915-2006), downscaled to the same locations, was also obtained from the CIG. These data were described in a study conducted by Cuo et al. (2010) of the effects of future climate and landcover change on Puget Sound river hydrology.

Two other two sets of output were also obtained from the CIG (Table 2). These were generated using dynamic downscaling approach with WRF that included use of a regional climate model with bias correction (Rosenberg et al. 2010). These two data sets included an "optimistic" scenario based on a modest increase in greenhouse gas emissions (A1B) and a GCM that is less sensitive to greenhouse gas emissions (ECHAM5), and a "pessimistic" scenario based on higher greenhouse gas emissions (A2) and a GCM that is more sensitive

to greenhouse gas emissions (CCSM3). These data sets include precipitation in 1-hour time increments for historical (1970-2000) and future (2020-2050) conditions.

**Table 1. 20 Global climate models with output under A1B greenhouse gas emission scenario that was previously statistically downscaled to daily time steps at Kent, Washington and used for analysis (Cuo et al. 2010).**

| Global Climate Model | Institution | Simulation Period |
|---|---|---|
| BCCR | Bjerknes Center for Climate Research, Norway | 2000-2098 |
| CCSM3 | National Centre for Atmospheric Research, USA | 2000-2098 |
| CGMCM 3.1 T47 | Canadian Center for Climate Modeling and Analysis, Canada | 2001-2098 |
| CGMCM 3.1 T63 | Canadian Center for Climate Modeling and Analysis, Canada | 2001-2098 |
| CNRM_CM3 | Centre National de Recherches Meteorologiques, France | 2001-2098 |
| CSIRO_3_5 | Australia's Commonwealth Scientific and Industrial Research Organization, Australia | 2000-2098 |
| ECHAM5 | Max-Planck-Institute for Meteorology, Germany | 2001-2098 |
| ECHO_G | Meteorological Institute, University of Bonn, Germany, Meteorological Research Institute of KMA, Korea, and Model and Data Group at MPI-M, Germany | 1999-2098 |
| FGOALS_0_G | Institute of Atmospheric Physics, China | 2000-2098 |
| GFDL_CM2_0 | Geophysical Fluid Dynamics Laboratory, USA | 2001-2098 |
| GFDL_CM2_1 | Geophysical Fluid Dynamics Laboratory, USA | 2001-2098 |
| GISS_AOM | Goddard Institute for Space Studies, USA | 2001-2098 |
| GISS_ER | Goddard Institute for Space Studies, USA | 2004-2098 |
| HADCM | Met Office, UK | 2000-2098 |
| HADGEM1 | Hadley Center Global Environment Model, v 1, UK | 2000-2098 |
| INMCM3_0 | Institute for Numerical Mathematics, Russia | 2001-2098 |
| IPSL_CM4 | IPSL (Institute Pierre Simon Laplace), Paris, France | 2000-2098 |
| MIROC_3.2 | National Institute for Environmental Studies, Japan | 2001-2098 |
| MIROC_3.2_HI | National Institute for Environmental Studies, Japan | 2001-2098 |
| PCM1 | National Centre for Atmospheric Research, USA | 2000-2098 |

**Table 2. Summary of dynamically downscaled GCM output for Sea-Tac Airport used in this analysis (Rosenberg et al. 2010).**

| Scenario | GCM | Emission | Downscale | Time step |
|---|---|---|---|---|
| Optimistic | ECHAM5 | A1B | WRF + Bias-Correction | 1-hour |
| Pessimistic | CCSM3 | A2 | | |

The output locations of GCM simulations (Cuo et al. 2010; Rosenberg et al. 2010) used in this analysis are shown in Figure 3. Figure 3 also shows the variation in historical total annual rainfall (PRISM 2000) across the study area.

The two downscaling methods, statistical downscaling and dynamic downscaling with bias correction, generate substantially different data sets. The statistical downscaling approach generated daily rainfall totals (Cuo et al. 2010). Daily data are generally considered inadequate for designing stormwater flow control and water treatment facilities (e.g., ponds) or for modeling urban watershed hydrology, especially at smaller drainage scales with peak responses on the order of hours or minutes. The stormwater design manuals specify the use of hourly (or sub-hourly) data for pond design and sizing. The dynamic downscaling approach generated 1-hour rainfall totals (Rosenberg et al. 2010). These data are consistent with the standards of stormwater facility design and urban watershed hydrology modeling.

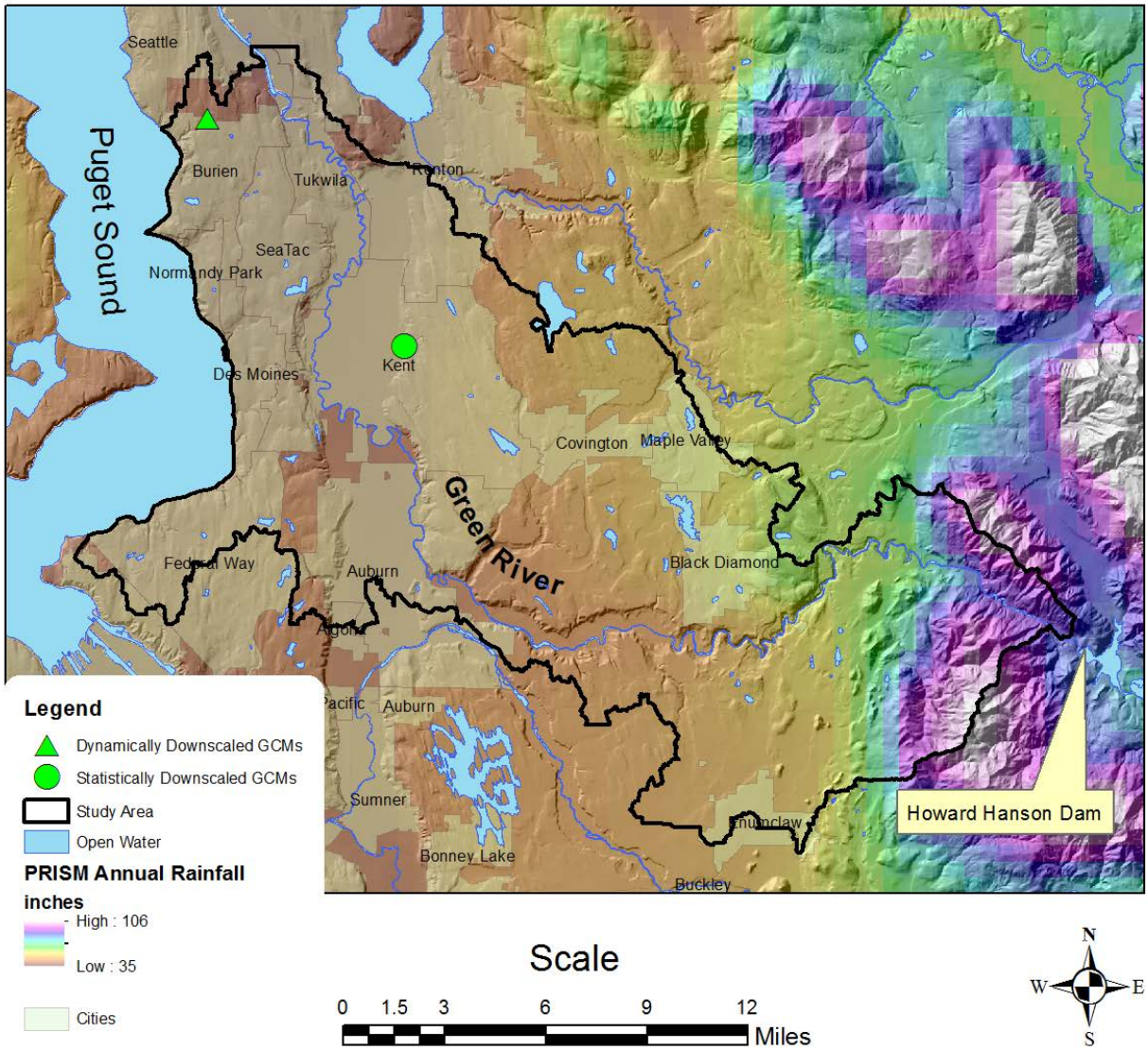


**Figure 3. Study area, distributed estimated mean annual rainfall (PRISM 2000), and locations of GCM outputs used for this analysis.**

## 2.2 Changes in Precipitation Patterns

The statistically downscaled daily precipitation outputs from the 20 GCMs were analyzed using approaches similar to those used by Rosenberg et al. (2010). Further evaluation of the dynamically downscaled and bias corrected "optimistic" and "pessimistic" scenario output was not conducted because Rosenberg et al. (2010) previously completed a thorough analysis of this data. The four analyses conducted include:

- The average of modeled future and modeled historical annual maximum daily rainfall totals were compared using the Wilcoxon rank-sum test. Two lengths of time were analyzed; change between the same two 30 year periods analyzed by Rosenberg et al. (1970-2000 vs. 2020-2050) and change between the entire available historical (1915-2006) and future (2001[1]-2098) data sets.
- The cumulative frequency distribution of the historical and future annual maximum daily rainfall totals were compared using the Kolmogorov-Smirnov test (for both data sets over the same two intervals as above).
- The trend in future annual maximum daily rainfall totals (for both data sets over the same time intervals) were analyzed using the Mann-Kendall test.
- The slopes of the future trend in annual maximum daily rainfall totals (for both data sets over the same time intervals) were calculated using the Sen's slope.

The relative change in the magnitude of annual maximum rainfall totals was computed using Equation 1. Relative changes in magnitude between future and historical totals were calculated for the minimum, maximum, and average annual maximum daily rainfall totals, as well as for a set of percentiles (99, 95, 90, 75, 50, 25, 10, 5, and 1). The relative change was calculated for both time intervals.

**Equation 1. Relative percent difference in maximum annual daily rainfall events**

$$Rainfall_{RPD} = \frac{Future_{percentile} - Historical_{percentile}}{Historical_{percentile}} * 100$$

As an example, if the 95th percentile of daily rainfall for a future scenario is 2.0 inches and 1.5 inches for historical conditions, then the relative change for that comparison would be: RPD = [(2.0 – 1.5) / 1.5] * 100 = +33 percent.

## 2.3 Changes in Stormwater Pond Volumes

The "optimistic" and "pessimistic" dynamically downscaled and bias corrected hourly precipitation output was used to model stormwater pond size requirements (see Table 2). Stormwater ponds were sized for both historical (1970-2000) and future (2020-2050)

[1] For completeness purposes, the entire future data set was used for all 20 GCMs, even though the start date differed between GCMs. Output from one GCM started in January 1999, eight started in January 2000, ten started in January 2001, and one started in January 2004. It is believed that the uncertainty introduced by using different start dates is small and unlikely to alter the results.

climatic conditions. Pond sizes were determined using Ecology's approved stormwater pond sizing software (WWHM2012[2]). Stormwater pond sizing requires rainfall at hourly (or sub-hourly) increments. Ponds were designed using King County Level 2 target conditions (i.e., matching runoff flow duration curves between half the 2-year and 50-year flood frequency magnitudes[3]) based on conversion from fully forested landscape.

Pond sizing design constraints included:

- 4-ft pond depth
- 3:1 side slopes
- 3-orifice or single orifice with notched weir outlet structure
- Square footprint
- No infiltration
- Groundwater bypasses facility

Ponds were sized for flow control for a hypothetical 100-acre catchment. The catchment was assumed to be a homogenous residential landscape comprised of 4.6 acres of road, 4.7 acres of roof tops, and 90.7 acres of grass lawns. The theoretical catchment used for sizing stormwater ponds replicated the low density residential land cover distributions defined in the King County Watershed Model Development report (Table 29 in King County 2013). The point of compliance was assigned to the outlet of the pond structure.

Stormwater ponds were sized using the internal optimization routines in WWHM2012 that best achieved design targets. The stormwater pond volumes derived from simulated future climate conditions were compared to ponds sized using the simulated historical climate conditions for the same land cover distribution. Even with the use of the optimization tools, some small uncertainty remains regarding the level of success in optimization (i.e., minimizing pond volumes while achieving design targets). This uncertainty translates into some uncertainty surrounding the estimated change in pond volumes under future climate scenarios.

## 2.4 Changes in High Pulse Count Flashiness Metric

The "optimistic" and "pessimistic" dynamically downscaled and bias corrected hourly precipitation output was used to model rainfall runoff flashiness (see Table 2). Rainfall runoff flashiness was modeled for both historical (1970-2000) and future (2020-2050) climatic conditions. Rainfall runoff flashiness is modeled using the 2012 Western Washington Hydrologic Model (WWHM2012; Ecology 2012b).

Rain runoff flashiness was assessed using a flow metric known as High Pulse Count (HPC). HPC was one of the three metrics selected for evaluation of stormwater management scenarios in the WRIA 9 Stormwater Retrofit study (Horner 2013). This flashiness metric

[2] http://www.ecy.wa.gov/PROgrams/wq/stormwater/wwhmtraining/index.html

[3] Flood frequency is for a given magnitude, the probability that it will occur in any given year. For example, a 50-year flood is a very large flood that occurs on average once every 50 years.

has shown to be correlated with macroinvertebrate community health as quantified by the Benthic Index of Biotic Integrity (BIBI) (Horner 2013).

> High Pulse Count is defined as the number of events per water year when the daily average flow rate exceed two times the long term mean annual flow rate. A pulse event is when flow for one or more consecutive days rises above the defined threshold. An event ends when flow falls below the defined threshold.

Three land cover scenarios (forested, low density urban, and high density urban) were used in WWHM2012 to generate flow rates driven by the hourly dynamically downscaled and bias corrected climate data. The characteristics of the three land cover scenarios are presented in Table 3.

**Table 3. Characteristics of the three land cover scenarios modeled to assess potential climate change impacts on high pulse count.**

| Scenario | % Forested | % Lawn | % Impervious | Slope | Soil |
|---|---|---|---|---|---|
| Forested | 100 | 0 | 0 | Flat | Low Permeability Till |
| Low Density Urban | 0 | 90.7 | 9.3 | Flat | Low Permeability Till |
| High Density Urban | 0 | 34.2 | 65.8 | Flat | Low Permeability Till |

Forested landscape is used as benchmark to compare the effects of climate change in an undisturbed environment.

Differences between the average and distribution of modeled 1970-2000 and 2020-2050 HPC generated from these land cover scenarios were evaluated. Statistically significant differences between historical and future climate scenarios were evaluated using non-parametric statistical tests, including the Kolmogorov-Smirnov test for differences in distributions and the Wilcoxon rank-sum for testing differences in means. In each test, a *p*-value equal to or less than 0.05 are considered statistically different.

# 3.0. RESULTS

## 3.1 Changes in Annual Daily Maximum Rainfall

Near-term (2020-2050) and long-term (2001-2098) annual daily maximum rainfall amounts were compared to historical annual daily maximum rainfall amounts for the statistically downscaled daily precipitation output from 20 GCMs. The relative change between modeled historical and future minimum, average, and maximum of the annual daily maximum rainfall totals are presented for each of the 20 GCMs for 30-year and over 90-year time periods (Table 4). The ensemble average change is also presented.

**Table 4. Relative percent differences in annual daily maximum rainfall totals for two historical and future time periods.**

| | 1970-2000 vs 2020-2050 | | | 1915-2006 vs 2001-2098 | | |
|---|---|---|---|---|---|---|
| **GCM** | **Min** | **Max** | **Median** | **Min** | **Max** | **Median** |
| BCCR | 8% | -5% | 14% | -14% | 28% | **9%** |
| CGMCM 3.1 T47 | 1% | 51% | **18%** | 1% | 51% | **36%** |
| CGMCM 3.1 T63 | -2% | 37% | 18% | -2% | 37% | **19%** |
| CCSM3 | -19% | 33% | 17% | -29% | 33% | **13%** |
| CNRM_CM3 | 7% | 9% | 20% | -34% | 95% | **11%** |
| CSIRO_3_5 | -8% | -12% | 14% | -8% | 20% | **11%** |
| ECHAM5 | 11% | 4% | 13% | -5% | 12% | 14% |
| ECHO_G | 12% | 5% | 7% | -3% | 60% | **9%** |
| FGOALS_0_G | -23% | 6% | 9% | -28% | 11% | 8% |
| GFDL_CM2_0 | 5% | 9% | 11% | 2% | 46% | **12%** |
| GFDL_CM2_1 | 2% | 67% | 9% | -3% | 67% | 10% |
| GISS_AOM | 16% | 37% | 21% | -3% | 55% | **18%** |
| GISS_ER | 12% | 18% | 12% | -8% | 40% | **15%** |
| HADCM | 14% | 19% | 18% | 4% | 60% | **11%** |
| HADGEM1 | 1% | 31% | 14% | -8% | 31% | **12%** |
| INMCM3_0 | 4% | 32% | **21%** | -23% | 32% | **18%** |
| IPSL_CM4 | 5% | 16% | 15% | -2% | 29% | **17%** |
| MIROC_3.2 | 21% | 21% | 18% | -18% | 21% | **25%** |
| MIROC_3.2_HI | 14% | 22% | 16% | 3% | 22% | **15%** |
| PCM1 | 5% | 30% | 6% | -17% | 63% | **13%** |
| ENSEMBLE AVERAGE | 4% | 22% | 15% | -10% | 41% | 15% |

Statistically significant differences are in **bold**.

Near-term (2020-2050) future output from two of the statistically downscaled GCMs (CGMCM 3.1 T47 and INMCM3_0) showed statistically significant ($p<0.05$) increases in the average and statistically significant ($p<0.05$) changes to the distribution of the annual maximum daily rainfall totals relative to historical (1970-2000) rainfall. Long-term future

(2001-2098) output from 17 of the 20 statistically downscaled GCMs show statistically significant ($p \leq 0.05$) increases in the average of the annual maximum daily rainfall totals relative to simulated long-term historical (1915-2006) rainfall. Output from 10 of the 20 GCMs show statistically significant ($p \leq 0.05$) changes in the distribution of annual maximum daily rainfall totals.

**Table 5. Statistical comparison of future and historical annual daily maximum rainfall totals for 20 statistically downscaled GCMs for two time periods.**

| GCM | 1970-2000 vs 2020-2050 | | 1915-2006 vs 2001-2098 | |
|---|---|---|---|---|
| | Wilcoxon Rank Sum (*p*) | Kolmogorov-Smirnov (*p*) | Wilcoxon Rank Sum (*p*) | Kolmogorov-Smirnov (*p*) |
| BCCR | 0.267 | 0.200 | **0.025** | 0.122 |
| CGMCM 3.1 T47 | **0.031** | **0.026** | **0.000** | **0.000** |
| CGMCM 3.1 T63 | 0.228 | 0.200 | **0.000** | **0.001** |
| CCSM3 | 0.130 | 0.200 | **0.029** | **0.042** |
| CNRM_CM3 | 0.133 | 0.200 | **0.023** | 0.077 |
| CSIRO_3_5 | 0.412 | 0.342 | **0.034** | 0.129 |
| ECHAM5 | 0.191 | 0.200 | 0.057 | 0.103 |
| ECHO_G | 0.501 | 0.342 | **0.027** | 0.135 |
| FGOALS_0_G | 0.912 | 0.760 | 0.430 | 0.398 |
| GFDL_CM2_0 | 0.420 | 0.537 | **0.034** | 0.145 |
| GFDL_CM2_1 | 0.412 | 0.760 | 0.192 | 0.322 |
| GISS_AOM | 0.196 | 0.109 | **0.002** | **0.005** |
| GISS_ER | 0.178 | 0.200 | **0.010** | **0.026** |
| HADCM | 0.095 | 0.055 | **0.013** | **0.017** |
| HADGEM1 | 0.348 | 0.342 | **0.043** | 0.170 |
| INMCM3_0 | **0.035** | **0.005** | **0.000** | **0.000** |
| IPSL_CM4 | 0.154 | 0.200 | **0.000** | **0.002** |
| MIROC_3.2 | 0.107 | 0.200 | **0.000** | **0.000** |
| MIROC_3.2_HI | 0.064 | 0.109 | **0.001** | **0.002** |
| PCM1 | 0.412 | 0.537 | **0.029** | 0.161 |

*tau* = strength of trend, *p* = significance of trend, Sens's Slope = magnitude of trend. Statistically significant trends are in **bold**.

Output from three of the statistically downscaled GCMs have statistically significant ( $\leq 0.05$) and relatively strong trends ($0.30 \geq tau \geq 0.50$) of increasing magnitudes for the annual maximum daily rainfall event (Table 6) over the 30 year period. Output from eight of the 2001-2098 statistically downscaled GCMs have statistically significant ($p \leq 0.05$) increasing magnitudes for the annual maximum daily rainfall event (Table 6) over the 97 year period.

**Table 6. Statistical analysis of trends for near-term (2020-2050) and long-term (2001-2098) annual daily maximum rainfall totals for 20 statistically downscaled GCMs.**

| GCM | 2020-2050 | | | 2001-2098 | | |
|---|---|---|---|---|---|---|
| | Mann-Kendall | | Sen's Slope (inches/yr) | Mann-Kendall | | Sen's Slope (inches/yr) |
| | *tau* | *p* | | *tau* | *p* | |
| BCCR | 0.31 | **0.019** | 0.31 | 0.10 | 0.156 | 0.002 |
| CGMCM 3.1 T47 | 0.40 | **0.002** | 0.40 | 0.12 | 0.086 | 0.003 |
| CGMCM 3.1 T63 | 0.25 | 0.054 | 0.25 | 0.10 | 0.166 | 0.002 |
| CCSM3 | 0.08 | 0.568 | 0.08 | 0.00 | 0.993 | 0.000 |
| CNRM_CM3 | 0.06 | 0.669 | 0.06 | 0.24 | **0.000** | 0.006 |
| CSIRO_3_5 | 0.20 | 0.134 | 0.20 | 0.21 | **0.002** | 0.005 |
| ECHAM5 | 0.15 | 0.254 | 0.15 | 0.18 | **0.008** | 0.005 |
| ECHO_G | 0.03 | 0.830 | 0.03 | 0.18 | **0.007** | 0.004 |
| FGOALS_0_G | 0.06 | 0.643 | 0.06 | 0.01 | 0.922 | 0.000 |
| GFDL_CM2_0 | 0.22 | 0.087 | 0.22 | 0.15 | **0.033** | 0.004 |
| GFDL_CM2_1 | 0.31 | **0.017** | 0.31 | -0.01 | 0.906 | 0.000 |
| GISS_AOM | -0.09 | 0.521 | -0.09 | 0.11 | 0.104 | 0.002 |
| GISS_ER | 0.01 | 0.943 | 0.01 | 0.14 | 0.053 | 0.004 |
| HADCM | -0.04 | 0.748 | -0.04 | 0.11 | 0.104 | 0.002 |
| HADGEM1 | 0.03 | 0.803 | 0.03 | 0.09 | 0.215 | 0.002 |
| INMCM3_0 | 0.03 | 0.830 | 0.03 | 0.12 | 0.080 | 0.003 |
| IPSL_CM4 | -0.06 | 0.669 | -0.06 | 0.22 | **0.002** | 0.006 |
| MIROC_3.2 | 0.05 | 0.695 | 0.05 | 0.14 | **0.041** | 0.004 |
| MIROC_3.2_HI | 0.18 | 0.164 | 0.18 | 0.25 | **0.000** | 0.005 |
| PCM1 | 0.13 | 0.335 | 0.13 | 0.06 | 0.394 | 0.001 |

*tau* = strength of trend, *p* = significance of trend, Sens's Slope = magnitude and direction of trend. Statistically significant trends ($p \leq 0.05$) are in **bold**.

As illustrated in Figure 4 below, there is a general pattern of increases for the very large annual events (99 percentile and annual maximum) and the smaller events in the 5 to 50 percentile range.

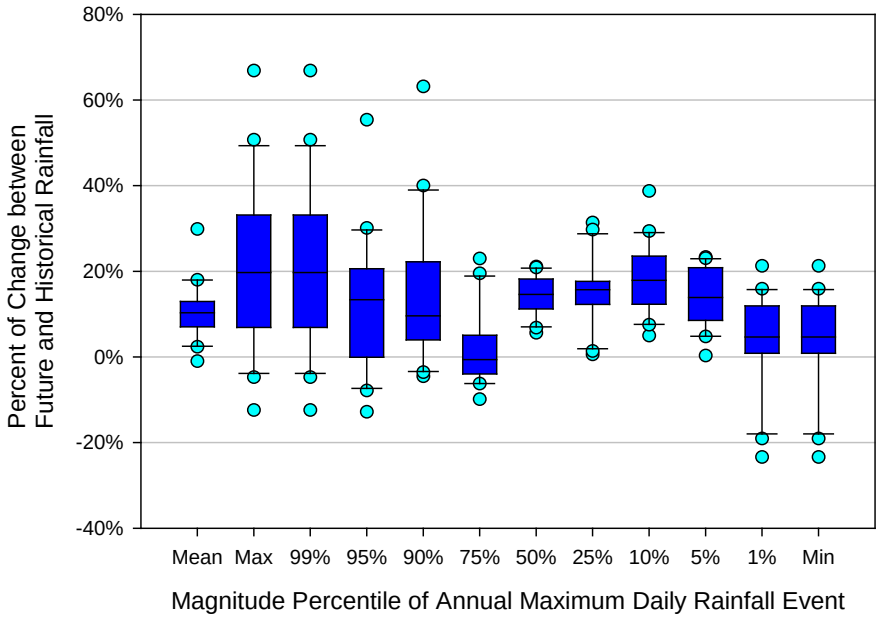


**Figure 4. Box plot of relative change in annual maximum daily rainfall totals between historical (1970-200) and future (2020-2050) simulations for 20 statistically downscaled GCMs.**

Analysis of the relative change between historical (1970-2000) and future (2020-2050) conditions in the distribution of annual maximum daily rainfall totals of the dynamically downscaled optimistic and pessimistic scenarios evaluated by Rosenberg et al. (2010) showed starkly different changes. Under the optimistic scenario, smaller 1-day storms get smaller, and larger 1-day storms get bigger (Table 7). The largest increase in storm magnitudes occurs at the 95 percentile with a 10 percent increase in storm magnitude between historical and future projections. The largest reduction in the small storms occurs at the 5th-percentile (magnitudes are reduced 17 percent).

Simulations from the pessimistic scenario combination showed increases ranging from 11 to 53 percent for all size classes of annual storms (Table 7). The largest relative increases in rainfall volumes occurred at the extreme ends of the distribution—top and bottom 1-percent (i.e., the largest and smallest annual storms increase). The in-between class size storms moderately increase relative to historical ranging from 11 to 29 percent.

**Table 7. Relative change among class sizes in annual maximum rainfall events between Historical (1970-2000) and Future (2020-2050).**

| Statistic | Optimistic Scenario (ECHAM5 GCM and A1B greenhouse gas scenario) | Pessimistic Scenario (CCSM3 GCM and A2 greenhouse gas scenario) |
|---|---|---|
| Mean | 4% | 18% |
| 100% | 6% | 53% |
| 99% | 7% | 48% |
| 95% | 10% | 29% |
| 90% | -6% | 20% |
| 75% | 8% | 11% |
| 50% | 8% | 17% |
| 25% | 2% | 12% |
| 10% | -9% | 22% |
| 5% | -17% | 25% |
| 1% | -14% | 40% |
| 0% | -10% | 46% |

## 3.2 Changes in Stormwater Pond Volumes

The "optimistic" and "pessimistic" dynamically downscaled and bias corrected hourly precipitation output was used to model stormwater pond size requirements. Theoretical future stormwater pond sizes are compared to theoretical historical pond sizes in Table 8. These ponds were sized based on the assumptions previously described in Section 2.3.

**Table 8. Theoretical stormwater pond sizes (acre-feet) for 100 acres of residential development under different model, emission scenario, and time periods.**

| Scenario | Greenhouse Gas Scenario | GCM | 1970-2000 | 2020-2050 | Percent Increase |
|---|---|---|---|---|---|
| Optimistic | A1B | ECHAM5 | 20.90 | 21.01 | 0.5% |
| Pessimistic | A2 | CCSM3 | 18.85 | 20.85 | 11% |

Similar theoretical stormwater pond volumes were calculated for the historical and future time periods for the optimistic scenario. The pessimistic scenario from 2020-2050 resulted in an 11 percent increase in theoretical pond volumes relative to the 1970-2000 time period. Final pond designs for each climate scenario result in ponds that were slightly over sized to achieve design targets (Figure 5 through Figure 8).

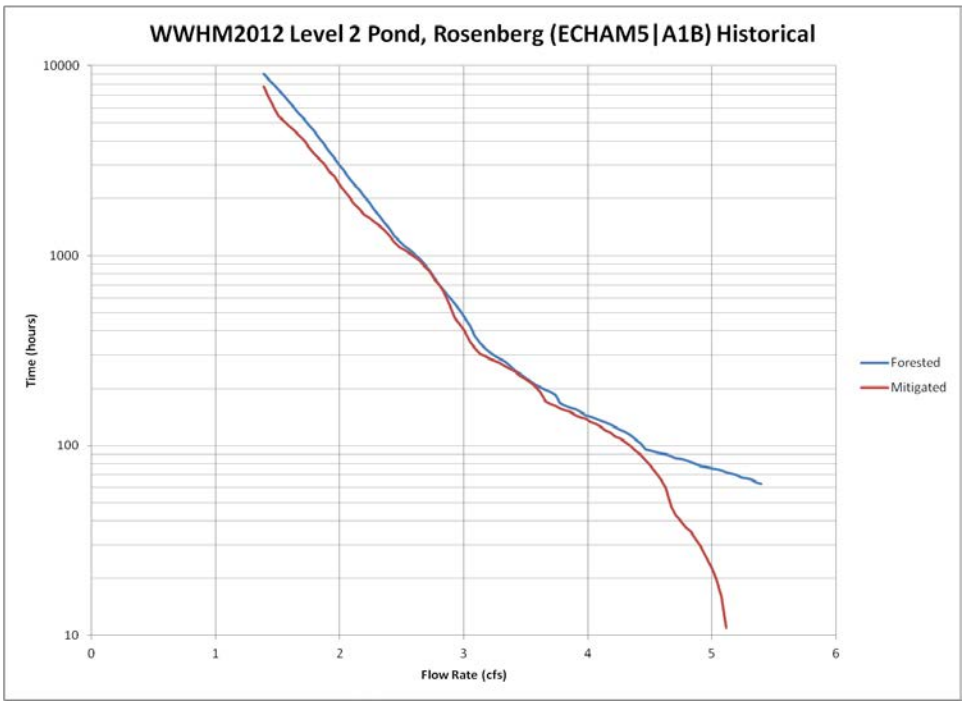


**Figure 5. Mitigation pond performance for the dynamically downscaled ECHAM5 GCM and A1B emission scenario, 1970-2000.**

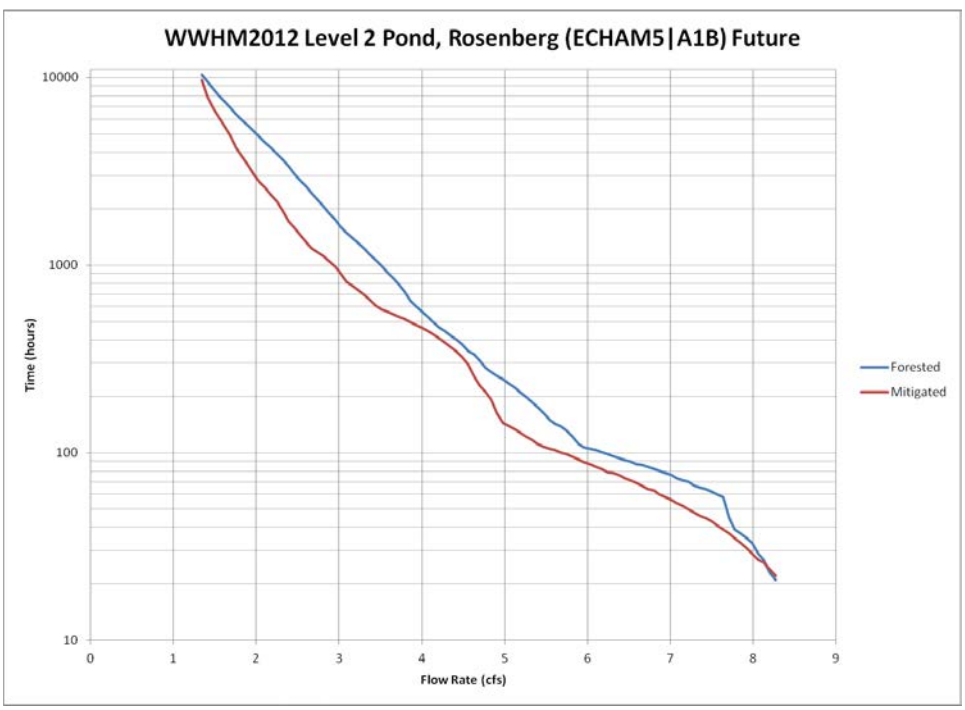


**Figure 6. Mitigation pond performance for dynamically downscaled ECHAM5 GCM and A1B emission scenario, 2020-2050.**

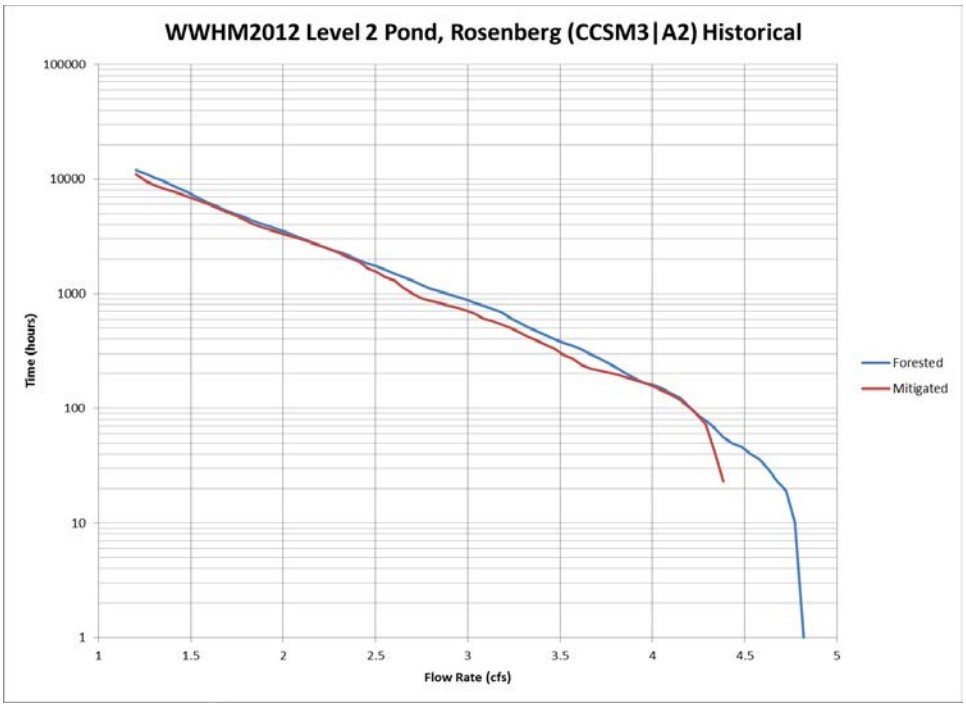


**Figure 7. Mitigation pond performance for Rosenberg dynamically downscaled CCSM3 GCM and A2 emission scenario, 1970-2000.**

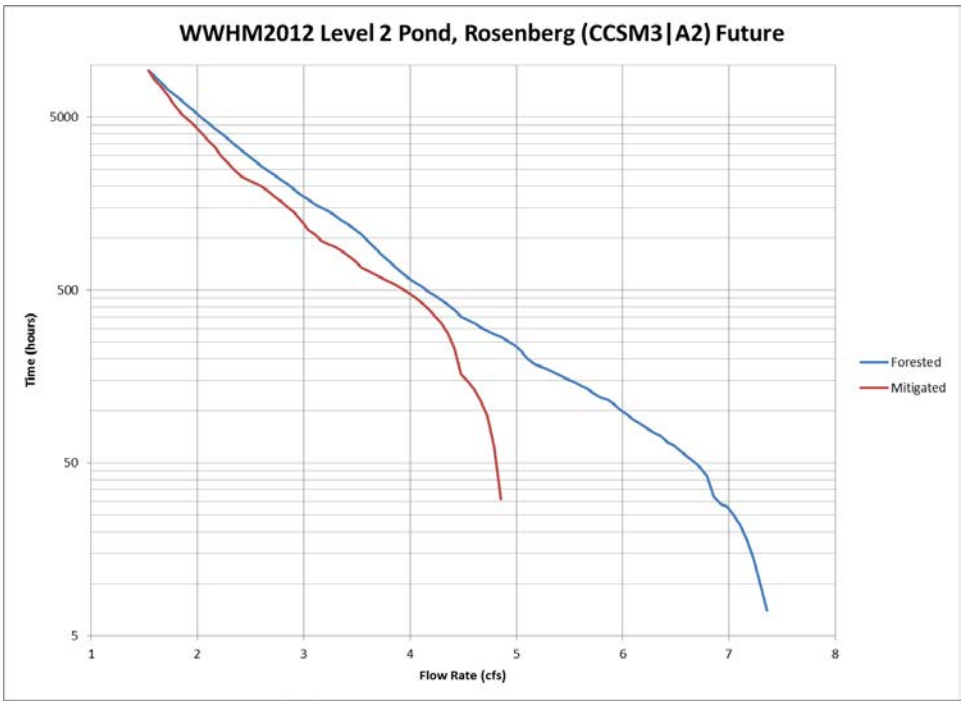


**Figure 8. Mitigation pond performance for Rosenberg dynamically downscaled CCSM3 GCM and A2 emission scenario, 2020-2050.**

## 3.3 Impacts on High Pulse Count

The annual number of HPCs was calculated for 1970-2000 and 2020-2050 for three land use scenarios and two combinations of dynamically downscaled GCMs and GHG emissions scenarios, an optimistic scenario using the ECHAM5 GCM and the A1B emission scenario and a pessimistic scenario using the CCSM3 GCM and the A2 model. Modeled HPCs for the hypothetical catchments are summarized in Table 9.

**Table 9. Summary statistics of High Pulse Count from hypothetical catchment models.**

| Time Period | Scenario | Land Use | Min | 25th percentile | Median | 75th percentile | Max |
|---|---|---|---|---|---|---|---|
| 1970-2000 | Optimistic (ECHAM5 GCM and A1B emissions scenario) | Forested | 0 | 5 | 7 | 9 | 11 |
| | | Low Density Urban | 9 | 12 | 13 | 14 | 20 |
| | | High Density Urban | 20 | 25 | 28 | 31 | 40 |
| | Pessimistic (CCSM3 GCM and A2 emissions scenario) | Forested | 2 | 4 | 6 | 8 | 12 |
| | | Low Density Urban | 7 | 10 | 12 | 15 | 19 |
| | | High Density Urban | 20 | 24 | 27 | 29 | 36 |
| 2020-2050 | Optimistic (ECHAM5 GCM and A1B emissions scenario) | Forested | 2 | 5 | 7 | 11 | 15 |
| | | Low Density Urban | 7 | 11 | 16 | 18 | 24 |
| | | High Density Urban | 18 | 26 | 29 | 32 | 37 |
| | Pessimistic (CCSM3 GCM and A2 emissions scenario) | Forested | 3 | 6 | 8 | 9 | 14 |
| | | Low Density Urban | 6 | 10 | 12 | 14 | 16 |
| | | High Density Urban | 16 | 22 | 25 | 29 | 35 |

Statistical differences in the average HPC and distribution of HPC were assessed between the two time periods (Table 10). The pessimistic scenario (based on the CCSM3 GCM model and the A2 emission scenario) generated statistical differences in the simulated mean HPC means for forested land use conditions. None of the other comparisons produced statistically significant differences (Table 10).

**Table 10. Tests of statistical significance between simulated 1970-2000 and 2020-2050 High Pulse Counts.**

| Scenario | Land Use Land Cover | Wilcoxon Rank Sum (p) | Kolmogorov-Smirnov (p) |
|---|---|---|---|
| Optimistic (ECHAM5 GCM and A1B emission scenario) | Forest | 0.572 | 0.200 |
| | Low Density Urban | 0.265 | 0.055 |
| | High Density Urban | 0.463 | 0.936 |
| Pessimistic (CCSM3 GCM and A2 emission scenario) | Forest | **0.011** | 0.109 |
| | Low Density Urban | 0.893 | 0.537 |
| | High Density Urban | 0.057 | 0.342 |

Note: Bold indicate p-values ≤ 0.05.

The average HPC for the pessimistic scenario under forested conditions was projected to increase by 27 percent. The historic and future average HPCs for all other scenario and land use combinations were not statistically different and ranged from a decrease of 8 percent to an increase of 11 percent (Table 11).

**Table 11. Relative change between historical and future average high pulse count for forested and unmitigated low and high density urban landscapes.**

| Scenario | Forested | Low Density Urban | High Density Urban |
|---|---|---|---|
| Optimistic (ECHAM5 GCM and A1B emission scenario) | 11% | 10% | 2% |
| Pessimistic (CCSM3 GCM and A2 emission scenario) | **27%** | -3% | -8% |

# 4.0. DISCUSSION

Three types of evaluations were conducted to assess the potential for future climate change to affect stormwater management. The three lines of evidence include:

- Statistical analysis of modeled future and historical annual maximum daily rainfall totals
- Comparison of modeled future and historical stormwater pond volumes for hypothetical drainage basins
- Comparison of modeled future and historical stormwater runoff HPC for drainage basins with three different hypothetical land uses.

Evaluation of potential future changes in annual maximum daily rainfall totals provided an indication of whether changes in precipitation patterns might be anticipated at the scale relevant to stormwater management. Two of the 20 GCMs downscaled to daily totals at the watershed scale showed statistically significant higher averages of the annual maximum daily rainfall totals for the future time period 2020-2050. However, 17 of the 20 models show significant increases over a longer time period. The average of the annual maximum daily rainfall totals increased about 15 percent in both the near-term and long-term analyses. The model output suggests that the variability between years is likely to increase, with the largest storms becoming substantially larger and smaller storms becoming even smaller events. Hourly rainfall totals from the pessimistic dynamically downscaled scenario (i.e., output from the CCSM3 GCM combined with the A2 emission scenario) showed future increases in all storm sizes, which is likely related to the increase in total precipitation projected in this scenario. Hourly rainfall totals from the optimistic dynamically downscaled scenario (i.e., output from the ECHAM5 GCM and the A1B emission scenario) was similar to the statistically downscaled output in that the larger storms are projected to increase in size and the smaller storms are projected to decrease.

Focusing on maximum annual daily rainfall events does not fully characterize impacts on stormwater infrastructure, but can be a good indicator of potential impacts. Stormwater conveyance systems are designed using hourly (or sub-hourly) rainfall totals rather than daily totals. For example, the King County (2009) Stormwater Design Manual requires stormwater mitigation ponds to be designed using continuous hourly precipitation data spanning multiple decades. This design methodology takes into account variable antecedent conditions which can compromise designs as the effectiveness varies depending on soil moisture in the drainage basin leading up to the event.

To characterize potential impacts of climate change on stormwater pond designs, four stormwater ponds were designed using WWHM2012 software for historical and future conditions under the optimistic (ECHAM5 GCM and A1B emission scenario) and pessimistic (CCSM3 GCM and the A2 emission scenario) scenarios. Changes in storage volumes are presented as relative changes to historical conditions. Comparing climate induced changes in required stormwater mitigation pond sizes provide insight on future stormwater planning efforts.

Resources required to dynamically downscale global climate models using regional climate models (e.g., WRF) is substantial, limiting the amount of analyses that can be conducted in the stormwater modeling community. The less computationally intensive statistical downscaling method produces temporally coarser rainfall (i.e., daily) that is not ideal for designing stormwater ponds that treat runoff from small drainage systems. However, a substantially greater number of GCMs and greenhouse gas emission scenario combinations can be downscaled using the statistical approach. It would be beneficial to both dynamically downscale additional GCM and greenhouse gas combinations, and also to develop a methodology for using the statistical downscaling output in stormwater system analysis.

It is possible that changes in large rainfall events (e.g., distributions of maximum annual rainfall events) could be related to stormwater facility designs. If this relationship were developed, it would provide a commonality between scenarios when the majority of available model outputs are inadequate for pond designs but provide greater possible outcomes in future climatic conditions. For example, if a climate scenario with data adequate to design a stormwater pond results in a 10 percent increase in pond volumes, and the 95$^{th}$ percentile storm is projected to increase in volume by 10 percent, other climate scenarios inadequate for designing stormwater ponds may be anticipated to produce similar results if changes in the rainfall distributions (e.g., rainfall volumes at the 95$^{th}$ percentile) were similar.

The interaction between land use and climate change scenario produces interesting differences in HPCs between historic and future conditions. It appears that as large storms are expected to get larger, that forested HPCs are projected to increase and forested streams would be flashier under climate change conditions. However, as urban areas, especially high density urban areas, are already extremely flashy with high HPCs, there is less of an impact under these land uses, since it appears the size of the storms, not necessarily the number of storms, is projected to increase.

Output from the ECHAM5 GCM combined with the A1B emission scenario has been downscaled using both dynamic and statistical approaches. The dynamic downscaling showed a statistical difference between historical and future annual daily maximum rainfall distributions; whereas the statistical downscaling did not reveal a statistically significantly difference. This difference in results between downscaling approaches highlights how downscaling methods can affect conclusions about the potential effects of climate change on stormwater management.

As was mentioned in Ecology (2012a), observed greenhouse gas emissions are tracking faster than previously defined for the A1B and B1 emission scenarios and are more reflective of the A2 emission scenarios. The IPCC (2013) recently completed their fifth assessment report (AR5) where the methodology for designing emission scenarios has been substantially revised (Representative Concentration Pathways—RCP2.6, RCP4.5, RCP6, etc.), while loosely reflecting the emission scenarios from the IPCC (2007) 4$^{th}$ Assessment Report (A1B, B1, A2, etc.) used in climate studies up to this point (Salathé 2014). No downscaled GCM output was available using the new emission scenarios.

# 5.0. CONCLUSIONS AND RECOMMENDATIONS

Three lines of evidence were examined to assess the potential impacts of climate change on stormwater BMP needs. Few articles were identified in the literature review that focused on climate change impacts on precipitation at the hourly timescale that is relevant to stormwater management. However, available literature does suggest an increase in the variability in the size of large storms in future years. An evaluation of an ensemble of 20 GCMs for the A1B emission scenario showed a modest increase (15 percent) in the average of the annual daily maximum rainfall total, with larger storms generally predicted to be larger and smaller storms generally predicted to be smaller.

Using two dynamically downscaled sets of output to size a Level 2 stormwater pond based on a theoretical catchment of low density residential development, pond volumes marginally increased less than 1 percent in the optimistic scenario. Stormwater pond volumes calculated under a pessimistic scenario increased approximately 11 percent. Impacts of climate change on stream flashiness (as measured by HPC) range from a decrease of 8 percent to an increase of 27 percent, depending on scenario and modeled land use.

Presented with this large variability of possible changes in rainfall and subsequent impacts on stormwater facility sizes, there remains a high degree of uncertainty in planning for stormwater management under future conditions. This study isolated some of the various aspects in the climate model forecasts, and in a limited perspective, illustrated the amount of variability in impacts to stormwater pond sizes and stream flashiness. Given the range of modeled projected changes in rainfall totals, pond volumes, and HPC, a 10 percent increase in stormwater treatment pond size appears to be an appropriate estimate for planning purposes as part of this study. Additional research into the impacts of climate change on stormwater facility sizing is recommended. Of key interest is the use of additional global climate models and newer emission scenarios, use of bias-corrected dynamical downscaling techniques, and the evaluation of a variety of stormwater facility types to assess the overall sensitivity of stormwater design calculations to climate change.

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