DRAFT

Evaluation of Potential Climate Change Impacts on Stormwater Management

February 2014

King County

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Citation

King County. 2013. Evaluation of Potential Climate Change Impacts on Stormwater Management. Prepared by Jeff Burkey, Science and Technical Support Section, Water and Land Resources Division. Seattle, Washington.

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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 (King County 2010b).[1] 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. It documents the evaluation of possible effects of climate change on receiving streams and stormwater system networks.

Obtained from University of Washington Climate Impacts Group were multiple global climate model (GCM) outputs downscaled for assessments at watershed scale. Twenty of the modeling scenarios rainfall were statistically downscaled from 20 different GCMs based on one emission scenario (A1B); where it is assumed global energy production in the future is balanced between fossil fuels and non-fossil energy sources. Emissions from carbon dioxide (a green house gas) slowly increase to a peak in year 2050, then declines to the year 2100, approximately 30% greater than year 2000 emissions. Two of the 20 GCMs used were downscaled differently using a regional climate model and statistically bias corrected. One of those two GCMs used a different emission scenario (A2). The A2 scenario assumes a slow progress transitioning from fossil fuel based energy to cleaner emission technologies with carbon dioxide emissions increasing through the end of the twenty-first century—the year 2100.

The area evaluated in this study covers 278 square miles of the middle and lower Green River watershed below Howard Hanson Dam and the Puget Sound drainages of WRIA 9. Lands within Seattle are not included in the study area because a vast majority of Seattle's lands within WRIA 9 are served by a combined sewer and stormwater system and a combined sewer overflow (CSO) control program is in progress for that area. The area of WRIA 9 upstream of Howard Hanson Dam is not included in the study area because it is primarily forested and maintained to protect Tacoma Public Utilities' water supply.

Climate model outputs are spatially distributed covering vast areas of the landscape. One output location was selected from each modeling ensemble to reflect rainfall conditions in study area. Data used for analysis include synthesized thirty years of historical conditions spanning from 1970 to 2000 and thirty years of simulated future rainfall projected in 2020 through 2050. Errors and accuracy limitations using outputs from climate modeling warrants comparisons made should be relative within a modeling ensemble, diminishing sensitivities in interpretations of the results. Thus, evaluations are made by calculating differences relative to synthesized historical conditions.

[1] http://your.kingcounty.gov/dnrp/library/water-and-land/watersheds/green-duwamish/stormwater-retrofit-project/stormwater-retrofit-workplan.pdf

Three types of comparisons are made to characterize possible climate change impacts on stormwater: 1) rainfall storm events, 2) storage volumes in theoretically designed stormwater ponds, and 3) perceived flashiness in surface runoff generated from rainfall.

Relative percent differences in annual maximum daily rainfall events generally increase in the future for most magnitudes (i.e. ≥ 5th percentile) evaluated averaging between 3 and 24 percent increase. Six of the twenty GCM models project decreases from near 0 to 21% in the smallest size storms (i.e. < 5th percentile). One of the 20 GCMs evaluated did project mean annual storm volumes to decrease one percent in the future.

Stormwater pond efficiencies depend not only on the size of the storm event, but the antecedent moisture conditions leading up to a storm event. Thus, theoretical stormwater ponds are designed using the 30-years of variable 1-hour rainfall simulations for historical and future conditions for both the A1B and A2 emission scenarios downscaled using a regional climate model method. Results show the moderate emission scenario (A1B) has less than 1 percent increase in stormwater pond volumes in the future. Whereas, the higher carbon dioxide emission scenario (A2) yields stormwater ponds increase in size approximately 11 percent.

Impacts of climate change on stream flashiness indicate that under forested landscapes, high pulse counts will relatively increase in the future more so than increases of HPC on developed landscapes. In fact, the more aggressive CO_2 emission scenario (A2) generates less HPCs in the future then historical—a decrease in HPCs in the future. This suggests, the increase in annual volumes of rainfall generating mean annual runoff nullifies some of the smaller storm events in the future on an annual basis—signifying other metrics of biological relevance should be included in future analyses.

Presented with this large variability of possible impacts to rainfall and stormwater infrastructure, accurately planning for future conditions is tenuous. At this point, it appears likely that climate change will increase needed stormwater facility sizes and costs in the future for rain dominated landscapes, but by how much is best quantified using ranges from the climate scenarios results. If one were to associate the emission scenario A2 represents an upper end of storm frequency and magnitudes, and then based on the evaluated landscape conditions in this report, an 11 % increase in stormwater pond volumes may be representative of the upper range of impacts to stormwater pond volumes for low density residential development. Including more emission scenarios, landscape conditions, and modeling frameworks will only increase the range of possibilities increasing the likelihood future conditions will be among the ensemble.

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 to implement stormwater Best Management Practices (BMPs) in developed areas of WRIA 9 built primarily without adequate stormwater controls.

This report provides an evaluation of the possible effects of climate change on the design of stormwater facilities sized using current and future climate conditions. Simulated projected rainfall from multiple global climate models were compared to simulated historical conditions to provide some insight into possible impacts on stream flashiness and cost-effectiveness of conventional stormwater retention/detention ponds.

1.1 Background

Research evaluating historical precipitation trends on a global scale and continental US show increases in frequency and magnitude of storms over the last century (e.g., Kunkel 2008, Karl and Knight 1998). These increases in frequency and magnitude are supported by projected warming of air temperatures in the lower atmosphere (Trenberth et al., 2003, and NRC, 2011). Looking at historical trends of more extreme precipitation events, there have been statistically significant trends found in the Pacific Northwest. However, these trends can be in different directions when, for example, comparing Washington (positive) to Oregon (negative) (Madsen and Figdor, 2007). Locally, depending on location and time period, changes in simulated future annual precipitation for Washington State range from -11% to +20% (Climate Impacts Group 2009) when compared to 1970-1999 averages.

Most research looking for trends in precipitation focused on metrics that capture monthly, seasonal and annual volumes, frequency and magnitudes rather than overall distributions (e.g., Mote and Salathe 2010, Adelsman and Ekrem 2012, and Dalton et al. 2013). The future projected climate data available and necessary for evaluating distributions of precipitation is limited and requires resource intensive regional scale climate modeling to downscale global climate modeling (GCM) simulations (Climate Impacts Group 2009). Current stormwater design standards in King County and Washington State require these types of distributions of rainfall (i.e. continuous time series of historical rainfall at sub-daily time increments) to generate variable runoff rates reflective of fast responding systems. It is these distributions that Rosenberg et al. (2010) used to characterize potential impacts to stormwater infrastructure using historical and projected future rainfall in the Pacific Northwest.

Rosenberg et al. (2010) found the largest increases in historical extreme precipitation events were between the 1-day and 2-day annual maximum events. The largest trend increase for observed Sea-Tac rainfall occurs in the 95-percentile for the 1 day (midnight to midnight) duration. Thus for the WRIA 9 retrofit project, comparing precipitation events among the scenarios are based on 1-day rainfall totals.

Each of these modeling systems has known errors and biases (Sun et al., 2006 and Tebaldi et al., 2006). Therefore it is most appropriate to use a relative difference method when comparing results from the various climate modeling outputs like was done, for example, in Rosenberg et al. (2010), Cuo et al. (2010) and U.S. EPA (2013).

1.2 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).

1.3 Goals and Objectives

The overall goal of the project is to assess strategies and associated costs to meet defined goals for biological protection and restoration. Included in these analyses are the possible effects of climate change to stormwater management systems. Changes in future rainfall have potential to render current stormwater design standards less effective and/or increase costs when adapting to a changing hydrologic regime. Evaluations of simulated conditions will provide guidance strategizing improvements in stormwater management.

This report leverages previously downscaled outcomes from climate change studies recently conducted in the region (Rosenberg et al., 2010 and Cuo et al. 2010) and characterize possible impacts on stormwater mitigation specific to the study area—no additional downscaling was performed

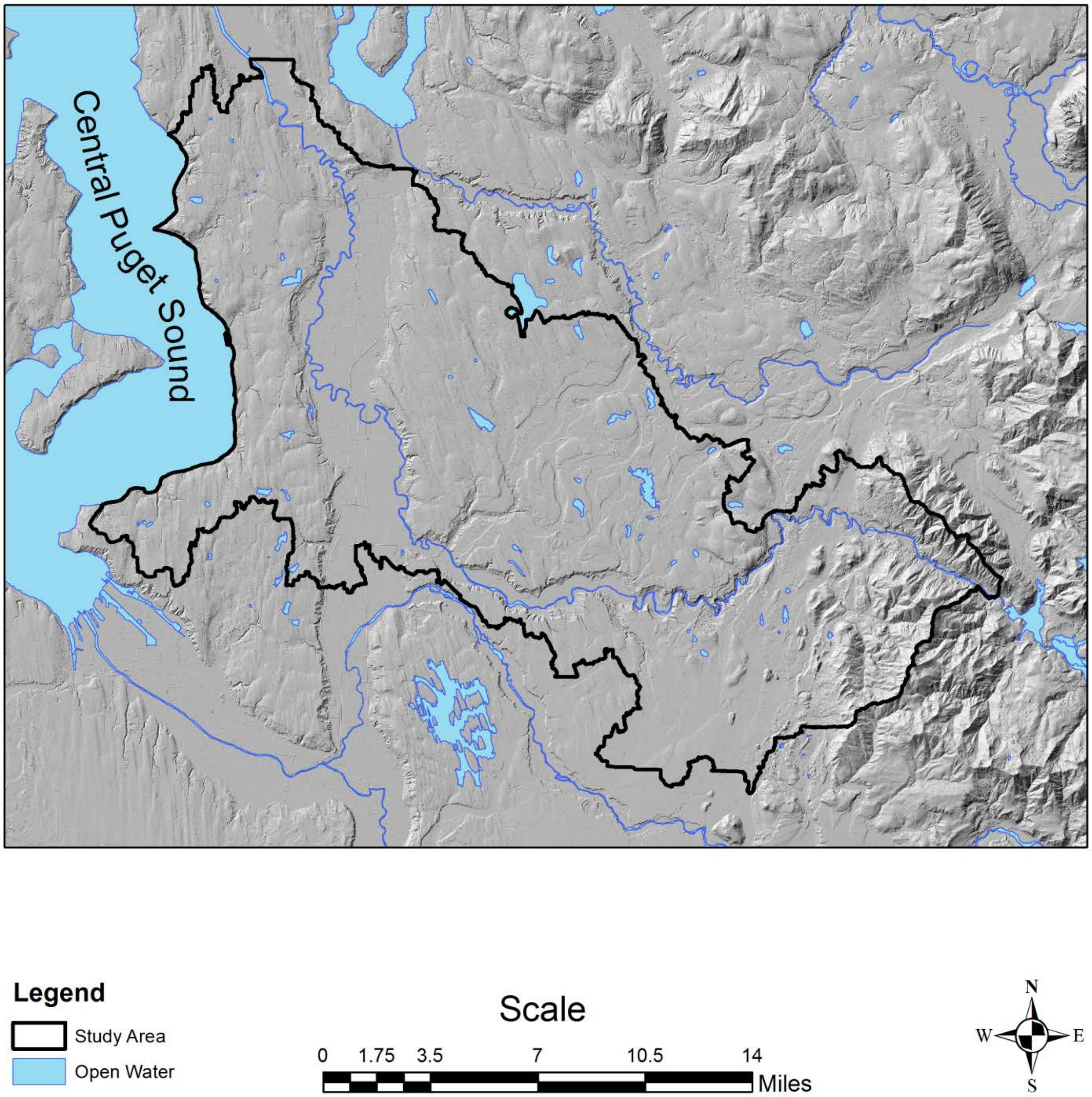

Figure 1 Map of project study.

2.0. METHODS AND DATA USED

Three methods used to characterize the effects of climate change on rainfall and potential impacts to stormwater infrastructure include: 1) compare changes in daily rainfall volumes among the various GCMs, 2) compare changes in theoretically designed stormwater pond volumes, and 3) compare changes in runoff flashiness.

2.1 GCM Data

Readily available for use from the University of Washington Climate Impacts Group are 22 climate model scenario outputs (Table 1). Twenty of the scenarios are statistically downscaled outputs from 20 different GCMs (Cuo et al., 2010) forced using a single emission scenario—A1B. This scenario is considered a moderate emission scenario and often used in climate change analyses. These projected future scenarios generally span between 1/1/2001 through 12/2098 and have daily rainfall totals evenly distributed in three-hour time increments. In addition to this ensemble, is a historical time series (1915-2006) generated for comparing future projections to historical (Cuo et al., 2009).

Two of the 20 GCMs (ECHAM5[2] and CCSM3[3]) were downscaled differently from Cuo using a regional climate model (RCM) and bias corrected (Rosenberg et al., 2010). The Weather Research and Forecast (WRF) regional climate model was used to downscale rainfall to 1-hour time increments for historical (1970-2000) and future (2020-2050) conditions. One of the WRF downscaled GCMs (CCSM3) is driven by a different emission scenario (A2).

Table 1 Summary of climate scenarios used for analysis.

GSM	Emission	Downscale	Time step	Source
CGMCM 3.1 T47	A1B	BCSD	Daily	Cuo et al., 2010
CGMCM 3.1 T63				
CNRM_CM3				
ECHAM5				
HADCM				
HADGEM1				
IPSL_CM4				
BCCR				
CCSM3				
CSIRO_3_5				
ECHO_G				
FGOALS_0_G				
GFDL_CM2_0				

[2] Max-Planck-Institute for Meteorology, Germany

[3] National Center for Atmospheric Research, USA

GSM	Emission	Downscale	Time step	Source
GFDL_CM2_1				
GISS_AOM				
GISS_ER				
INMCM3_0				
MIROC_3.2				
MIROC_3.2_HI				
PCM1				
ECHAM5[1]		WRF + BCSD	1-hour	Rosenberg et al., 2010
CCSM3[2]	A2			

[1]Duplicate GSM used for same emission scenario different downscaling

[2]Duplicate GSM used for different emission scenario and different downscaling.

Based on the geographic location of the study area, output locations of GCM simulations (Cuo et al. 2010 and Rosenberg et al. 2010) used in this analysis are shown in Figure 2. Illustrated for reference, estimated total annual rainfall (PRISM 2000) variation across the study area is shown in Figure 2. The area weighted mean annual rainfall calculated from this distribution in the study area is estimated to be 49 inches per year (45 inches per year, median).

In addition to GCM model error and biases, the downscaling methods performed by Cuo and Rosenberg on the GCMs are significantly different and not directly comparable. The 3-hour evenly distributed rainfall (Cuo) represents daily totals which is inadequate for designing stormwater ponds intended to mitigate storm runoff that occurs in minutes and hours. Rosenberg et al. simulations projected 1-hour variability in rainfall intensity necessary for designing stormwater facilities. Thus, all comparisons between historical and future scenarios are based on relative differences within each suite of models within each study.

Given the study area is focusing on streams in the Puget Sound lowlands, effects of temperature on snow pack and rain-on-snow are not part of this analysis.

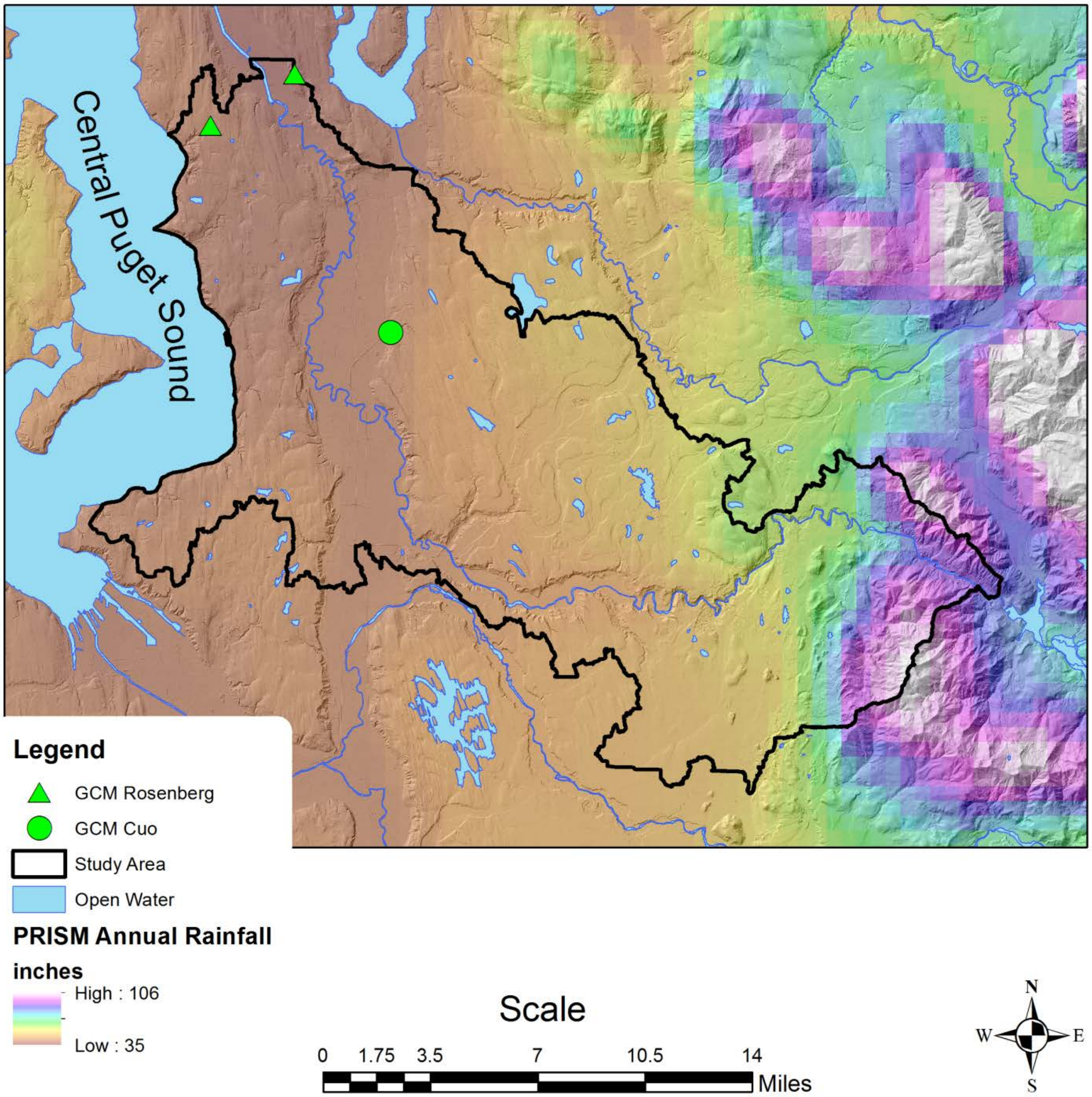

Figure 2 Study area, distributed estimated mean annual rainfall (PRISM, 2000), and locations of GCM outputs used for this analysis.

The time span of the data available includes:

- Cuo—Historical 10/1/1915 - 9/30/2006
- Cuo—Future 10/1/2001 - 9/30/2097 (start dates are slightly variable among the simulations)
- Rosenberg—Historical 10/1/1970 - 9/30/2000
- Rosenberg—Future 10/1/2020 - 9/30/2050

2.1.1 Description of A1B Emission Scenarios

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). Figure 3a 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.

2.1.2 Description of A2 Emission Scenarios

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 3b illustrates the global total carbon dioxide emissions from all energy sources. In the A2 scenario, global carbon dioxide emissions steadily increase throughout the century to about 29 GtC/yr by 2100.

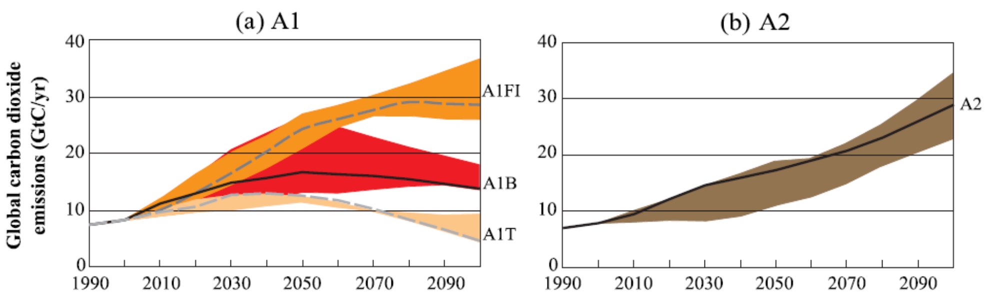

Figure 3 ***Total global annual CO2 emissions from all sources (energy, industry, and land-use change) from 1990 to 2100 (in gigatonnes of carbon (GtC/yr)) for two of the four families (A1 and A2) and four of six scenario groups (A1FI, A1B, A1T, and A2). Each colored emission band shows the range of emissions within each group (IPCC 2000).***

For each of the scenario groups an illustrative scenario is provided, including the two illustrative marker scenarios (A1B and A2 solid lines) and two illustrative scenarios for A1FI and A1T (dashed lines). In accordance with a decision of the IPCC Bureau in 1998 to release draft scenarios to climate modelers for their input in the Third Assessment Report, and subsequently to solicit comments during the open process, one marker scenario was chosen from each of four of the scenario groups based on the storylines. The choice of the markers was based on which of the initial quantifications best reflected the storyline, and features of specific models. Marker scenarios are no more or less likely than any other scenarios, but are considered by the Special Report Emissions Scenarios (SRES) writing team as illustrative of a *particular storyline. These scenarios have received the closest scrutiny of the entire writing team and via the SRES open process.* (IPCC, 2000).

2.2 Relative Percent Difference (RPD) in Annual Maximum Rainfall Events

Summary statistics were performed on 24-hour duration events (midnight to midnight) based on annual maximums for changes between historical and future simulations. The relative percent difference (Equation 1) is computed for the average and a set of percentiles (Max, 99, 95, 90, 75, 50, 25, 10, 5, 1, Min) characterizing the range of annual maximum daily rainfall amounts. Given the higher level of temporal resolution in Rosenberg's time series, more complex methods (see section 2.3) of comparisons can be performed. Comparisons made within Cuo's ensemble are given context by relating the RPD in rainfall events between the two scenario sources (i.e. Cuo and Rosenberg). Calculated statistics using Cuo's simulations were constrained using same time periods available in Rosenberg's (i.e., 1970-2000 and 2020-2050).

Equation 1 Relative percent difference in maximum annual daily rainfall events

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

2.3 Relative Percent Difference (RPD) in Stormwater Pond Volumes

Four stormwater ponds are sized by importing the 1-hour precipitation time series of Rosenberg et al. (Table 1) into Ecology's approved stormwater pond sizing software (WWHM2012[4]) for historical (1970-2000) and future (2020-2050) climatic conditions. As previously mentioned, sizing of stormwater ponds requires rainfall at hourly or even 15-minute increments which Cuo's time series will not support. Ponds were designed using King County Level 2 target conditions (i.e., matching runoff durations between half the 2-year and 50-year flood frequency magnitudes[5]) based on conversion from fully forested landscape.

Design constraints sizing the ponds include:

- 4-ft pond depth
- 3:1 side slopes
- 3-orifice or single orifice with notched weir outlet structure

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

[5] 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.

- Square footprint
- No infiltration
- Groundwater bypasses facility

The theoretical catchments used for sizing stormwater ponds replicate land cover distributions defined in the King County Watershed Model Development report (King County 2013, Table 29). For this exercise, low density residential was selected for comparative purposes among the Rosenberg scenarios. The theoretical catchment is assumed to be 100 acres of homogenous residential landscape and comprised of 4.6 acres road, 4.7 acres roof tops, and 90.7 acres of grass lawns. Point of compliance is assigned to the outlet of the pond structure.

Stormwater ponds are then sized using the internal optimization routines in WWHM2012 that best achieve design targets. The stormwater pond volumes derived from simulated future climate conditions are compared to ponds sized using the simulated historical climate conditions for the same land cover distributions. However, the level of success in optimization (i.e., minimizing pond volumes while achieving design targets) can be variable and would affect the calculated relative percent difference in pond volumes. Given the same input conditions, better optimized pond volumes will be smaller, thus inducing a "changed" condition that otherwise should not exist.

The relative difference between pond volumes using the Rosenberg emission scenarios are calculated using Equation 2 below.

Equation 2 Relative percent difference in stormwater pond volumes using Rosenberg scenarios

$$Pond\ Volume_{RPD} = \frac{Volume_{Future} - Volume_{Historical}}{Volume_{Historical}} * 100$$

2.4 High Pulse Counts Flashiness Metric

High Pulse Counts (HPC) is one of the three metrics selected for evaluation of stormwater management scenarios in the WRIA 9 Stormwater Retrofit study (Horner, 2013). This flashiness metric has been identified as statistically relevant when correlating to macro invertebrates (Horner, 2013) quantified using the Benthic Index of Biotic Integrity (BIBI)—an integrated measure of stream health.

> <u>High Pulse Count</u> 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) are used in WWHM2012 to generate flow rates driven by the 1-hour time increment (i.e., Rosenberg) climate scenarios. Forested landscape is used as benchmark to compare the effects of climate change in an undisturbed environment. Low density urban (synonymous with low density residential) is assumed 9.3% impervious and 90.7% lawns. High density urban (i.e., commercial/industrial) is 65.8% impervious and 34.2% lawns. All three are defined to be flat slope and underlain with low permeability (till) soils.

Similar to the previous equations, Equation 3 defines how the relative percent differences are computed for HPCs.

Equation 3 Relative percent different in High Pulse Counts

$$Future_{HPC} = \frac{HPC_{future} - HPC_{historical}}{HPC_{historical}} * 100$$

A comparison is made using the same GCM (ECHAM5) and emission scenario (A1B) between Rosenberg and Cuo. Differences in downscaling methods are quantified using high pulse counts. The effect of differing time step increments on HPCs are removed by redistributing variable 1-hour rainfall in Rosenberg scenarios to evenly distributed daily rainfall reflective in Cuo's simulations. (Equation 4).

Equation 4 Relative percent difference in HPCs based on downscaling method

$$DS_{HPC} = \frac{HPC_{Rosenberg} - HPC_{Cuo}}{HPC_{Cuo}} * 100$$

Another comparison is made quantifying sensitivity when dissolving 1-hour variable rainfall into evenly distributed daily rainfall at 1-hour increments as reflected in Cuo's simulations. Using the exact same future climate scenario from Rosenberg (ECHAM5|A1B), HPCs were calculated based on 1-hour variable and the same rainfall evenly distributed (Equation 5).

Equation 5 Relative percent difference in HPCs based on variable versus evenly distributed rainfall

$$Temporal_{HPC} = \frac{HPC_{24hr} - HPC_{1hr}}{HPC_{1hr}} * 100$$

3.0. RESULTS

Results comparing a suite of simulated historical and future climate conditions are presented in this section characterizing differences in: rainfall volumes, designed stormwater pond volumes, and hydrologic flashiness as measured with high pulse counts.

3.1 Relative Percent Differences in Rainfall

3.1.1 Rosenberg Scenarios

Relative percent differences between historical and future conditions in annual maximum daily rainfall totals varied depending on the magnitude of the storm for the Rosenberg ECHAM5|A1B emission scenario. There is a shift in the distribution such that smaller 1-day storms get smaller, and larger 1-day storms get bigger (Table 2). The largest increase in storm magnitudes occurs at the 95 percentile with a 10% 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%).

Simulations from the Rosenberg CCSM3|A2 scenario show increases ranging from 11 to 53 percent for all size classes of annual storms (Table 2). The largest relative increases in rainfall volumes occur 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.

3.1.2 Cuo's Scenarios

Cuo's ensemble of GCM simulations were summarized using time spans consistent with Rosenberg (i.e., 1970-2000 and 2020-2050). The average increase in annual maximum daily rainfall among the 20 GCMs is 11 percent, but range from a slight (-1%) decrease to a large (29%) increase (Table 2). Three of the GCMs (CSIRO, ECHO, and FGOALS) had smaller average increases in storm magnitudes of 4%, 3%, and -1%, respectively; while three (CGCM 3.1T43, INNCM3, and MIROC_HI) averaged larger increases of 29%, 18%, and 18%, respectively. The remainder of the GCMs averaged between 7% and 17% increases in rainfall volumes (Table 3 and Table 4).

Comparing like global climate models and emission scenarios (ECHAM5|A1B), Cuo's downscaling method generated larger future storm volumes (8 percent increase in mean annual maximum daily rainfall events) relative to Rosenberg's 4 percent increase. Storm class sizes at the 5 and 10 percentiles increase in magnitude (+12% and +22%) evaluating Cuo and decrease in magnitude (-9% and -17%) based on Rosenberg.

Table 2 Relative percent differences among class sizes (i.e. percentiles) in annual maximum rainfall events between Historical and Future. Darker the blue the larger the increase, the darker the orange the larger the decrease.

	Rosenberg		Cuo A1B[1]		
Statistic	ECHAM5 | A1B	CCSM3 | A2	Avg[2]	Min[2]	Max[2]
Mean	4%	18%	11%	-1%	29%
100%	6%	53%	24%	-8%	68%
99%	7%	48%	20%	-9%	51%
95%	10%	29%	14%	-7%	56%
90%	-6%	20%	12%	-5%	63%
75%	8%	11%	3%	-10%	19%
50%	8%	17%	13%	3%	22%
25%	2%	12%	18%	6%	32%
10%	-9%	22%	19%	7%	41%
5%	-17%	25%	12%	-2%	24%
1%	-14%	40%	5%	-16%	19%
0%	-10%	46%	4%	-21%	19%

[1]Average for all 20 GCMs in Table 3 and Table 4

[2]Based on matching Rosenberg time spans, 1970-2000 and 2020-2050

Table 3 Relative percent difference among class sizes (i.e., percentiles) in annual maximum daily rainfall between Historical and Future (Cuo, reduced (2020-2050) time span).

Statistic	BCCR	CGCM 3.1 T47	CGCM 3.1 T63	CCSM3	CNRM_CM3	CSIRO_3_5	ECHAM5	ECHO_G	FGOALS_0_G	GFDL_CM2_0
Mean	7%	29%	13%	17%	11%	4%	8%	3%	-1%	8%
100%	-1%	51%	37%	38%	13%	-8%	10%	6%	11%	11%
99%	-2%	51%	31%	35%	11%	-9%	7%	2%	6%	10%
95%	4%	56%	14%	32%	13%	-7%	8%	1%	-6%	9%
90%	0%	63%	6%	37%	11%	-5%	13%	1%	-5%	11%
75%	-3%	15%	0%	19%	13%	-2%	0%	-10%	-3%	3%
50%	10%	21%	22%	12%	15%	15%	11%	5%	7%	11%
25%	22%	32%	17%	20%	8%	20%	14%	16%	6%	17%
10%	25%	14%	13%	11%	8%	20%	22%	24%	7%	13%
5%	15%	9%	6%	-2%	7%	14%	12%	12%	5%	3%
1%	10%	-3%	3%	-16%	5%	-4%	-1%	12%	-12%	4%
0%	11%	-6%	3%	-21%	5%	-10%	-5%	12%	-20%	5%

Table 4 Cont'd—Relative percent difference among class sizes (i.e., percentiles) in annual maximum daily rainfall between Historical and Future (Cuo, reduced time span).

Statistic	GFDL_CM2_1	GISS_AOM	GISS_ER	HADCM	HADGEM1	INNCM3_0	IPSL_CM4	MIROC_3.2	MIROC_HI	PCM1
Mean	8%	10%	11%	12%	10%	18%	12%	12%	18%	8%
100%	68%	38%	18%	19%	32%	33%	20%	21%	28%	37%
99%	51%	32%	16%	18%	22%	28%	19%	16%	26%	32%
95%	9%	8%	15%	13%	4%	19%	27%	9%	28%	26%
90%	3%	-5%	15%	5%	9%	13%	10%	13%	21%	13%
75%	4%	-5%	2%	3%	1%	8%	-1%	7%	9%	-3%
50%	3%	19%	15%	17%	17%	21%	14%	15%	13%	5%
25%	7%	18%	23%	21%	15%	32%	26%	14%	27%	8%
10%	15%	19%	15%	21%	22%	41%	13%	25%	33%	15%
5%	11%	13%	11%	14%	15%	22%	10%	23%	24%	8%
1%	0%	15%	7%	13%	8%	12%	9%	18%	19%	6%
0%	-5%	17%	7%	14%	6%	8%	10%	16%	19%	7%

As illustrated in Figure 4 below, there is a general pattern of increases for the very large annual events (99 percentile) and the smaller events in the 10 to 25 percentile range.

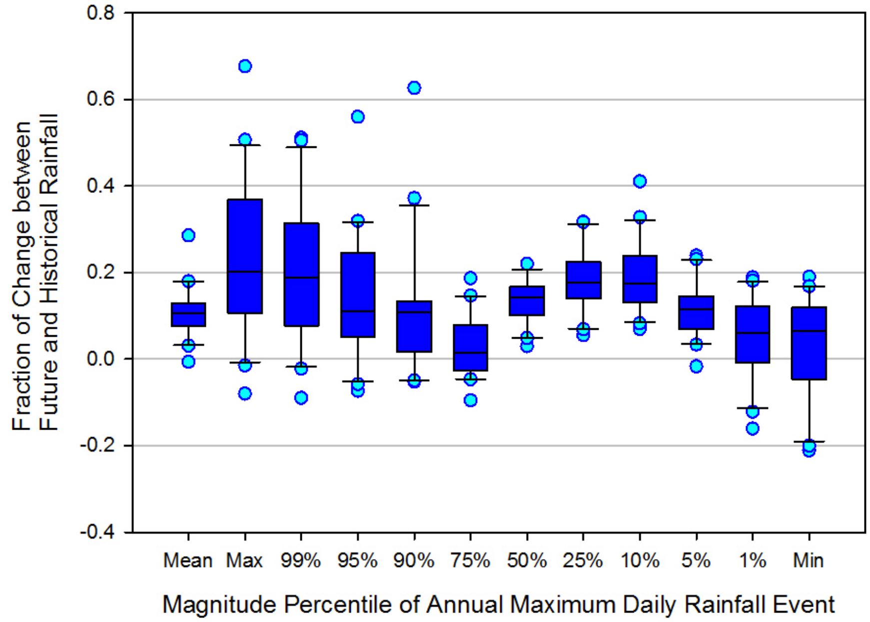

Figure 4 Box plot summarizing relative fraction of change in annual maximum rainfall events between future and historical Cuo GCMs (A1B) simulations using consistent period of record (1970-2000 and 2020-2050).

3.2 Relative Difference in Designed Stormwater Pond volumes

Using the Rosenberg (2010) data, relative percent increases in pond volumes were negligible (slightly less than 1%) for the ECHAM5|A1B scenario. The CCSM3|A2 simulation from 2020-2050 resulted in an 11% increase on pond volumes. Final pond designs for each climate scenario result in ponds that are slightly over mitigating. As duration curves diverge between forested and mitigated, ponds are over mitigating. Figure 5 illustrates Rosenberg A1B historical simulations result in curves diverging at the higher flow rates—thus the mitigation pond is larger than necessary for those larger events. Similarly, Figure 6 illustrates using Rosenberg A1B future conditions, the mitigated pond slightly over compensates for the entire range of flow rates when compared to the targeted forested conditions.

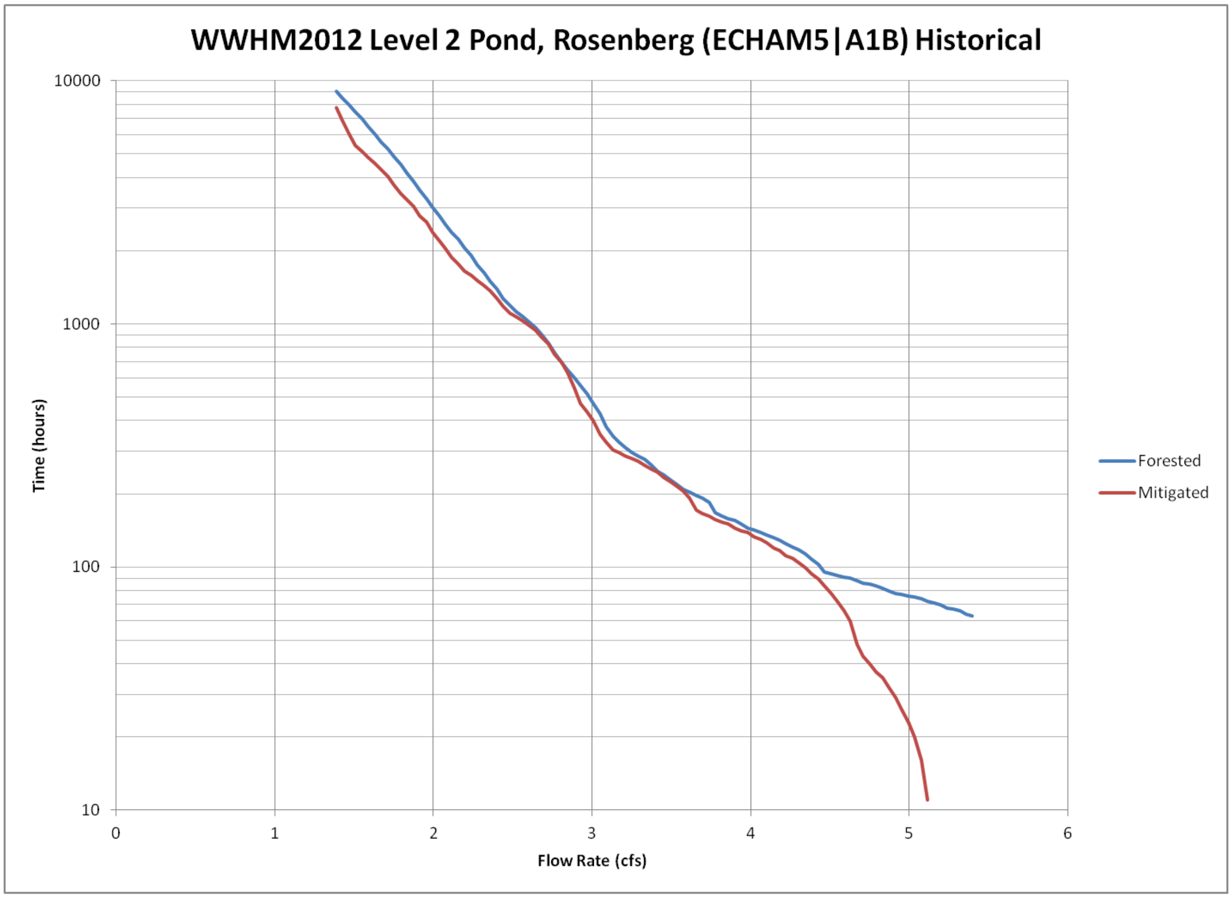

Figure 5 Mitigation pond performance for Rosenberg A1B, Historical.

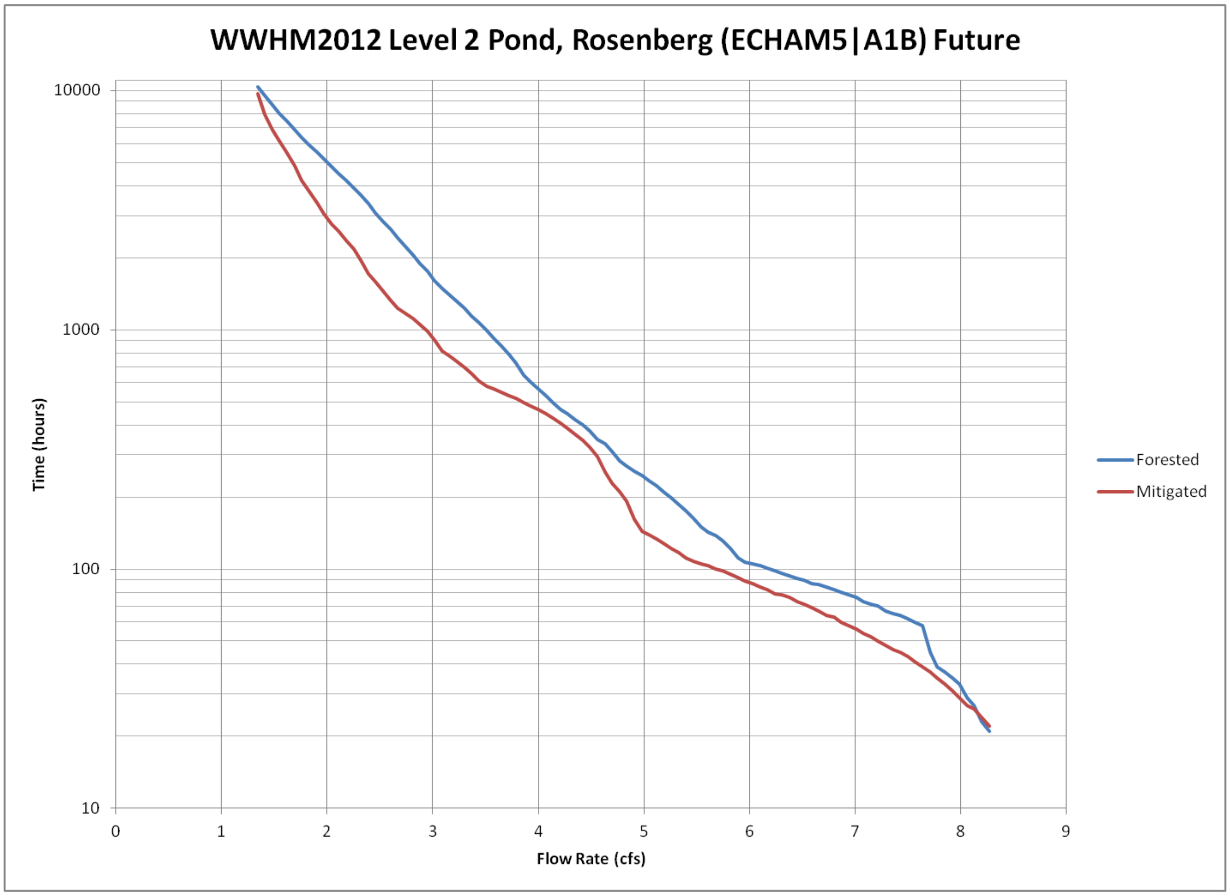

Figure 6 Mitigation pond performance for Rosenberg A1B, Future.

3.3 Impacts on High Pulse Count

Scenarios evaluated for high pulse counts include Rosenberg's two GCMs at 1-hour time steps, Rosenberg's ECHAM5|A1B with evenly distributed daily volumes, and Cuo's ECHAM5|A1B evenly distributed daily rainfall. Furthermore, subsets of the time span from Cuo's ECHAM5|A1B model was selected to match Rosenberg simulations.

Comparing future to historical climate scenarios had mixed results among the three land cover distributions defined. Future high pulse counts (HPC) for forested conditions increased ranging from 3 to 28-percent depending on the scenario. However, HPC for low density urban (i.e., low density residential) and high density urban (i.e., commercial/industrial) either increased or decreased depending the modeling scenario. A2 emissions scenario decreased HPC flashiness by 5% for Low Density Urban and 11% for High Density Urban while Rosenberg A1B slightly increased between 1 and 2-percent (Table 5).

Comparing Rosenberg's and Cuo's evenly distributed daily rainfall scenarios, Rosenberg's relative percent differences ranged between ±1 percent for the example developments while Cuo's rainfall yields a reverse in direction with 7 percent increase for low density urban and 3-percent decrease for high density urban.

Comparing the HPCs using the same future climate model but one with variable hourly rainfall and one evenly distributed, resulted in less flashiness (13% to 40% reduction) using the evenly distributed[6].

Comparing like time periods using evenly distributed rainfall shows Rosenberg simulations were more flashy than Cuo ranging from near 0 to 19% increase in HPCs for historical and future climate scenarios.

Table 5 Relative percent difference between historical (H) and future (F) average high pulse counts for forested and unmitigated low and high density urban landscapes.

Scenario	Time Step	Comparison	High Pulse Counts		
			Forested	LD Urban	HD Urban
Rosenberg ECHAM5 | A1B	1-hour	(F-H)/H	10%	2%	<1%
Rosenberg CCSM3 | A2	1-hour	(F-H)/H	28%	-5%	-11%
Rosenberg ECHAM5 | A1B (24hr)	24-hour	(F-H)/H	3%	-1%	<1%
Cuo ECHAM5 | A1B	24-hour	(F-H)/H	7%	7%	-3%
Rosenberg ECHAM5 | A1B (1hr|24hr)	1-hr, 24-hr	(F24hr – F1hr)/F1hr	-40%	-33%	-13%
Rosenberg | Cuo ECHAM5|A1B (24hr)	24-hour	(H24hr-H24hr)/H24hr	<1%	10%	9%
Rosenberg | Cuo ECHAM5|A1B (24hr)	24-hour	(F24hr – F24hr)/F24hr	4%	19%	6%

Note: 24hr represents evenly distributed rainfall based on daily volumes. Yellow identifies increases in flashiness, green identifies decreases in flashiness.

[6] WWHM2012 models were all run at 1-hour time steps.

4.0. DISCUSSION

Comparisons made among the global climate models are based on comparing a range of statistical metrics (i.e., mean annuals, 100, 99, 95, 90, 75, 50, 25, 10, 5, 1, 0 percentiles) on annual maximum daily rainfalls volumes. This selection is meant to provide the user some insight on possible impacts to stormwater management resultant from climate change influences on rainfall. In general, the pattern across all scenarios examined shows increases in maximum annual daily rainfall events, but with a lot of variability. At least one GCM in half of the class size of storms evaluated results in a decrease in storm volumes compared to historical conditions.

Focusing on maximum annual daily rainfall events does not fully characterize impacts on stormwater infrastructure, but can be a good indicator identifying potential impacts. Stormwater conveyance systems are designed using variable hourly (or sub-hourly) rainfall intensities rather than daily volumes. More specifically for example, King County Stormwater Design Manual requires stormwater mitigation ponds to be designed using continuous hourly hydrologic conditions spanning multiple decades. This design methodology takes into account variable antecedent conditions which can compromise designs when the effectiveness becomes variable for similar size storms depending on soil moisture in the drainage basin leading up to the event.

In an attempt to quantify this complexity, four stormwater ponds were designed using WWHM2012 software and Rosenberg's GCMs (ECHAM5|A1B and CCSM3|A2) for historical and future conditions. Changes in storage volumes are presented as relative changes to historical conditions—it is intentional that no explicit volumetric values (i.e., rainfall inches, stormwater pond volumes acre-ft) are presented that may mislead the reader when there is no certainty in which GCM may be more accurate in future projections. Nonetheless, comparing climate induced changes in sized theoretical stormwater ponds provide insight on future stormwater planning efforts.

Resources necessary to dynamically downscale global climate models using regional atmospheric models (e.g., WRF) designing stormwater ponds is substantial, limiting the amount of analyses conducted in the modeling community. Cuo's less computationally intensive downscaling method produces temporally courser rainfall (i.e., daily) not adequate for designing stormwater ponds on stream systems, but include a greater number of climate models and emission scenarios. Rainfall events, characterized in a meaningful way (e.g., distributions of maximum annual rainfall events) related to designing stormwater ponds, provides 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. Context can be leveraged from the ensemble, using for example, and changes in rainfall distributions among similar class size storms relative to their distributions.

For example, if a climate scenario with data adequate to design a stormwater pond results in a 10 percent increase in pond volumes, and storm volume increases 10 percent at 95 percentile, other climate scenarios inadequate for designing stormwater ponds may produce similar results if changes in the rainfall distributions (e.g., maximum annual daily rainfall) were similar in magnitude.

4.1 Uncertainty

As has been previously stated and well documented in previous studies (e.g., Cuo et al. 2010, Dalton et al. 2013), there is large variability in outcomes based on pollutant emissions, GCMs used, and downscaling methodology. The ensemble of 20 GCM models forced with one emission scenario (A1B) can be used to illustrate GCM model uncertainty (Cuo et al. 2010, Dalton et al. 2013) for this evaluation. In fact, the more emission scenarios used among the GCM models, the more likely future conditions will materialize within the range of outcomes simulated. As was mentioned in Adelsman et al. (2012), observed green house gas emissions are tracking faster than defined for A1B and B1 and are more reflective of A2 emission scenarios at that point in time. In fact, IPCC recently completed their fifth assessment report (AR5) where the methodology designing emission scenarios have been substantially revised (Representative Concentration Pathways—RCP2.6, RCP4.5, RCP6, etc.), and loosely reflective of the SRES emission scenarios (A1B, B1, A2, etc.) used in climate studies up to this point (Salathe, 2014).

5.0. CONCLUSIONS

Relative percent changes in annual maximum daily rainfall events generally increase in the future for all magnitudes evaluated averaging between 3 and 24 percent increase. However within the ensemble of 20 GCMs forced with the moderate A1B emission scenario, one model in particular (FGOALS) projects most of the storms reduce in magnitude (mean annual storm reduces 1% in future) with the moderate size storms increasing approximately 6% between the 5^{th} and 50^{th} percentiles.

Using Rosenberg's climate modeling scenarios 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 ECHAM5|A1B scenario. Stormwater pond volumes based on the more pessimistic emission scenario (CCSM3|A2) increase approximately 11 percent. Assuming that any one or more of the storm class sizes for annual maximum rainfall events evaluated in the ensemble of Cuo's 20 GCMs can influence design of stormwater ponds, the relative changes in future storms suggests ponds sizes could be ranging from no increase to possibly double depending on the sensitivity of the pond design to changes in similar storm class sizes.

Comparing like global climate models and emission scenarios, Cuo's downscaling method generated larger future storm volumes relative to Rosenberg's increases. This one example quantifies measureable differences in projected storm volumes changing one element in a complex modeling environment.

Impacts of climate change on stream flashiness indicate that under forested landscapes, high pulse counts will relatively increase in the future more so than increases of HPC on developed landscapes. In fact, the more aggressive CO_2 emission scenario (A2) generates less HPCs in the future then historical. HPC is a metric measuring flashiness in a stream in terms of frequency, not magnitude. This suggests, the increase in annual volumes of rainfall generating mean annual runoff nullifies some of the smaller storm events in the future on an annual basis—signifying other metrics of biological relevance should be included in future analyses.

Presented with this large variability of possible impacts to rainfall and stormwater infrastructure, accurately planning for future conditions may be tenuous. As computational power improves allowing for more complete physical models of the environment, the amount of uncertainly in future projections should diminish. This study isolates some of the various aspects in the climate modeling, and in a limited perspective illustrates the amount of variability in impacts to stormwater and stream flashiness. If one were to associate the emission scenario A2 representing an upper end of storm frequency and magnitudes, then based on the evaluated landscape conditions in this study, an 11 % increase in stormwater pond volumes may be representative of the upper range of impacts to stormwater pond volumes for low density residential development.

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