Evaluation of Potential Climate Change Impacts on Stormwater Facility Size and Cost

November 2019

King County

Department of Natural Resources and Parks
Water and Land Resources Division
Science and Technical Support Section
King Street Center, KSC-NR-0704
201 South Jackson Street, Suite 704
Seattle, WA 98104
206-477-4800 TTY Relay: 711
www.kingcounty.gov/EnvironmentalScience

Evaluation of Potential Climate Change Impacts on Stormwater Facility Size and Cost

Prepared for:

Washington State Department of Ecology for grant award WQC-2016-KCWLRD-00136.

Submitted by:

Jeff Burkey, King County Water and Land Resources (WLR) Division
Jeff Pray, King County WLR Division

Funding was provided by:

Washington State Department of Ecology Centennial Grant
King County Wastewater Treatment Division
King County Water and Land Resources Division

King County
Department of
Natural Resources and Parks
Water and Land Resources Division

Acknowledgements

These analyses would not be possible if not for the effort of downscaling global climate model rainfall led by Dr. Guillaume Mauger, from University of Washington, Climate Impacts Group. The project team members (Jessica Engel, Lara Whitely Binder, and Mark Wilgus) also provided insight and clarity to the outcomes presented.

Funding for this work was a combination of King County Department of Natural Resources and Parks (DNRP) funding ($187,000) and a Washington State Department of Ecology Centennial grant ($250,000) totaling $437,000. The DNRP funding was split between the Wastewater Treatment Division and the Water and Land Resources Division.

Citation

King County. 2019. Evaluation of Potential Climate Change Impacts on Stormwater Facility Size and Cost. Prepared by Jeff Burkey and Jeff Pray, Water and Land Resources Division. Seattle, Washington.

Table of Contents

Tables

Figures

EXECUTIVE SUMMARY

Why are we doing this?

Recent studies evaluating historical and projected future rainfall indicate more intense precipitation events in the Puget Sound region. This suggests that flooding and stormwater facilities built using current design standards are likely to be undersized for future conditions. This is an important consideration for local jurisdictions and stormwater managers, as stormwater facilities are typically intended to last several decades and mitigate projections of future rainfall.

What is the purpose of this study?

The goal of this study is to identify a range of impacts when designing stormwater facilities in King County and support possible modifications for updates to King County's stormwater design manual. To achieve this goal, comparisons are made evaluating changes in sizes of stormwater facilities using standard stormwater design practices and future rainfall projections.

How did we predict future rainfall?

Global climate models and downscaling techniques have evolved over time to support more refined assessments at a local scale. This project uses the latest global greenhouse gas scenarios generated in 2011, the latest set of global climate models (GCMs) obtained from Climate Model Intercomparison Project, phase 5 (aka CMIP5), and a regional weather model (i.e., Weather Research and Forecasting model—WRF) to develop detailed projections of changing precipitation in the Puget Sound region. King County partnered with the University of Washington Climate Impacts Group to develop these regional rainfall projections for use in evaluating impacts when designing stormwater mitigation facilities.

Two global climate model ensembles were downscaled to convert very coarse landscape and atmospheric conditions and more accurately reflect local rainfall patterns within King County (Mauger, et al., 2018). The two ensembles are described as *dry* (a drier climate scenario) and *wet* (a wetter climate scenario) referring to the seasonal rainfall less than and more than the average climate model projections for the future. Both GCM ensembles project greater rainfall intensities in the future when compared to *historical* (i.e., 1990s) conditions. The GCM that produces a smaller increase in seasonal rainfall volumes (ACCESS 1.0) was paired with the lower emissions scenario (Representative Concentration Pathway [RCP] 4.5). The GCM producing a larger increase in future seasonal rainfall (GFDL CM3) was paired with the higher emission scenario (RCP 8.5). Both GCM outputs were used as input for the Weather Research Forecast (WRF) rainfall model to downscale to local conditions for the Pacific Northwest. While the time periods available from the downscaling spans from 1970 through 2099, the time periods used for comparisons include 30-year windows—water years 1980-2009 (hereafter: 1990s) and 2070-2099 (hereafter: 2080s). For further detail on methodology in downscaling GCM rainfall, please refer to *New Projections of changing Heavy Precipitation in King County* (Muager, et al., 2018).

How did we test the impacts of stormwater facility design alternatives?

We used a stormwater facility design software package (WWHM) to define the amount of storage volume and/or capacity to achieve current King County flow control and water quality treatment standards for six types of facilities: detention ponds, infiltration ponds, wet ponds, sand filters, biofiltration swales, and bioretention cells. Additionally, because so much of the existing stormwater infrastructure in King County is based on less effective older design methods, the two prevalent types of stormwater ponds (i.e., detention pond and wet pond) in King County were also sized using these older design standards to evaluate how much storage volume design criteria might need to be increased (i.e., through retrofits) to meet current design standards using observed rainfall. In all, there were 136 Best Management Practices (BMPs) facilities sized to characterize the range of outcomes when taking into account two land use templates (rural residential and commercial), two soil infiltration rates (high and low), two time periods (1990s and 2080s), and three sources of rainfall (observed, dry, and wet).

What are the results?

We anticipated needing larger increases in BMP capacities for the wet scenario when compared to the dry scenario. Instead, the projected changes in facility design sizes in response to future climate conditions were varied and not consistent between the two future scenarios. Some BMPs in the dry scenario had larger increases than in the wet scenario and vice versa. However, among all BMPs and climate scenarios, storage volumes and treatment capacities increased ranging from 10% to 100+%—depending on land use intensity, soil infiltration, facility type, and GCM ensemble.

In summary, a few themes emerged when comparing volumes (or footprints) of BMPs sized for the 2080s relative to the 1990s climate.

1) Increases in BMP storage volumes needed were similar between the dry and wet scenarios;
2) Increases in BMP storage volumes for outwash soils were more pronounced than for till soils;
3) On average, BMPs sized for commercial land use required smaller capacity increases than for residential land uses in high soil-infiltration areas;
4) Cost estimates were assumed proportional to increases in BMP capacities, thus costs increase anywhere from 10 to 100 percent to mitigate future conditions;

5) There was substantial and consistent over estimation (i.e., bias) (10% to 60%) in the dry scenario when sizing the BMPs using GCM simulated 1990s climate data and observed 1990s data. This means that when all things are equal, using the dry climate scenario automatically increases the size of the BMPs from 10-60 percent before taking into account any increases in future rainfall projections. And,
6) Conversely, the bias in BMP capacities for the wet scenario were smaller and mostly under estimating capacities, ranging from 0% to -20% except for detention ponds on till soils, they were over estimated by 10%.

What are the recommendations and policy implications?

Although this study consistently identified the need for BMPs with larger capacities to accommodate 2080s rainfall projections, we cannot make specific quantitative recommendations for implementation into King County's stormwater design standards at this time.

In this study, two scenarios, *dry* and *wet*, were intended to bracket a range of possible results. Instead, the dry scenario at times produced a larger relative increase in BMPs when comparing the 2080s to the 1990s than the wet scenario, and BMPs designed for land uses in high infiltration landscapes had substantially larger increases relative to the 1990s than low infiltration till soils. Because the downscaling of the two climate models did not produce anticipated results, further analyses are needed to identify what are the driving factors that influence a BMPs effectiveness when considering the differences in the continuum of rainfall over 30-year periods. Consequently, we need to further refine projections toward a more defensible result.

Doing nothing now will also have negative impacts for the future. Large scale engineered stormwater facilities are built with intended lifespans, which if properly maintained, should last almost indefinitely. Therefore, <u>we recommend</u> that a future study be completed to evaluate the sensitivities to rainfall patterns when sizing stormwater facilities once additional climate scenarios become available. At that time, analyzing a larger ensemble of projections and at more locations would also likely better bracket the range of possibilities and support development of updated King County design standards.

This page intentionally left blank.

1.0 INTRODUCTION

King County has conducted a study of projected climate change under a grant from Washington State Department of Ecology (Ecology). The study included an evaluation of the change in the size of standard stormwater facilities per the *King County Surface Water Design Manual (SWDM)* in response to projected climate changes in western King County, Washington.

The evaluation used the Western Washington Hydrology Model[1] (WWHM) for sizing facilities as scoped in the grant requirements. Facilities were sized for the 1990s period (water years[2] 1980–2009) and the projected 2080s period (Water Year (WY) 2070–2099) to allow evaluation of a projected increase (or decrease) of facility sizes to meet Level 2 Flow Control and Basic Water Quality requirements[3]. The facility sizing benchmark for comparison in the study employed the climate records that come provided with WWHM2012 (i.e., Sea-Tac observed record) to produce reference facility sizes for the *historical* period coincident with the simulated climate 1990s period (WY 1980–2009). Climate data files for projected precipitation, evaporation, and transpiration produced by the University of Washington Climate Impacts Group (UW CIG) were imported into WWHM, first to compare and evaluate the bias between the historical observed record using Sea-Tac data and the simulated 1990s climate period (WY 1980–2009) on facility designs, then to determine the facility sizes for the projected period (WY 2070–2099) resulting from the simulated UW CIG climate change data.

This report describes the methodology, assumptions applied for the modeling of the stormwater facilities, and a discussion of the results that includes the projected impacts to facility sizing with associated costs.

1.1 Background

Recent studies evaluating historical rainfall patterns (e.g., Mass et al. 2011) and projected future rainfall patterns (e.g., Rosenberg et al. 2010, Salathe et al. 2014) indicate increases in extreme precipitation magnitudes in the Puget Sound region. This projected change in precipitation patterns suggests that stormwater facilities built using current design standards are likely to be undersized for future conditions, providing inadequate

[1] https://ecology.wa.gov/Regulations-Permits/Guidance-technical-assistance/Stormwater-permittee-guidance-resources/Stormwater-manuals/Western-Washington-Hydrology-Model

[2] Water Year (WY) is defined as 10/1 in the previous year to 9/30 in the current year. Thus 10/1/1999 – 9/30/2000 is referred to as WY 2000.

[3] Level 2 flow control standard: Match historic (i.e., forested) durations for 50% of 2-yr through 50-year peaks AND match historic 2- and 10-year peaks. Basic Water Quality standard: Treat the water quality design storm volume, as estimated by an approved continuous runoff model with 15-minute time steps calibrated to site conditions, equal to the simulated daily volume that represents the upper limit of the range of daily volumes that accounts for 91% of the entire runoff volume over a multi-decade period of record. For flow-based water quality facilities, at a minimum, 91% of the total runoff volume must pass through the treatment facility(ies) at or below the approved hydraulic loading rate for the facility(ies).

stormwater management. This is an important consideration, as stormwater facilities are typically intended to last several decades—if not "indefinitely," if well maintained.

1.2 Goals and Objectives

The goal of this effort is to provide insight on possible impacts to stormwater management in the future given current projections of future rainfall. The objective of this study is to compare results from sizing stormwater facilities using standard stormwater design practices and future rainfall projections.

2.0 DATA AND METHODS

Stormwater facility modeling for this study was completed using the WWHM stormwater model. Precipitation and evaporation data used in the study included the standard WWHM data provided with the software installation for the historical record and simulated climate data provided by UW CIG. These continuous time series data were used for facility sizing and comparison.

Facilities selected to be modeled per the grant agreement represented the typical range of current stormwater flow control and water quality treatment design. Facility design followed the regulatory guidelines in the SWDM and the user's manual for WWHM and represented urban and rural residential land use design scenarios.

2.1 Climate Data

2.1.1 Climate Scenarios

A subset of global climate models (GCMs) was previously evaluated to identify models that most accurately simulated heavy rainfall in the Pacific Northwest (Mauger et al. 2018). Among those GCMs, two were chosen to *book-end* future projections—a GCM that typically simulates smaller increase in volumes of rainfall (ACCESS 1.0) and a GCM that typically simulates larger increase in volumes of rainfall (GFDL CM3) when compared to average increases of simulated rainfall volumes in the future. The lower emission (van Vuuren et al. 2011) scenario Representative Concentration Pathway 4.5 (RCP 4.5) coupled with the ACCESS 1.0 global model is then considered to be the *dry* climate scenario (i.e., a GCM yielding lower volumes of rainfall with lower emissions). Conversely, the higher emission scenario (RCP 8.5) coupled with the GFDL CM3 is the *wet* scenario (i.e., a GCM yielding higher volumes of rainfall with higher emissions). Both dry and wet scenarios generate greater rainfall intensities in the future when compared to an historical time period.

Outputs from the GCM scenarios were then dynamically downscaled and bias corrected by UW CIG for western King County (Mauger et al. 2018) using local rain gauges. The bias-corrected downscaled time series for the Sea-Tac area was used for stormwater facility modeling to represent typical facility designs for western King County.

2.1.2 Time Periods Used

Projected climate data provided by UW CIG spanned the period of WY 1970–2099, whereas the WWHM climate data files spanned WY 1949–2009. The evaluation using the available WWHM historical period of rainfall was truncated to a thirty-year window (WY 1980–2009) to be consistent with the available overlap in climate modeling outputs.

For the projected climate evaluation and comparison (i.e., 2080s), the imported UW CIG climate file was truncated to the thirty-year window, WY 2070–2099. Additionally, a Regional Scale Factor (RSF) of 1.0 was used in WWHM to reflect a Sea-Tac geographic location.

By default, WWHM time step is set to 15-minute increments. The UW CIG climate model output files provided are in one-hour time steps. Thus, WWHM time steps were set to 1-hour in the software, for consistency. However, flow-based water quality BMPs (e.g., bioswale) sizing applied the 15-minute adjusted flow rate based on the 1-hour time step.

Tables 1 and 2 summarize the scenarios and time periods used for sizing BMPs in WWHM.

Table 1. Scenarios used for BMP sizing.

Scenario	Model Rainfall	Emission/Source
Historic*	WWHM2012	Sea-Tac
Dry	ACCESS 1.0	RCP 4.5
Wet	GFDL CM3	RCP 8.5

*Truncation of the WWHM standard precipitation record - The WWHM-default precipitation record for the historic scenarios was truncated to begin at WY 1980 to coincide with the projected climate file study. This truncation must be done each time the file is opened in WWHM, as WWHM does not retain the shortened time period when the scenario is saved/closed.

Table 2. Time periods used for BMP sizing.

Time Period Name	Time Period Range	Data Source
Historic	10/1/1979–9/30/2009	WWHM2012
1990s	10/1/1979–9/30/2009	UW CIG
2080s	10/1/2069–9/30/2099	UW CIG

2.2 Facilities Evaluated in this Study

The selection of which facilities to include for evaluation is meant to represent typical BMPs considered during stormwater design practices (Ecology 2014). The facilities modeled[4] for the study include:

- Detention ponds (till soils only) following WA Ecology's BMP T10.40
- Infiltration ponds (outwash soils only) following WA Ecology's BMP T7.10
- Water quality wet ponds following WA Ecology's BMPs T10.40 and T10.10
- Sand filters following WA Ecology's BMP T8.10
- Bioswales following WA Ecology's BMPs T9.10
- Bioretention following WA Ecology's BMP T17.30

[4] Originally, two additional BMPs were to be evaluated, BMP T5.20 and BMP T9.20. BMP T5.20 is a Rainwater Harvesting BMP not allowed in King County's Stormwater Design Manual and was replaced with a sand filter BMP T8.10. BMP T9.20 is a Wet Biofiltration Swale with longitudinal slopes greater than 1.5 percent. The difference in design between a Basic and Wet bioswales is the longitudinal slope, and the design slope for the swale used in this study was set to 1.5-percent Lastly, the intended number of scenarios expanded from 50-60 to over 140. These changes in scope were approved per agreement between King County and Ecology back in May 2018.

Ponds (detention, infiltration, wet pond) were sized as single-celled facilities. Combined detention/water quality ponds were evaluated for the two separate components of detention (live storage) and water quality (dead storage) ponds. Infiltration ponds were assumed to represent detention in outwash soils and sized accordingly. Sand filters and bioswales were sized for upstream and downstream locations relative to detention facilities. For practical considerations, upsizing infiltration ponds to eliminate sand filter requirement downstream were ignored.

Facility design criteria[5] for entry into WWHM are described in Table 3.

Table 3. Modeling methodology and facility design criteria.

Facilities to size		Facility details/WWHM inputs	Method
BMP T10.40	Combined Detention and Wetpool Facility (till soils only) (see BMP T10.10 for wetpool element)	3' live storage depth except where noted/4' dead storage depth (see BMP T10.10 for wetpool)/1' freeboard/single cell pond/3:1 side slopes / no precipitation/evaporation applied to detention facility	Determine detention and water quality volume as separate facilities; model optimized detention pond for till; obtain WWHM WQ volume and generate WQ pond geometry in WWHM (no WQ flow routing)
BMP T7.10	Infiltration Basin with Wetpool Pretreatment Facility (outwash soils only) (see BMP T10.10 for wetpool element of treatment train)	3' live storage depth except where noted/4' dead storage depth (see BMP T10.10 for wetpool)/1' freeboard/single cell pond/3:1 side slopes / no precipitation/evaporation applied to infiltration facility/ no side slope infiltration	Determine infiltration and WQ volume as separate facilities; model Level 2 compliant infiltration pond for outwash; obtain WWHM WQ volume and generate WQ pond geometry in WWHM (no WQ flow routing)
BMP T10.10	Wetpool (water quality element of BMPs T7.10 and T10.40)	4' dead storage depth/L:W=3:1/ 1' freeboard/single cell pond/3:1 side slopes	Obtain WWHM WQ volume and generate WQ pond geometry in WWHM (no WQ flow routing)
BMP T9.10/ BMP T9.20	Basic Biofiltration Swale / Wet Biofiltration Swale	2% grade/3H:1V side slopes Use Basic Biofiltration Swale geometry and design flow; use wet biofiltration swale when s<1.5% or in saturated soils	UPSTREAM FROM FLOW CONTROL FACILITY: Size using Off-line 15-min Flow rate reported by WWHM; flow rate receives a multiplier adjustment during facility design per SWDM Table 6.2.1.A DOWNSTREAM FROM FLOW CONTROL FACILITY: Size using 2-yr discharge from flow control facility (1-hr timesteps since no 15-min timesteps available in Climate2018b.wdm file)

[5] Single-event modeling of detention ponds and wet ponds was conducted to allow comparison of these facilities with the later continuous modeling designs. The modeling was completed in spreadsheets assembled for the purpose since modeling software provided with the pre-1998 SWDM no longer functions on modern computers. Single-event modeling used a Type 1A storm distribution and a constant infiltration rate (i.e., not varying with head).

Facilities to size		Facility details/WWHM inputs	Method
BMP T8.10	Basic Sand Filter	Size for WWHM 91% treatment volume, vertical sides, L:W = 2:1, 3' depth above sand, no precip/evap applied	Size for upstream and downstream from facility sized in this analysis; Obtain 91% treatment volume of developed condition from WWHM and size using sand filter element in WWHM
BMP T7.30	Bioretention Cells, Swales and Planter Boxes	Report bioretention cell only; 1' live storage depth/3:1 side slopes	WWHM-modeled bioretention sizing for 1000 sqft of roof; No reservoir applied

2.2.1 Unit Costs of Facilities

Facility unit costs for capital improvement, operations, and maintenance were developed in a previous study for the Bear Creek drainage basin in King County (King County 2018). Costs are based on a 100-year time frame to account for life cycle estimates that differ by BMP type during a 100-year time period. Publicly maintained detention ponds, wet ponds, and sand filters were considered to have a 30-year life cycle. Privately maintained BMPs (bioswales and bioretention) were assumed to receive more regular maintenance and were assumed to have a 50-year life cycle. All costs were based on 2015 dollars and were not adjusted for inflation or discount rates and are scaled up based on the size of BMP footprint or volume. See Table 4 for a summary of defined BMP costs.

Table 4. Unit costs for modeled facilities (2015 dollars, unadjusted).

Facility/BMP	Unit Costs (2015 dollars)		
	Capital (design / land acquisition / construction)	100-yr (maintenance / replacement / no inflation or discount rates)	Total
BMP T10.40 Detention pond ($/cu. ft.)	$13.43	$2.38	$15.82
BMP T7.10 Infiltration pond ($/cu. ft.)	$13.53	$5.73	$19.26
BMP T10.10 Wet pond ($/cu. ft.)	$12.67	$7.60	$20.27
BMP T8.10 Basic sand filter ($/sq. ft.)	$62.50	$208.73	$271.23
BMP T9.20 Wet biofiltration swale ($/sq. ft.)	$16.25	$159.21	$175.46
BMP T7.30 Bioretention Cell ($/cu. ft.)	$41.10	$208.73	$249.82

2.3 Modeling Scenarios Used To Develop the Facilities

Land use Assumptions

Two land use categories were defined for pond and pool sizing—a five-acre low impervious rural area (RA-5), and a commercially zoned one-acre drainage area. The maximum impervious area allowed by zoning regulations was assumed. Bioretention was sized for the required volume serving 1,000 square feet of impervious area. Design targets of BMPs are all based on forested pre-developed conditions using the same time period as for the post-developed scenario. Table 5 summarizes these conditions.

Table 5. Landscape assumptions used in WWHM2012 for BMP sizing.

Scenario	Land Use	Description
Mitigated scenarios	RA-5 (rural residential)	20% impervious area allowed by KCC (code has percentage exceptions for Ag buildings and Patterson/Issaquah Creek drainage basins, not applied in this analysis), flat slope; remainder grass (80%), flat slope
	Commercial	90% impervious area allowed by KCC, flat, remainder grass (10%), flat slope
	Impervious area unit	Bioretention modeled for 1000 sq. ft. unit tributary area
Pre-development scenarios	All	Forested, flat slope

Infiltration Rates

Infiltration rates used in the scenarios were the same as those applied in the King County Stormwater Design Manual (KCSWDM). Prescribed infiltration rates are summarized in Table 6.

Table 6. Soil types and infiltration rates used for modeling in WWHM2012.

Soil types / Slope Category	Infiltration Rates (inches per hour)
Till – Flat	0.15
Outwash – Flat	2.00
Bioretention Soils Media (BSM)	6.00
BSM small area (FS=2)	12.0

2.4 Design Standards Used To Develop the Facilities

Prior to 1998 (i.e., King Count 1990 SWDM), Standard Peak Rate Runoff Control was required as the flow control standard for development in King County. The standard utilized a single-event hydrograph methodology. In addition, most of the development in the county occurred prior to implementation of the 1998 design standard (King County 2018b).

> **Standard Peak Rate Runoff Control –** Facilities must be designed to produce post-development peak runoff rates at or below the predevelopment (i.e. existing conditions) curve for the 2- and 10-year, 24-hour duration design storm events. Additional control to reduce the post-developed peak runoff for the 100-year, 24-hour duration design storm event may be required.[6]. Once the design volume of detention facilities used to meet the standard performance curve is determined, a 30 percent increase in storage volumes is added as a safety factor.

With the 1998 SWDM (and later), the methodology changed from a single event to a continuous hydrologic time series. King County developed a continuous runoff time series referred to as KCRTS, which enabled designs to be based on the duration of flows. The design standard most commonly applied in King County is defined as *Level 2 Flow Control* (formerly known as Conservation Flow Control) which is based on flow duration analyses. This study applied Level 2 Flow Control (described below) in the WWHM facility modeling.

> **Level 2 (aka Conservation) Flow Control –** Match developed discharge durations to pre-developed durations for the range of pre-developed discharge rates from 50% of the 2-year peak flow up to the full 50-year peak flow, while also matching developed peak discharge rates to pre-developed peak discharge rates for the 2- and 10-year return periods. Pre-developed land use was assumed forested for all facility sizing.

2.4.1 Application of the Single-event (SBUH) Analysis

County-wide, much of the development occurred during the 1980s and 1990s when the facility design standard methodologies and computer resources had not yet advanced to the general use of continuous record modeling. Single-event methods were typically employed for flow control and water quality design.

Since WWHM was used for the modeling baseline of this study, a Santa Barbara Unit Hydrograph (SBUH) analysis was included with the study to demonstrate the variation in detention pond (i.e., BMP T10.40) volumes that might be observed between ponds designed and built prior to 1998 and the WWHM-designed ponds that would result from

[6] The required performance above the 10-year, 24-hour duration design storm up to the 100-year, 24-hour duration design storm event is dependent upon downstream conditions and how much attenuation the peak rate runoff control facility designed for 2- and 10-year, 24-hour duration design storm events provides for the 100 year, 24-hour duration design storm event

the same scenario inputs. This information will be useful in the future for estimating the total cumulative volume increase and associated cost necessary for detention ponds in most of the developed landscape in King County to achieve the climate change requirements projected by the WWHM modeling.

The SBUH for the Standard Peak Rate Runoff Control method (previously described) was one option mandated in the 1990 SWDM[7] and used here. It should be noted that the shift from single-event modeling methods to continuous record modeling approximately coincided with a change in pre-developed conditions mandated by King County's core requirements for runoff analysis. *Forested* land use replaced *existing conditions* land use as the pre-developed condition used to generate target release rates for facility design. This more stringent target was certainly a significant influence in increased facility size, in addition to the size increase resulting from the move to continuous runoff modeling. The separate effect due to the change in pre-developed conditions was not evaluated in this study.

The SBUH method was used per the guidelines in the 1990 SWDM. For this study, the SBUH analysis assumed the 100-yr peak runoff from the pond would not create downstream issues. Thus, the 100-yr peak flow impact evaluation for the Standard Peak Rate Runoff Control was ignored. This is consistent with the use of Level 2 Flow Control for the later ponds (Level 3 would be the increased requirement that would capture the 100-yr peak flow).

[7] The Soil Conservation Services (SCS) hydrograph method, the Rational Method, and the Santa Barbara Urban Hydrograph (SBUH) method were among the prescribed approaches to runoff modeling and facility design in the 1990s. King County developed their HYD and RDFAC software for using the SBUH method with the 1990 King County Surface Water Design Manual (SWDM) and the 1995 update to that manual. These methods were replaced with continuous runoff modeling using King County's KCRTS software when the 1998 SWDM was issued.

3.0 MODELING RESULTS

Facilities developed in the study using a continuous runoff record were sized in WWHM2012 to achieve compliance with current SWDM requirements. Detention and infiltration ponds met the Level 2 flow control standard. Water quality ponds, sand filters, and swales were sized to meet the 91% water quality treatment volume requirement. Bioretention volumes were modeled to achieve the Low Impact Development (LID) Performance Standard.[8] Facilities developed using the single-event method (SBUH) were sized to achieve the standards in place for the 1990 SWDM (i.e., match existing 2-year and 10-year peaks).

3.1 Time Periods Used for Comparisons

GCM|RCP (2080s vs. 1990s)

Comparisons are provided for the two GCM|RCP scenarios (see section 2.1) selected for the study. For each BMP in Table 7, the two columns (Dry & Wet) reflect the relative percent change in size using UW CIG climate data for both time periods for the 2080s (WY 2070 – 2099) versus the 1990s (WY 1980—2009). Thus, any differences induced by the GCM|RCP ensembles are carried forward yielding the net effect from climate change and not from the inaccuracies in the climate modelling results.

GCM|RCP (1990s) vs. Observed (1990s)

The GCM|RCP model biases (Table 8) were evaluated by comparing the relative percent change in BMP sizes using UW CIG simulated 1990s (Dry & Wet) versus Historical (1990s) using observed Sea-Tac rainfall. These comparisons help identify the bias induced by inaccuracies in the simulated rainfall generated by the GCM|RCP ensembles. Ideally, there should be minimal difference using the same design standard and overlapping time periods (1990s) for all three scenarios (Historical, Dry, and Wet).

3.2 Comparisons of Storage Volumes and Surface Areas

The magnitudes of the projected size increases are more pronounced for the residential land use scenario (i.e., low impervious) in high infiltration soil areas (i.e., outwash soils) compared to the commercial (i.e., high impervious) land use scenario (Table 7 and Figure 1). Under the low infiltration soil areas (i.e., till soils), the projected size increase of facilities was similar between dry and wet scenarios, and between rural residential and commercial.

[8] Level 2 Flow Control Standard: Match flow durations from 50% (2-yr peak flow) to the 50-yr peak flow while matching the 2- and 10-yr peak flows. 91% WQ treatment volume: 91% of the annual average daily runoff from the developed site. LID Performance Standard: Match durations between 8%(2-yr peak flow) and 50%(2-yr peak flow)

Sand filters did not appear in the SWDM prior to the 1998 edition. The absence of changes in BMP sizes for sand filters and bioswales downstream of infiltration ponds (Table 7) is because standard practice is to size the infiltration ponds large enough to eliminate the need for those treatments downstream of the pond.

Table 7. Relative percent change of facility sizes resulting from projected climate data for the dry and wet climate scenarios. Columns show the percent change in 2080s (WY 2070–2099) facility sizes compared to the 1990s (WY 1980–2009) both using UW CIG data. Absolute values can be found in Table 9.

Land Cover	BMP	Soil Type	Percent change in 2080s facility size relative to 1990s	
			Dry (ACCESS|RCP4.5)	Wet (GFDL|RCP8.5)
RA-5	Detention (acre*feet)	Outwash*	85%	32%
		Till	25%	24%
	Wetpond (acre*feet)	Outwash	56%	32%
		Till	39%	28%
	Basic Sand Filter (up) (sq. ft)	Outwash	42%	32%
		Till	30%	25%
	Basic Sand Filter (dn) (sq ft)	Outwash**	N/A	N/A
		Till	34%	35%
	Wet biofiltration swale (up) (sq. ft)	Outwash	71%	70%
		Till	62%	63%
	Wet biofiltration swale (dn) (sq ft)	Outwash**	N/A	N/A
		Till	35%	19%
	Bioretention Cell (cu. Ft)	Outwash	108%	18%
		Till	15%	15%
Commercial	Detention (acre*feet)	Outwash*	42%	31%
		Till	12%	23%
	Wetpond (acre*feet)	Outwash	25%	29%
		Till	25%	29%
	Basic Sand Filter (up) (sq. ft)	Outwash	22%	27%
		Till	21%	27%
	Basic Sand Filter (dn) (sq ft)	Outwash**	N/A	N/A
		Till	35%	42%
	Wet biofiltration swale (up) (sq. ft)	Outwash	49%	64%
		Till	49%	64%
	Wet biofiltration swale (dn) (sq ft)	Outwash**	N/A	N/A
		Till	40%	22%
	Bioretention Cell (cu. Ft)	Outwash	108%	18%
		Till	15%	15%

*Detention ponds in outwash soils are infiltration ponds.

**There is no outflow through the control structure for infiltration ponds, so BMPs downstream of an infiltration are not sized.

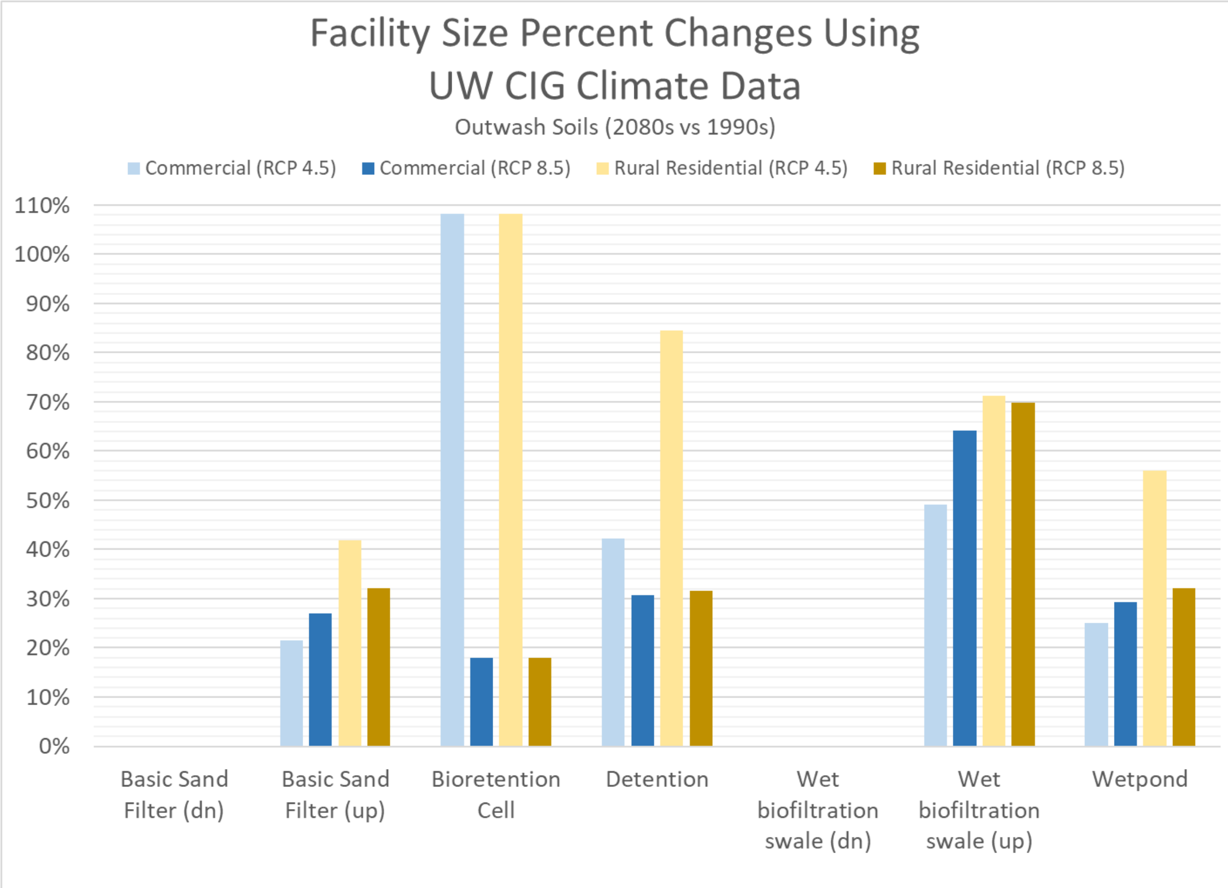

Figure 1. Outwash (high infiltration soils) underlain facility size percentage increase using the UW CIG climate scenarios (Dry and Wet). Percent changes for the 2080s (WY 2070-2099) facility volume (ponds, bioretention) or surface area (sand filters, bioswales) are relative to those sized using the 1990s (WY 1980-2009) UW CIG climate data. Evaluation of sand filter and bioswales are not applicable in sequence downstream of infiltration facilities.

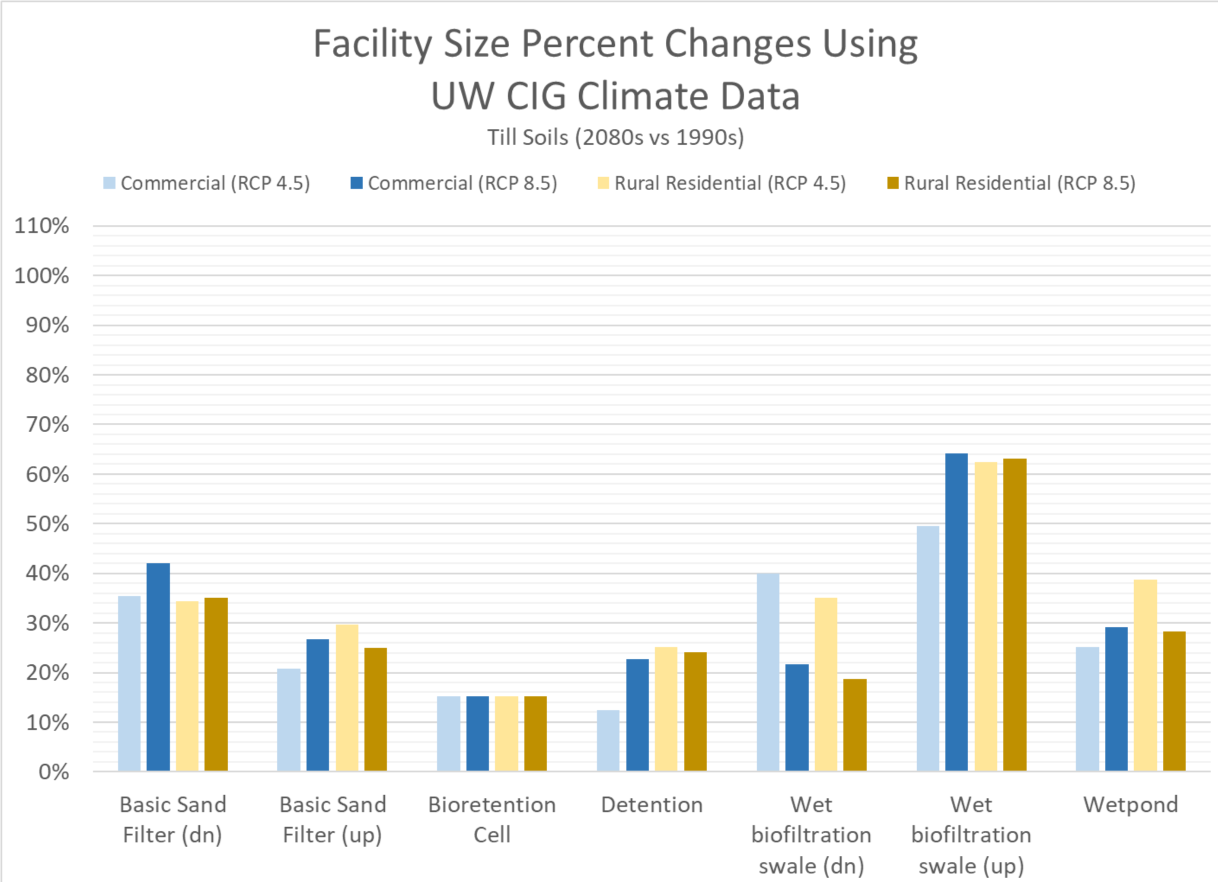

Figure 2. **Till (low infiltration soils) underlain facility size percentage increase using the UW CIG climate scenarios (Dry and Wet). Percent changes for the 2080s (WY 2070-2099) facility volume (ponds, bioretention) or surface area (sand filters, bioswales) are relative to those sized using the 1990s (WY 1980-2009) UW CIG climate data.**

3.3 Differences Between Design Standards and Rainfall Scenarios

The design methods for facilities constructed in King County over the last several decades have progressed through single-event methods (Y&W, SBUH) to continuous modeling using KCRTS until the 2009 SWDM and, ultimately, to WWHM2012 as of the 2016 SWDM (King County 2016).

Facility size variations are a function of using different methods (e.g., SBUH Type 1A vs. WWHM2012) and different climate rainfall scenarios (e.g., Sea-Tac observed vs. GCMs|RCPs). These differences are relevant for establishing the baseline of comparison for projecting facility sizes. For retrofit design, it would be useful to evaluate the facility size difference resulting from the change in design methods using the same rainfall scenarios and time periods in this study. The general effect of the change from single-event to continuous hydrologic evaluation on facility design sizes was reported by Booth and Jackson (1997). Booth and Jackson (1997) found that ponds sized based on single event hydrology would need to be much larger if they were to meet actual design performance goals under continuous flow conditions. Thus, early facilities would typically have less treatment volume and cover less land area than later facilities designed with continuous record modeling.

For this study, detention ponds and wet ponds were sized with the SBUH single-event method to provide a rough basis for projecting the additional size increase anticipated for retrofit of these early ponds when including impacts from climate change. Full replacement would likely be considered for very early, smaller ponds designed under the Y&W method.

The differences between KCRTS and WWHM2012 were not evaluated in this study

3.3.1 WWHM2012 Bias

The bias between using the Sea-Tac observed rainfall and the UW CIG projected climate data for the WY 1980–2009 time period are summarized in the Table 8. Figures 3 and 4 display the comparison graphically for outwash (i.e., high infiltration soils, Figure 3) and till (i.e., low infiltration soils, Figure 4) scenarios. The magnitude in the bias for the dry scenario (ranging from 5% to 60%) was substantially larger than for the wet scenario (0% to -20%). Notably, the 1990s dry climate scenario consistently oversized BMPs compared to 1990s historical (with one exception). The wet scenario's bias was to undersize the BMPs but by a smaller margin.

The magnitude of the WWHM2012 bias appears to be somewhat more pronounced for the residential (i.e., low impervious) land use scenario (Figure 3 and 4) compared to the commercial (i.e., high impervious) land use scenario (Figure 3 and 4) regardless of which climate scenario (i.e., wet & dry).

Table 8. The percent change bias between facilities sized using historical 1990s rainfall and simulated GCM|RCP scenarios (wet and dry) for the same 1990s time period (WY 1980–2009). Absolute values can be found in Table 9.

Land Cover	BMP	Soil Type	Bias Percent Change in 1990s facility size relative to Historical 1990s	
			Dry (ACCESS|RCP4.5)	Wet (GFDL|RCP8.5)
RA-5	Detention (acre*feet)	Outwash	44%	-7%
		Till	62%	13%
	Wetpond (acre*feet)	Outwash	40%	-13%
		Till	28%	-13%
	Basic Sand Filter (up) (sq. ft)	Outwash	40%	-7%
		Till	36%	-9%
	Basic Sand Filter (dn) (sq ft)	Outwash	N/A	N/A
		Till	51%	-3%
	Wet biofiltration swale (up) (sq. ft)	Outwash	42%	-12%
		Till	48%	-17%
	Wet biofiltration swale (dn) (sq ft)	Outwash	N/A	N/A
		Till	19%	-6%
	Bioretention Cell (cu. Ft)	Outwash	-24%	-6%
		Till	7%	-2%
Commercial	Detention (acre*feet)	Outwash	-3%	-19%
		Till	44%	-1%
	Wetpond (acre*feet)	Outwash	27%	-10%
		Till	29%	-10%
	Basic Sand Filter (up) (sq. ft)	Outwash	28%	-6%
		Till	30%	-6%
	Basic Sand Filter (dn) (sq ft)	Outwash	N/A	N/A
		Till	46%	-4%
	Wet biofiltration swale (up) (sq. ft)	Outwash	31%	-12%
		Till	31%	-12%
	Wet biofiltration swale (dn) (sq ft)	Outwash	N/A	N/A
		Till	15%	-5%
	Bioretention Cell (cu. Ft)	Outwash	-24%	-6%
		Till	7%	-2%

Table 9. Computed storage volumes and surface areas for BMPs evaluated.

Land Cover	BMP	Soil Type	Modeled Facility Size: Historical 1980–2010	RCP 45 1980–2010	RCP 45 2070–2099	RCP 85 1980–2010	RCP 85 2070–2099
RA-5	Detention (acre*feet)	Outwash	0.229	0.330	0.609	0.2129	0.28
		Till	0.893	1.449	1.813	1.0068	1.249
	Wet pond (acre*feet)	Outwash	0.143	0.200	0.311	0.1237	0.1635
		Till	0.354	0.453	0.628	0.3066	0.3931
	Basic Sand Filter (up) (sq. ft)	Outwash	635	888	1260	589	778
		Till	1305	1777	2304	1186.3	1482
	Basic Sand Filter (dn) (sq ft)	Outwash	n/a	n/a	n/a	n/a	n/a
		Till	652	986	1325	631.2	853
	Wet biofiltration swale (up) (sq. ft)	Outwash	1437	2035	3483	1258	2136
		Till	1747	2587	4202	1455	2373
	Wet biofiltration swale (dn) (sq ft)	Outwash	n/a	n/a	n/a	n/a	n/a
		Till	387	462	623	363	431
	Bioretention Cell (cu. ft)	Outwash	96	73	151	89.9	106
		Till	125	133	154	122.9	141.5
Commercial	Detention (acre*feet)	Outwash	0.957	0.925	1.315	0.78	1.019
		Till	2.234	3.227	3.628	2.215	2.719
	Wet pond (acre*feet)	Outwash	0.605	0.768	0.961	0.542	0.7004
		Till	0.618	0.794	0.993	0.5547	0.7161
	Basic Sand Filter (up) (sq. ft)	Outwash	2710	3475	4225	2540	3226
		Till	2745	3564	4303	2581	3271
	Basic Sand Filter (dn) (sq ft)	Outwash	n/a	n/a	n/a	n/a	n/a
		Till	611	894	1211	588	835
	Wet biofiltration swale (up) (sq. ft)	Outwash	5933	7746	11544	5214	8558
		Till	5861	7665	11456	5138	8435
	Wet biofiltration swale (dn) (sq ft)	Outwash	n/a	n/a	n/a	n/a	n/a
		Till	380	437	612	360	438
	Bioretention Cell (cu. ft)	Outwash	96	73	151	89.9	106
		Till	125	133	154	122.9	141.5

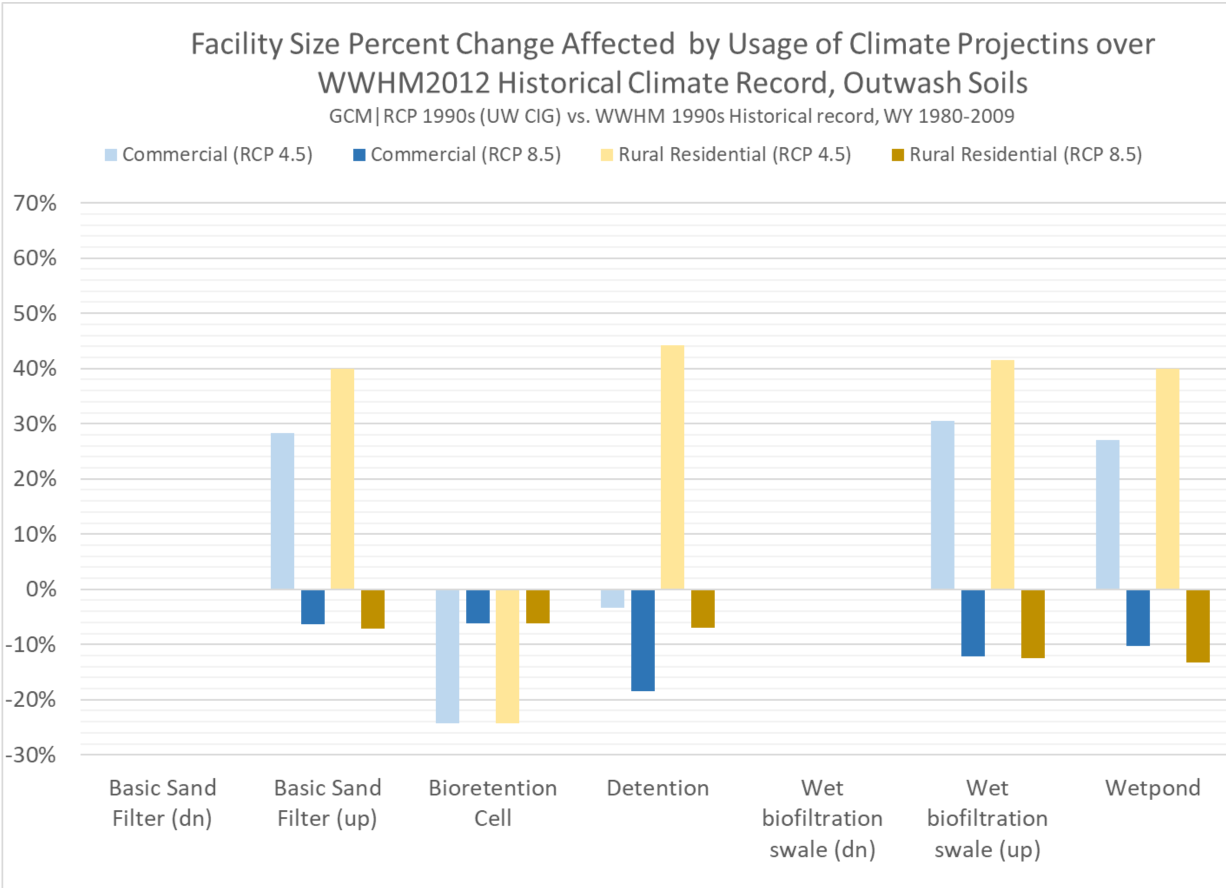

Figure 3. **Facility size percent change affected by the UW climate scenarios. After developing facilities based on historical WWHM2012 climate files, the projected climate data was imported into WWHM2012 to develop the associated set of projected facilities for outwash soils (i.e., simulated 1990s vs. observed 1990s). Evaluation of sand filter and bioswales are not applicable in sequence downstream of infiltration facilities.**

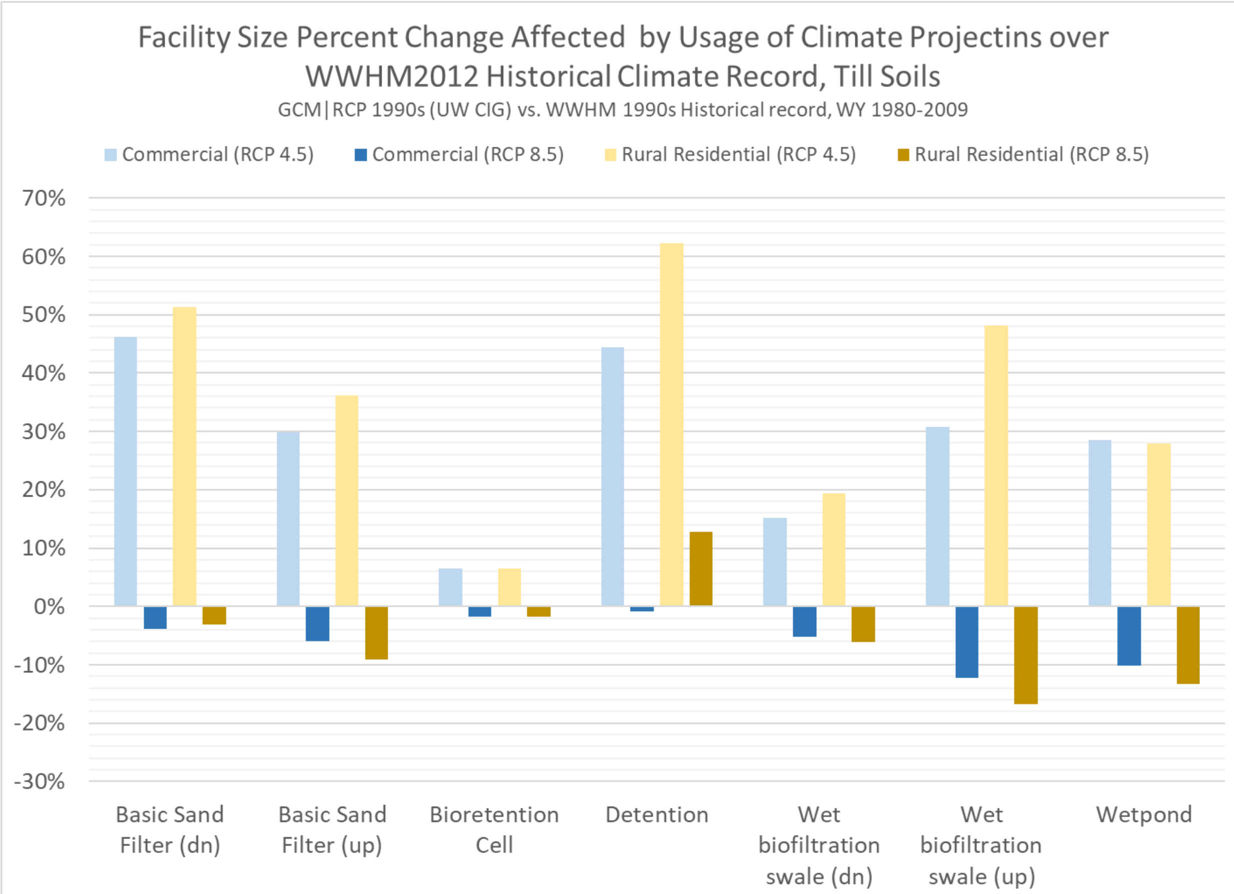

Figure 4. Facility size percent change affected by the UW climate scenarios. After developing facilities based on historical WWHM2012 climate files, the projected climate data was imported into WWHM2012 to develop the associated set of projected facilities for till soils (i.e., simulated 1990s vs. observed 1990s).

3.3.2 Single-event vs. Continuous Hydrologic Simulation

Much of King County was developed prior to 1998 when continuous runoff modeling requirements took effect. Single event models used up to that time, combined with less stringent pre-developed scenario requirements, produced much smaller facilities than those produced later using KCRTS under the 1998 SWDM (Booth and Jackson 1997).

Results of the modeling using historical rainfall suggest detention ponds in till soils would triple in size, and also suggest a doubling of wet pond volume, from single-event to continuous record design methods (Table 10). Detention ponds in outwash soils (i.e., infiltration ponds) appear to be less affected (Table 10).

Table 10. The percent change in required facility sizes resulting from a transition from single-event modeling (i.e., SBUH) to continuous time series modeling (e.g. WWHM2012, KCRTS). Water quality treatment requirements during the period were addressed with bioswales. Wet ponds were required only under special conditions per Special Requirement #5.

Land Cover	BMP	Soil Type	Modeled Facility Size		Percentage Change in SBUH Facility Size
			SBUH§	Historical	
RA-5	Detention (acre*feet)	Outwash	0.377	0.229	-39%
		Till	0.238	0.893	275%
	Wet pond§§ (acre*feet)	Outwash	0.047	0.143	204%
		Till	0.079	0.354	348%
Commercial	Detention (acre*feet)	Outwash	0.783	0.957	22%
		Till	0.541	2.234	313%
	Wet pond§§ (acre*feet)	Outwash	0.213	0.605	184%
		Till	0.217	0.618	185%

§Detention includes 30% factor of safety volume required by SWDM 1990 (rev. 1995)
§§Before SWDM 1998, required only if draining to a sensitive water body via overland/interflow, or if onsite detention is not provided, per SWDM (1990 rev. 1995) Special Requirement #5

Bioswale design through progressive editions of the SWDM (1990 and later) did not vary significantly. Methods to determine design flow rates varied, but water quality treatment flow rates determined from continuous modeling are adjusted with an empirical factor to align them with earlier single event methods to retain their original design intent, i.e. treatment of the 91% of the mean annual post-developed runoff water quality volume.

3.4 Increased Cost of Facilities

Facility costs for construction and maintenance increase proportionally with the increase in facility size. However, given the model bias in the sizing of the facilities, the presented costs in this study are based on the estimated historical costs, then scaled up (or down) using the relative percent differences between 2080s and 1990s for both climate scenarios.

The historical costs for the stormwater ponds range from $170K to $700K for residential land use (Table 11) and between $730K and $1.7M for commercial development (Table 13). Applying the relative changes (between 2080s and 1990s) to these residential cost estimates yields a range of $270K to $900K for the dry scenario, and $250K to $1.2M for the wet scenario (Table 12). Similarly, for commercial land use, stormwater pond costs ranged from $930K to $2.0M for dry, and $850K to $2.4M for wet scenario (Table 13).

The bioswales and bioretention BMPs range in cost from $24K to $68K for historical designs. Applying the projections of changes in rainfall, the total costs increase to a range of $24K to $73K. The costs for a biofiltration swale with no upstream flow control are similar to costs for a detention pond (i.e., $1M to $1.5M) or about 5× to 9× more than the other LID type BMPs.

The estimated historical costs for residential and commercial are summarized in Table 11 and Table 13. The increases (or decreases) in costs for the 2080s relative to the 1990s are summarized in Table 12 and Table 14.

Retrofit of ponds originally designed under single-event criteria would add additional volume requirements (and associated cost) of 2 to 3 times that of the original single-event design (see Section 3.3.2).

Costs for design and associated professional services would likely be unaffected by the increased facility sizes but would be expected to increase according to industry demands. Land acquisition cost for facility location is included in the unit cost estimates, which would increase with the increase in facility size, although the real estate market would likely be a primary influence on land costs in the future.

Table 11. Capital, operations and maintenance (O&M), and total costs for residential sized historical BMPs (2015 dollars, unadjusted).

Land Cover	BMP	Soil Type	Historical		
			Capital	100yr O&M	Total
RA-5	Detention (acre*feet)	Outwash	$133,930	$23,761	$157,691
		Till	$522,556	$92,707	$615,263
	Wet pond (acre*feet)	Outwash	$78,654	$47,147	$125,801
		Till	$195,227	$117,025	$312,252
	Basic Sand Filter (up) (sq. ft)	Outwash	$39,656	$132,441	$172,098
		Till	$81,575	$272,439	$354,014
	Basic Sand Filter (dn) (sq. ft)	Outwash			
		Till	$40,725	$136,011	$176,736
	Wet biofiltration swale (up) (sq. ft)	Outwash	$23,358	$228,844	$252,201
		Till	$28,386	$278,102	$306,487
	Wet biofiltration swale (dn) (sq. ft)	Outwash			
		Till	$6,282	$61,550	$67,833
	Bioretention Cell (cu. ft)	Outwash	$3,937	$20,092	$24,028
		Till	$5,145	$26,258	$31,402

O&M = 100 years of maintenance and replacements and end of life cycles.

Table 12. Future costs are based on applying the relative percent increases (and decreases) in residential sized BMPs when comparing 2080s to 1990s for both climate scenarios (wet and dry) (see Table 7 for RPDs) to the historical costs. Capital, operations and maintenance (O&M), and total costs are summarized (2015 dollars, unadjusted).

Land Cover	BMP	Soil Type	(1 +RPD) * Historical			(1+ RPD) * Historical		
			Dry			Wet		
			Capital	O&M	Total	Capital	O&M	Total
RA-5	Detention (acre*feet)	Outwash	$247,162	$43,849	$291,012	$176,141	$31,249	$207,391
		Till	$653,826	$115,996	$769,822	$648,264	$115,010	$763,274
	Wet pond (acre*feet)	Outwash	$122,771	$73,593	$196,364	$103,961	$62,317	$166,278
		Till	$270,989	$162,438	$433,427	$250,306	$150,041	$400,347
	Basic Sand Filter (up) (sq. ft)	Outwash	$56,269	$187,923	$244,192	$52,381	$174,939	$227,321
		Till	$105,767	$353,235	$459,003	$101,909	$340,347	$442,256
	Basic Sand Filter (dn) (sq ft)	Outwash						
		Till	$54,727	$182,773	$237,500	$55,036	$183,804	$238,840
	Wet biofiltration swale (up) (sq. ft)	Outwash	$39,978	$391,677	$431,655	$39,660	$388,561	$428,221
		Till	$46,106	$451,714	$497,820	$46,295	$453,564	$499,859
	Wet biofiltration swale (dn) (sq ft)	Outwash						
		Till	$8,481	$83,087	$91,567	$7,459	$73,081	$80,540
	Bioretention Cell (cu. Ft)	Outwash	$8,199	$41,846	$50,045	$4,642	$23,690	$28,331
		Till	$5,931	$30,273	$36,204	$5,923	$30,232	$36,155

O&M = 100 years of maintenance and replacement costs
RPD = relative percent differences tabulated in Table 7.

Table 13. Capital, operations and maintenance (O&M), and Total costs for commercial sized historical BMPs (2015 dollars, unadjusted).

Land Cover	BMP	Soil Type	Historical		
			Capital	O&M	Total
Commercial	Detention (acre*feet)	Outwash	$560,178	$99,382	$659,560
		Till	$1,307,004	$231,878	$1,538,882
	Wet pond (acre*feet)	Outwash	$333,658	$200,004	$533,663
		Till	$340,834	$204,306	$545,139
	Basic Sand Filter (up) (sq. ft)	Outwash	$169,349	$565,580	$734,928
		Till	$171,588	$573,056	$744,644
	Basic Sand Filter (dn) (sq ft)	Outwash			
		Till	$38,216	$127,630	$165,846
	Wet biofiltration swale (up) (sq. ft)	Outwash	$96,419	$944,638	$1,041,056
		Till	$95,239	$933,081	$1,028,320
	Wet biofiltration swale (dn) (sq ft)	Outwash			
		Till	$6,168	$60,428	$66,596
	Bioretention Cell (cu. Ft)	Outwash	$3,937	$20,092	$24,028
		Till	$5,145	$26,258	$31,402

O&M = 100 years of maintenance and replacement costs

Table 14. Future costs are based on applying the relative percent increases (and decreases) in commercial size of BMPs when comparing 2080s to 1990s for both climate scenarios (dry and wet) (see Table 7 for RPDs) to the Historical costs. Capital, O&M, and Total costs are summarized (2015 dollars, unadjusted).

Land Cover	BMP	Soil Type	(1+RPD) * Historical			(1+RPD) * Historical		
			Dry			Wet		
			Capital	O&M	Total	Capital	O&M	Total
Commercial	Detention (acre*feet)	Outwash	$796,361	$141,284	$937,645	$731,822	$129,834	$861,656
		Till	$1,469,418	$260,692	$1,730,110	$1,604,399	$284,639	$1,889,038
	Wet pond (acre*feet)	Outwash	$417,399	$250,201	$667,600	$431,170	$258,456	$689,626
		Till	$426,235	$255,498	$681,733	$440,005	$263,752	$703,758
	Basic Sand Filter (up) (sq. ft)	Outwash	$205,899	$687,647	$893,546	$215,086	$718,331	$933,417
		Till	$207,166	$691,880	$899,047	$217,459	$726,256	$943,716
	Basic Sand Filter (dn) (sq. ft)	Outwash						
		Till	$51,766	$172,886	$224,652	$54,269	$181,243	$235,512
	Wet biofiltration swale (up) (sq. ft)	Outwash	$143,694	$1,407,810	$1,551,505	$158,257	$1,550,481	$1,708,738
		Till	$142,343	$1,394,570	$1,536,912	$156,353	$1,531,829	$1,688,182
	Wet biofiltration swale (dn) (sq. ft)	Outwash						
		Till	$8,631	$84,556	$93,187	$7,504	$73,521	$81,025
	Bioretention Cell (cu. ft)	Outwash	$8,199	$41,846	$50,045	$4,642	$23,690	$28,331
		Till	$5,931	$30,273	$36,204	$5,923	$30,232	$36,155

O&M = 100 years of maintenance and replacement costs
RPD = relative percent differences tabulated in Table 7.

4.0 BMP DESIGN CONSIDERATIONS

4.1 Challenges in Pond Optimization

The detention ponds in this study were designed with a live storage depth of three feet. The projected climate files used in this study demonstrated a characteristic of wetter wet periods and drier dry periods. The reduced rainfall during the dry periods posed a challenge for designing the relatively shallow ponds in the study.

Substantially reduced peaks and increased durations occurring at the low threshold (50% of the 2-yr pre-developed peak flow) of the pre-developed scenario durations curve became more difficult to match for compliance in mitigated scenarios with orifice-controlled releases. Lateral expansion of the pond footprint to capture high flows also increased durations in the low flows, exacerbating the issue. Thus, some of the pond sizing were not fully optimized and needed to be done manually because WWHM could not converge on a meaningful solution, and at times the software would crash.

4.2 Using Sea-Tac Location

The Sea-Tac monitoring station location was used for this study. There are 64 more King County stations available for use, and another 20 for City of Seattle area. A casual examination of some the other locations downscaled suggests that the variable and inconsistent results might be due at least as much to the two scenarios as to the choice in location of data used.

4.3 Hydrologic Modeling

The projected future volumes of rainfall are just enough to trigger generation of surface runoff in high infiltration conditions that does not occur under current conditions. The greater volumes of surface runoff generated in the high infiltration soil (i.e., Outwash) scenarios may be more of a function of how the hydrologic models are parameterized versus true behavior of the landscape. If hydrologic model parameters were re-evaluated in areas with greater rainfall, the relative increase in surface runoff may be less or even closer to current conditions, which would lead to less of an impact on BMP volumes in high infiltration areas. Of course, the reverse condition could also apply exacerbating the deficiency in effectiveness.

5.0 SUMMARY

Two global climate scenarios were downscaled to reflect local rainfall patterns within King County. These scenarios are described as *dry* and *wet* referring to simulated seasonal rainfall less than and more than the simulated future average. The GCM that produced less rainfall (ACCESS 1.0) was paired with the lower emissions scenario (RCP 4.5). The GCM producing above average seasonal rainfall (GFDL CM3) was paired with the higher emission scenario (RCP 8.5). Both GCM outputs were used as boundary conditions for the Weather Research Forest (WRF) rainfall model to downscale to local conditions here in the Puget Sound region. The time periods used for comparisons included WYs 1980–2009 (i.e., 1990s) and 2070–2099 (i.e., 2080s).

A stormwater design software package (WWHM2012) was used to size six types of facilities that include: detention ponds, wet ponds, infiltration ponds, sand filters, biofiltration swales, and bioretention cells. Sand filters and biofiltration swale BMPs were sized two ways that included siting their placement upstream and downstream of assumed flow control facilities on till soils. Additionally, because so much of the existing stormwater infrastructure in King County is based on less effective older design methods, the two prevalent types of stormwater ponds (i.e., detention pond and wet pond) in King County were also sized using these older techniques to evaluate how much storage volumes might need to be increased to retrofit existing ponds to current design standards. In all, there were 136 BMPs sized when taking into account two land use templates (rural residential and commercial), two soil infiltration rates (high and low) for most BMPs, two time periods (1990s and 2080s), three climate scenarios (historical, RCP 4.5, and RCP 8.5), and older design methods.

Using the average to characterize results, a few themes emerged when comparing volumes (or footprints) of BMPs sized for the 2080s vs 1990s climate.

1) The relative percent increase in footprint was greater for BMPs sized using the dry scenario (40%) versus the wet (30%) scenario for rural residential land use;
2) The range of size increases was smaller for the wet scenario (15% to 70%) than the dry scenario (12% to 108%);
3) Increases in BMPs sized for outwash soils (45%) was more pronounced than for till soils (28%);
4) On average, BMPs sized for commercial land use resulted in less of an increase (35%) than for residential land use (41%);
5) BMPs sized for commercial land use were similar in size increases for dry (30%) and wet (28%) scenarios.
6) Changes in BMP sizes for the wet scenario were similar regardless of land use or soil type (the average RPDs ranged between 30% and 37%);
7) Using the relative changes in BMP sizes and applying them to the BMP designed using observed historical rainfall, total costs of facilities sized using 2080s rainfall

range from \$166K to \$1.9M for detention ponds, wet ponds, and infiltration ponds. Bioswales upstream of detention ponds ranged in costs from \$428K to \$1.7M, and \$80K and \$93K downstream of detention ponds. Total costs ranged from \$28K to \$50K for bioretention cells; and

8) There was substantial (and nearly consistently oversized) model bias sizing the BMPs using dry climate scenario (avg: 27%, range: -24% to +62%) when compared to historical observed. The wet scenario had much less bias, but nearly consistently slightly under-sized BMPs (avg: -7%, range: -19% to + 13%).

6.0 CONCLUSION

Among all BMPs evaluated, all showed a need to increase their size to adequately mitigate 2080s rainfall projections. However, the results of the changes in BMP sizes when considering projections of future rainfall were inconsistent with presumed outcomes using the selected models for the dry and wet climate change scenarios. The selection was meant to bracket the range of possibilities. Instead, the dry scenario at times produced a larger increase in BMPs than the wet scenario, and BMPs designed for land uses in high infiltration landscapes had substantially larger increases relative to the 1990s than low infiltration till soils.

It is unknown how the outcomes from these two climate projection scenarios would compare against a greater number of GCMs used. Results from these two projections may end up being considered low, high, or anything in between, when evaluated among a larger data set of results. This precludes providing any quantifiable support to policy changes at this time.

6.1 Recommendation

It is the recommendation of this study to continue to evaluate the sizing of stormwater facilities when additional climate scenarios become available. At that time, a larger ensemble of projections may address a key uncertainty by better bracketing the range of possibilities and support development of updated design standards.

In addition to sizing BMPs using more GCMs and locations, sensitivity analyses should be conducted to identify how changes in rainfall projections influences projections in BMP designs. This may lead to a simplified analog approach that will allow for scaling observed rainfall data in different ways that adequately characterize impacts as if based on GCM derived projections, but using observed data. The simplicity of this approach may allow for a more expansive consideration of ranges in rainfall projections and their impacts on stormwater management.

7.0 REFERENCES

Ecology 2014. 2014 Stormwater Management Manual for Western Washington. Prepared by Washington State Department of Ecology, Water Quality Program. Publication: 14-10-055. https://ecology.wa.gov/Regulations-Permits/Guidance-technical-assistance/Stormwater-permittee-guidance-resources/Stormwater-manuals

King County. 1990. King County Surface Water Design Manual. https://your.kingcounty.gov/dnrp/library/water-and-land/stormwater/1990_SWDM.pdf

King County. 2016. King County Surface Water Design Manual. https://kingcounty.gov/services/environment/water-and-land/stormwater/documents/surface-water-design-manual.aspx

King County. 2018(a). Bear Creek Watershed Management Study. Prepared by Timothy Clark, Sevin Bilir, Jeff Burkey, Jessica Engel, Eric Ferguson, Claire Jonson, Josh Kubo, Scott Miller, Jen Vanderhoof, and Mark Wilgus, Water and Land Resources Division. Seattle, Washington.

King County. 2018(b). Updated Estimate of the Annual Average Volume of Treated and Untreated Stormwater Runoff from developed lands in King County. A Technical Memorandum from Jeff Burkey to Josh Baldi, November 28, 2018.

Mass, C., A. Skalenakis, and M. Warner 2011. Extreme precipitation over the West Coast of North America: ls there a trend? Journal of Hydrometeorology, 12, 310-318, https://doi.org/10.1175/2010JHM1341.1

Mauger, G.S., J.S. Won, K. Hegewisch, C. Lynch, R. Lorente Plazas, and E. P. Salathé Jr. 2018. New Projections of Changing Heavy Precipitation in King County. Report prepared for the King County Department of Natural Resources and Parks. Climate Impacts Group, University of Washington, Seattle.

Salathé Jr, E.P., A.F Hamlet, C.F. Mass , S.Y. Lee, M. Stumbaugh & R. Steed, 2014. Estimates of 21st century flood risk in the Pacific Northwest based on regional climate model simulations. Journal of Hydrometeorology, 15, 1881-1899, https://doi.org/10.1175/JHM-D-13-0137.1.

Rosenberg, E.A., P.W. Keys, D.B. Booth, et al. 2010. Precipitation extremes and the impacts of climate change on stormwater infrastructure in Washington State. Climatic Change (2010) 102: 319. https://doi.org/10.1007/s10584-010-9847-0 van Vuuren, D.P., L. Bouwman, S.J. Smith, F. Dentener. 2011. Global projections for anthropogenic reactive nitrogen emissions to the atmosphere: an assessment of scenarios in the scientific literature. Current opinion in Environmental Sustainability, 3(5). Link to PBL website: http://www.pbl.nl/en/publications/2011/global-projections-anthropogenic-reactive-nitrogen-emissions-to-the-atmosphere

WWHM2012. Western Washington Hydrology Model 2012. Developed by Clear Creek Solutions, Inc. https://ecology.wa.gov/Regulations-Permits/Guidance-technical-assistance/Stormwater-permittee-guidance-resources/Stormwater-manuals/Western-Washington-Hydrology-Model