Modeling of Possible Future Climate Change Scenarios

Effects on King County Wastewater Treatment Division Combined Sewer Overflow Control Volumes – Phases 1 & 2

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Prepared by:

Bob Swarner

Bruce Crawford

Brian Phillips

Homero Flores

Liz Clark

Hal Mullis

Liaqat Khan

King County

Protecting Our Waters

Doing our part on rainy days

For comments or questions, contact:
Bob Swarner
King County Department of Natural Resources and Parks
Wastewater Treatment Division
201 S. Jackson St.
KSC-NR-0503
Seattle, WA 98104-3855
(206) 477-5628
Bob.Swarner@kingcounty.gov

Alternative Formats Available

206-477-5371 (voice) or 711 (TTY)

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1.0 Executive Summary

King County Wastewater Treatment Division (KCWTD) has 39 permitted locations (outfalls) from which combined sewage can overflow during storm events (CSOs). KCWTD has a consent decree with the Washington State Department of Ecology (DOE) and the U.S. Environmental Protection Agency (EPA) that stipulates that WTD will construct CSO projects to limit the CSO frequency at each location to an average of one event per year, over any 20-year period.

Global Climate models indicate that rainfall will increase in the Pacific Northwest due to climate change. The University of Washington Climate Impacts Group (UWCIG) used a regional climate model to downscale the output from two global climate models, using two greenhouse gas emissions trajectories, to estimate the future climate conditions on the climate in the Puget Sound region (which includes Seattle, WA). The rainfall characteristics associated with the 2070 – 2099 time period were used to factor the historical rainfall based on rainfall intensities. The factored historical rainfall time series were then used as surrogates for future climate conditions.

Models of the existing sewer system were run using historical rainfall and using the two different climate projections (for the end of the 21st century) to estimate the possible impacts of climate change on CSO control volumes. The results of the model simulations of the KCWTD wastewater conveyance system, including all regulators and pump stations, reveal potential CSO control volume impacts due to climate change.

It was found that the sum of the control volumes necessary to achieve CSO control in the two possible future climate conditions are 40 percent – 54 percent larger than the sum of those required to achieve regulatory control using historical rainfall only. The total volume required would increase from 147 million gallons to between 208 and 230 million gallons, an increase of 59 – 81 million gallons.

This technical memorandum (TM) documents results of the latest WTD modeling to estimate the differences in CSO control volumes that, if constructed, would result in a one-per-year average CSO frequency under existing (historical) climate and the control volumes that would result in the same frequency (one/year) in the two possible future (approximately 2085) climate conditions. The CSO control volume differences, the changes in peak overflow rates, and the changes in CSO frequencies at each CSO location are documented in this TM.

2.0 Introduction

King County Wastewater Treatment Division (WTD) has 39 locations (outfalls) from which combined sewage can overflow during storm events (CSOs). All but two of the outfalls are contained in the West Point Treatment Plant (West Point) service area while the other two are in the Norfolk/Henderson Basin (from which wastewater mostly flows to the South Plant in Renton). WTD has a consent decree with the Department of Ecology (DOE) and with the Environmental Protection Agency (EPA) that stipulates CSO projects that WTD will construct to limit the frequency at each CSO location to an average of one event per year, over any 20-year period.

Global Climate models indicate that rainfall will increase in the Pacific Northwest due to climate change, and the question arose regarding how much impact climate change might have on the required CSO facilities that would be necessary to limit CSOs to the one per year standard. Models of the existing sewer system were run using historical rainfall and using two different climate projections to estimate the impacts of climate change on CSO control volumes.

This technical memorandum (TM) documents results of the latest WTD modeling to estimate the differences in CSO control volumes that, if constructed, would result in a one-per-year average CSO frequency under existing (historical) climate and the control volumes that would result in the same frequency (one/year) in a couple possible future (approximately 2085) climate conditions.

King County's 2015 Strategic Climate Adaptation Plan (SCAP) contained a variety of actions that reduce the county's greenhouse gas emissions and help King County prepare for the impacts of climate change. Specifically, this TM addresses the "Assess Climate Impacts on Rainfall Patterns" priority action in King County's 2015 SCAP, and "Preparing for Climate Change Impacts" section, under "Priority Actions by 2020, Science and Research." The 2015 SCAP states: "The Water and Land Resources Division, in cooperation with the Wastewater Treatment Division, and partially supported by a grant from the Washington State Department of Ecology, will implement a study in collaboration with the University of Washington to assess climate change impacts on local rainfall patterns." The results of that research were then to be used by WTD to assess potential impacts on wastewater conveyance and treatment, and the results of the assessment will be incorporated into future updates of the King County Combined Sewer Overflow Control Plan. The analysis presented in this TM fulfills this priority action item from the 2015 SCAP, and it is one of nineteen priority action items from the 2015 SCAP that have been completed.

The modeling performed during this analysis was done in two phases due to models being ready to run for some CSO locations earlier than others. The first phase included CSO locations that are generally in the smaller CSO basins and/or are upstream of the main WTD interceptors. The Phase 2 location results required major model updates to combine several component models such that downstream effects are appropriately reflected in the model simulations. This TM covers the methods and results for both phases of the analysis.

Table 1 presents the Phase 1 and Phase 2 CSO locations. Figure 1 shows the locations of the Phase 1 sites where the CSOs leave the combined system, and Figure 2 shows the locations of the Phase 2 sites.

Table 1. CSO locations of climate change impact assessments in Phases 1 and 2

	Phase 1 Locations		Phase 2 Locations
1	Barton PS	18	Ballard Regulator
2	Belvoir PS	19	Canal St. Overflow Weir
3	Dexter Ave. Regulator	20	Chelan Ave. Regulator
4	East Marginal PS	21	8th Ave. S. Regulator
5	53rd Ave. PS	22	Denny/Elliott W. Regulators/Weirs
6	Henderson PS	23	East Duwamish
7	Matthews Park Pump Station	24	West Duwamish
8	MLK Way	25	11th Ave. NW Overflow Weir
9	Murray Ave. PS	26	Hanford Regulator
10	Norfolk Regulator Station	27	Harbor Regulator
11	North Beach PS Wet Well	28	King St. Regulator
12	North Beach PS Inlet	29	Kingdome Regulator
13	Rainier Valley Storage (includes Bayview North, Bayview South, Hanford @ Rainier, & Hanford #1)	30	Lander St. Regulator
14	Rainier PS	31	Montlake Regulator
15	S. Brandon St. Regulator	32	63rd Ave. PS
16	S. Michigan St. Regulator	33	S. Magnolia Overflow Weir
17	30th Ave. PS	34	SW Alaska St.
		35	Terminal 115 Overflow Weir
		36	3rd Ave. W. Overflow Weir
		37	University Regulator
		38	W. Marginal PS
		39	W. Michigan Regulator

PS = pump station
WWTS = wet weather treatment station

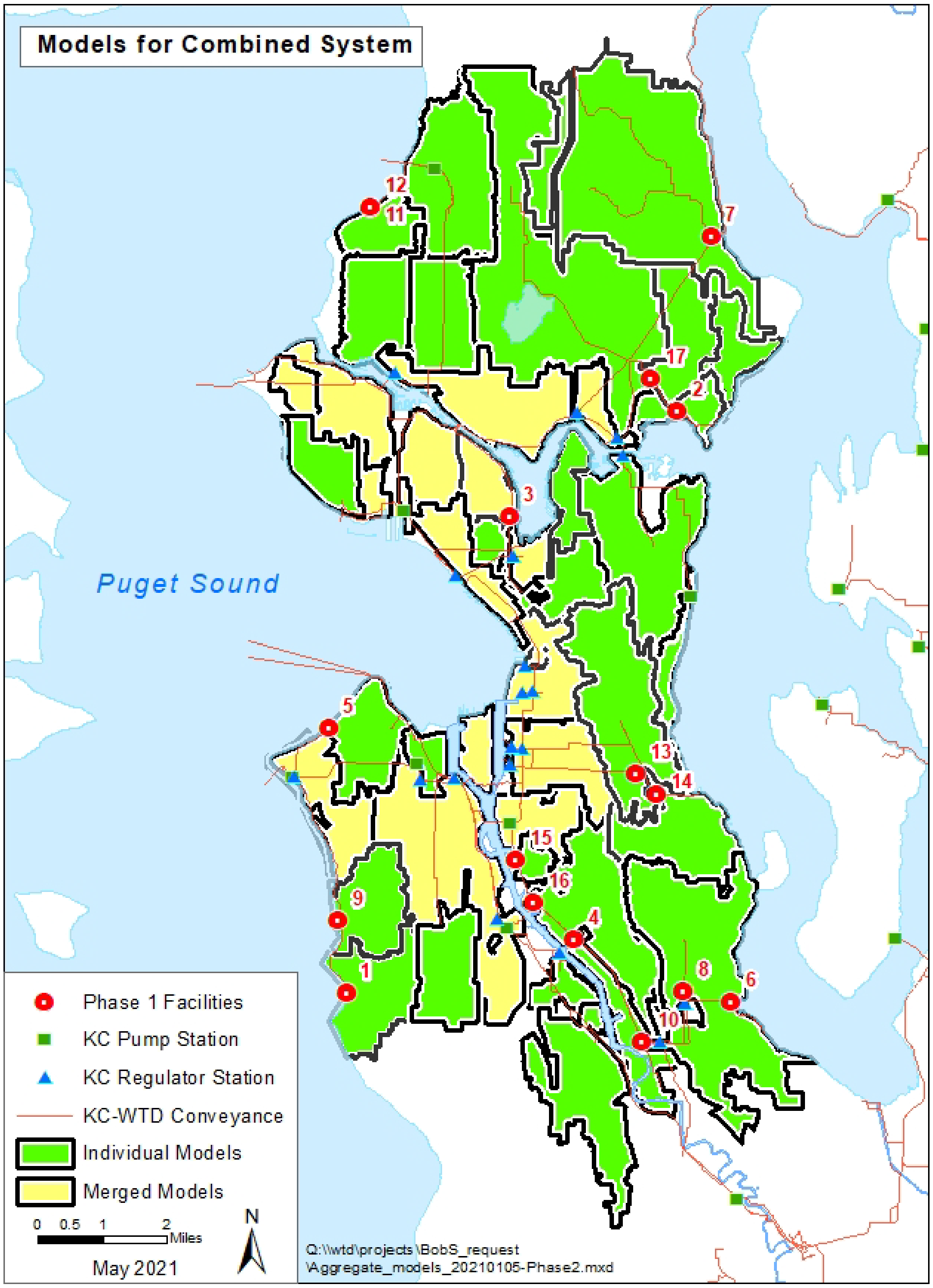

Figure 1. Phase 1 CSO locations

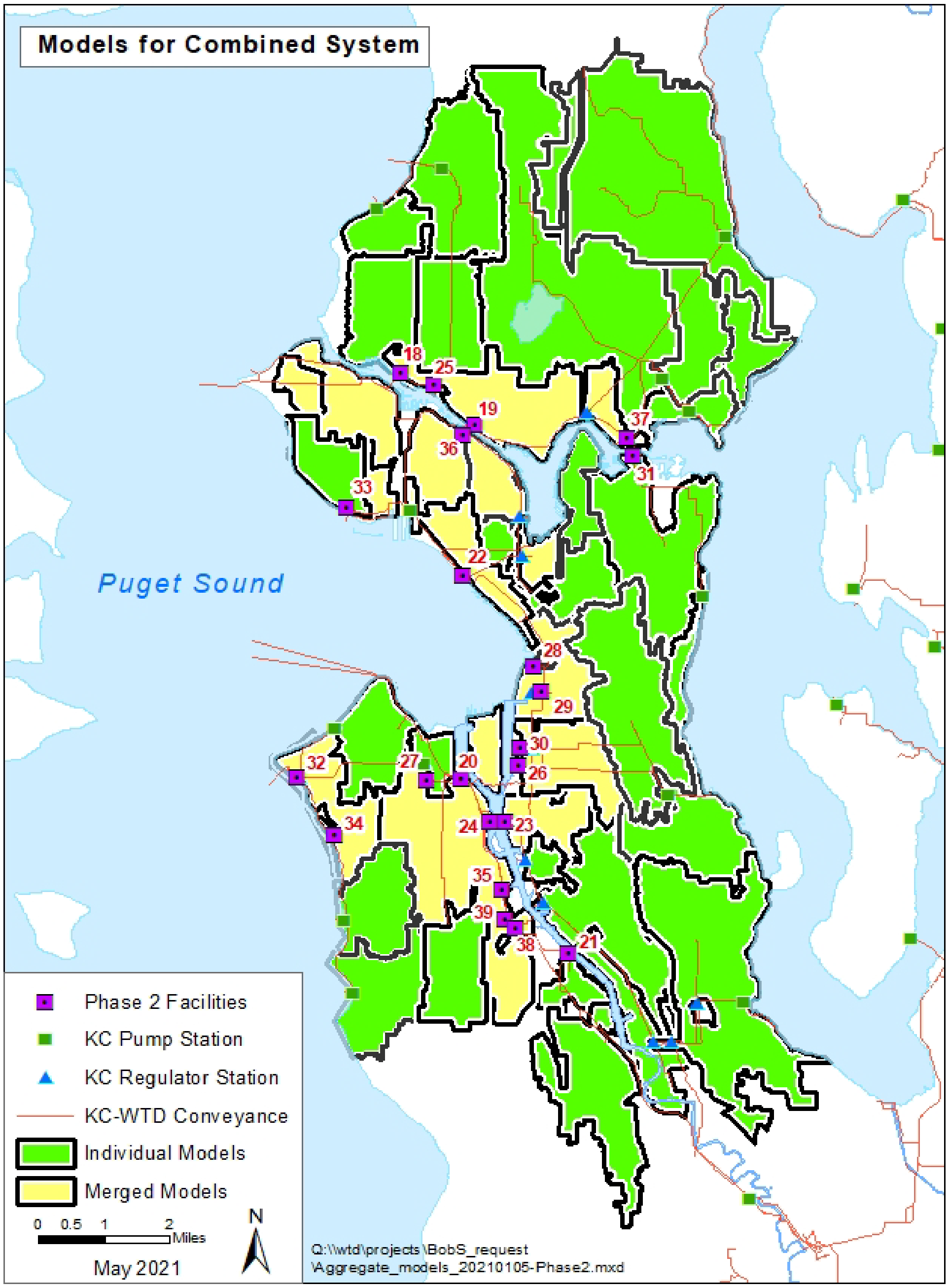

Figure 2. Phase 2 CSO locations

3.0 Background and Purpose

The procedure for sizing CSO control facilities in King County involves simulating flows in the wastewater collection and conveyance system with calibrated hydrologic and hydraulic computer models using rain data from 17 rain gauges spread throughout the City of Seattle. The detailed rainfall record for City of Seattle gauges begins in January 1978 and extends to the present day.

CSO compliance is measured by counting the number of CSO events in a 20-year period; each CSO outfall is to have less than, or equal to, 20 untreated CSO events in the latest 20-year period to meet the current National Pollutant Discharge Elimination System (NPDES) CSO criteria. Washington State Department of Ecology (Ecology) and the U.S. Environmental Protection Agency (EPA) are the agencies responsible for regulating compliance with NPDES CSO criteria. For the analysis in this TM, model simulation results have been generated by WTD for the period from 1978 through 2018 (41 years) to estimate the control volumes and peak flowrates that would be necessary to keep CSO outfalls limited to an average of one untreated CSO event per year over the long term, and over any 20-year period during the historical record.

Recent research indicates that future heavy rain events will be more intense in the Pacific Northwest (Mauger et al. 2018; Warner et al., 2015). Therefore, this Climate Change impact analysis was designed to answer the following question: “What impact might climate change have on the control volumes that would be necessary to achieve and/or maintain compliance with the current CSO regulatory compliance criteria, assuming all other factors were unchanged?” (Other factors that could change over time that might affect CSO control volumes are changes in the local sewer system, redevelopment of the basins upstream of the CSO outfalls, control modifications, flow diversions, green stormwater infrastructure projects, etc.) This TM documents the methodology and results of the analysis.

4.0 Methodology

4.1 Future Rainfall

Once the CSO control volumes are estimated using models of the existing system and using historical rainfall, the next step in answering the aforementioned question is to obtain future precipitation projections that might reflect the climate in the future.

A contract with the Climate Impacts Group at the University of Washington was completed in 2018 to generate future altered rainfall time series to be used as model input. The work was funded by the King County Department of Natural Resources and Parks and the Washington state Department of Ecology. Additional support came from the Critical Infrastructure Resilience Institute, a U.S. Department of Homeland Security Science and Technology Center of Excellence. It was decided to simulate the climate at the end of the current century (2070 to

2099) to quantify the changes expected in the 21st century. The resulting rainfall input data and model output are labeled “2085 conditions” (mid-point of the 30-year period) for brevity.

The work in the Climate Impacts Group contract was documented in the report, “New Projections of Changing Heavy Precipitation in King County” (Mauger et al., 2018). Subsequent to this report being released in April 2018, an error was found in the GFDL CM3 (RCP 8.5) Weather Research and Forecasting (WRF) simulation. The error was corrected, and the report was updated in August 2019 with the correct information.

The specific objectives of the contract were to:

- **Produce two new regional climate model (RCM) projections.** Evaluate global climate models (GCMs) and develop projections representing a low- and a high-end scenario for 21st century change in precipitation. Archive hourly precipitation and other fields (e.g., evapotranspiration, wind speed, and direction) for the entire model domain.
- **Synthesize projections to support wastewater conveyance and treatment system impacts assessment.** Evaluate changes in the intensity, duration, and magnitude of heavy precipitation events in the region. Explore the possibility of developing a statistically derived pseudo-ensemble of projected changes by relating large-scale global model projections to local-scale exceedance probabilities.
- **Synthesize projections to support countywide stormwater design.** Develop hourly precipitation time series (1970 to 2099) for hydrologic model input points.

The following steps were used to derive future rainfall:

1. Select GCMs that simulate future atmospheric conditions.
2. Select the global carbon emissions scenarios (representative concentration pathways) that will be simulated.
3. Use an RCM to downscale the GCM to reflect Puget Sound lowland conditions.
4. Determine the method to scale historical rainfall to reflect the future conditions.

Sections 3.1.1 through 3.1.6 present details on each of these steps.

4.1.1 Global Climate Model

GCMs were evaluated against a range of performance metrics aimed at identifying models that best capture the dynamics governing large-scale precipitation in the region. Global models were selected based on two criteria: (1) accuracy in simulating Pacific Northwest climate and (2) sensitivity to greenhouse gas (GHG) emissions. A set of metrics particularly relevant to Pacific Northwest weather patterns were used to rank 29 GCMs. The GCMs that were selected were the ACCESS 1-0 model and the GFDL-CM3 model (Table 2). (See Mauger et al. 2018 for details on this selection process.)

Table 2. Global models selected for downscaling using the WRF regional climate model

Global Model	Citation	Greenhouse Gas Scenario	Descriptor
GFDL-CM3	Griffies et al. 2011	RCP 8.5 (High emissions)	"High-High"
ACCESS 1-0	Bi et al. 2013	RCP 4.5 (Low emissions)	"Low-Low"

4.1.2 Representative Concentration Pathways

Two representative concentration pathway (RCP) scenarios – RCP 4.5 and RCP 8.5 -- were selected from the scenarios used by the Intergovernmental Panel on Climate Change for the Fifth Assessment Report (IPCC, 2014). The RCPs represent the concentration of greenhouse gasses in the atmosphere resulting from different levels of greenhouse gas emissions. RCP values refer to the amount of energy, in watts per square meter in 2100 associated with those concentrations. Figure 3 presents graphs showing the projected Carbon emissions and resulting CO_2 atmospheric concentrations associated with four RCPs through 2100.

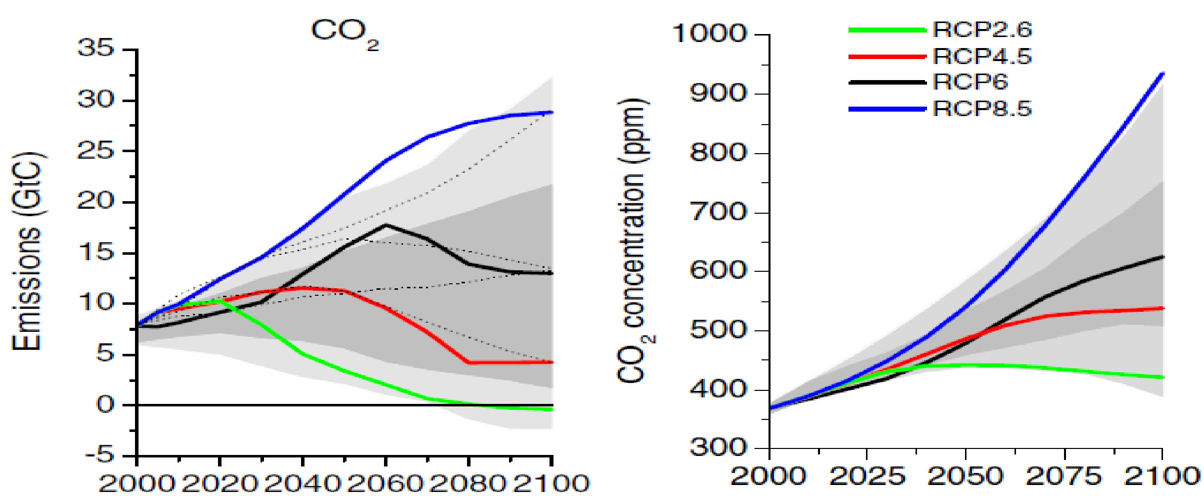

Figure 3. (Left) Projected carbon dioxide (CO_2) emissions, in gigatons of carbon, through 2100, for four of the IPCC's RCPs.

(Right) Projected concentration of CO_2 in the atmosphere for the same RCPs, in parts per million. Grey area indicates the 98th and 90th percentiles (light/dark grey). The dotted lines in the figure on the left indicate CO_2 emissions projections from the previous generation of IPCC emission scenarios. (Source: van Vuuren et al., 2011).

In RCP 4.5, emissions decline substantially by the end of the 21st century and greenhouse gas concentrations peak before 2100. RCP 8.5 is the only scenario in which emissions are not stabilized in the 21st century, instead continuing to grow throughout the 21st century.

Figure 4 presents ranges of average temperature and precipitation changes in the Puget Sound region as simulated using Global Climate Models with RCP values of 4.5 and 8.5.

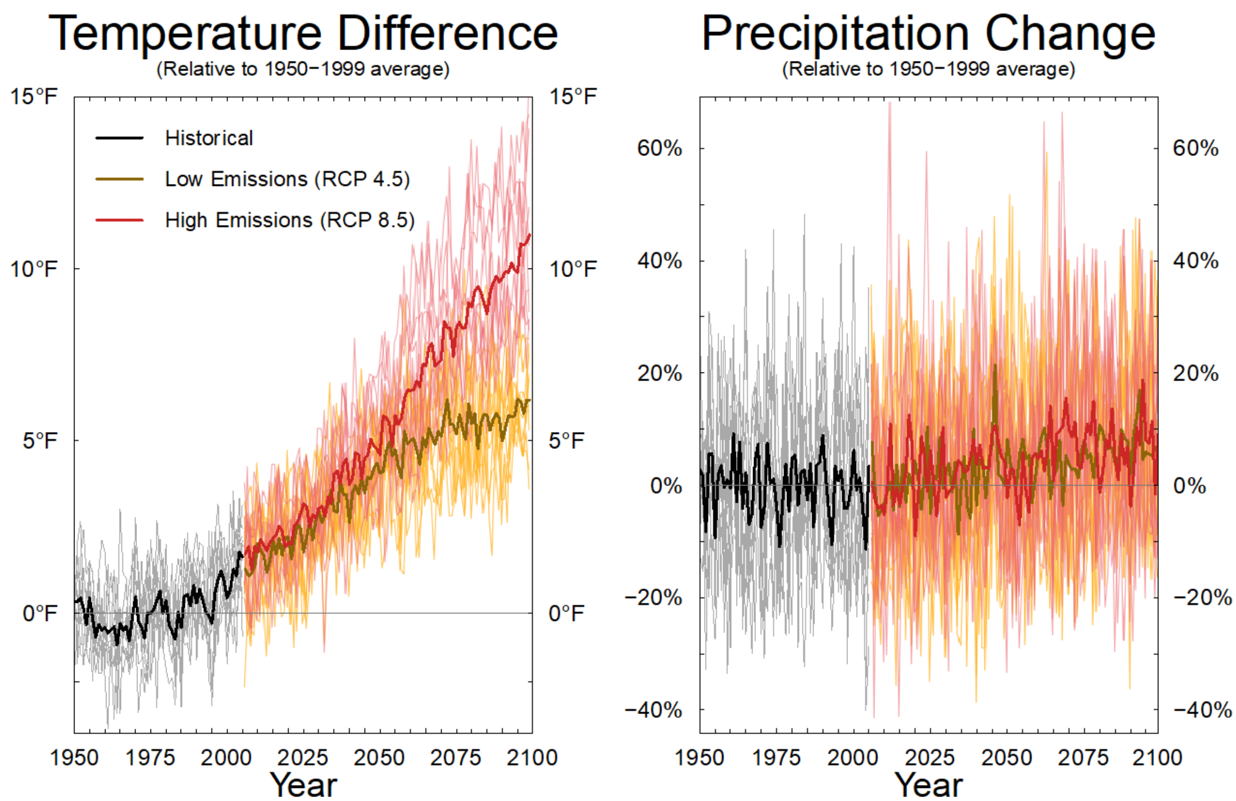

Figure 4. Projected changes in annual average temperature and precipitation for the Puget Sound region under low (RCP 4.5) and high (RCP 8.5) greenhouse gas scenarios.

The graphs show average yearly air temperature and precipitation for the Puget Sound region, relative to the average for 1950–1999 (horizontal gray line, corresponding to an annual average temperature of 44°F and an annual total precipitation of 43.6 inches). The black line shows the average simulated air temperature or precipitation for 1950–2005, based on the individual model results indicated by the thin grey lines. The thick colored lines show the average among model projections for two emissions scenarios (low: RCP 4.5, and high: RCP 8.5 – see Section 1), while the thin colored lines show individual model projections for each scenario. Data source: Downscaled climate projections developed by Abatzoglou and Brown 2011. (Source: Mauger et al., 2015).

In this study, WTD used the RCP 4.5 and 8.5 scenarios to represent the low and high end of likely future emissions (Clarke et al., 2014; IPCC, 2014). Each RCP scenario was coupled with a global climate model for the study. The ACCESS 1-0/4.5 (ACCESS 1-0 with RCP 4.5) model output was selected to denote a possible future climate if relatively aggressive steps are taken to reduce GHG emissions). The GFDL-CM3/8.5 (GFDL-CM3 with RCP 8.5) model was selected to produce results if GHG emissions continued to increase rapidly into the 22nd century.

4.1.3 Regional Climate Model

Studies have shown that a physics-based approach ("dynamical downscaling") is needed to capture changes in precipitation extremes and the associated impacts (Salathé et al., 2014). In dynamical downscaling, output from the GCMs serve as drivers for a regional climate model, which is used to simulate local-scale changes in climate. According to Mauger, et. al. (2019), using a regional climate model leads to a better representation of changes in the physical processes at these scales. This distinction is particularly important for precipitation because dynamical downscaling can explicitly represent the interactions of weather systems with the complex terrain of the Pacific Northwest.

Because regional weather and climate patterns are influenced by conditions in other parts of the globe (e.g., atmospheric rivers), GCMs are appropriate to use as boundary conditions for regional climate simulations. Previous studies have shown that global models are capable of representing the key aspects of atmospheric rivers, but they lack the resolution to capture the local consequences for precipitation given the complex topography of the Pacific Northwest. The outputs from the GCMs are used as boundary conditions for the regional climate model simulations. The regional climate models are able to estimate local-scale changes in extreme precipitation.

The Climate Impacts Group used the WRF (Skamarock et al., 2005) regional climate model (http://www.wrf-model.org) to produce two dynamically downscaled projections of future climate. A key feature of these projections is that they provide hourly estimates of future weather conditions (temperature, precipitation, humidity, wind, etc.). This is critical given that many CSO events are caused by short-duration rainfall intensities.

Nested 36- and 12-kilometer (km) grids were used in the RCM to downscale from the global atmospheric fields with grid spacings of approximately 100 to 200 km. The inner 12-km domain spans the region from northern California to southern British Columbia, and from the coastal ocean to the Rocky Mountains (Figure 5).

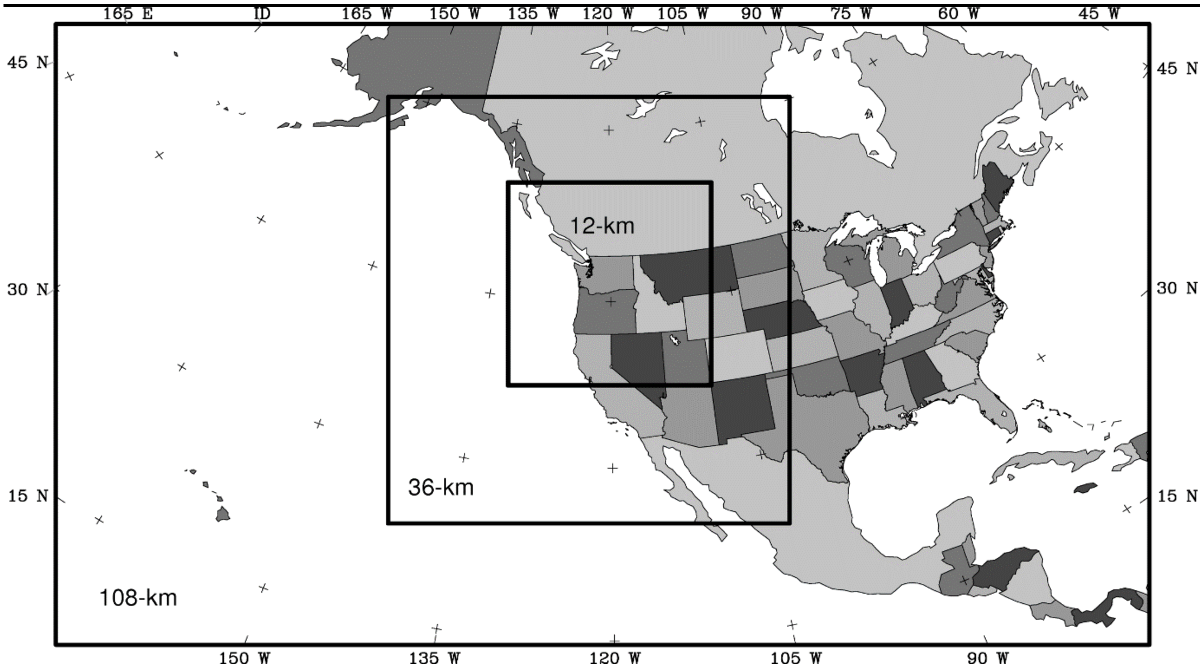

Figure 5. WRF model domains: Western U.S. at 36-km grid and Pacific Northwest at 12-km grid

Each WRF simulation extended from 1970 through 2099, providing continuous hourly estimates of precipitation, temperature, and other variables for each 130-year simulation. For the current analysis, hourly precipitation values were extracted for the WRF model grid point nearest Seattle-Tacoma International Airport (SeaTac).

4.1.4 Projected Rainfall from GCMs and RCMs

The results of the GCM and RCM simulations show the potential for large increases in future rainfall intensity by the 2080s (e.g., a 7 to 54 percent increase in the 10-year hourly rainfall extreme at Sea-Tac). However, results differ substantially among seasons and for the two climate projections considered. Although most projections indicate an increase in precipitation intensity, results for the ACCESS 1-0/4.5 model simulation project a decrease in precipitation intensity for some statistics and durations (e.g., the 25-, 50-, and 100-year extremes in hourly precipitation at SeaTac). Similarly, most of the projected changes for summer suggest a decrease in precipitation intensity, although this may be affected by the model's limited ability to capture convective events such as thunderstorms.

Table 3 presents the changes simulated by the GCMs, comparing the rainfall in the mid-1990s (1980 to 2009) to the rainfall simulated in the future period (2070 to 2099). The annual average rainfall is projected to increase about seven percent, but the change is not uniform over the entire year. The increases vary by model and by quarter, but both models simulate a decrease of 38 percent in the June to August quarter, which is the lowest rainfall quarter in the Seattle area. According to Mauger et al. (2018) "Although global models are more consistent in projecting drier summers, these results are unusual in projecting such large and consistent decreases in summer precipitation. In addition, precipitation extremes in summer can occasionally come in the form of thunderstorms. Whereas atmospheric river events are well captured by both the GCMs and the WRF model, thunderstorms are not well captured by either."

Table 3. Rainfall comparisons: 1980–2009 compared with two GCMs in 2070–2099

	Global Climate Model & RCP	Change in Precipitation 2080s vs. 1990s** (%)	Change in 2-year (1-hour duration)* Precipitation 2080s vs. 1990s (%)
Water Year	ACCESS 1-0 RCP 4.5 (Low)	+6.4	+12.6
	GFDL-CM3 RCP 8.5 (High)	+6.8	+33.2
Dec.–Feb.	ACCESS 1-0 RCP 4.5 (Low)	+6.6	+17.3
	GFDL-CM3 RCP 8.5 (High)	+15	+14.1
March–May	ACCESS 1-0 RCP 4.5 (Low)	-7.3	+1.3
	GFDL-CM3-RCP 8.5 (High)	+20	+12.4
June–Aug.	ACCESS 1-0 RCP 4.5 (Low)	-52	-37.3
	GFDL-CM3 RCP 8.5 (High)	-36	-3.9
Sept.–Nov.	ACCESS 1-0 RCP 4.5 (Low)	+20	+35.2
	GFDL-CM3 RCP 8.5 (High)	+5.2	+40.9

* The two-year (one-hour duration) storm is a peak one-hour precipitation that occurs, on average, once every two years.
** Rainfall analyzed for 10/1/1979-9/30/2009 and 10/1/2069-9/30/2099, inclusive.

4.1.5 Conversion of Regional Climate Model Results to Historical Rain Gauge Data

A contract with CH2M Hill and Herrera Environmental Consultants produced the methodology for converting the regional climate model results at a 12-km grid to the historical rainfall data collected at the 17 Seattle Public Utilities (SPU) rain gauges. Using rainfall output from the 12-km RCM directly in modeling CSOs would not provide the spatial variability of rainfall that characterizes Seattle's sewer service area, most of which feeds the West Point Treatment Plant. The easiest way to capture the rainfall variability across the service area for quantifying impacts to CSOs is to factor rainfall data that has been collected over four decades at each gauge. Four methods for converting the rainfall data were assessed, and it was decided that a cumulative distribution function (CDF) method be used for this analysis. (See Jantzen & Matsumura, 2017, for details on the methods.)

As stated in the report, "Processing King County Climate Model Data for Use in CSO Model" (Jantzen & Matsumura, 2017):

"Four precipitation perturbing methods were tested on a 38-year record for RG-09, projecting a baseline time series centered around 1995 to a future time series centered around 2085. Based on those results, the CDF method was selected for application to all 17 [gauges] because it focuses scaling on more frequent precipitation than the [intensity-duration-frequency-storage] and [intensity-duration-frequency-flow] method. Because of its ability to produce high temporal resolution (five-minute) precipitation time series suitable for CSO modeling and representing potential future climate conditions, the CDF perturbing method described in this technical memorandum is a valuable tool for evaluating potential impacts of climate change on CSO and other systems."

The CDF method applied to historical rain data has the following characteristics and precautions:

1. The *existing* gauged precipitation is factored. It does not change the duration of precipitation events or add new events. In this manner, the rainfall variability across the service area is maintained according to the historical record (past 38 years). Spatial variability of rainfall is very important to modeling CSO events. Using the RCM results directly would not provide the needed variability within a 12-km model grid.
2. Using the observed (gauge) data maintains the historical storm tracks. However, the historical storm movement across the county may not actually be an accurate representation of future storm tracks.
3. The CDF method only *increases* gauged precipitation. (Scaling factors are 1.0 or greater.) Although the climate model shows some months where monthly precipitation decreases, there are increases in precipitation intensity in all months. The CDF method does not replicate the precipitation decreases, but it does replicate the increase in intensity. This is appropriately conservative for the intended use for CSO modeling, where the concern is increased intensity, and CSOs are not common during the summer months. The CDF method is not appropriate for applications in which decreases in longer-term (monthly) precipitation averages are important.

For estimating the impacts of climate change on CSO volumes, it was deemed more important to apply the historical spatial rainfall variability throughout the year and to apply increases in winter storm intensities than to lower summer rainfall volumes, since the latter is not expected to substantially affect the once-per-year CSO volumes associated with CSO control regulations.

4.1.5.1 Cumulative Distribution Function Methodology

The one-hour rainfall data from the RCM for the years 1980 through 2009 is sorted by intensity and grouped into cumulative distribution function (CDF) bins. Figure 6 shows the sorted rainfall data for the 1980 to 2009 period as simulated by the GFDL-CM3 model with RCP of 8.5. The lowest 20 percent of rainfall intensities are sorted into the lowest 20 percent bin (0 – 20 percent; Bin 1 in Figure 6); the next lowest 20 percent of the hourly rainfall data is placed in the second bin (20 – 40 percent; Bin 2 in Figure 6); and so on for the 40 – 60 percent bin. The upper 40 percent of the rainfall data were grouped into smaller bins, since there was much more change in the higher intensity rainfall, resulting in a total of 17 bins. Rainfall from the RCM output for the years 2070 to 2099 is also sorted and grouped into the same number of bins, by rainfall intensity. For the lowest bin (the lowest 0 to 20 percent of the rainfall intensities), the one-hour rainfall at the bin mid-point (ten percent in this case) is divided by the one-hour rainfall for the same bin from the 1980 to 2009 RCM rainfall data output. The resulting ratio is the factor that is then used to multiply the lowest 20 percent rainfall intensity values from the historical data. Similarly, rainfall from the next bin (20 to 40 percent) is factored the same way by taking the ratio of the rainfall values at the middle (30 percent) of the bin; and so on for the rainfall intensities of all the bins. The resulting factored historical rainfall is then considered the representative rainfall for the 2070–2099 (say, “2085”) period under the climate scenario that is run.

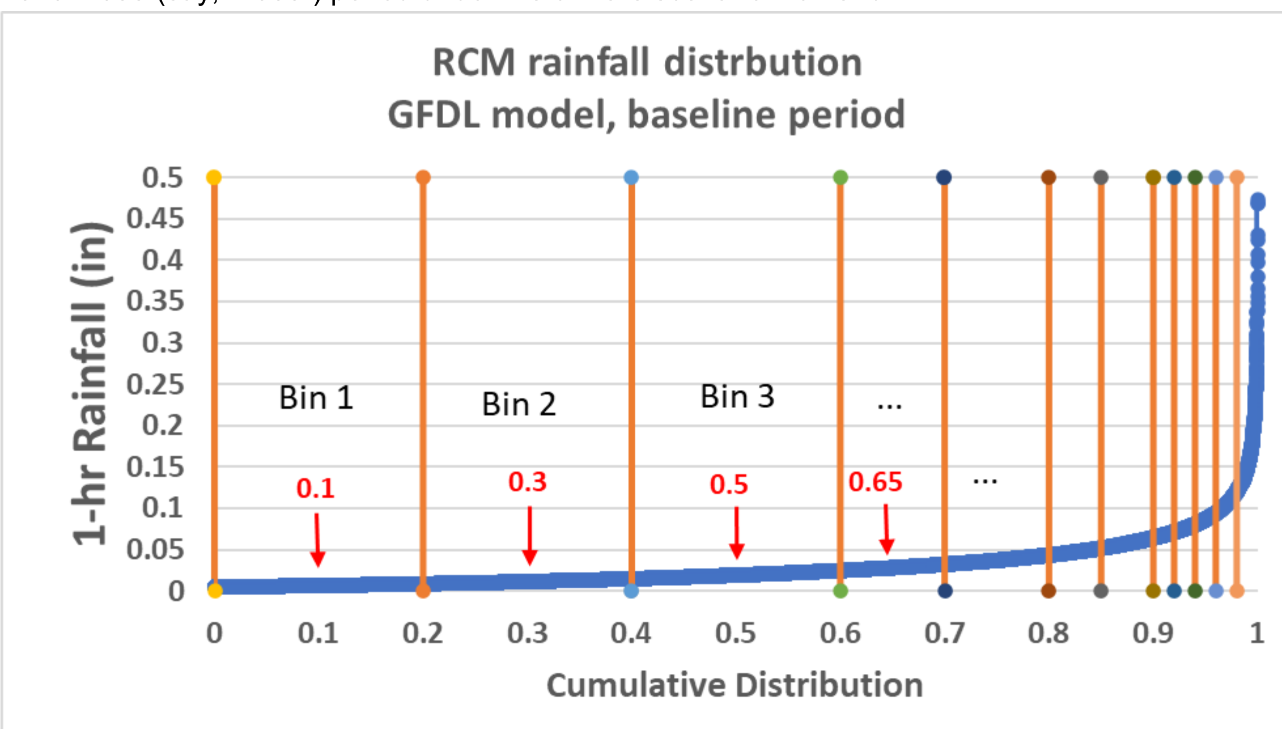

Figure 6. Hourly rainfall from 1980–2009, sorted by intensity for the GFDL-CM3/8.5 RCM baseline output.

Orange vertical lines represent the boundaries of the bins into which the data was aggregated in order to compare future rainfall with past rainfall (at the midpoints of each bin).

The bins used are as follows (all ranges are in percent): 0 to 20; 20 to 40; 40 to 60; 60 to 70; 70 to 80; 80 to 85; 85 to 90; 90 to 92; 92 to 94; 94 to 96; 96 to 98; 98 to 99; 99 to 99.2; 99.2 to 99.4; 99.4 to 99.6; 99.6 to 99.8; and 99.8 to 100. More bins were used for the higher intensities because the ratios of rainfall (2085 values over 1995 values) changed rapidly at these higher intensities. (See Table 4 for the factors used for each bin.)

A more detailed description of the process for converting the historic rainfall to future rainfall is documented in “Attachment F: Instructions for running CDF method using R and Microsoft Excel spreadsheet” from the report, “Processing King County Climate Model Data for Use in CSO Model” (Jantzen & Matsumura, 2017).

The red squares in Figure 7 show where the Regional Climate Model produced output. Output from the three RCM grid points in the City of Seattle were analyzed according to the CDF method described above. The statistical analyses for these sites were used to adjust the rainfall data at the SPU gauges, shown as yellow stars in Figure 7. The analysis of the nearest RCM grid point was used to adjust the historical rainfall at each of the SPU rain gauges shown in Figure 7. Therefore, RG01 was factored according to the RCM analysis of the grid point farthest north in the City of Seattle. Rain gauges 02, 03, 04, 07, 08, 09, 11, 12, and 25 used the factors associated with the RCM grid point near RG03. The rain data from the southern seven rain gauges used the factors from the RCM grid point near RG16. Once the historical rainfall was scaled by the factors from the nearest RCM output location, the resulting “future” rainfall data were then used for simulating the future runoff over the collection system and through King County’s wastewater conveyance system.

4.1.6 Future Rainfall Factor Results

Table 4 presents the factors that were used to multiply the precipitation data in the historical record to represent the climate around the year 2085 under the Access 1-0/4.5 and the GFDL-CM3/8.5 climate scenarios, for the three RCM output locations. Historical rainfall data were sorted into intensity bins, and each rainfall data point was multiplied by a factor depending on the bin corresponding to the hourly rain intensity, location, and scenario. The scaling factors for both climate scenarios were 1.00 for the three lowest bins (those with the lowest rainfall intensities). In other words, 60 percent of the rainfall data points were not scaled up. Only the top 40 percent of rainfall intensities were scaled by factors greater than 1.0. The factors ranged from 1.0 for the light intensity rainfall in the lowest 3 bins to 1.2 in the highest bins for the Access 1-0/4.5 climate scenario, and from 1.0 to 1.308 for the GFDL-GCM/8.5 scenario. The dip in the rainfall factor in the highest bin (0.998–1.0) for the ACCESS 1-0/4.5 model is a result of the 1980 – 2009 rainfall in the RCM output for that bin was a larger fraction of the rainfall in that bin for the 2070 – 2099 model output, and, therefore, required a smaller factor. A larger bin size would have resulted in a smoother curve.

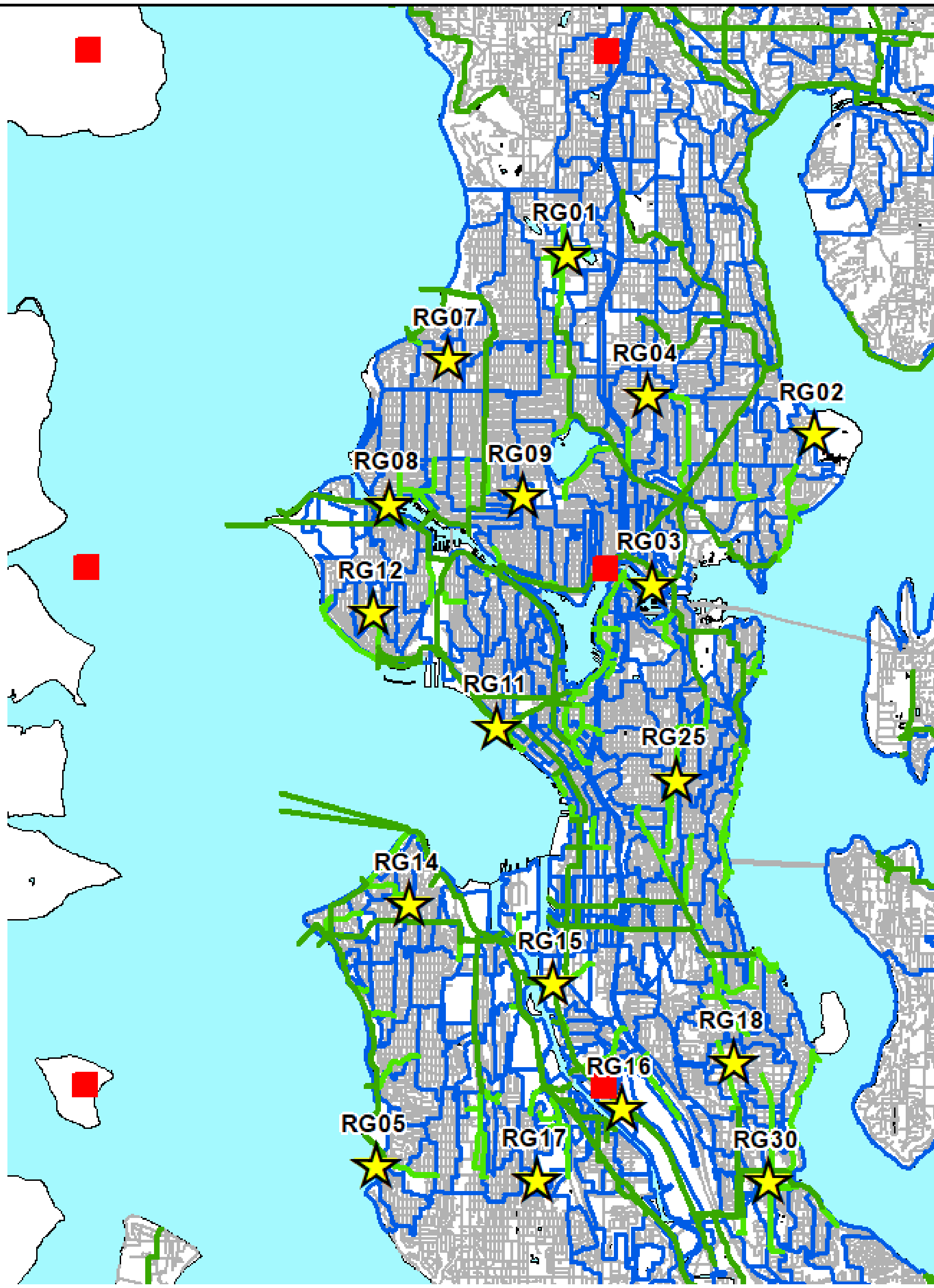

Figure 7. Seattle Public Utilities rain gauge locations relative to 12-km-grid Regional Climate Model (RCM) output locations (red squares)

Table 4. Climate change rainfall factors for ~2070–2099 conditions

	ACCESS 1-0_RCP 4.5			GFDL-CM3_RCP 8.5		
Percentile Bin Range	Far North - Near RG01	North – Near RG03	South – Near RG16	Far North - Near RG01	North – Near RG03	South – Near RG16
0–0.2	1.000	1.000	1.000	1.000	1.000	1.000
0.2–0.4	1.000	1.000	1.000	1.000	1.000	1.000
0.4–0.6	1.000	1.000	1.002	1.000	1.000	1.000
0.6–0.7	1.016	1.036	1.040	1.030	1.043	1.021
0.7–0.8	1.047	1.048	1.055	1.064	1.084	1.061
0.8–0.85	1.072	1.079	1.078	1.090	1.104	1.097
0.85–0.9	1.085	1.093	1.089	1.113	1.122	1.116
0.9–0.92	1.100	1.109	1.102	1.126	1.137	1.131
0.92–0.94	1.110	1.120	1.114	1.136	1.150	1.121
0.94–0.96	1.122	1.120	1.131	1.144	1.154	1.132
0.96–0/98	1.141	1.135	1.144	1.147	1.156	1.151
0.98–0.99	1.121	1.166	1.151	1.150	1.166	1.178
0.99–0.992	1.132	1.162	1.161	1.160	1.191	1.195
0.992–0.994	1.129	1.172	1.165	1.152	1.188	1.205
0.994–0.996	1.141	1.182	1.190	1.164	1.169	1.206
0.996–0.998	1.184	1.200	1.191	1.232	1.198	1.217
0.998–1.0	1.143	1.154	1.156	1.289	1.198	1.308

Factoring the rainfall data resulted in increased annual rainfall that was slightly different at each rain gauge. Table 5 presents the annual volumes and the differences from the baseline simulations. Generally, the ACCESS 1-0/4.5 adjustments added ~6.9 percent to the average annual rainfall at each gauge for the 2085 condition compared to the 1978–2018 (midpoint 1998) condition. The factors used for the GFDL-CM3/8.5 climate scenario resulted in an average increase of 8.3 percent to the annual rainfall from the 1998 condition.

Table 5. Annual average rainfall at the 17 Seattle rain gauges

Baseline (historical – 1978 through 2018), ACCESS 1-0/4.5 (2070 through 2099), and GFDL-CM3/8.5 (2070 through 2099)					
Gauge	**Baseline**	**ACCESS 1-0/4.5**	**Ratio* ACCESS 1-0/4.5: Baseline**	**GFDL-CM3/8.5**	**Ratio* GFDL-CM3/8.5: Baseline**
RG01	35.3	37.5	1.061	38.1	1.077
RG02	36.4	39.0	1.069	39.6	1.086
RG03	34.1	36.5	1.069	37.1	1.085
RG04	36.2	38.7	1.069	39.3	1.085
RG05	32.6	34.8	1.069	35.2	1.079
RG07	36.5	39.0	1.070	39.6	1.087
RG08	34.9	37.3	1.069	37.9	1.086
RG09	34.3	36.7	1.071	37.4	1.090
RG10	38.3	41.1	1.071	41.4	1.081
RG11	31.5	33.6	1.068	34.2	1.084
RG12	35.0	37.5	1.069	38.0	1.086
RG14	35.8	38.3	1.070	38.6	1.080
RG15	34.9	37.3	1.069	37.7	1.079
RG16	35.4	37.8	1.070	38.2	1.079
RG17	38.8	41.6	1.071	42.0	1.081
RG18	37.2	39.8	1.070	40.2	1.080
RG20	35.6	38.1	1.069	38.7	1.086
Average	35.5	37.9	1.069	38.4	1.083

*A ratio of 1.127 means that there is a 12.7 percent increase in annual rainfall volume between the baseline (1978-2018) period and the climate change run period (2070–2099).

Figure 8 presents a graph of the factors used for adjusting the historical data for the two climate change scenarios.

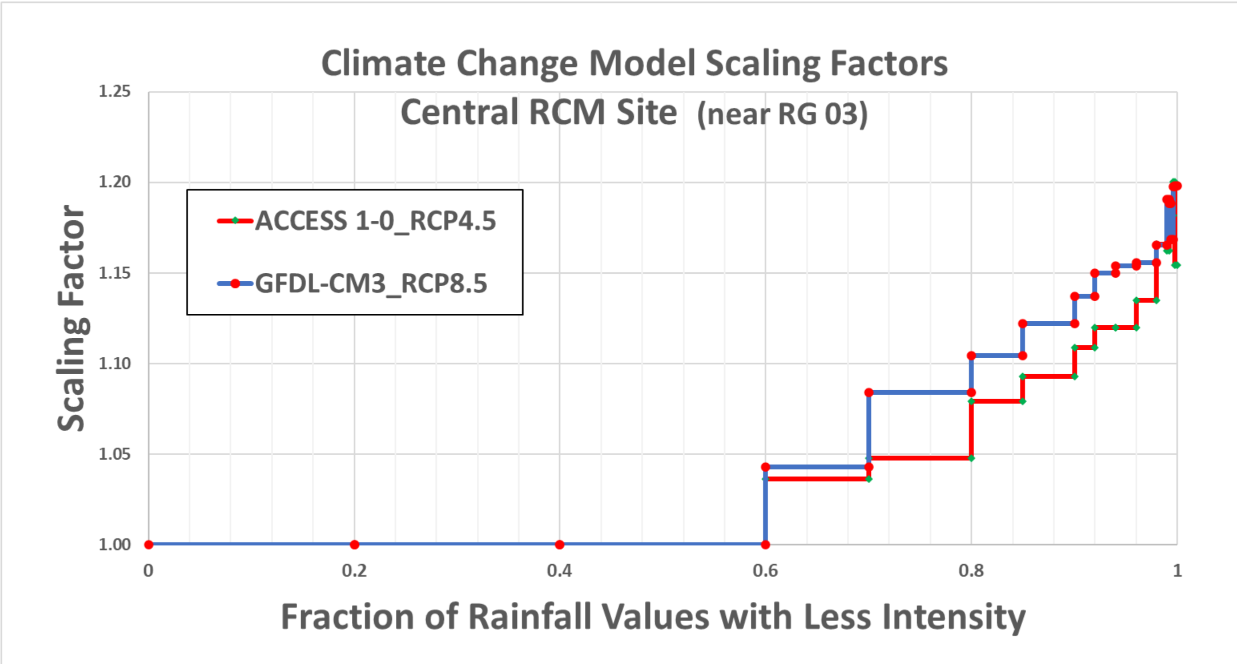

Figure 8. Rainfall factors used for converting historical (1978–2018) rainfall to 2070–2099 (2085) conditions

4.2 Collection and Conveyance System Modeling

4.2.1 Hydrologic Model Calibration

WTD has completed a large effort of building MIKE Urban hydrologic and hydraulic models of the entire West Point system and the Henderson/Norfolk system, which drains to South Plant. The wastewater flow and hydrologic response of the basins been calibrated to flowmeter data at many locations using Model B and the RDII module of MIKE Urban. This process has been underway for the past ten plus years, and the models have been applied to several WTD CSO projects as they were developed and calibrated.

Calibration is the process of using local rainfall as input to the model and adjusting model parameters such that the model output (flow and level at the downstream location) matches the metered data. Several storms are matched so that there is confidence that the model can replicate the basin response under a variety of dry and wet weather conditions. Figure 9 shows an example calibration graphic for three rainfall events in the South Magnolia basin.

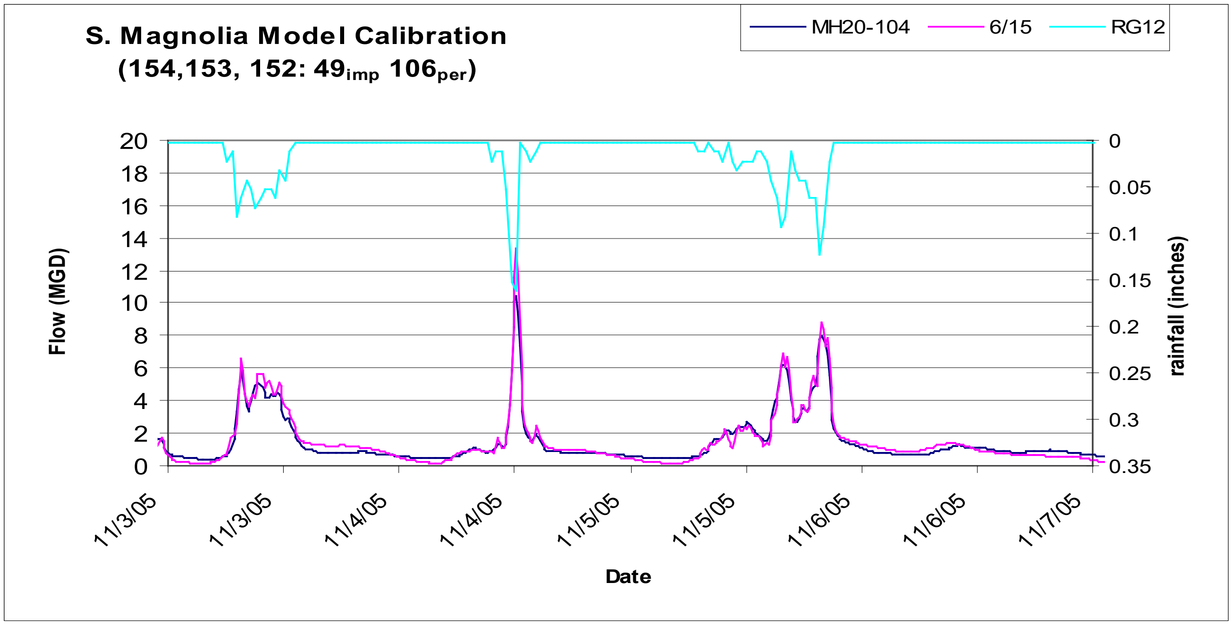

Figure 9. Result of a model calibration for a portion of the South Magnolia basin.

Light blue line denotes rainfall (right axis); dark blue line denotes metered flow data (left axis); magenta line denotes modeled flow (left axis).

4.2.2 Hydraulic Model Simulations

WTD recently completed an effort to merge the lower basin and conveyance models into a "core model" such that appropriate control schemes could be placed in the hydraulic model that reflect the way the system operates as a whole. The merged core model includes:

- the West Marginal Pump Station (PS) basin;
- the Duwamish PS basin, downstream from the Georgetown Wet Weather Treatment Station (WWTS);
- the West Seattle PS basin, downstream of 53rd Ave. PS and Murray Ave. PS;
- the Interbay PS basin, downstream of the Bayview and Hanford tunnels;
- and the North Interceptor model downstream from the East Pine and 30th Ave. Pump Stations and downstream from the Green Lake Trunk.

The model simulations completed for the upstream basins (those upstream of those modeled in the merged model) produced the CSO estimates from the locations designated as Phase 1 locations. The modeling areas included in Phase 1 locations are shown in green in Figure 1. The extent of the merged downstream models that quantify the CSO volumes for the Phase 2 locations are shown in yellow in Figure 2.

Rainfall is used as input to the MIKE Urban hydrologic and hydraulic models. Each basin in the model uses the rainfall from the nearest SPU rain gauge. Actual rainfall data were used for the baseline simulations, after a check was performed to ensure erroneous data spikes were removed. [This QA/QC check could include the following rainfall modifications: for example, if a very large rainfall "spike" is recorded at a gauge when no other gauges recorded rainfall that day, it is assumed maintenance was being performed on the former gauge, and therefore, the data spike is removed. Conversely, if one gauge reads substantially lower than all other gauges for an entire day, the gauge may be partially or totally plugged by leaves or other debris, and the data from a nearby gauge may be substituted for the gauge that is consistently recording low values.]

After any QA/QC corrections, historic rainfall from the 17 SPU rain gauges was adjusted such that the statistical parameters reflect the output from the ACCESS 1-0/4.5 and GFDL-CM3/8.5 climate model simulations, as described previously. The climate-altered historical rain data from the City of Seattle was used as input to the hydrologic and hydraulic models to reflect two possible future conditions simulated by the two GCMs with two greenhouse gas emission scenarios. By using the altered rainfall data, WTD could run its existing collection and conveyance system calibrated models to obtain two possible future CSO control volumes at each CSO location.

Simulations were run for the period from 1978 through 2018 (41 years) using historical rainfall and are considered a "baseline" condition with a mid-point of 1998. Model simulations were also made using 41 years of adjusted rainfall to reflect possible future climate conditions in 2070 – 2099 (with a mid-point of 2085), as reflected in the ACCESS 1-0/4.5 and GFDL-CM3/8.5 GCMs/RCMs. Treated and untreated CSO flowrates and volumes were tallied for each CSO location and for each CSO treatment facility.

5.0 Climate Change Impacts -- Modeling Results

5.1 Climate Change Impacts on CSO Control Volumes

Table 6 presents the increase in CSO control volumes (in million gallons) at the Phase 1 locations – the volumes that would need to be controlled to achieve 20 events per year in the worst 20-year period of simulation for each respective future climate scenario. These volumes are in addition to the volume required to bring the sites into compliance under the current climate condition. The increases listed in Table 6 assume there were no other substantial changes in the basins that would affect the hydrologic responses.

Fourteen of the sites in Table 6 (marked with a superscript "a") were modeled as being in CSO compliance under current (historical) climate conditions, assuming the Georgetown WWTS is completed (completion expected in 2022). The GWWTS is expected to bring the S. Michigan and the S. Brandon St. Regulator stations into CSO compliance, but the model simulations indicate that, if the climate projections pan out as modeled, more would be needed at S.

Table 6. Modeled One-year CSO Control Volume Differences due to Impacts of climate change from years 1978-2018 to 2070-2099 for Phase 1 locations

		Phase 1 Locations 1-Year CSO Control Volume Changes from Baseline [MG]			
		Long-Term (41 Years) 1978–2018		Maximum 20-Yr Period	
#[d]	CSO Location	ACCESS 1-0 RCP 4.5	GFDL-CM3 RCP 8.5	ACCESS 1-0 RCP 4.5	GFDL-CM3 RCP 8.5
1	Barton PS CSO	0.03	0.07	0.05	0.12
2	Belvoir PS CSO	0.24	0.38	0.28	0.40
3	Dexter Regulator Station CSO [a, b]	0	0	0	0
4	East Marginal PS CSO [a]	0	0	0	0
5	53rd PS CSO [a]	0	0	0	0
	Georgetown WWTS [a]	See S. Brandon and S. Michigan Regulators			
6	Henderson PS CSO [a]	0	0	0	0
7	Matthews Park PS [a]	0	0	0	0
8	MLK Way Weir CSO [a]	0	0	0	0
9	Murray PS CSO [a]	0.12	0.39	0.39	0.63
10	Norfolk Regulator Station CSO [a]	0	0.13	0	0.19
11	North Beach PS Wet Well	0.27	0.40	0.22	0.35
12	North Beach PS Inlet [a]	0	0.02	0.004	0.03
13	Rainier Valley CSO Total CSO (Bayview North + Bayview South + Hanford at Rainier)	1.82	2.71	2.65	4.09
14	Rainier PS [a]	0	0	0	0
15	S. Brandon Regulator Station CSO [a, c]	0.07	0.18	0.07	0.22
16	S. Michigan Regulator Station CSO [a, c]	0.11	0.40	0.26	0.68
17	30th PS CSO [a]	0	0	0	0
	Total Additional Storage at Phase 1 sites	**2.66**	**4.68**	**3.92**	**6.72**

[a] Modeled as controlled in baseline
[b] Lower than observed because model does not represent traveling hydraulic jump
[c] Assumes the Georgetown WWTS is completed
[d] Number in Table 1 and Figure 2

Michigan St. and S. Brandon St. Regulators to keep these in compliance through 2100. Modeling also indicates the currently controlled sites at Murray Ave. PS and Norfolk Regulator Station will move to being out of compliance by 2100 under the simulated future climate conditions, although the Norfolk Regulator might be kept in control in the future with operational changes at the MLK Way Tunnel. Each of these CSO locations will be re-evaluated in the future to ascertain whether additional CSO facilities are required as the actual changes in rainfall due to climate change are experienced.

Table 7 presents the additional CSO control volumes required due to the impacts of two possible climate change scenarios (in approximately 2085) above what is required under baseline (current climate) conditions for CSO locations in the Phase 2 grouping. Those modeled as currently at the one-per-year control criteria or less are marked with a superscript "a". The Georgetown Wet Weather Treatment Station was included in the model simulations. The joint SPU/KC Ship Canal Water Quality Project tunnel (expected completion in 2025) was not included in the model simulations so that the change in control volumes could be quantified for each site that will contribute flow to the tunnel.

Five of the seven currently "controlled" Phase 2 sites would become out of control by late in the century under one or both future climate change scenarios. The additional volume that would be required at these five sites totals 0.75 million gallons [MG] in the ACCESS 1-0/4.5 simulation and 1.37 MG under the GFDL-GCM/8.5 scenario.

Overall, based on historical rainfall only, there is about 149 MG of control volume that needs to be addressed to bring all of the Phase 1 and 2 CSO sites into regulatory compliance (20 events or less in any 20-year period). Under the ACCESS 1-0/4.5 climate model scenario, the total control volume would increase by 59 MG, to 208 MG, an increase of 40 percent. Under the GFDL-GCM/8.5 model scenario, the control volume would increase by 81 MG, to 230 MG, by late in the century, a 54 percent increase over current/historical climate.

The increases in CSO control volumes in Tables 6 and 7 indicate the magnitude of climate change impacts at each CSO storage site. Control volumes may be addressed by a number of means, such as storage, treatment, and/or GSI (green stormwater infrastructure). By reporting the CSO impacts due to climate change in terms of control volumes, the impacts at each site can be compared on the same basis. The numbers in Tables 6 and 7 give a sense of the climate change impact, but the actual size of a facility would depend on the approach taken to control the CSO (e.g., storage, treatment, GSI, etc.)

5.2 Climate Change Impacts on Peak CSO Flowrates

The sizing of conveyance pipes associated with CSO facilities is usually optimized during design of the CSO facility. The minimum peak flow to be conveyed to a CSO treatment facility or a storage facility is the one-year peak flowrate. However, the size of treatment capacity may be reduced by equalization storage, which is typically optimized during design of the facility. The flow capacity to the equalization or storage tank is likely to be sized greater than the one-year peak flow, so that storms smaller in volume than the one-year storm can be conveyed to the facility, even if the smaller (by volume) storm has a higher peak intensity than the one-year peak. For the sake of comparing how climate change might affect peak CSO rates, the one-year peak CSO flowrate for each CSO is presented in Table 8 for the baseline simulation and for the two possible future climate condition simulations, at the Phase 1 locations. Table 9 presents the same information for the Phase 2 sites.

Table 7. Modeled differences between year 2070–2099 and 1978–2018 one-year CSO control volumes due to impacts of climate change for Phase 2 locations

		Phase 2 Locations 1-Year CSO Control Volume Changes from Baseline [MG]			
		Long-Term (41 Years) 1978 - 2018		Maximum 20-Yr Period	
# [d]	CSO Location	ACCESS 1-0 RCP 4.5	GFDL-CM3 RCP 8.5	ACCESS 1-0 RCP 4.5	GFDL-CM3 RCP 8.5
18	Ballard Regulator [a]	0	0	0	0
19	Canal St. Overflow Weir [a]	0	0.01	0	0.01
20	Chelan Ave. Regulator	2.73	3.45	3.1	3.77
21	8th Ave. S. Regulator [a]	0	0.05	0	0.10
22	Denny/Elliott W. Regulators/Weirs [a]	0.26	0.49	0.46	0.77
23	East Duwamish [a]	0	0.01	0.003	0.03
24	West Duwamish [a]	0.25	0.33	0.29	0.46
25	11th Ave. NW Overflow Weir [b]	2.10	4.25	2.01	3.91
26	Hanford #2 Regulator	16.07	21.89	17.17	20.92
27	Harbor Regulator	0.21	0.3	0.26	0.35
28	King St. Regulator	1.79	2.28	1.65	2.20
29	Kingdome Regulator	5.47	6.21	5.53	6.45
30	Lander St. Regulator	3.82	5.28	2.67	3.72
31	Montlake Regulator	4.59	5.48	4.69	5.97
32	63rd Ave. PS	1.97	2.84	2.49	3.32
33	S. Magnolia Overflow Weir	0.25	0.45	0.67	0.92
34	Terminal 115 Overflow Weir	0.58	0.77	0.79	0.93
35	SW Alaska St.	0.18	0.30	0.20	0.32
36	3rd Ave. W. [b]	2.09	3.07	1.98	3.26
37	University Regulator	10.18	15.76	10.53	16.12
38	W. Marginal PS [a]	0	0	0	0
39	W. Michigan St. Regulator	0.36	0.52	0.56	0.81
	Total Increase in Control Volume (MG)	52.9	73.7	55.1	74.3

[a] Modeled as controlled in baseline

[b] The Joint SPU/KC Ship Canal Water Quality Project Tunnel was not included in these simulations

[d] Number in Table 1 and Figure 3

Table 8. Modeled One--year Peak CSO Flowrates for Baseline and Climate Change Scenarios for Phase 1 locations

	Phase 1 Locations 1-Year Peak CSO Flowrates Worst 20-year period [MGD]			
		1978–2018	2070–2099	
#*	CSO Location	Baseline	ACCESS 1-0 RCP 4.5	GFDL-CM3 RCP 8.5
1	Barton PS CSO	1.3	5.9	9.9
2	Belvoir PS CSO	3.0	4.8	5.1
3	Dexter Regulator Station CSO [a, b]	0	0	0
4	East Marginal PS CSO [a]	0	0	0
5	53rd PS CSO [a]	0	0	0
	Georgetown WWTS [a]	See S. Michigan and S. Brandon Regulators		
6	Henderson PS CSO [a]	0	0	0
7	Matthews Park PS [a]	0	0	0
8	MLK Way Weir CSO [a]	0	0	0
9	Murray PS CSO [a]	0	18.2	26.0
10	Norfolk Regulator Station CSO [a]	0	0	13.2
11	North Beach PS Wet Well	4.0	5.9	6.1
12	North Beach PS Inlet [a]	0	1.0	3.1
13	Rainier Valley CSO Total CSO (Bayview North + Bayview South + Hanford at Rainier)	11.6	29.4	38.8
14	Rainier PS [a]	0	0	0
15	S. Brandon Regulator Station CSO [a, c]	0	6.0	17.5
16	S. Michigan Regulator Station CSO [a, c]	0	13.8	35.8
17	30th PS CSO [a]	0	0	0

[a] Modeled as controlled in baseline
[b] Lower than observed because model does not represent traveling hydraulic jump
[c] Assumes the Georgetown WWTS is completed
[d] Number in Table 1 and Figure 2

Table 9. Modeled One-year Peak CSO Flowrates for Baseline and Climate Change Scenarios for Phase 2 locations

	Phase 2 Locations 1-Year Peak CSO Flowrates [MGD]			
		1978–2018 Worst 20-year period	2070–2099 Worst 20-year period	
#*	CSO Location	Baseline	ACCESS 1-0 RCP 4.5	GFDL-CM3 RCP 8.5
18	Ballard Regulator [a]	0	0	0
19	Canal St. Overflow Weir [a]	0	0	2.9
20	Chelan, Hanford #2, Lander, Kingdome, King, (CHLKK)	266.2	317.1	338.3
21	8th Ave. S. Regulator [a]	0	0	5.8
22	Denny/Elliott W. Regulators/Weirs [a]	25.7	72.9	101.5
23	East Duwamish [a]	0	0.4	1.5
24	West Duwamish [a]	0	7.7	8.4
25	11th Ave. NW Overflow Weir [b]	50.0	67.3	83.3
26	Hanford #2 (See CHLKK)			
27	Harbor Regulator	4.6	22.6	31.2
28	King St. Regulator (See CHLKK)			
29	Kingdome Regulator (See CHLKK)			
30	Lander St. Regulator (See CHLKK)			
31	Montlake Regulator	101.7	126.3	138.7
32	63rd Ave. PS	25.2	51.5	57.7
33	S. Magnolia Overflow Weir	4.7	13.5	15.1
34	Terminal 115 Overflow Weir	3.5	9.7	10.1
35	SW Alaska St.	2.4	8.0	11.5
36	3rd Ave. W. [b]	49.5	65.5	74.3
37	University Regulator	139.4	188.6	204.2
38	W. Marginal PS [a]	0	0	0
39	W. Michigan St. Regulator	3.1	4.2	4.5

[a] Modeled as controlled in baseline
[b] The Joint SPU/KC Ship Canal Water Quality Project Tunnel was not included in these simulations
[d] Number in Table 1 and Figure 3

For the CSOs that will be controlled by storage, the change in capacity of the conveyance pipes to the storage facilities are not expected to have nearly the cost impact as the change in the necessary storage volume to meet the CSO requirements. But for CSO treatment facilities (e.g., CHLKK), the change in peak flow will likely be the largest factor affecting the change in costs due to climate change.

The results shown in Tables 8 and 9 reveal that there could be sizable conveyance differences due to climate change. The one-year peak flows at the largest CSO locations can increase by up to approximately 70 mgd (at CHLKK, University, and Denny/Elliott W.). The peak flow increases at sites not currently controlled range from 20 percent at the CHLKK site (ACCESS 1-0/4.5 scenario), which is earmarked for a wet weather treatment plant, up to 660 percent for a smaller CSO location with much smaller flows (Barton PS). At sites currently controlled, future peak flowrates that may need to be controlled go up to 26 mgd at Murray PS and 36 mgd at S. Michigan St.

5.3 Climate Change Impacts on CSO Frequency and Annual Volume in the Existing System

There is other interesting information that can be mined from the model simulations that have been performed in this study. Information about how the CSO frequency at each WTD CSO location would be affected due to climate change if the conveyance system remained as it is expected to be in 2022 (i.e., no additional CSO projects completed after the Georgetown WWTS) is presented in Appendix A. Except for those sites currently in control and expected to remain in control, the CSO frequency at each site would increase due to climate change if no CSO facilities were constructed.

The annual average CSO volumes at each of the KCWTD sites would also increase due to climate change if the wastewater system remained the same. The changes in the average annual CSO volumes at each KCWTD site were tallied for the baseline and two projected future climate scenarios from the existing system model runs and are also presented in Appendix A.

6.0 Summary of Results

As expected, the CSO control volumes required to achieve or maintain compliance with the one-per-year regulatory compliance measure are projected to increase, according to the model runs with two rainfall scenarios approximating 2085 climate conditions. Furthermore, the GFDL-CM3/8.5 climate runs produced higher one-year control volumes than the ACCESS 1-0/4.5 model runs, although there is a smaller difference between the two than the difference between each of them compared separately with the baseline condition. The ten CSO locations that are currently in control and are projected to continue to be in control, even with the elevated future rainfall, are as follows:

- East Marginal PS
- MLK Overflow Weir (upstream of the Henderson MLK Tunnel)
- Henderson PS
- Dexter Ave. Regulator Station
- 53rd Ave. PS
- 30th Ave. PS
- Rainier PS
- Ballard Regulator Station

- West Marginal PS
- Matthews Park PS

[Note: In practice, compliance with the regulatory criteria is actually based on measured CSO events over the past 20 years. When there is less than 20 years of data available after a CSO project is brought online, then modeling estimates are used to complete the 20-year period. In this technical memorandum, only modeling results are used for both baseline and future climate scenarios, so that the impact of projected rainfall changes can be assessed on an apples-to-apples basis. The baseline results may not exactly match up with the historical record, due to actual system operations and/or due to inaccuracies in rainfall estimates, flow data, and modeling simulations.]

Nine sites were simulated as currently in control but are projected to need additional measures to keep them in control through the end of this century. Some of these may be kept in control with operational changes, such as at Norfolk, S. Brandon St., and S. Michigan St. (the latter two being controlled by the GWWTS). Other locations may or may not be able to accommodate the extra control volume and may need additional CSO facilities constructed to maintain regulatory control. The nine sites modeled as currently in control but needing additional measures in the future are:

Norfolk	North Beach Inlet	8th Ave. S.
S. Brandon St	Murray PS	East Duwamish
S. Michigan S.	Canal St.	West Duwamish

The other 20 KCWTD CSO locations simulated in this modeling study are estimated to currently need CSO facilities to bring them into one-per-year control in the worst 20-year period, and they show projected increases in one-year CSO control volumes when simulating future projected climate conditions. The future CSO facilities could be initially sized to control the projected future control volume or be sized to come into regulatory compliance based on historical rainfall, with the expectation that additional measures could be implemented at various times in the next several decades on an as-needed basis. There also could be a hybrid approach where initial facilities are sized larger than that required based on historical rainfall, but not so large as to control the facility at the end of the 21st century, with the plan to provide additional measures if and when the future climate projections actually occur.

The 29 CSO locations that may or may not currently be in control (with the completion of the Georgetown WWTS) and would be out of control with the simulated 2085 conditions are as follows:

- SW Alaska St.
- Barton PS
- Belvoir PS
- S. Brandon St. Regulator
- Canal St. Overflow Weir
- Chelan Ave. Regulator
- Lander St. Regulator
- S. Magnolia Weir
- S. Michigan St. Regulator
- Montlake Regulator
- Murray Ave. PS
- Norfolk Regulator

- Denny/Elliott West/Interbay Regulators/Weirs
- East Duwamish
- West Duwamish
- 8th Ave. S. Regulator
- 11th Ave. NW Weir
- Hanford #2 Regulator
- Harbor Regulator
- King St. Regulator
- Kingdome Regulator
- North Beach PS Wet Well
- North Beach PS Inlet
- Rainier Valley CSO (Rainier Valley Storage)/Hanford #1
- 63rd Ave. PS
- Terminal 115 Weir
- 3rd Ave. W.
- University Regulator
- W. Michigan St. Regulator

It is expected that operational changes could be made at the Henderson/MLK CSO Project location that would eliminate the one-year CSO volume at Norfolk Regulator Station in 2085. At other sites, it may be more difficult to maintain regulatory control with operational changes only.

Barton PS is simulated as right on the edge of being in control based on past rainfall. The long-term average one-year volume is zero, but the volume required to meet a one-per-year regulatory requirement was 0.004 MG in the worst 20-year period of record. Ongoing monitoring is required to tell if this station is in control or if it will require additional work to bring it in control in the near term. However, it is estimated that it will be out of control in the two 2085 climate model scenarios.

The North Beach PS Wet Well and North Beach PS Inlet are currently being monitored to determine whether they achieve compliance with the CSO criteria in any 20-year period, as they are also very close to the one/year frequency.

Appendix B presents recurrence interval graphs for each of the CSO locations included in this Phase 1 analysis. The CSOs that are in control, based on the CSO compliance measure, will have zero storage volume shown at the one-year recurrence interval under baseline conditions, but will have greater than zero storage required if the simulations are expected to put the CSO location out of compliance (e.g., see the Murray Ave. PS graphs in Figures 51 and 52, Appendix B). As the figures show, the CSO volumes associated with any return interval greater than one year increase with the ACCESS 1-0/4.5 model run and increase further with the GFDL-CM3/8.5 model simulation. The figures also show that the recurrence curves for the ACCESS 1-0/4.5 and the GFDL-CM3/8.5 models are fairly close together, when compared to the baseline model results.

Increasing rainfall because of climate change is expected to reduce the return interval of any given rainfall event. Similarly, the return intervals of peak flows and CSO volumes are expected to be reduced. For example, at several locations, a two-year event (i.e., one that happens, on average, once every two years) under historical rainfall becomes a one-year event (i.e., one that happens once per year, on average) in 2085 conditions. This is the case, as shown in the figures in Appendix B, for Barton PS (Figures 28 and 29); Belvoir PS (Figures 30 and 31); Brandon St. Regulator Station (Figures 32 and 33); S. Michigan St. Regulator Station (Figures

56 and 57); Murray Ave. PS (Figures 62 and 63); Norfolk Regulator Station (Figures 64 and 65); and North Beach PS (Figures 66 and 67); and Rainier Valley Storage CSO (Figures 68 and 69).

The model results presented in this TM can be used to inform decision-makers on how climate change might impact CSO storage and treatment sizes if the current compliance criteria remain in place. Other risks and uncertainties in the monitoring and modeling efforts associated with sizing CSO facilities are not addressed in this TM.

7.0 Rainfall Factors for Other GCM Models

There are 11 additional GCM simulations that the University of Washington has downscaled for the Puget Sound region using the WRF RCM, similar to what was done for the two GCMs presented in this analysis (see Mauger et al., 2019). The 11 additional simulations are downscaled GCMs that all used a RCP of 8.5. The GCMs model key processes differently from each other and provide a sense of the scatter (uncertainty) that is associated with a larger sample size. The 13 total GCM/RCM results provide a wider range of possible rainfall conditions in the late 21st century than merely looking at the results using the ACCESS 1-0/4.5 and the GFDL-CM3/8.5 model simulations. The computation and analysis time to estimate the CSO impacts from the future conditions that result from these additional models could not be performed in a time frame such that they could be included in this TM.

This analysis did, however, compare the rainfall factors that would have been used if the CSO impacts from each of the 13 GCM results were analyzed. Figure 10 presents the results of the factors that would be used for each of the 13 downscaled GCM results. Figure 11 presents the same information focused on the top ten percent of the hourly rainfall values, which generally have the higher rainfall factors.

It was thought that the ACCESS 1-0 with RCP 4.5 and the GFDL-CM3 with RCP 8.5 would provide a “low” and a “high” estimate of climate change impact, with the latter model being the high scenario. One observation that can be made from Figures 10 and 11 is that the rainfall scaling factors from the GFDL-CM3 RCP8.5 model (red lines in Figures 10 and 11) and from the ACCESS 1-0 RCP4.5 model (orange lines in the figures) are significantly lower than all but two other GCMs for less intense rainfall. Furthermore, neither represents the highest or lowest factors in the more intense rainfall. The ACCESS 1-0 RCP 4.5 does not represent the lowest intensity projection, even though it is the only model run using an RCP of 4.5. Looking at the rainfall factors in Figures 10 and 11 it is clear that the GFDL-CM3 RCP8.5 model and the ACCESS 1-0 RCP4.5 are not far from the average of the 13 GCM results (purple dashed lines) in the highest 20 percent of the rainfall intensities. The GFDL-CM3/8.5 output is higher than the average of the 13 GCMs (purple line), but there are five GCM results that are higher in the top 10 percent of the rainfall intensities. Therefore, the thought that we might be bracketing the climate change impacts with the GCM model results we used is not substantiated. Using other GCM model results would likely produce higher or lower CSO control volume impacts than the ones analyzed in this technical memorandum.

Another observation is that the rainfall factors for any given GCM may be lower than the average for light and moderate intensity rainfall, but higher than average for the less frequent, higher intensity rainfall (CDF values > 0.8) (see ACCESS 1-3/8.5 in Figures 10 and 11). At the extreme end of the cumulative distribution function (CDF > 0.998), the rainfall factors do not follow a set pattern when compared to the other model output.

The models with higher factors at the low intensity end of the graph in Figure 10 (e.g., model noresm1-m_rcp85) generally indicate that there will be significantly more hours of lower intensity rainfall in the future climate than in the past climate. However, it is the top 10 – 20 percent (in intensity) of the rainfall data that is expected to have a much larger affect CSO control volumes than the lower intensity rainfall.

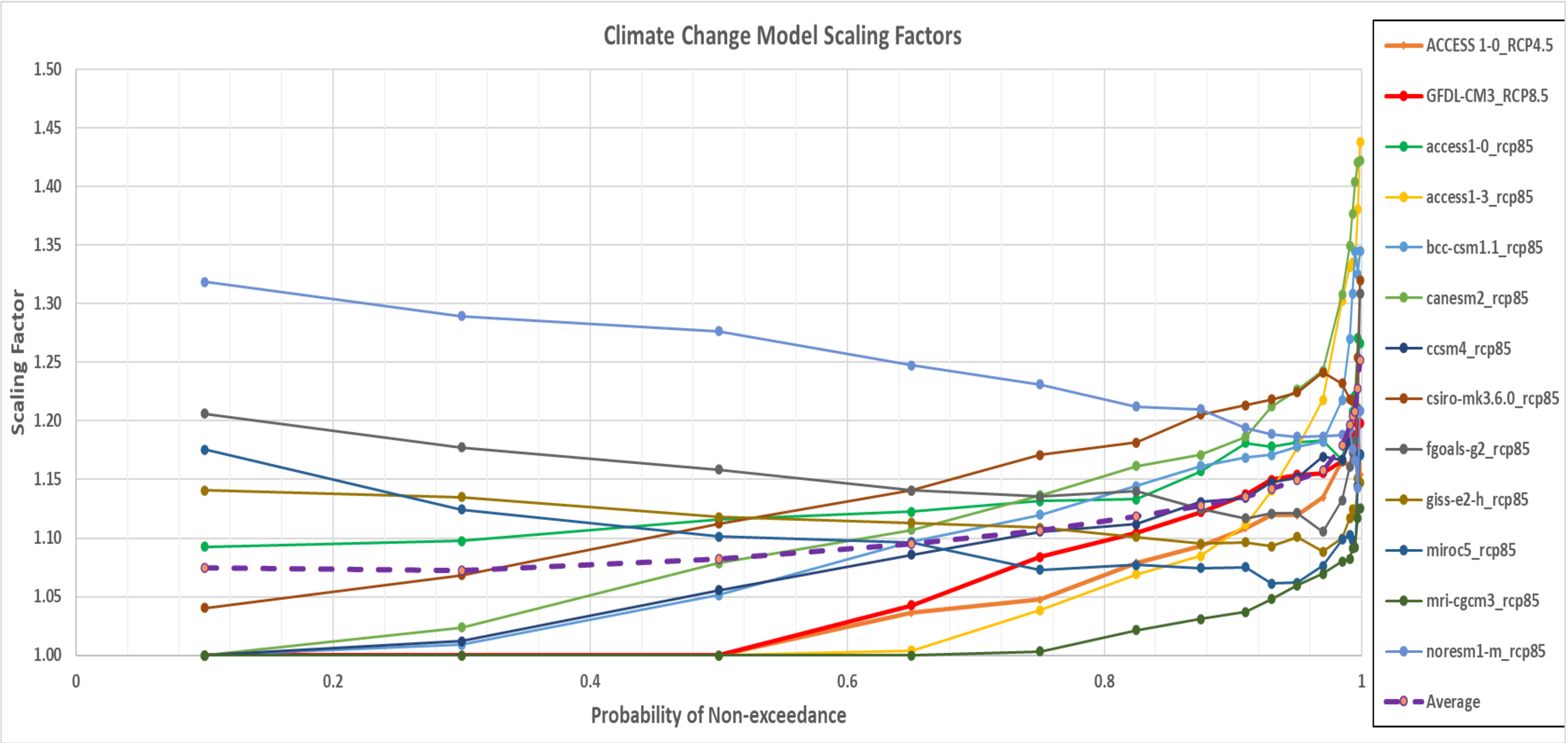

Figure 10. Scaling factors that would be used to convert historical rainfall to 2085 conditions to reflect output from 13 Global Climate Models

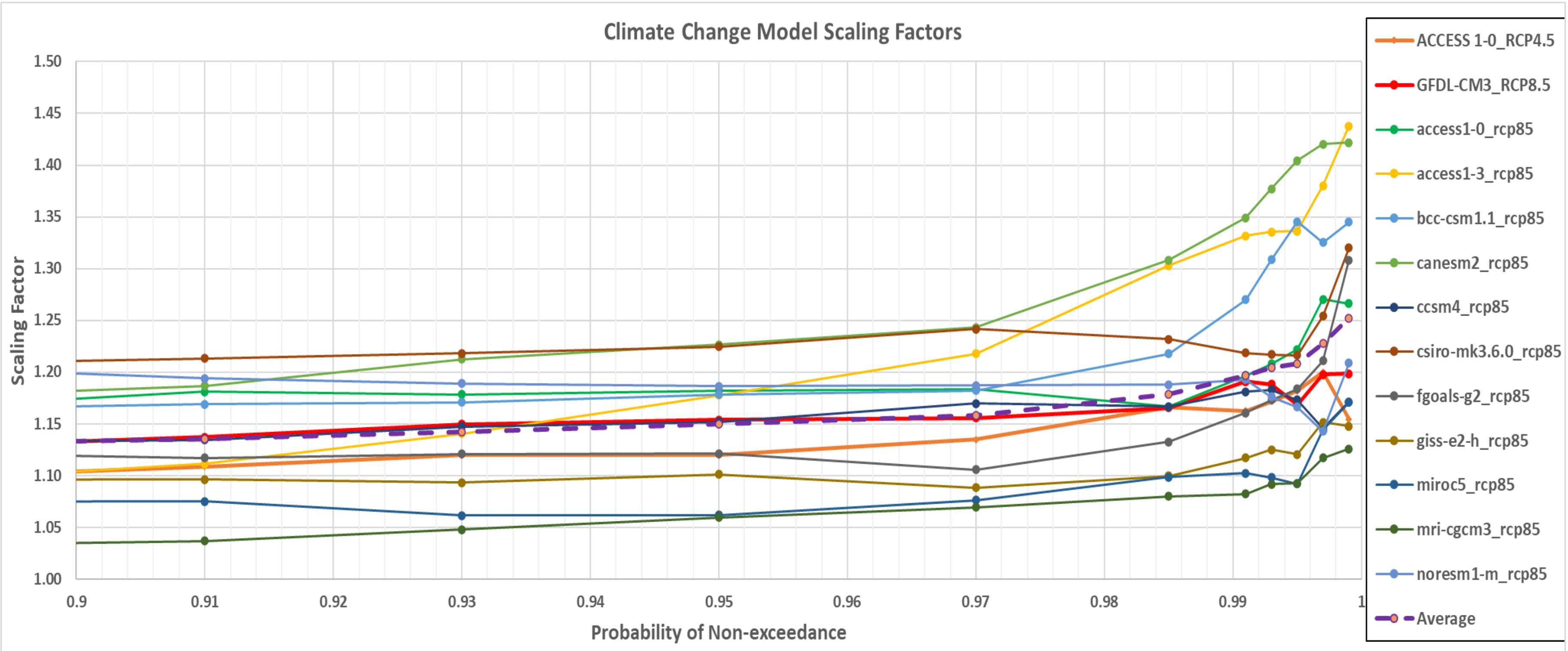

Figure 11. Scaling factors that would be used to convert historical rainfall to 2085 conditions to reflect output from 13 Global Climate Models (zoomed in to top 10 percent of distribution)

8.0 SPU's Approach to Sizing their CSO Facilities

SPU has constructed CSO storage tanks at Windermere and Genesee since 2012 that were sized to achieve the CSO Performance Standard of no more than overflow per year per outfall on a moving 20-year average. These facilities did not meet the Regulatory Standard due, in part, to changing weather patterns in the last decade as compared to the historical weather patterns during the period from 1978-2009 for which the facilities were sized. SPU does not have a set of specific decision criteria for sizing CSO facilities now, but rather considers a variety of information such as space constraints and opportunities, historical neighborhood construction context, asset management needs, cost effectiveness, and partnership potential. For the Ship Canal Water Quality Project (SCWQP), SPU simulated climatological conditions associated with a 2100 planning horizon and found that the tunnel was adequately sized to maintain its conformance with the CSO Performance Standard through 2100 with 95 percent certainty.

As of early 2021, SPU's general process for sizing CSO facilities was as follows:

For high-level planning, modeling of the anticipated 2035 climate is performed, and a volume associated with a 75th percentile of success (based on model uncertainties) is selected to carry in their long-term control plan.

When a project goes into options analysis, SPU uses the following four-step process:

Step 1: Modeling Work

- Determine range of control volumes (CVs):
    - Build and calibrate hydrologic and hydraulic model
    - Run model through long-term simulations to create CV curves – historic observed data, 2035 climate, 2100 climate
        - CVs based on the 20-year period yielding the highest 21st largest CSO storm event volume
        - The change in climatic planning horizon CVs helps determine a basin's sensitivity to rainfall and the need to either be conservative in their current approach (plan further) or be less conservative and allow for adaptability over time

Step 2: Determine if this is a Retrofit Project or New Infrastructure Project

- Determine project type: retrofit or new infrastructure
    - Retrofit: optimize existing infrastructure first and/or wait to plan with King County (KC) regionally if KC has uncontrolled downstream basin
    - New infrastructure: current infrastructure is optimized, unable to partner with KC, must reduce CV in-basin (allows for community partnerships, fixing other SPU/Seattle problems)

Step 3: Evaluate Local Constraints and Opportunities

- Retrofit sizing approach: Maximize CV within local constraints. For example:
    - Determine maximum pumping through existing force main, backsolve for CV

    - Determine maximum flowrate through existing gravity conveyance – backsolve for CV
    - Determine maximum flowrate acceptable from KC, backsolve for CV
    - Determine maximum safe weir elevation to protect grade lines, backsolve for CV
- New infrastructure approach:
    - Determine potential constraints
        - Available cashflow/budget (what can SPU actually afford?)
        - Siting opportunities (how large could a potential facility be so SPU makes full use of space?)
    - Determine opportunities
        - Community-based partnerships (how could SPU incrementally chip away at CVs through multi-benefit co-funded projects?)
        - Other SPU non-CSO related system needs within study area that could be solved with a shared facility – (reduces overall costs to co-fund within SPU)
        - Other City of Seattle related current and future endeavors that could have a CSO nexus through partnerships (same as above, but with City Family investment)
        - Cost efficiency of CV investment – Is it inexpensive to buy down CV non-compliance risk due to economies of scale? (the SCWQP is a good example of this)

Step 4: Selecting a Project Size

- Make a decision
    - Weigh the constraints against the opportunities to determine an acceptable initial investment on CV reduction as well as remaining residual CV (residual CV is the amount of CV that is not captured through an initial project) to understand what follow up on programmatic work may be necessary to meet the state standard if the initial investment turns out to not be enough

9.0 Next Steps for Modeling

Currently, no additional climate modeling has been scheduled. However, the following ideas have been suggested by WTD staff to build on this work:

- Multiple model methodologies and ensemble approaches are a recommended climate science best practice (Knutti et al., 2010) because there is a potential for considerable uncertainties in each climate model, as shown by Ntegeka et al. (2008) and Nguyen et al. (2008). The 11 additional GCM simulations that have been downsized by the UWCIG for the Puget Sound region using a regional climate model could be used to generate a larger sampling of what future rainfall may look like and how it might affect CSO sizing. The GCMs model key processes differently; using more GCM results is expected to provide a sense of the scatter that would better reflect the uncertainty in the future climate scenarios. Expanding WTD's assessment of how projected changes in rainfall intensity affect the wastewater system is Action Item 2.2 in King County's 2020 SCAP.

- It is anticipated that the results from this analysis will be considered by the WTD Climate Adaptation Work Group in developing strategies for dealing with climate change in regard to meeting CSO regulatory requirements. One of its tasks is to make a recommendation to WTD management regarding the sizing of CSO facilities in light of the changing climate.
- The results of the model simulations used in this analysis could be analyzed to estimate the change in frequency and volume of blending events at West Point Treatment Plant (mixing secondary and primary effluent prior to discharge to Puget Sound) by the latter part of this century.
- The approach to modeling future climate scenarios that is documented in this technical memorandum may also be applied in conveyance system improvement planning (separate sewer systems) and in treatment plant flow projection efforts.
- A different future window could be modeled to provide a curve showing how the CSO control volumes may change over time. For example, the 2050s could be selected to capture a decade in time between now and the 2080s.

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Appendix A

CSO Frequency and Annual Volume Impacts Due to Climate Change

for Phase 1 and Phase 2 Locations

Baseline—Historical Rainfall (1978–2018)

ACCESS 1-0 4.5 —Year 2070 - 2099 conditions under Global Climate Model ACCESS 1-0 with RCP 4.5

GFDL-CM3 8.5 —Year 2070 - 2099 climate conditions under Global Climate Model GFDL-CM3 with RCP 8.5

MIKE Urban models were used to simulate the hydrological and hydraulic response of the collection and conveyance system under three rainfall conditions corresponding to baseline conditions (historical rainfall from 1978 – 2018) and two possible future climate conditions at the end of the 21st century (2070 – 2099, with 2085 as the mid-point). The existing capacities of the West Point Treatment Plant and existing pump stations, as well as the existing regulator gate set points used in control logic, were used in all the simulations. The simulated flow to each regulator station, overflow weir, and pump station, and the combined sewer overflows at each CSO location were tallied from the model results. This appendix presents how the frequencies and annual discharge volumes would change if only the existing system was used (no new CSO facilities). The CSO frequencies and annual CSO volumes are presented for each CSO location analyzed in Phase 1 and in Phase 2 of this report.

Table 10 A-1 and Table 11 A-2 present the frequencies of CSOs under each of the three climate simulations at each location in King County's conveyance system. The model simulations are of the existing system with the Georgetown Wet Weather Treatment Station assumed to be completed and on-line (expected in 2022). No other new CSO facilities are included in the model. It is apparent that, over time, the changes in climate, as represented by the Global Climate Models and downscaled by the Regional Climate Model, would cause CSOs to increase in frequency. The table shows how much more frequent CSOs would be expected to occur in the existing system. The table also shows which sites were simulated as having less than one-event-per year, on a long-term average, under baseline conditions and under the two future climate scenarios. It also shows which sites would have less than one-CSO-per-year currently, but increase to more than one-per-year in the future climate scenarios.

Tables 12 A-3 and 13 A-4 present the average annual CSO discharge volumes at each King County WTD CSO location in the existing system under baseline and two possible future climate conditions near the end of the 21st century. The Georgetown WWTS is included in the model, but no other new CSO projects are simulated in the model. Similar to the frequency increases at most CSO locations, the annual CSO volume would increase at each of the CSO locations -- due solely to climate change.

Table 10 A-1. Modeled CSO Frequencies for Phase 1 locations – with and without climate change --in existing system

	Phase 1 Locations **CSO Frequencies in Existing System** [Events/yr]			
		1978 – 2018 **Long-term average**	**2070 – 2099** **Long-term average**	
#*	**CSO Location**	**Baseline**	**ACCESS 1-0 RCP 4.5**	**GFDL-CM3 RCP 8.5**
1	Barton PS CSO	0.7	1.3	1.5
2	Belvoir PS CSO	3.9	5.3	5.9
3	Dexter Regulator Station CSO [a, b]	0.05	0.1	0.2
4	East Marginal PS CSO [a]	0	0	0
5	53rd PS CSO [a]	0.1	0.2	0.3
6	Georgetown WWTS (See S. Michigan & S. Brandon)			
7	Henderson PS CSO [a]	0	0	0
8	MLK Way Weir CSO [a]	0	0	0
9	Murray PS CSO [a]	0.7	1.1	1.4
10	Norfolk Regulator Station CSO [a]	0.6	0.4	1.8
11	North Beach PS Wet Well	1.6	2.7	3.2
12	North Beach PS Inlet [a]	0.4	0.95	1.1
13	Rainier Valley CSO Total CSO (Bayview North + Bayview South + Hanford at Rainier)	1.6	2.8	3.1
14	13. Rainier PS	0	0	0
15	14. S. Brandon Regulator Station CSO [a, c]	0.8	1.1	1.6
16	15. S. Michigan Regulator Station CSO [a, c]	0.6	1.2	1.4
17	16. 30th PS CSO [b]	0	0.05	0.1

[a] Modeled as controlled in baseline
[b] Lower than observed because model does not represent traveling hydraulic jump
[c] Assumes the Georgetown WWTS is completed
[d] Number in Table 1 and Figure 2

Table 11 A-2. Modeled CSO Frequencies for Phase 1 locations – with and without climate change --in existing system

	Phase 2 Locations CSO Frequencies in Existing System [Events/yr]			
		1978 – 2018 Long-term average	2070 – 2099 Long-term average	
#*	CSO Location	Baseline	ACCESS 1-0 RCP 4.5	GFDL-CM3 RCP 8.5
18	Ballard Regulator [a]	0.05	0.05	0.1
19	Canal St. Overflow Weir [a]	0.3	0.7	1.2
20	Chelan	14	17	18
21	8th Ave. S. Regulator [a]	0.4	0.9	1.05
22	Denny/Elliott W. Regulators/Weirs [a]	0.8	1.5	1.9
23	Duwamish PS East siphon [a]	0.5	1.05	1.2
24	Duwamish PS West siphon [a]	0.8	1.7	2.1
25	11th Ave. NW Overflow Weir [b]	13.6	18.0	21.6
26	Hanford #2	22	25	26
27	Harbor Regulator	0.95	1.7	2.1
28	King St. Regulator	21	24	24
29	Kingdome Regulator)	13	16	17
30	Lander St. Regulator	15	18	19
31	Montlake Regulator	12	16	16
32	63rd Ave. PS	1.3	2.1	2.3
33	S. Magnolia Overflow Weir [a]	0.8	1.6	1.9
34	Terminal 115 Overflow Weir	1.3	2.4	2.8
35	SW Alaska St.	1.2	2.2	2.5
36	3rd Ave. W. [b]	9.4	13	14
37	University Regulator	4.9	7.6	9.1
38	W. Marginal PS [a]	0	0	0
39	W. Michigan St. Regulator	2.7	4.8	5.3

[a] Modeled as controlled in baseline

[b] The Joint SPU/KC Ship Canal Water Quality Project Tunnel was not included in these simulations

[d] Number in Table 1 and Figure 3

Table 12 A-3. Modeled Annual CSO Volumes for Phase 1 locations – with and without climate change

	Phase 1 Locations **Annual CSO Volumes** [MG]			
		1978–2018 Long-term average	2070–2099 Long-term average	
#*	CSO Location	Baseline	ACCESS 1-0 RCP 4.5	GFDL-CM3 RCP 8.5
1	Barton PS CSO	0.15	0.31	0.51
2	Belvoir PS CSO	0.72	1.5	1.8
3	Dexter Regulator Station CSO [a, b]	0.04	0.06	0.11
4	East Marginal PS CSO [a]	0	0	0
5	53rd PS CSO [a]	0.04	0.10	0.23
6	Georgetown WWTS (See S. Michigan & S. Brandon)			
7	Henderson PS CSO [a]	0	0	0
8	MLK Way Weir CSO [a]	0	0	0
9	Murray PS CSO [a]	1.6	3.2	4.1
10	Norfolk Regulator Station CSO [a]	0.24	0.56	1.1
11	North Beach PS Wet Well	1.1	2.0	3.2
12	North Beach PS Inlet [a]	0.1	0.4	0.5
12	Rainier Valley CSO Total CSO (Bayview North + Bayview South + Hanford at Rainier)	5.1	11.5	14.4
13	Rainier PS	0	0	0
14	S. Brandon Regulator Station CSO [a, c]	0.89	1.5	2.0
15	S. Michigan Regulator Station CSO [a, c]	2.2	4.2	5.7
17	30th PS CSO [b]	0	0.01	0.01

[a] Modeled as controlled in baseline
[b] Lower than observed because model does not represent traveling hydraulic jump
[c] Assumes the Georgetown WWTS is completed
[d] Number in Table 1 and Figure 2

Table 13 A-4. Modeled Annual CSO Volumes for Phase 2 locations – with and without climate change

	Phase 2 Locations Annual CSO Volumes [MG]			
		1978–2018 Long-term average	2070–2099 Long-term average	
#*	**CSO Location**	**Baseline**	**ACCESS 1-0 RCP 4.5**	**GFDL-CM3 RCP 8.5**
18	Ballard Regulator [a]	0.05	0.19	0.44
19	Canal St. Overflow Weir [a]	0.31	0.85	1.46
20	CHLKK -- Chelan, Hanford, Lander, Kingdome, King	549	733	799
21	8th Ave. S. Regulator [a]	0.37	0.84	1.23
22	Denny/Elliott W. Regulators/Weirs [a]	2.3	5.4	7.7
23	East Duwamish [a]	0.17	0.43	0.60
24	West Duwamish [a]	0.59	1.4	1.8
25	11th Ave. NW Overflow Weir [b]	13.9	23.3	34.4
26	Hanford #2 (See CHLKK)			
27	Harbor Regulator	1.0	2.0	2.9
28	King St. Regulator (See CHLKK)			
29	Kingdome Regulator (See CHLKK)			
30	Lander St. Regulator (See CHLKK)			
31	Montlake Regulator	32.6	53.5	61.2
32	63rd Ave. PS	6.1	9.9	11.5
33	S. Magnolia Overflow Weir [a]	1.8	3.4	4.1
34	Terminal 115 Overflow Weir	1.3	2.5	3.1
35	SW Alaska St.	0.8	1.4	1.8
36	3rd Ave. W. [b]	19.2	30.6	37.7
37	University Regulator	38.9	72.8	94.9
38	W. Marginal PS [a]	0	0	0
39	W. Michigan St. Regulator	1.3	2.5	3.0

[a] Modeled as controlled in baseline

[b] The Joint SPU/KC Ship Canal Water Quality Project Tunnel was not included in these simulations

[d] Number in Table 1 and Figure 3

Appendix B

CSO Volume and Flowrate Recurrence Graphs for Phase 1 and Phase 2 Locations

Baseline—Historical Rainfall (1978–2018)

ACCESS 1-0 4.5 —Year 2070 - 2099 conditions under Global Climate Model ACCESS 1-0 RCP 4.5

GFDL-CM3 8.5 —Year 2070 - 2099 climate conditions under Global Climate Model GFDL-CM3 RCP 8.5

MIKE Urban models were used to simulate the hydrological and hydraulic response to three rainfall conditions as they affect the flow of wastewater through King County Wastewater Treatment Division's conveyance system. This appendix presents the recurrence intervals of the combined sewer overflow (CSO) volumes and peak CSO flowrates at each CSO location analyzed in Phase 1 and in Phase 2. The CSO locations and (associated figure numbers) are as follows:

- 3rd Ave. W. Overflow Weir (Figures 12 and 13)
- 8th Ave. S. Regulator Station (Figures 14 and 15)
- 11th Ave. NW Overflow Weir (Figures 16 and 17)
- 30th Ave. Pump Station (Figures 18 and 19)
- 53rd Ave. Pump Station (Figures 20 and 21)
- 63rd Ave. Pump Station (Figures 22 and 23)
- Alaskan Way Overflow Weir (Figures 24 and 25)
- Ballard Regulator Station (Figures 26 and 27)
- Barton Pump Station (Figures 28 and 29)
- Belvoir Pump Station (Figures 30 and 31)
- S. Brandon St. Regulator Station after Georgetown Wet Weather Treatment Station (WWTS) is constructed (Figures 32 and 33)
- Canal St. Overflow Weir (Figures 34 and 35)
- Chelan Ave. Regulator (Figures 36 and 37)
- Denny/Elliott West/Interbay Regulators and Weirs (Figures 38 and 39)
- Dexter Regulator Station (Figures 40 and 41)
- Duwamish Pump Station (Figures 42 and 43)
- Hanford #2 Regulator Station (Figures 44 and 45)
- Harbor Regulator Station (Figures 46 and 47)
- King Street Regulator Station (Figures 48 and 49)
- Kingdome Regulator Station (Figures 50 and 51)
- Lander Street Regulator Station (Figures 52 and 53)
- S. Magnolia Overflow Weir (Figures 54 and 55)
- S. Michigan St. after Georgetown WWTS is constructed (Figures 56 and 57)
- W. Michigan Street Regulator Station (Figures 58 and 59)
- Montlake Regulator Station (Figures 60 and 61)
- Murray Ave. Pump Station (Figures 62 and 63)
- Norfolk Regulator Station Henderson/MLK Way (Includes Norfolk Regulator) (Figures 64 and 65)
- North Beach (Figures 66 and 67)
- Rainier Valley Storage (includes Bayview North, Bayview South, and Hanford @ Rainier) (Figures 68 and 69)
- Terminal 115 Overflow Weir (Figures 70 and 71)
- University Regulator Station (Figures 72 and 73)

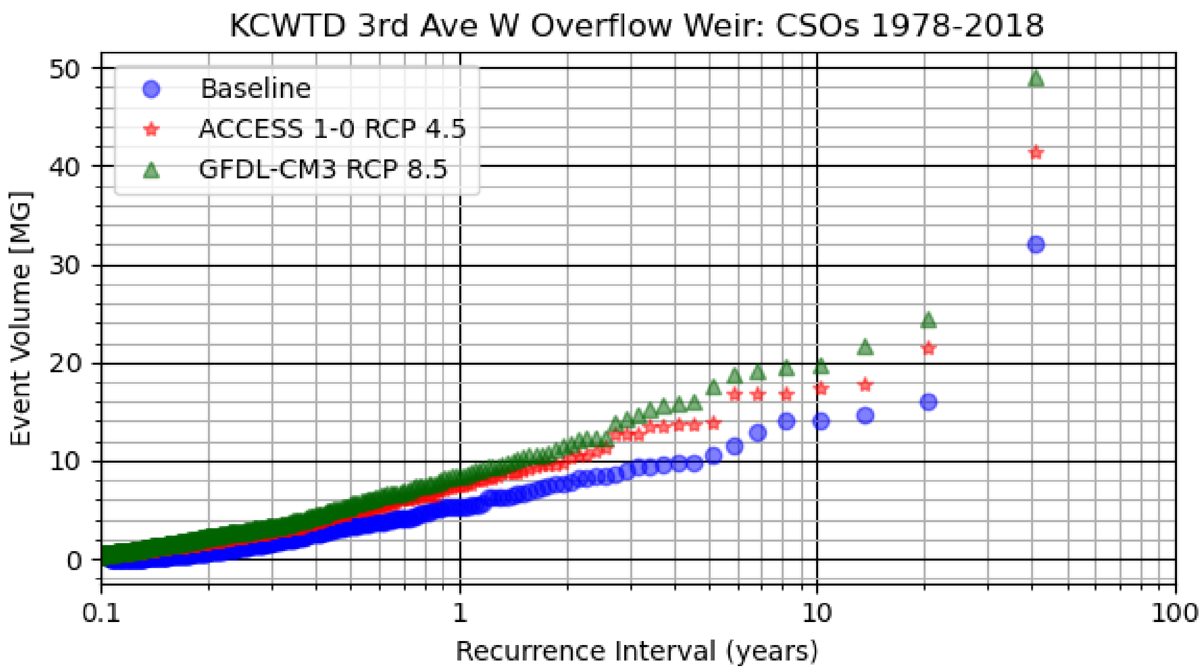

Figure 12. CSO volume recurrence interval for 3rd Ave. W Overflow Weir under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

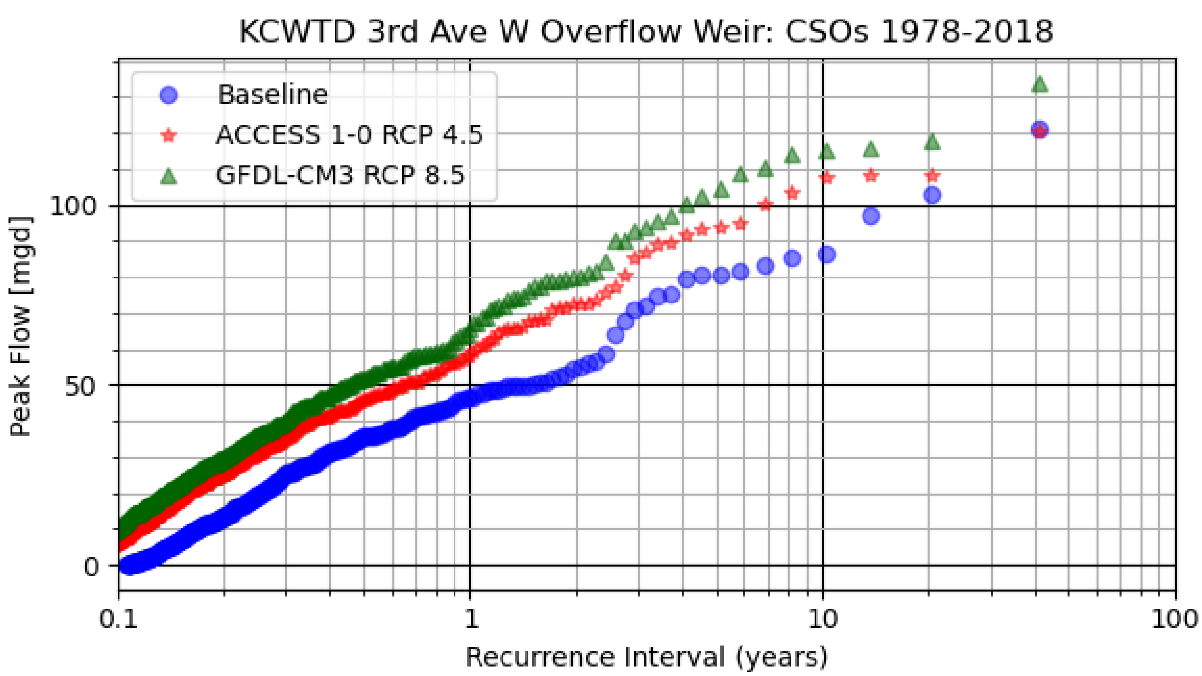

Figure 13. Peak untreated CSO flowrate recurrence interval for 3rd Ave. W Weir under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

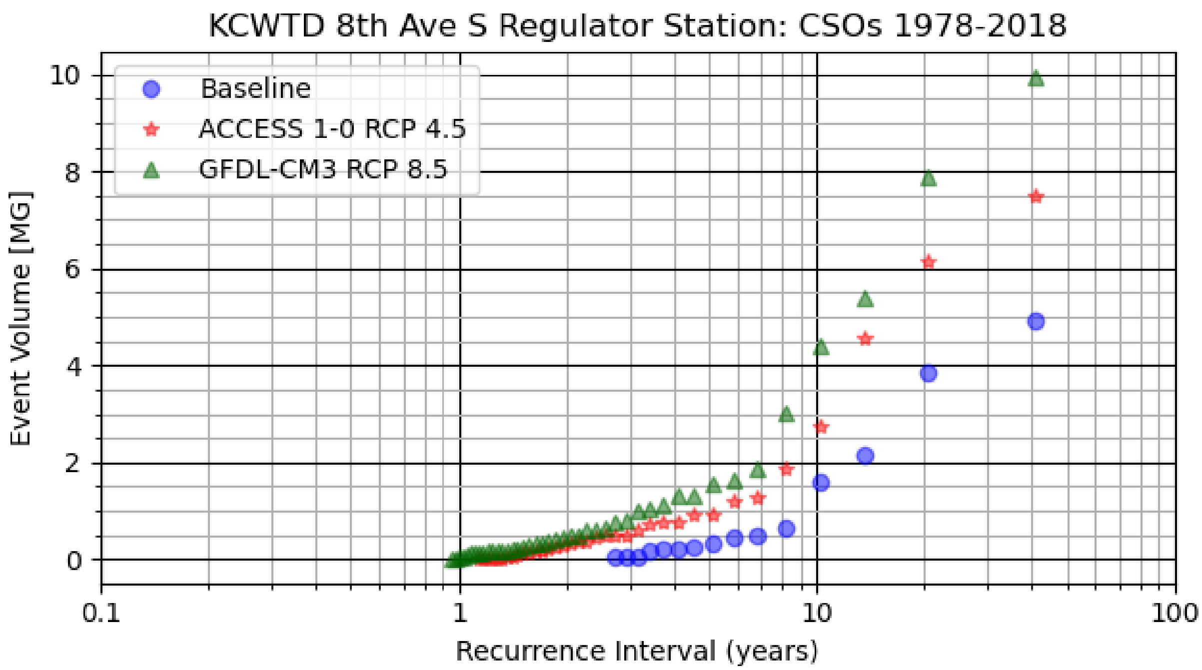

Figure 14. CSO volume recurrence interval for 8th Ave. S Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

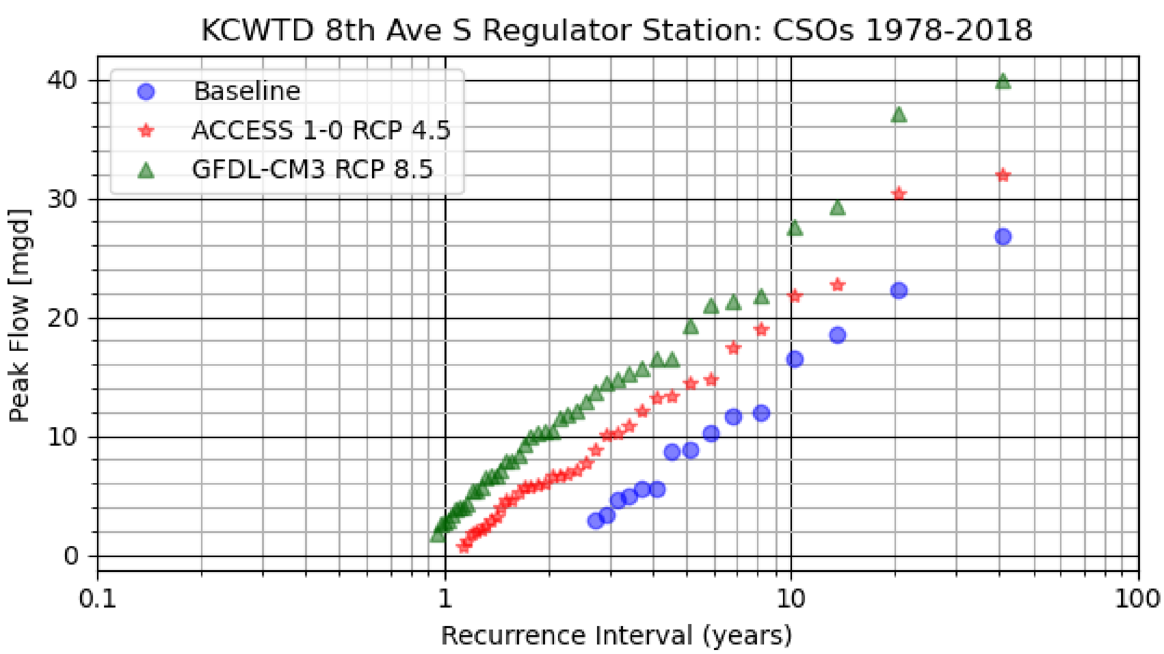

Figure 15. Peak untreated CSO flowrate recurrence interval for 8th Ave. S Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

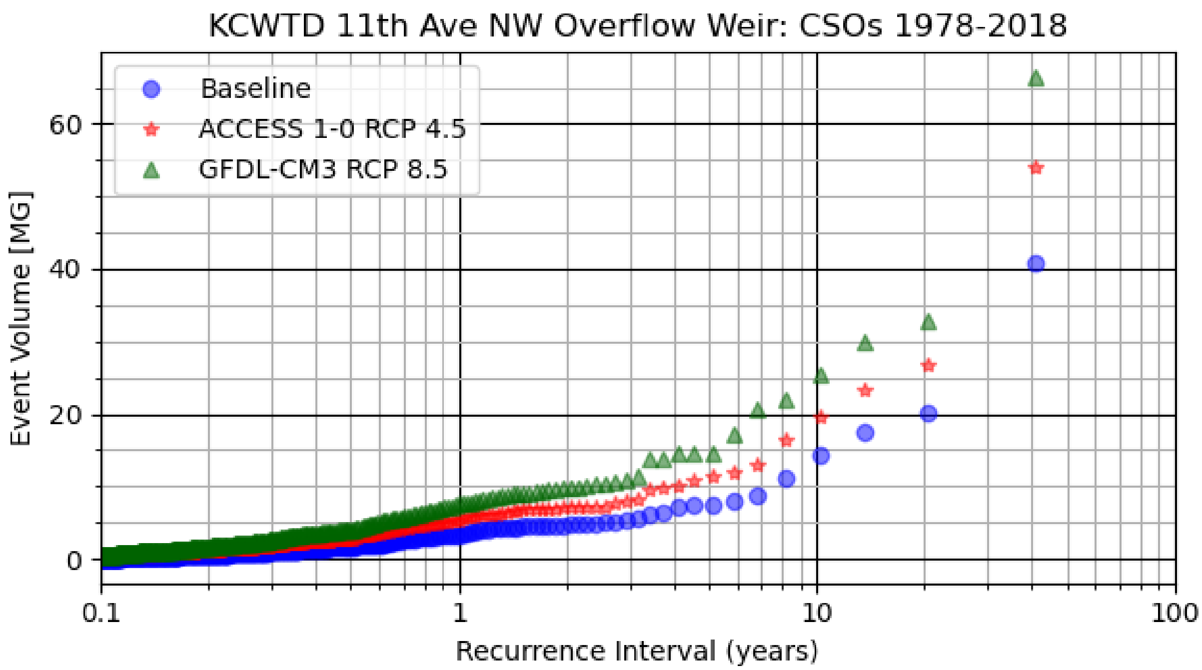

Figure 16. CSO volume recurrence interval for 11th Ave. NW Overflow Weir under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 4.5 and GFDL 8.5)

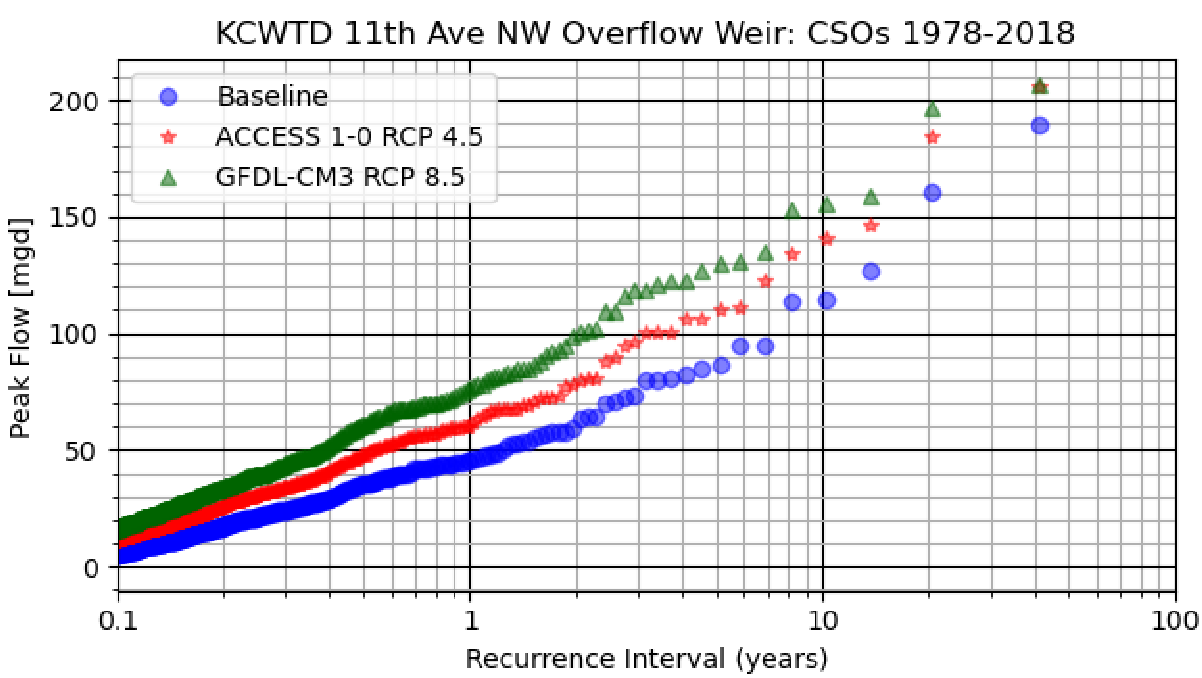

Figure 17. Peak untreated CSO flowrate recurrence interval for 11th Ave. NW Overflow Weir under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 4.5 and GFDL 8.5)

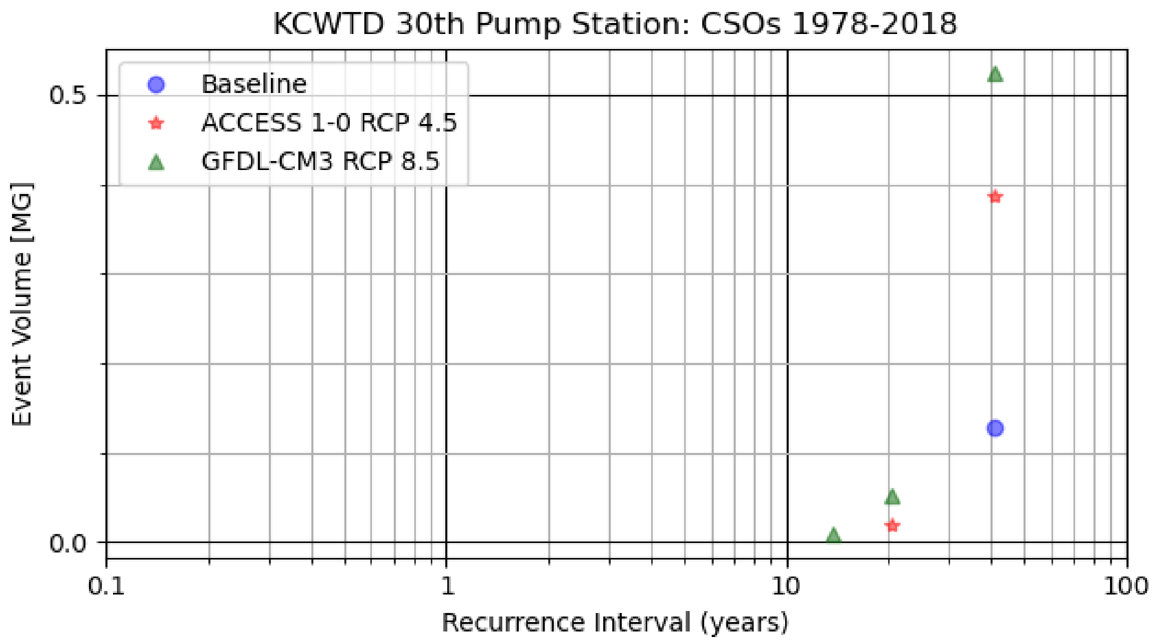

Figure 18. CSO volume recurrence interval for 30th Ave. Pump Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFD-CM3/ 8.5)

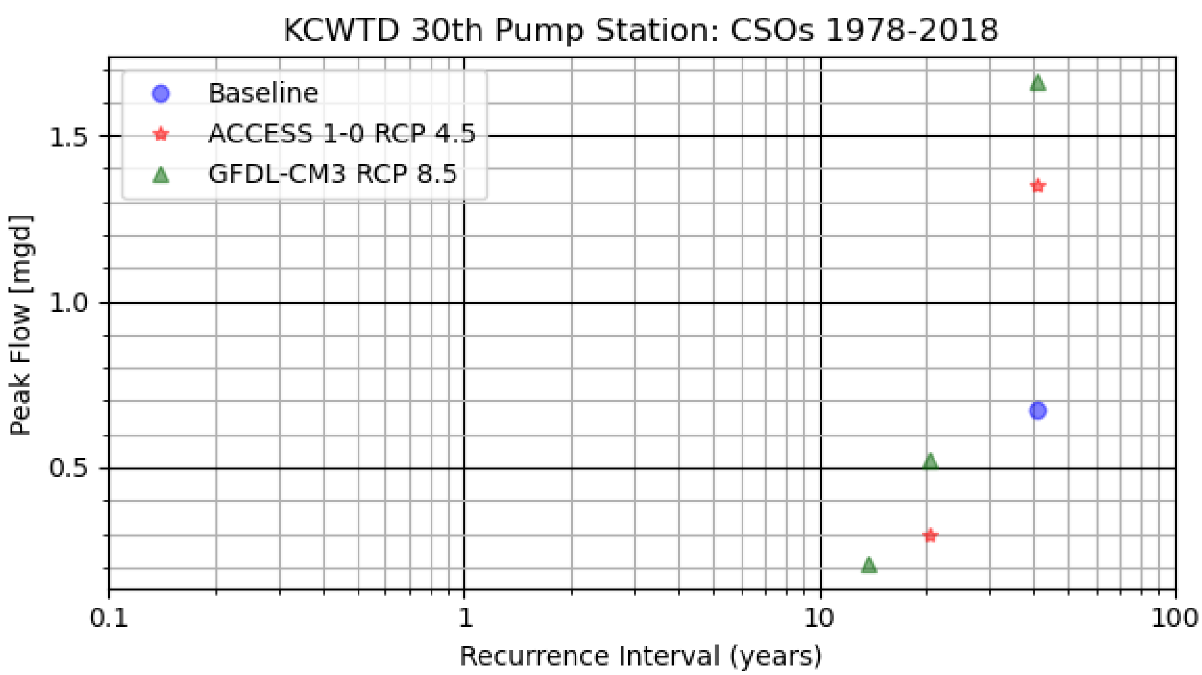

Figure 19. Peak untreated CSO flowrate recurrence interval for 30th Ave. Pump Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

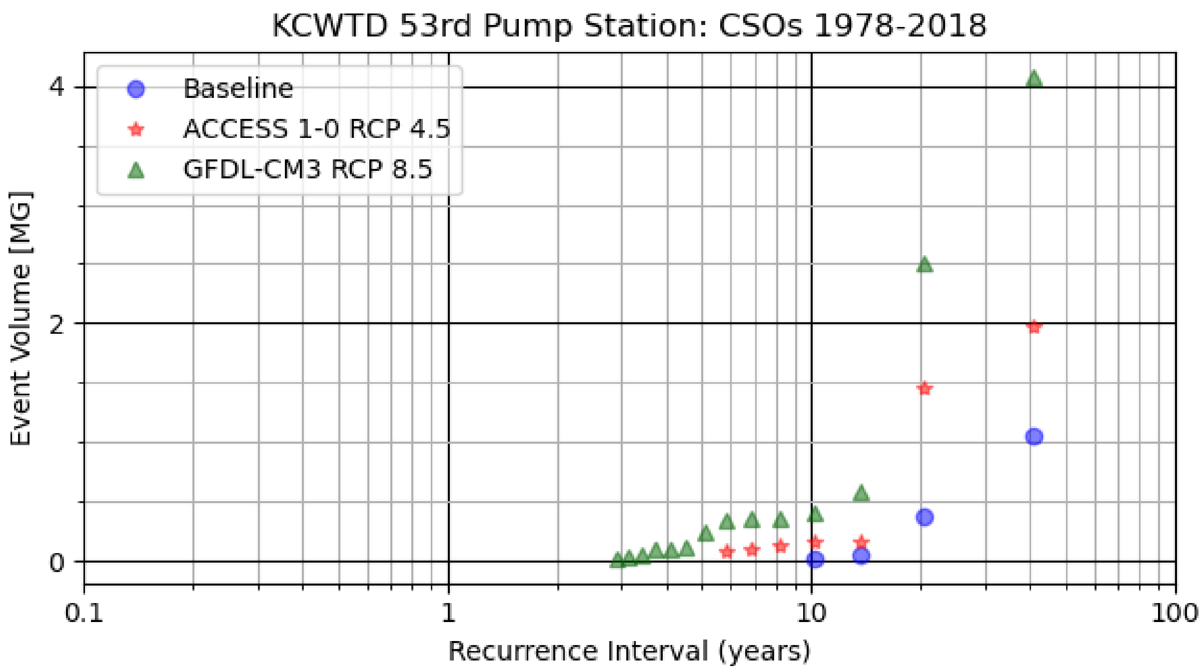

Figure 20. CSO volume recurrence Interval for 53rd Ave. Pump Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

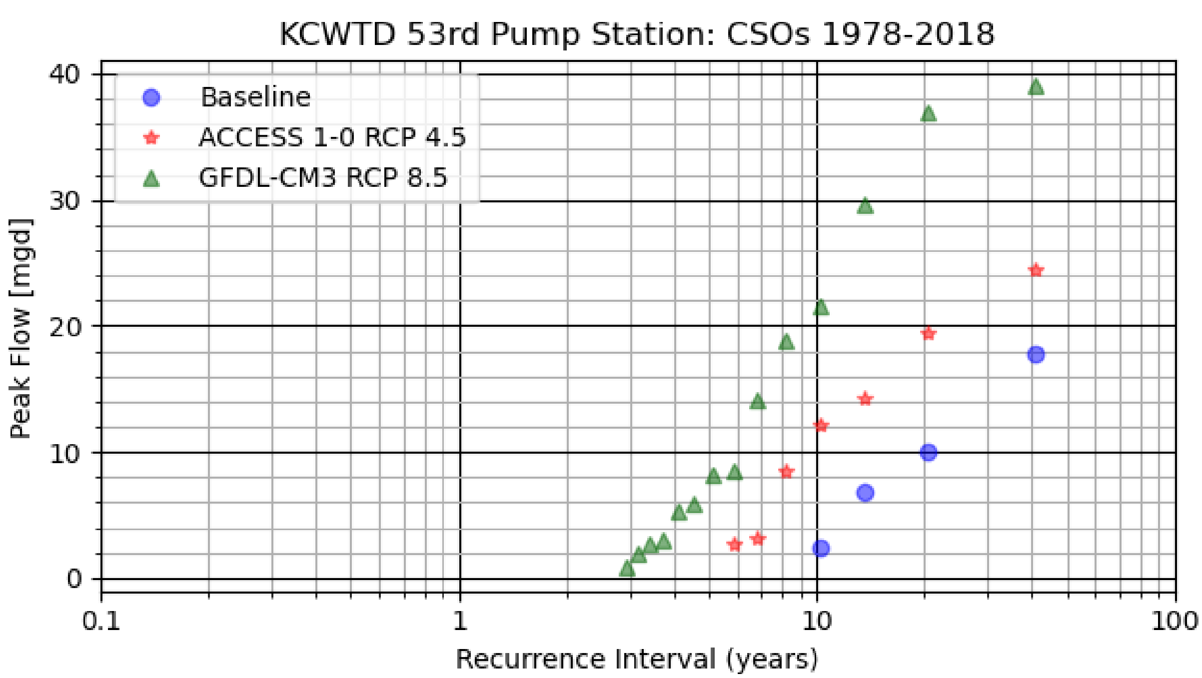

Figure 21. Peak untreated CSO flowrate recurrence interval for 53rd Ave. Pump Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/.5 and GFDL-CM3/8.5)

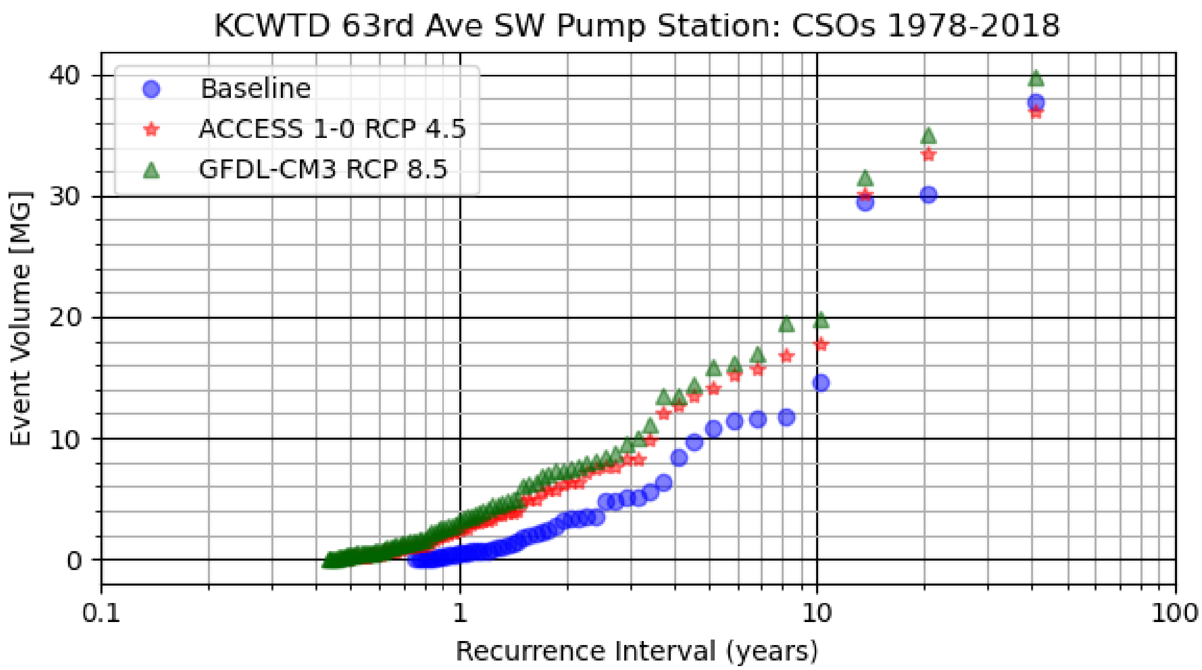

Figure 22. CSO volume recurrence Interval for 63rd Ave. Pump Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

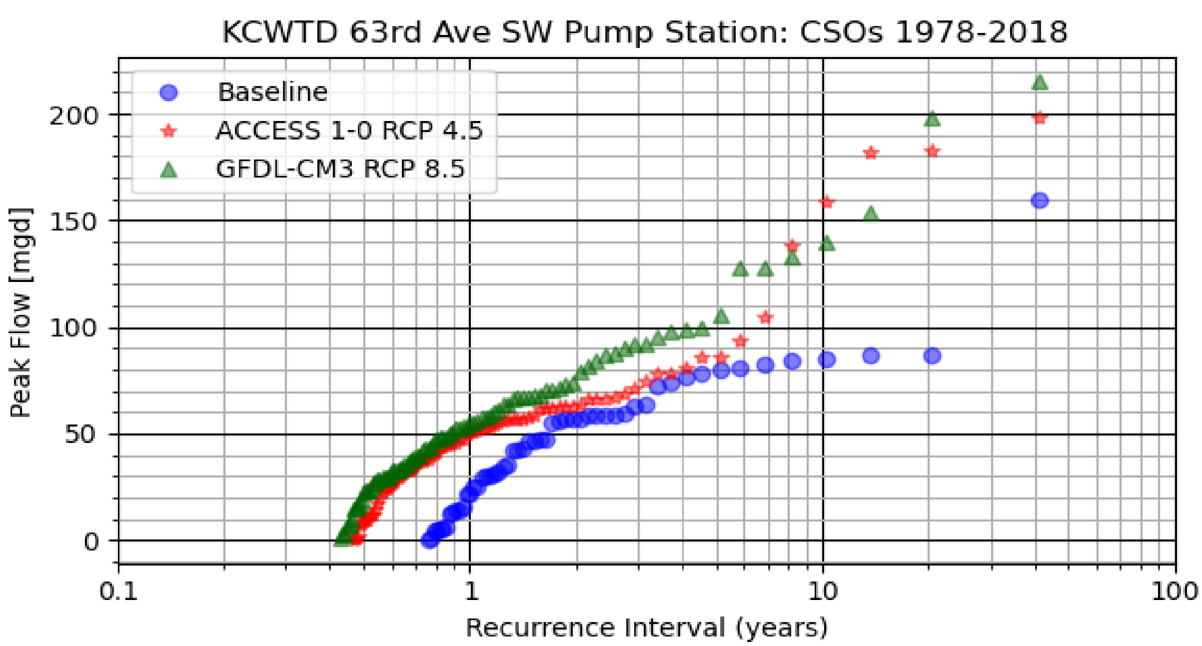

Figure 23. Peak untreated CSO flowrate recurrence interval for 63rd Ave. Pump Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

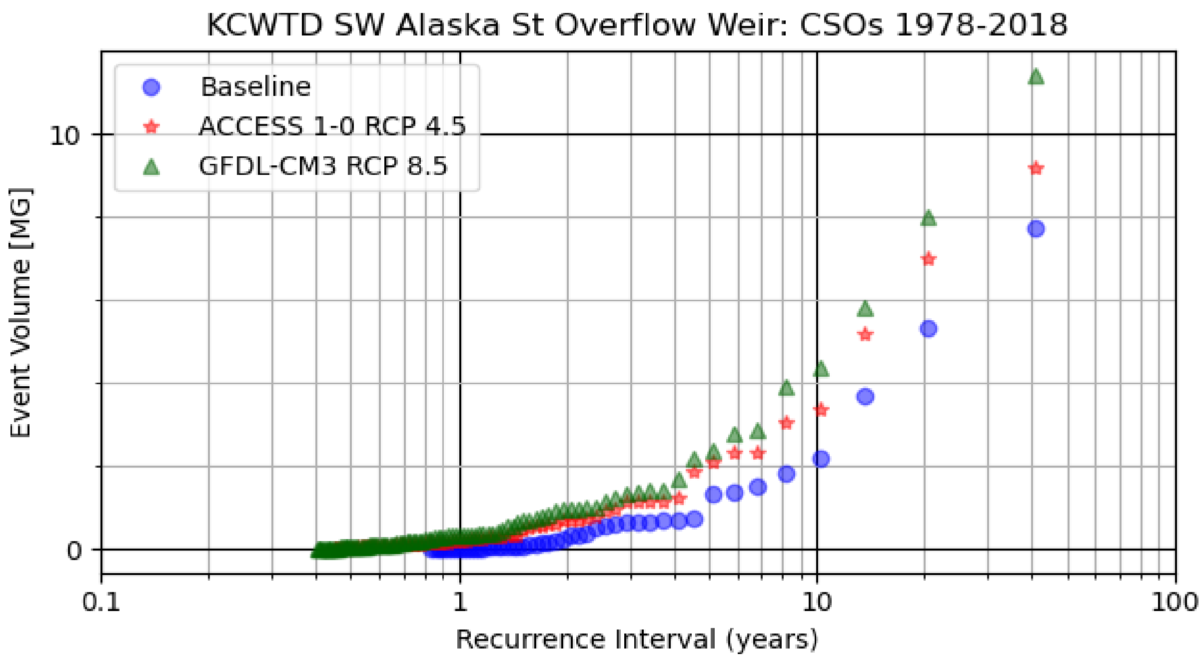

Figure 24. CSO volume recurrence Interval for SW Alaska St. Overflow Weir under baseline (historical) and 2-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFD-CM3/ 8.5)

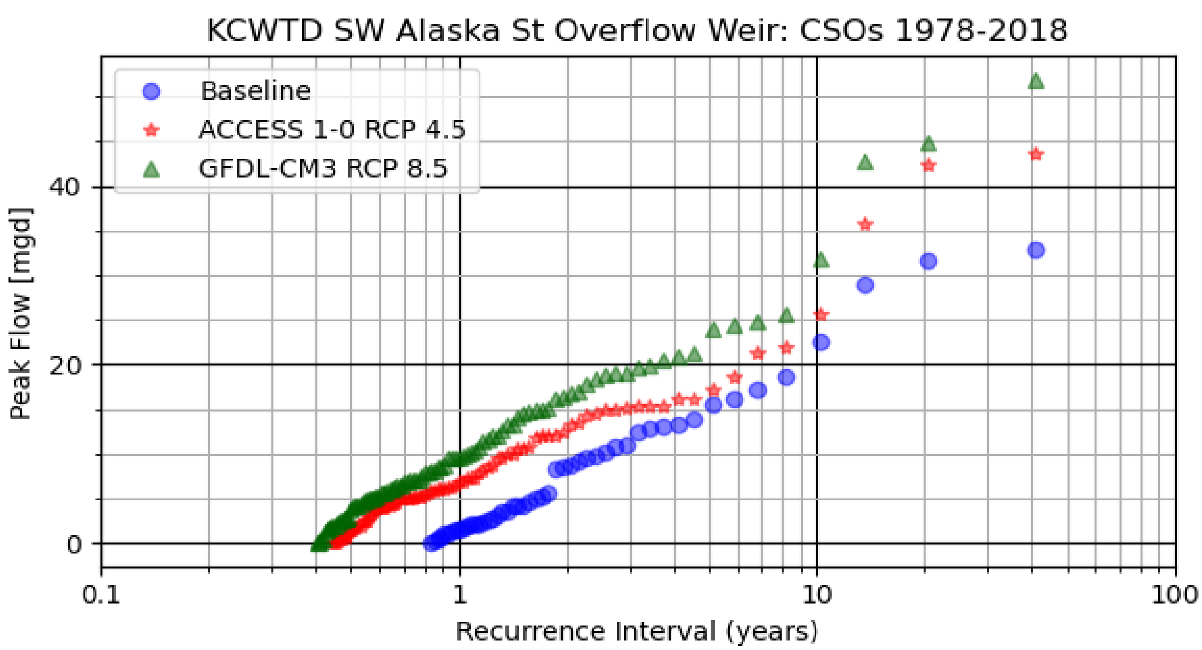

Figure 25. Peak untreated CSO flowrate recurrence interval for SW Alaska St. Overflow Weir under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

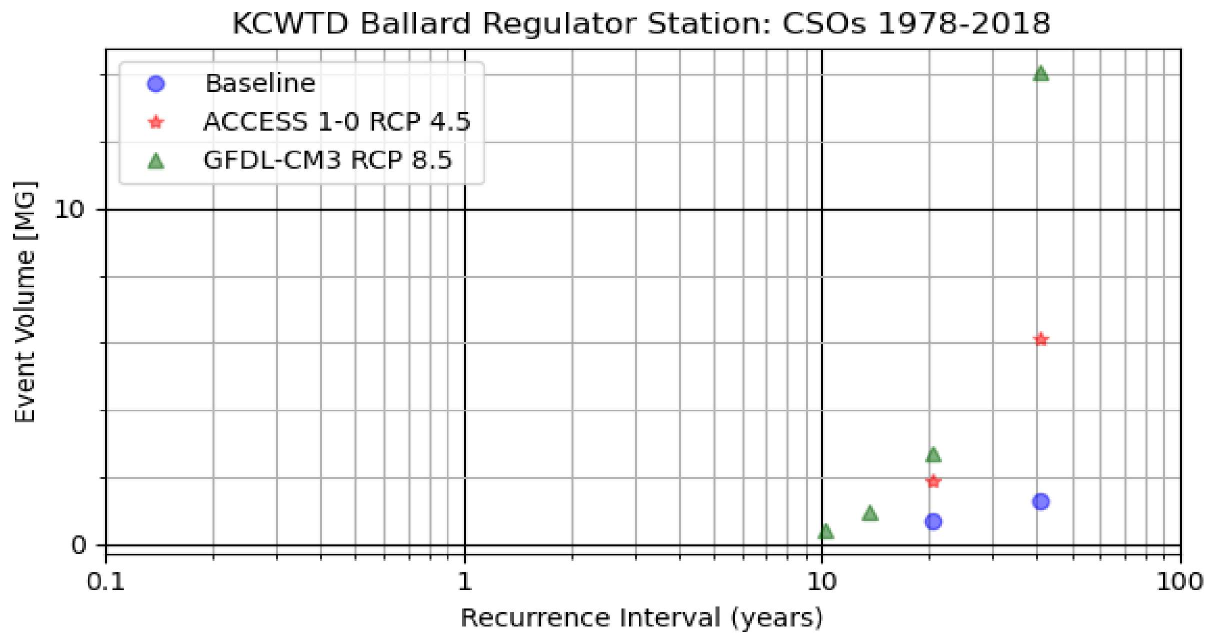

Figure 26. CSO volume recurrence Interval for Ballard Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

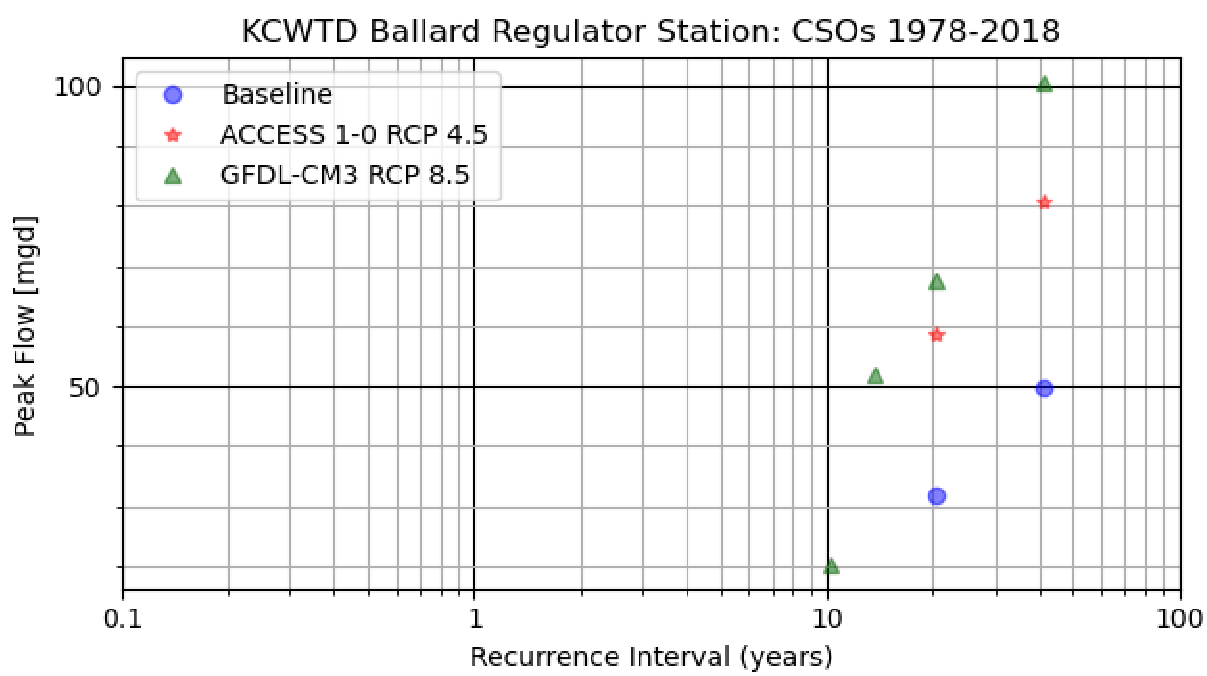

Figure 27. Peak untreated CSO flowrate recurrence interval for Ballard Regulaor Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

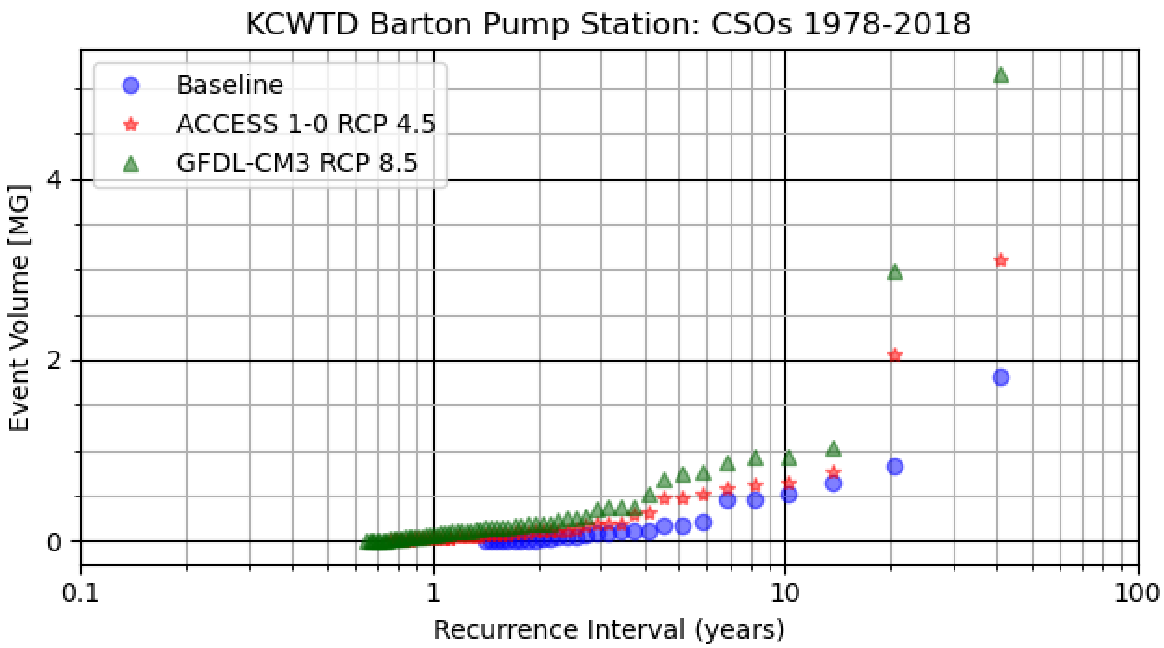

Figure 28. CSO volume recurrence literval for Barton Pump Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

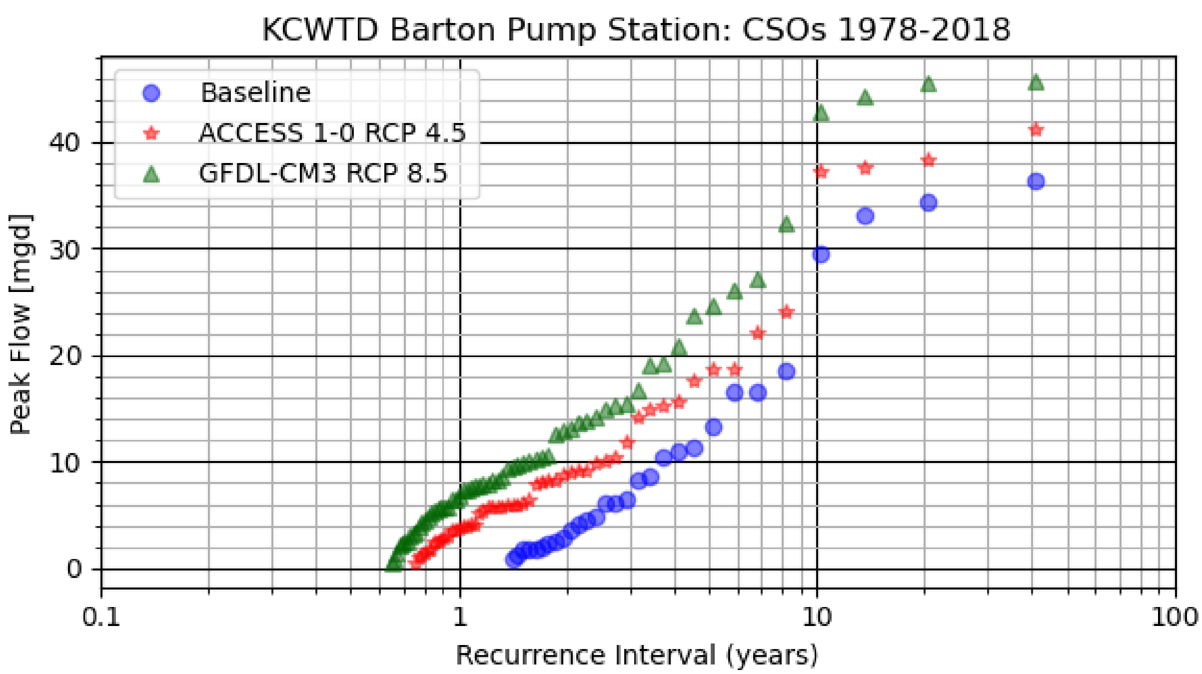

Figure 29. Peak untreated CSO flowrate recurrence interval for Barton Pump Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

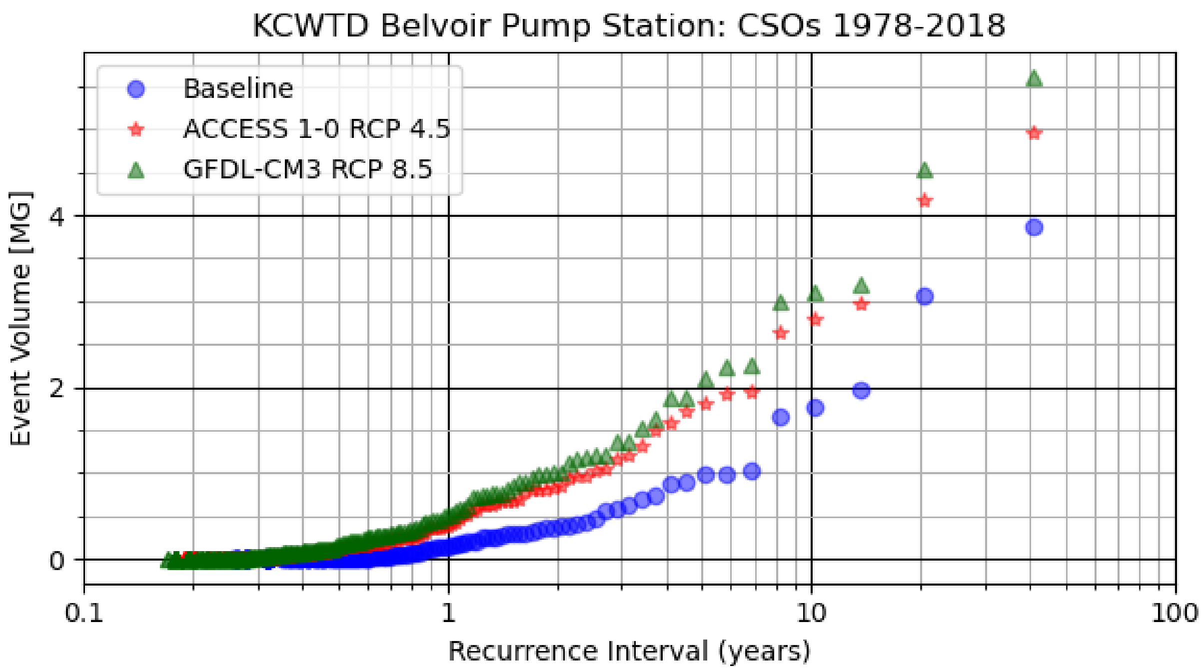

Figure 30. CSO volume recurrence interval for Belvoir Pump Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

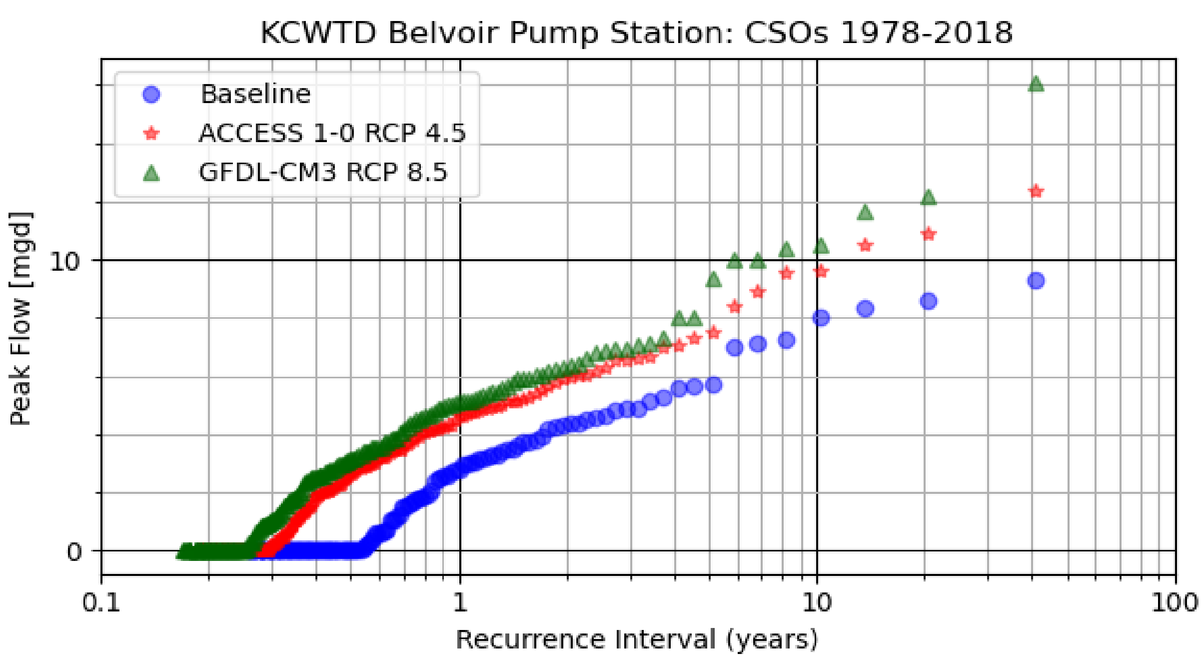

Figure 31. Peak untreated CSO flowrate recurrence interval for Belvoir Pump Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

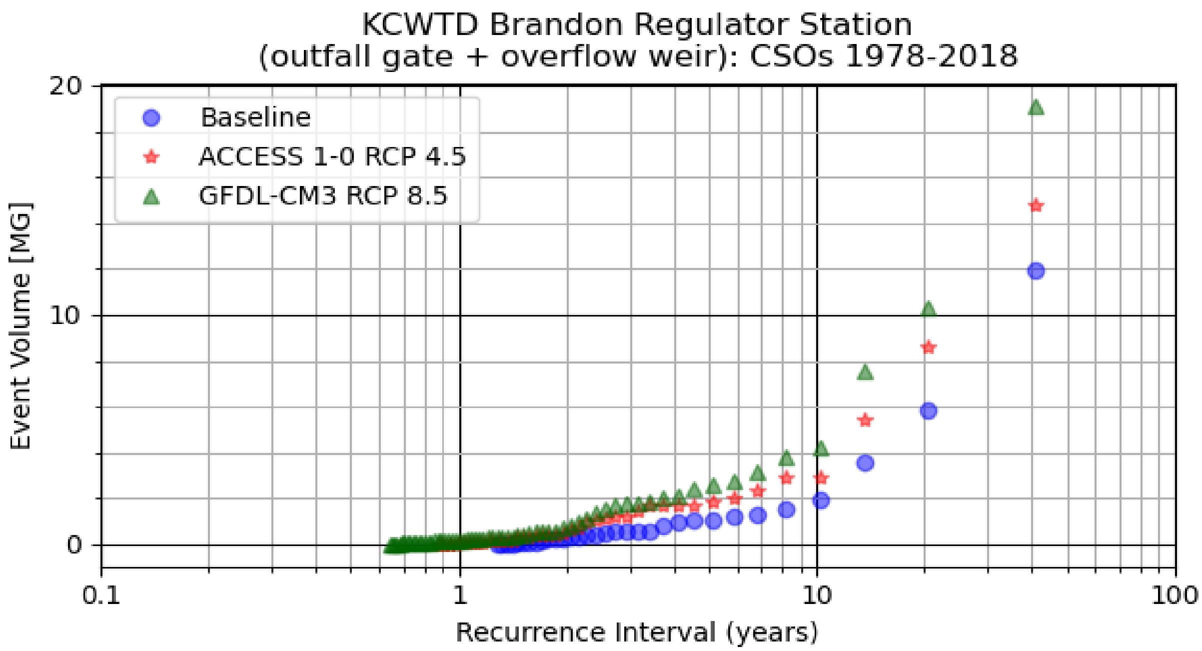

Figure 32. CSO volume recurrence interval for Brandon Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

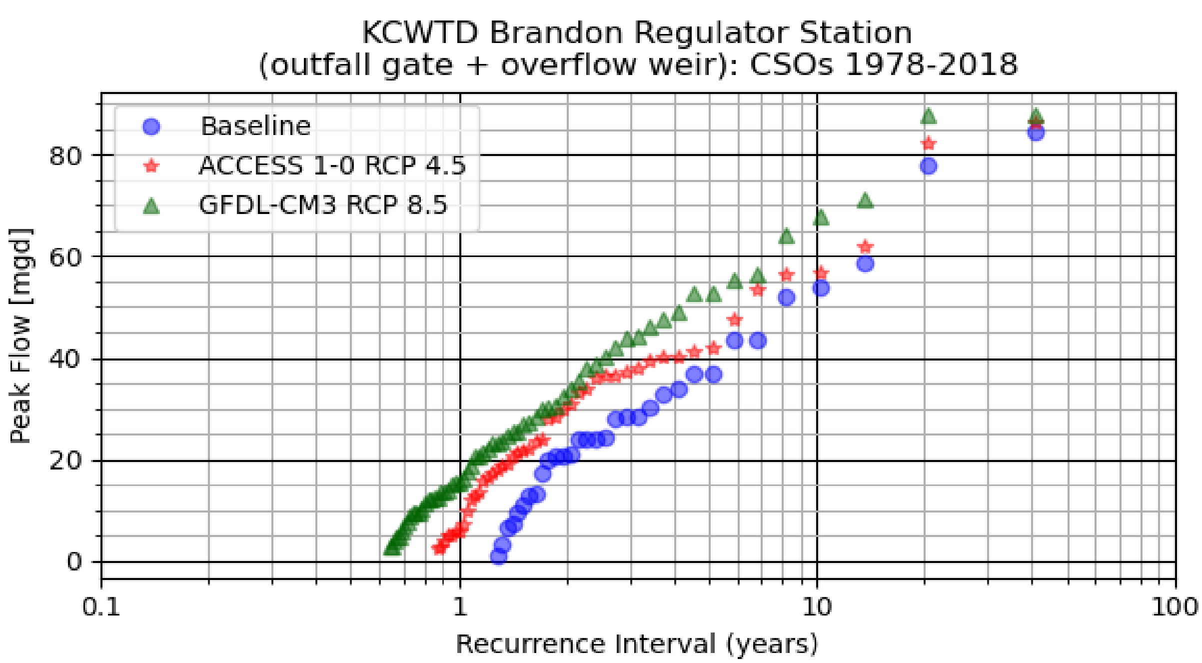

Figure 33. Peak untreated CSO flowrate recurrence interval for Brandon Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

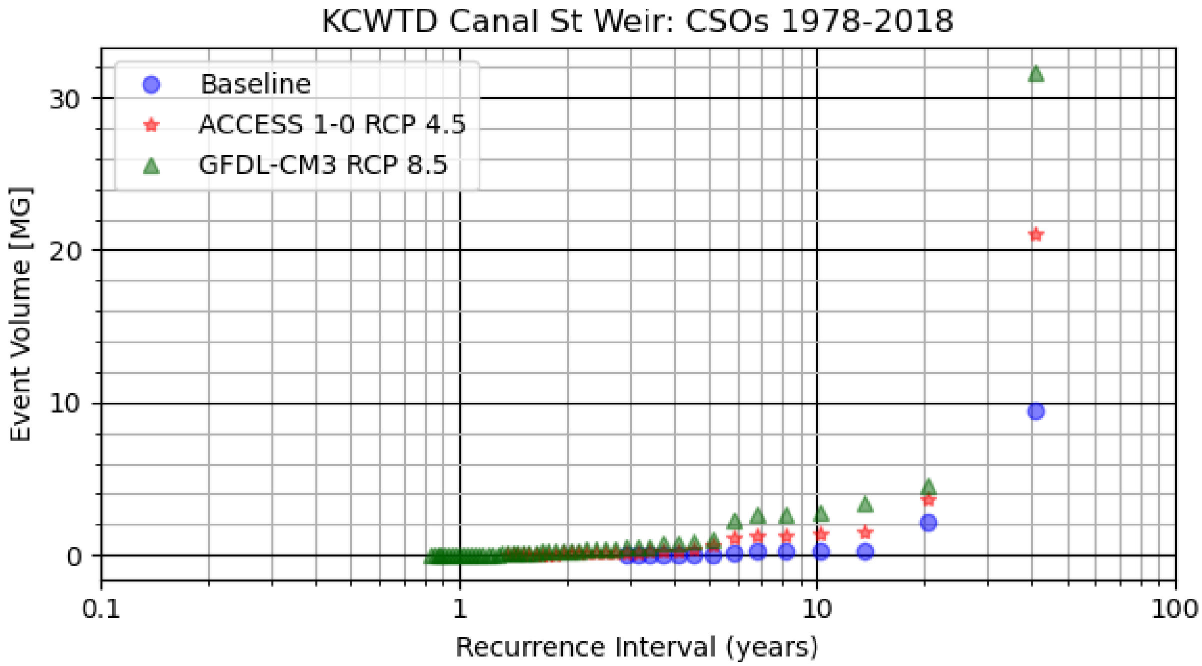

Figure 34. CSO volume recurrence Interval for Canal St. Weir under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

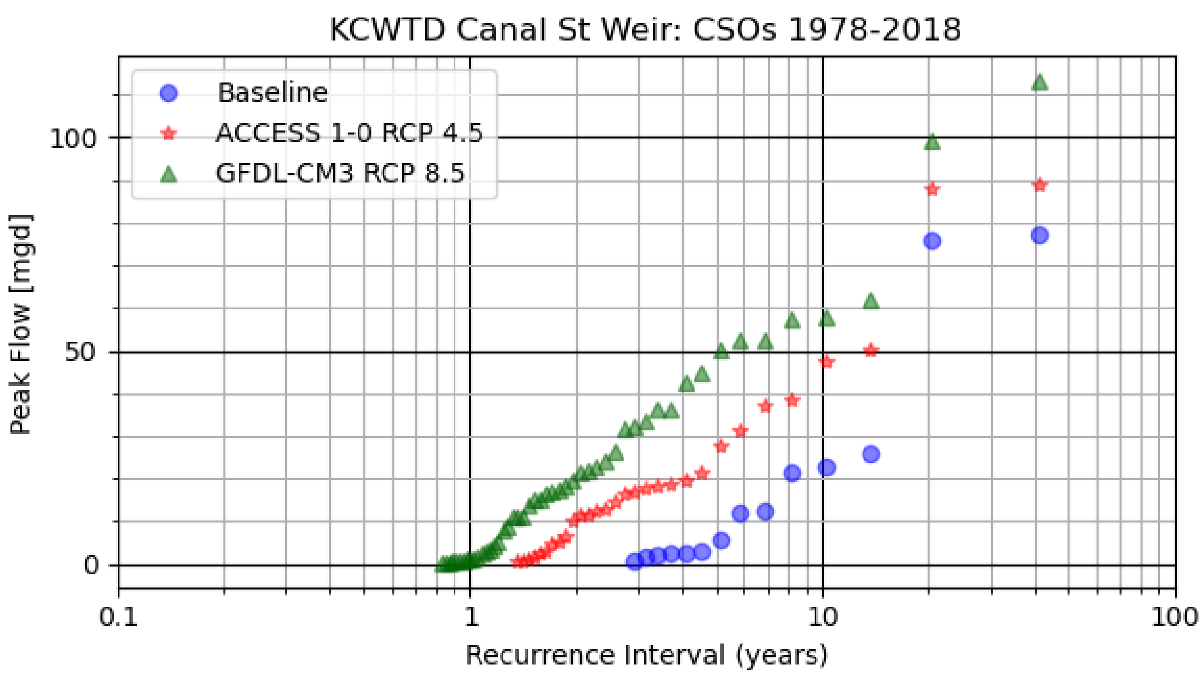

Figure 35. Peak untreated CSO flowrate recurrence interval for Canal St. Weir under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

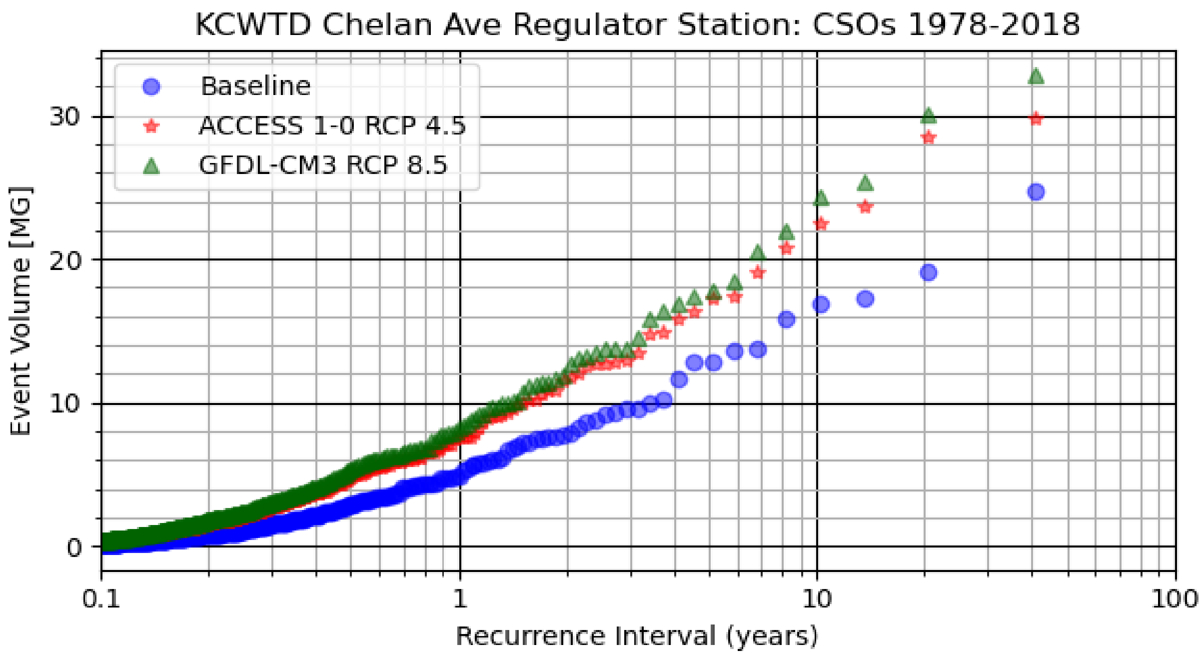

Figure 36. CSO volume recurrence Interval for Chelan Ave. Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

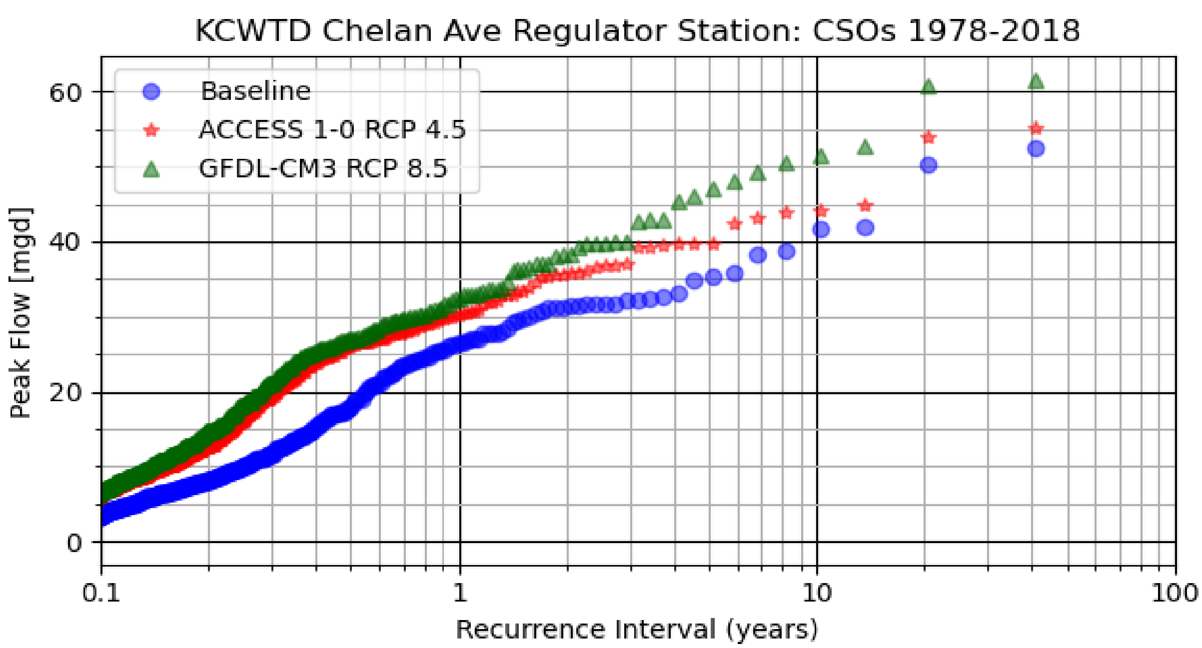

Figure 37. Peak untreated CSO flowrate recurrence interval for Chelan Ave. Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

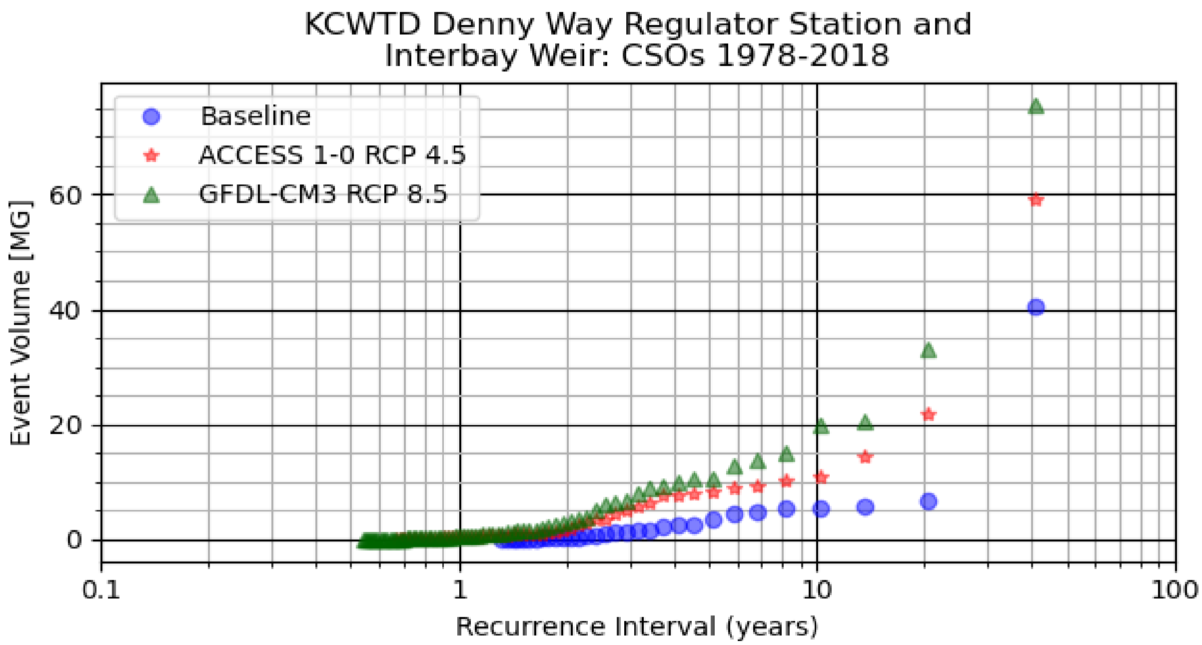

Figure 38. CSO volume recurrence interval for Denny Way Regulator Stations and Interbay Weir under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

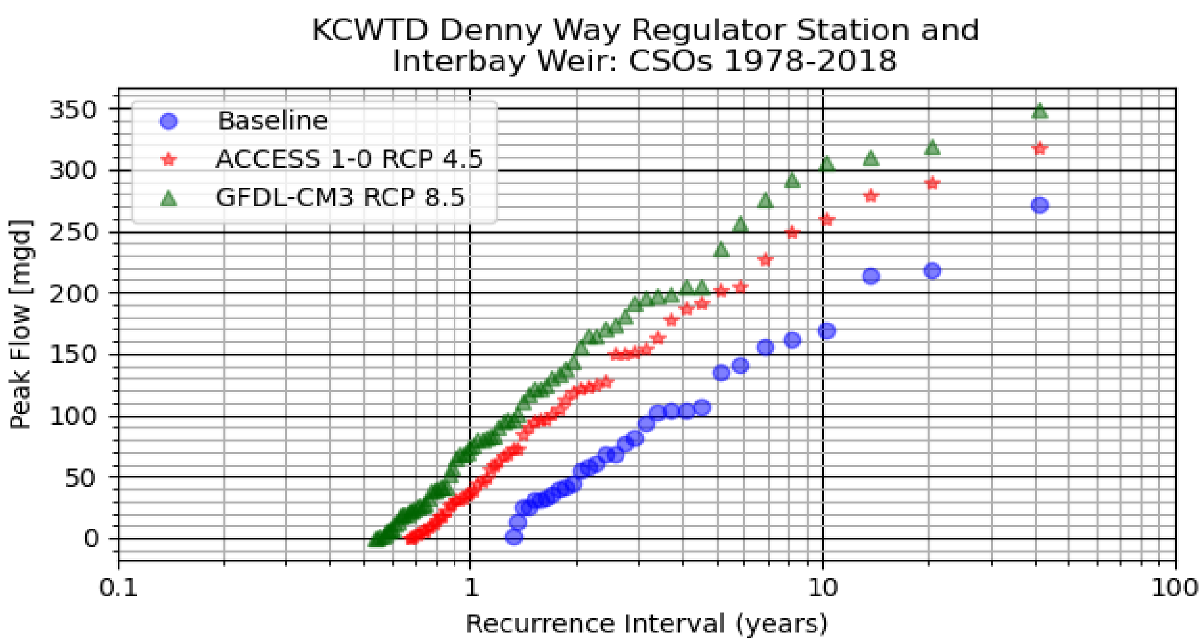

Figure 39. Peak untreated CSO flowrate recurrence interval for Denny Way Regulator Stations and Interbay Weir under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

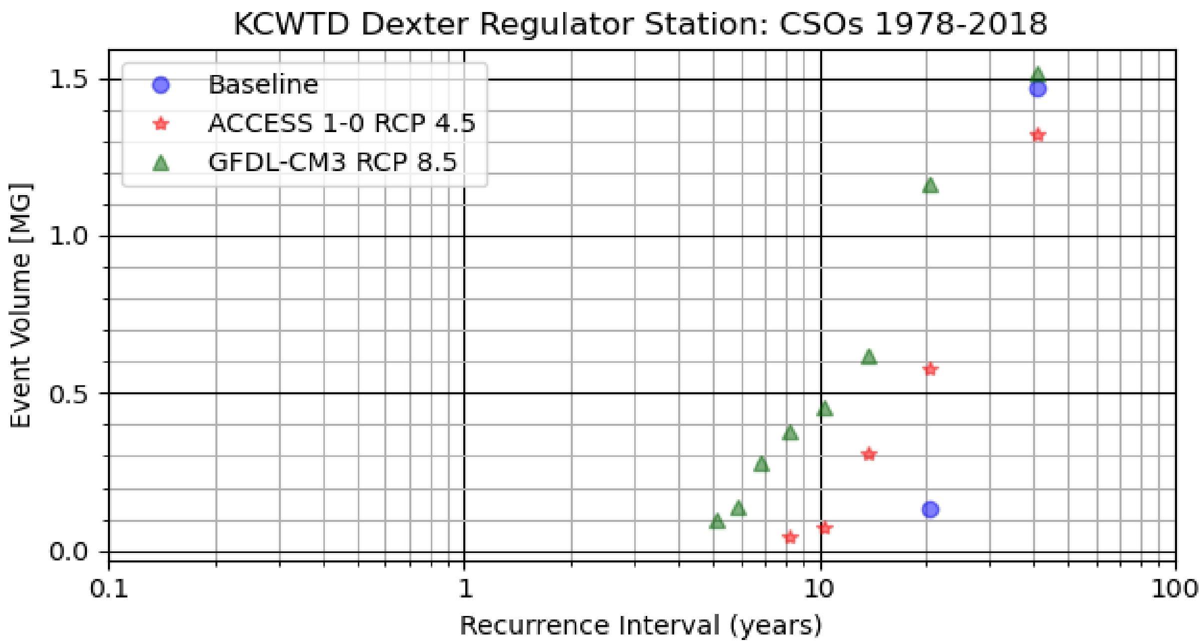

Figure 40. CSO volume recurrence interval for Dexter Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

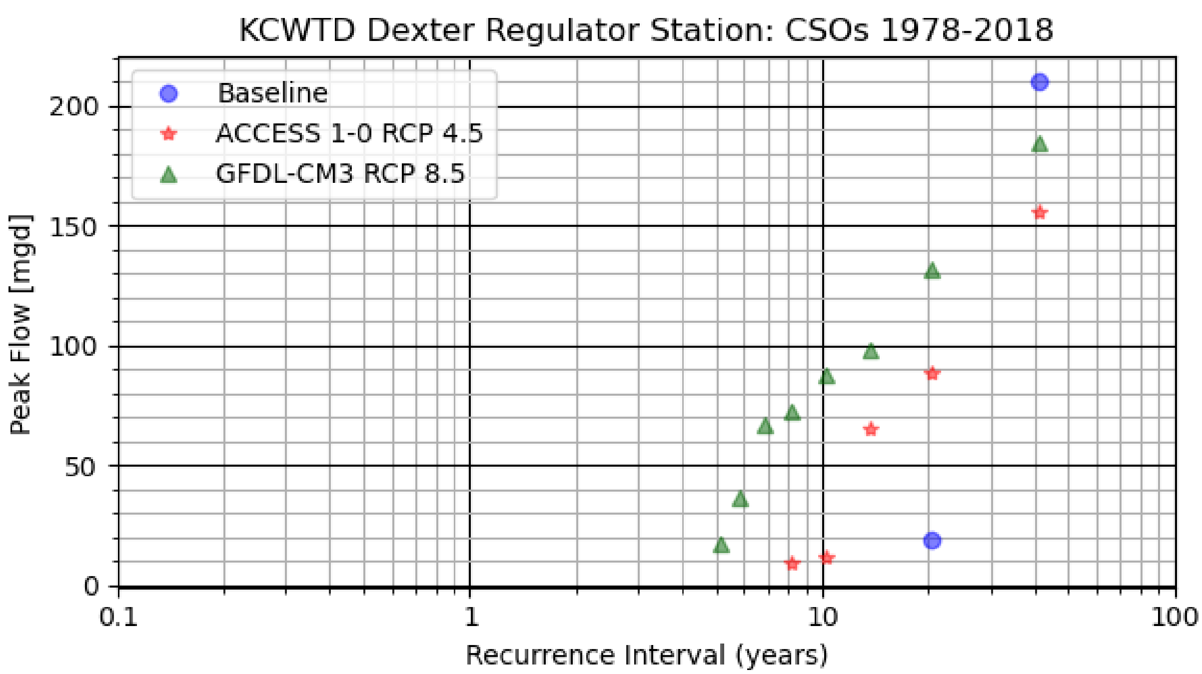

Figure 41. Peak untreated CSO flowrate recurrence interval for Dexter Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

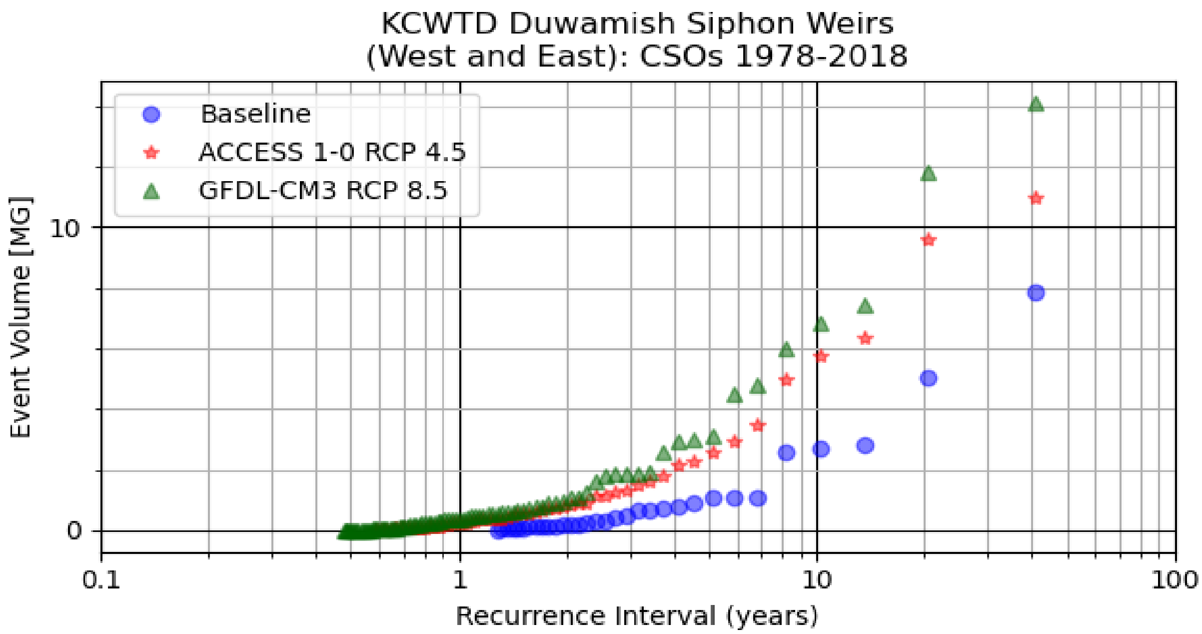

Figure 42. CSO volume recurrence Interval for Duwamish Siphon Weirs under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

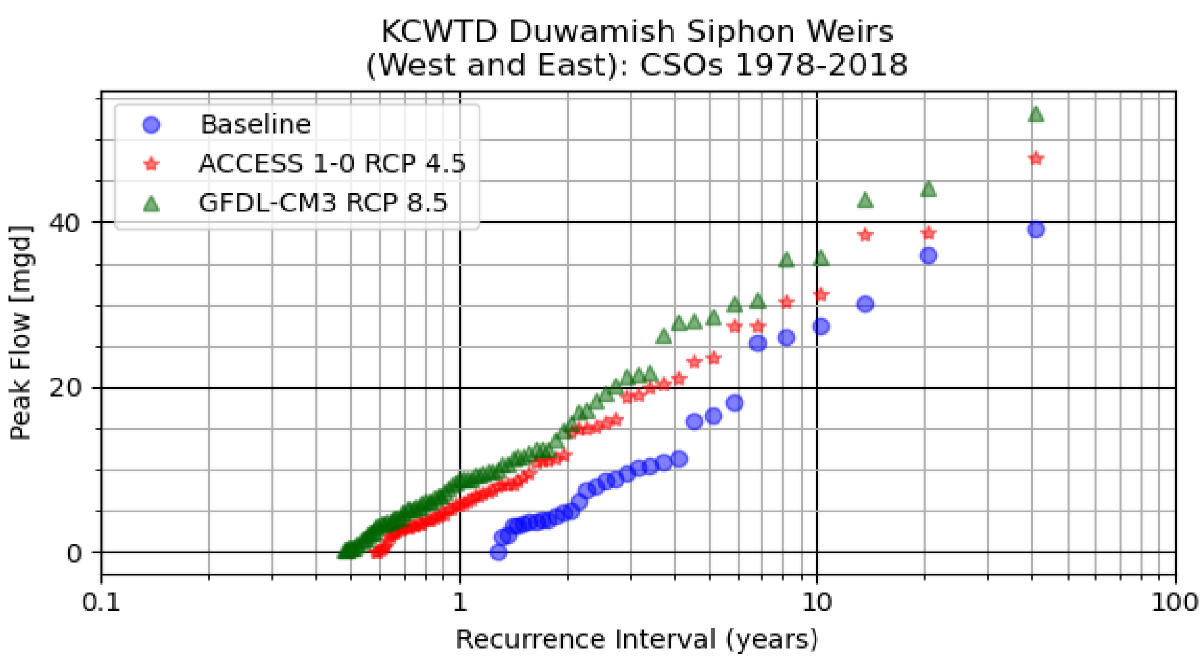

Figure 43. Peak untreated CSO flowrate recurrence interval for Duwamish Siphon Weirs under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

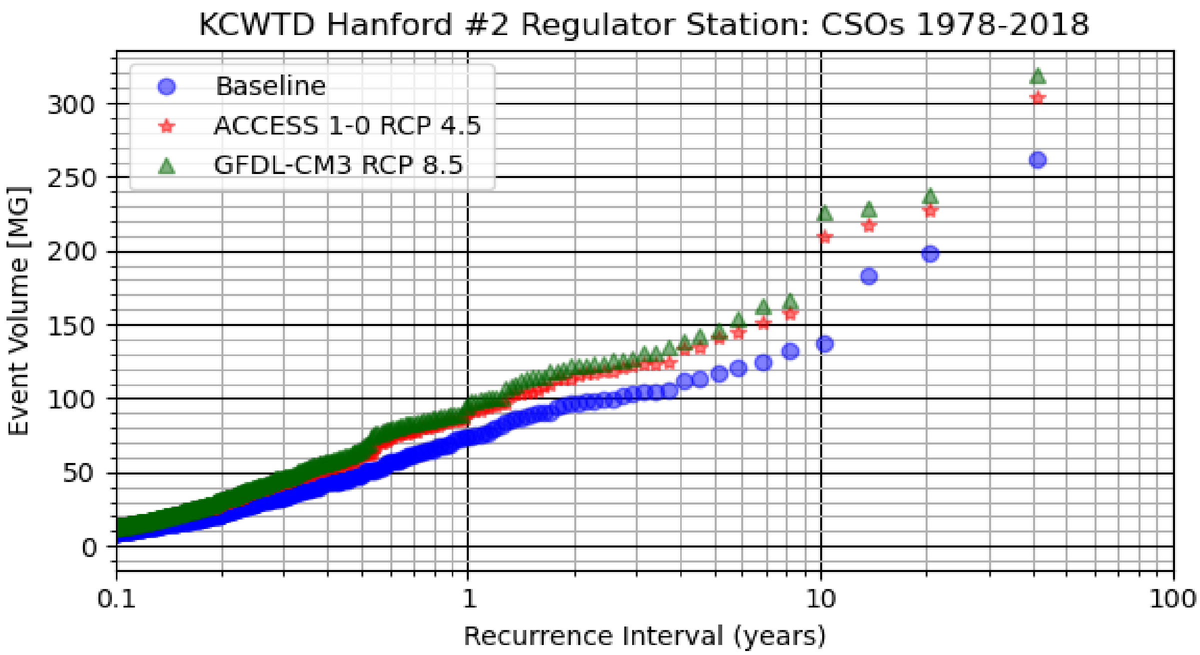

Figure 44. CSO volume recurrence Interval for Hanford #2 Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

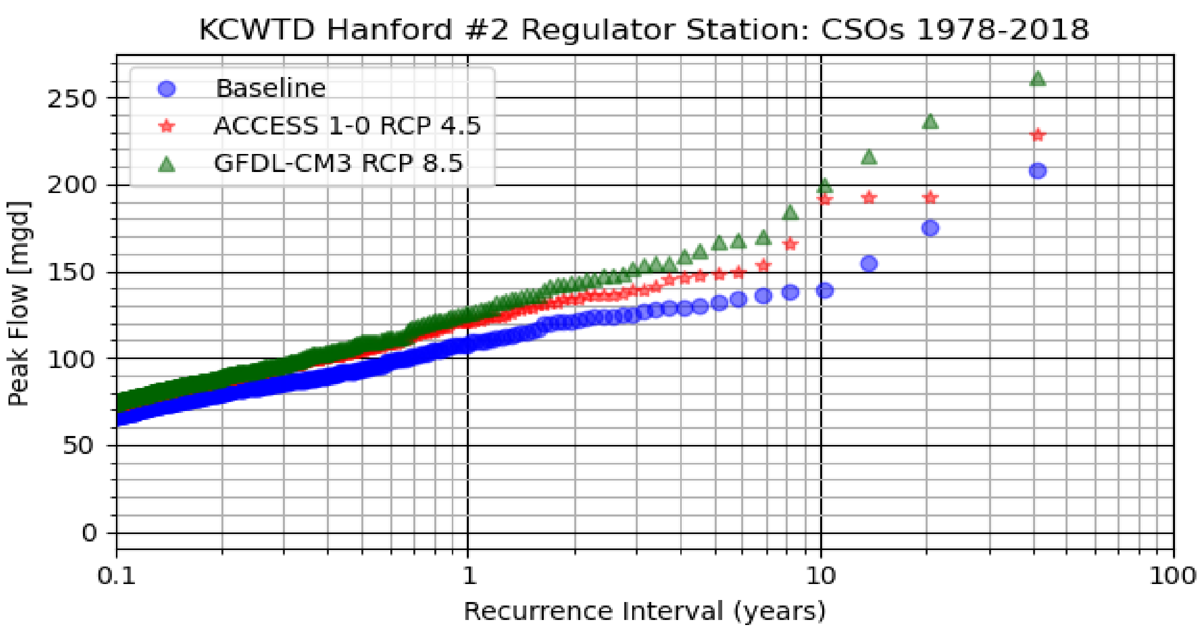

Figure 45. Peak untreated CSO flowrate recurrence interval for Hanford #2 Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

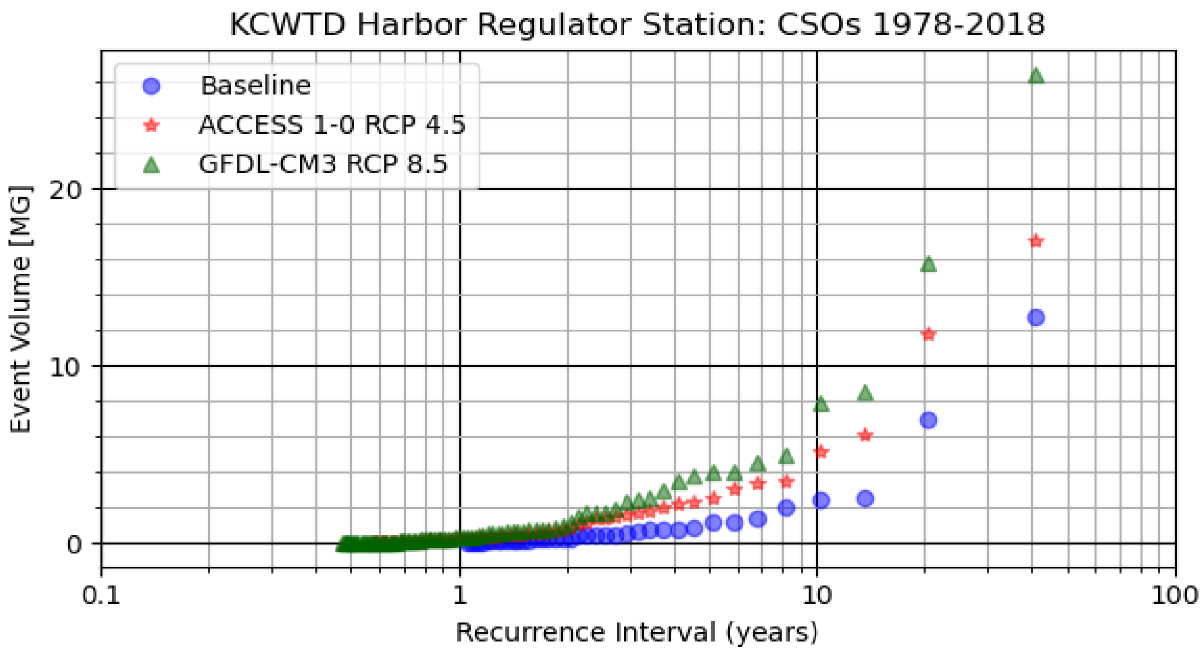

Figure 46. CSO volume recurrence Interval for Harbor Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

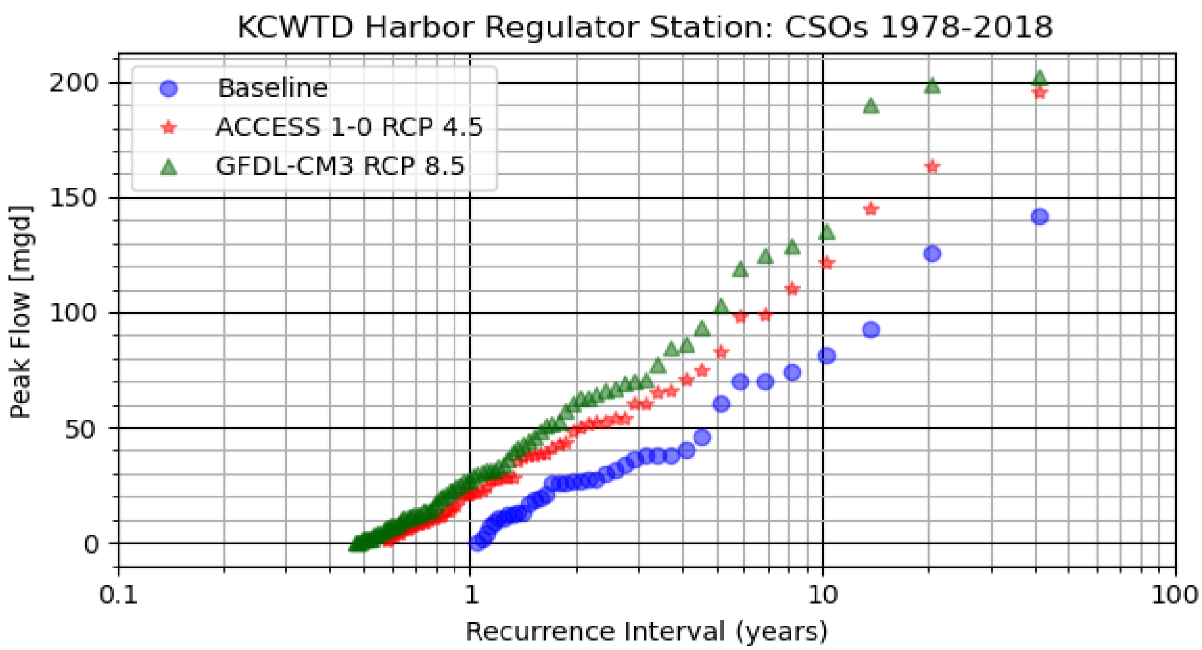

Figure 47. Peak untreated CSO flowrate recurrence interval for Harbor Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

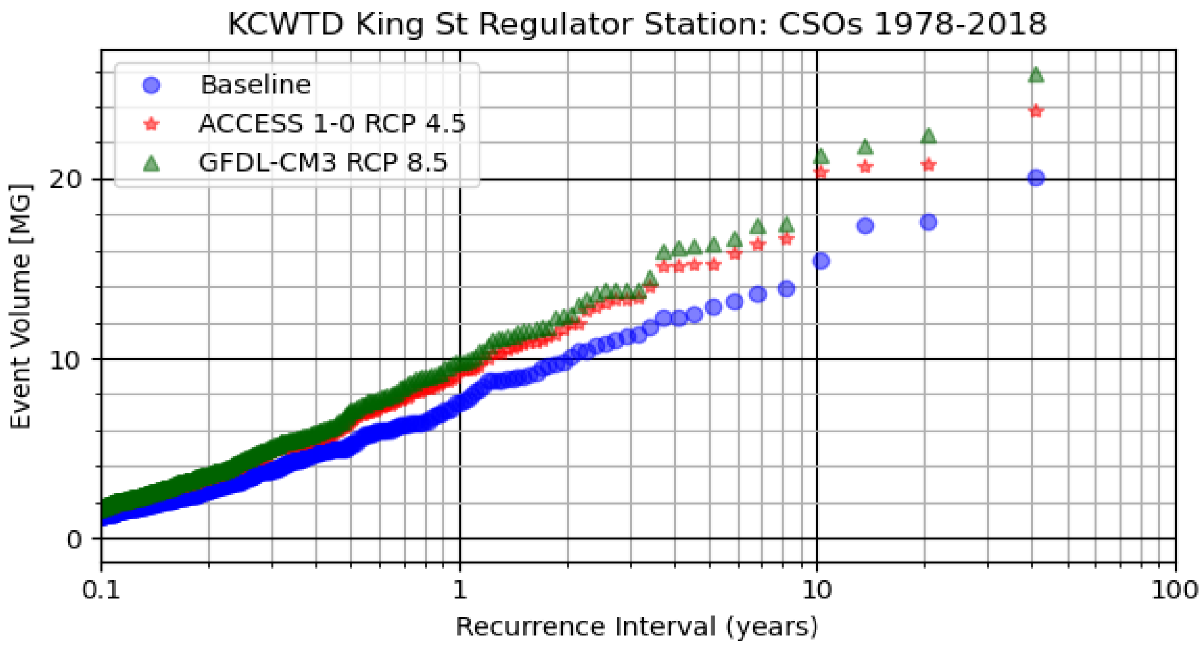

Figure 48. CSO volume recurrence Interval for King Street Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

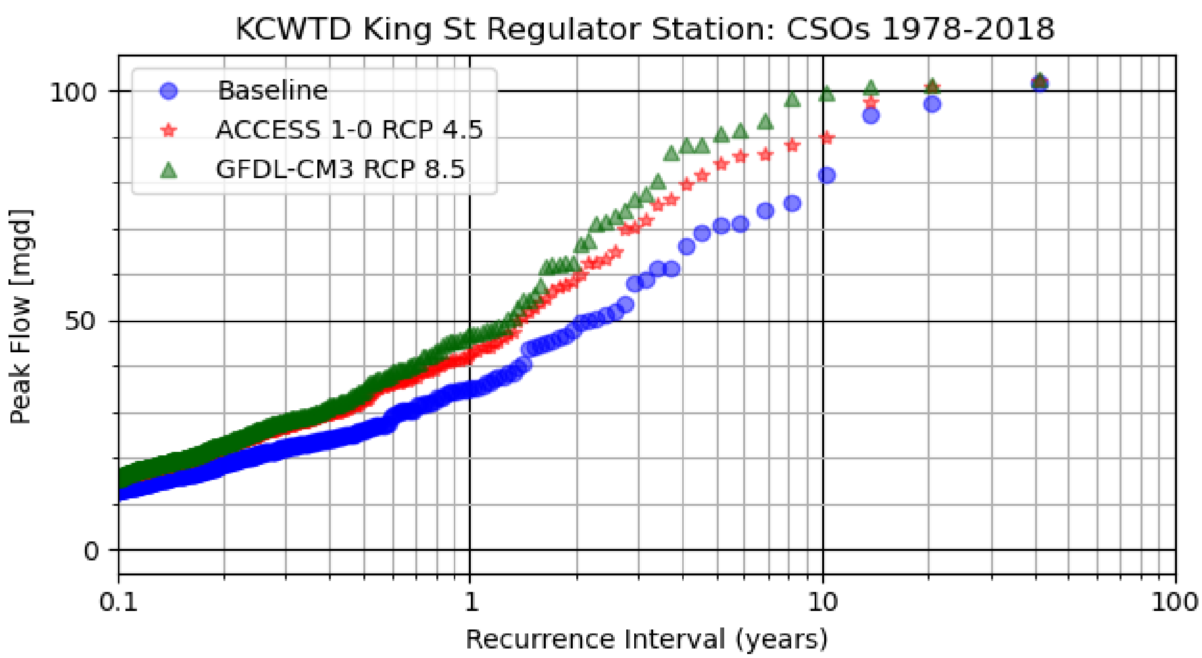

Figure 49. Peak untreated CSO flowrate recurrence interval for King Street Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

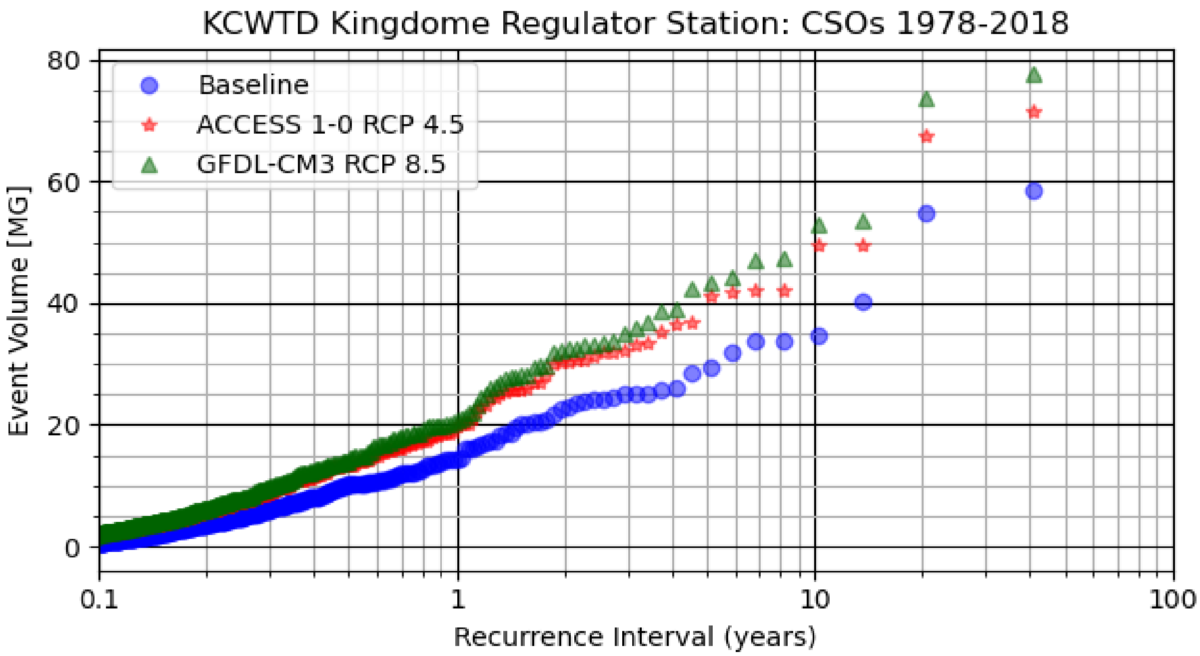

Figure 50. CSO volume recurrence Interval for Kingdome Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

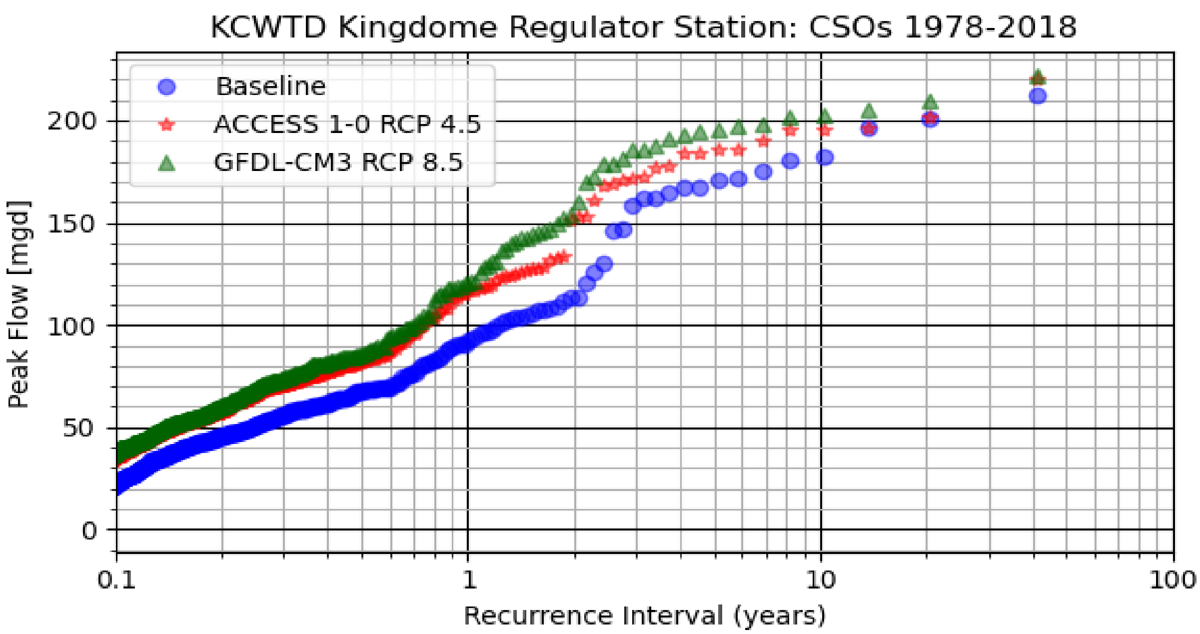

Figure 51. Peak untreated CSO flowrate recurrence interval for Kingdome Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

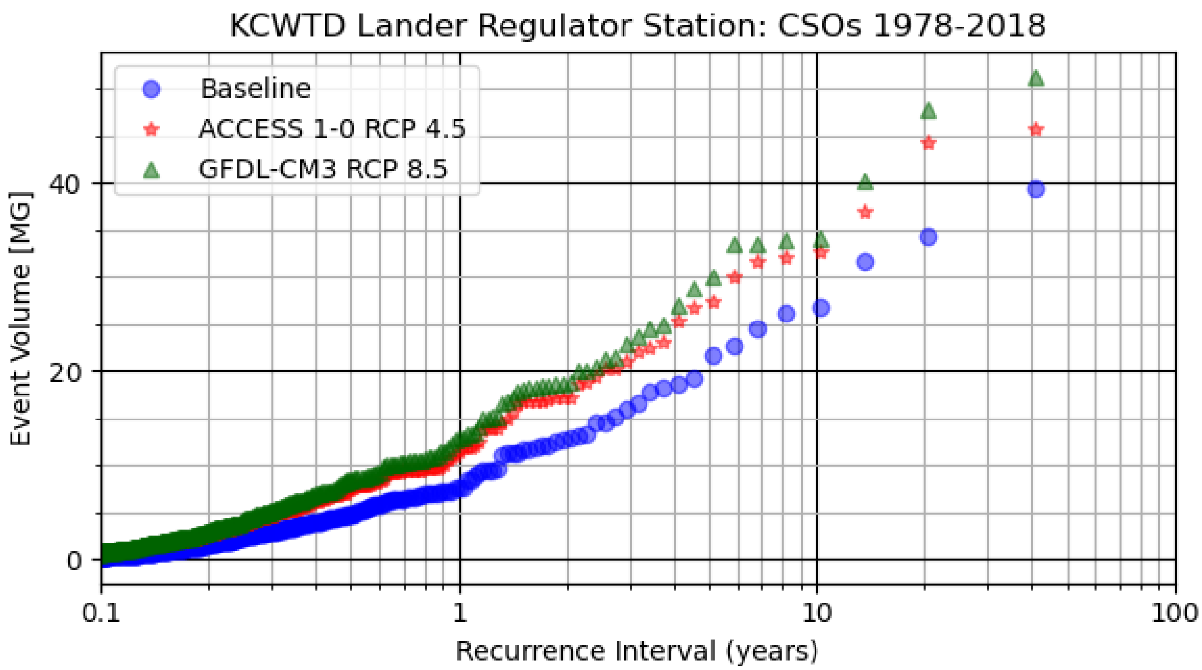

Figure 52. CSO volume recurrence Interval for Lander Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

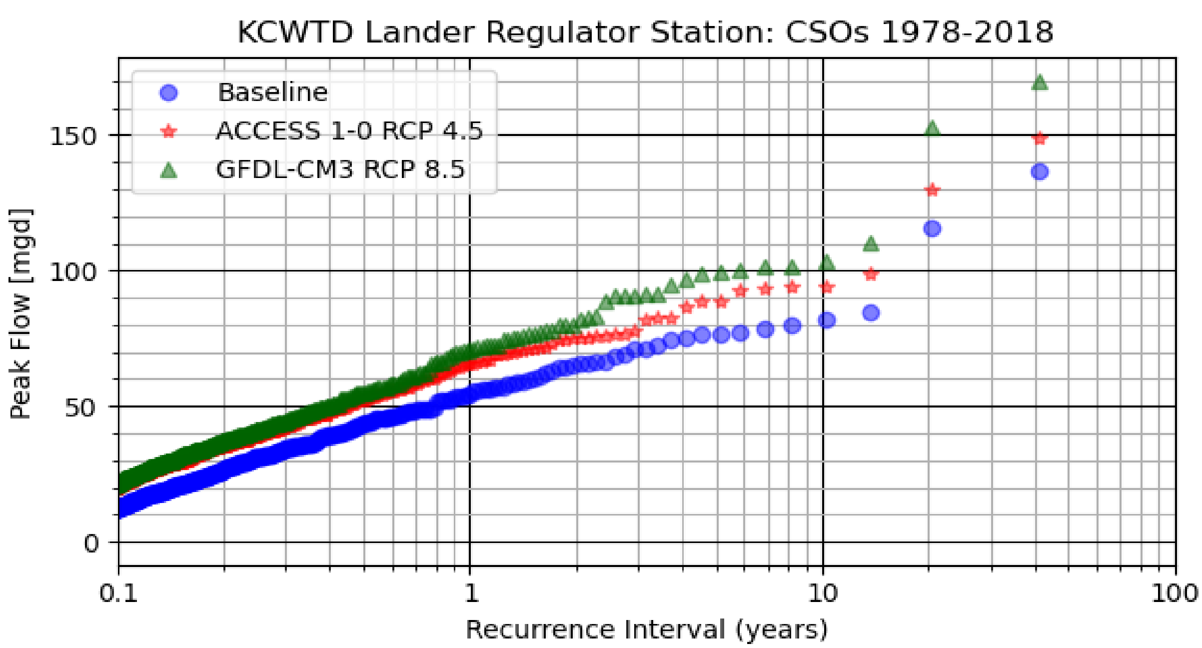

Figure 53. Peak untreated CSO flowrate recurrence interval for Lander Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

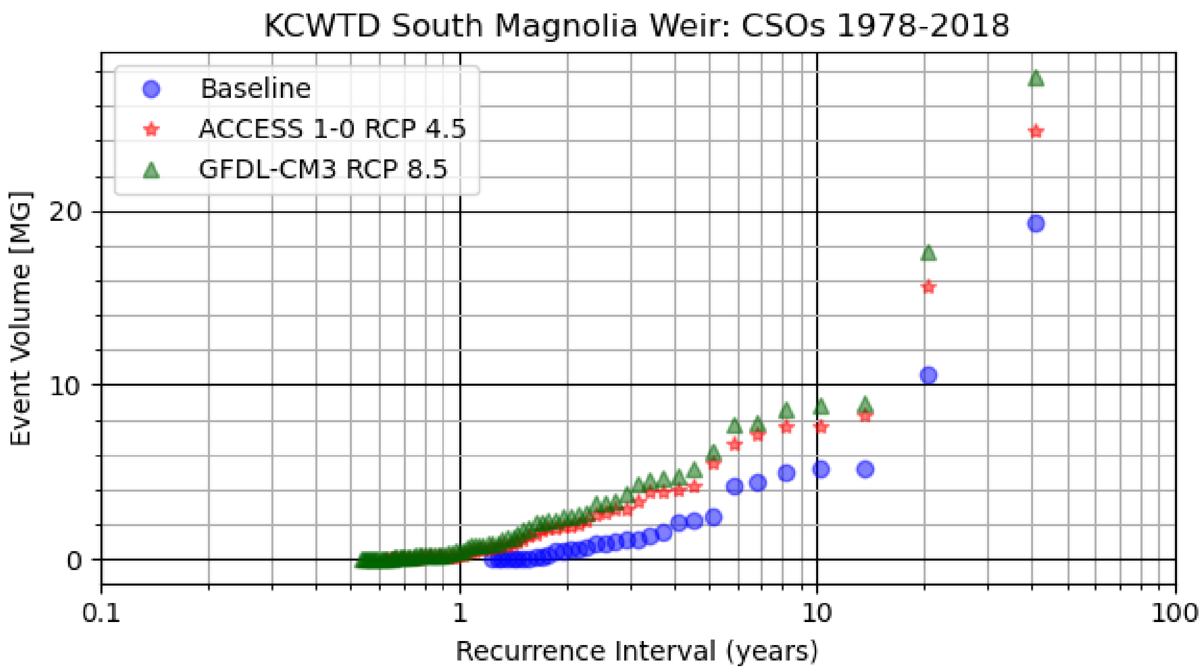

Figure 54. CSO volume recurrence Interval for South Magnolia Weir under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

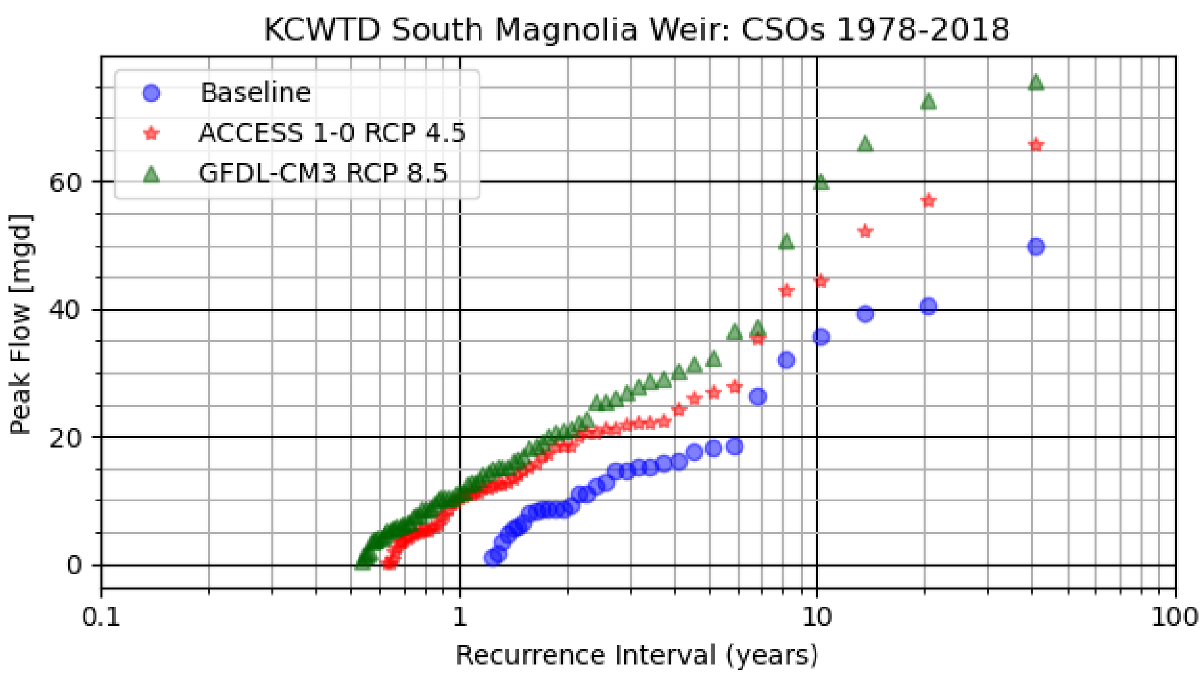

Figure 55. Peak untreated CSO flowrate recurrence interval for S. Magnolia Weir under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

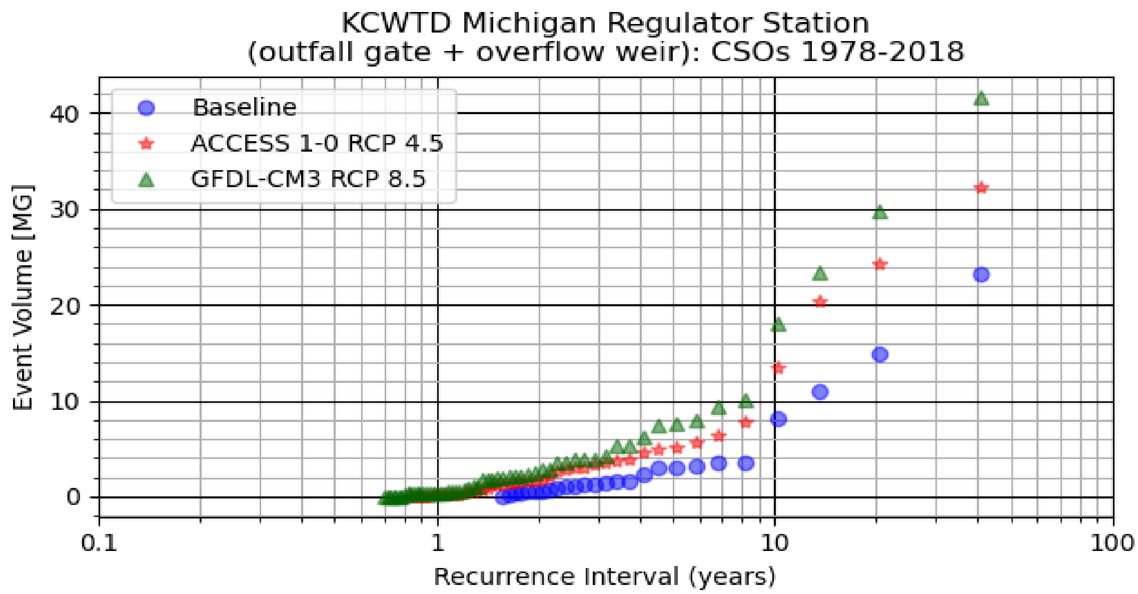

Figure 56. CSO volume recurrence interval for S. Michigan St. Regulator Station (with Georgetown WWTS complete) under Baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

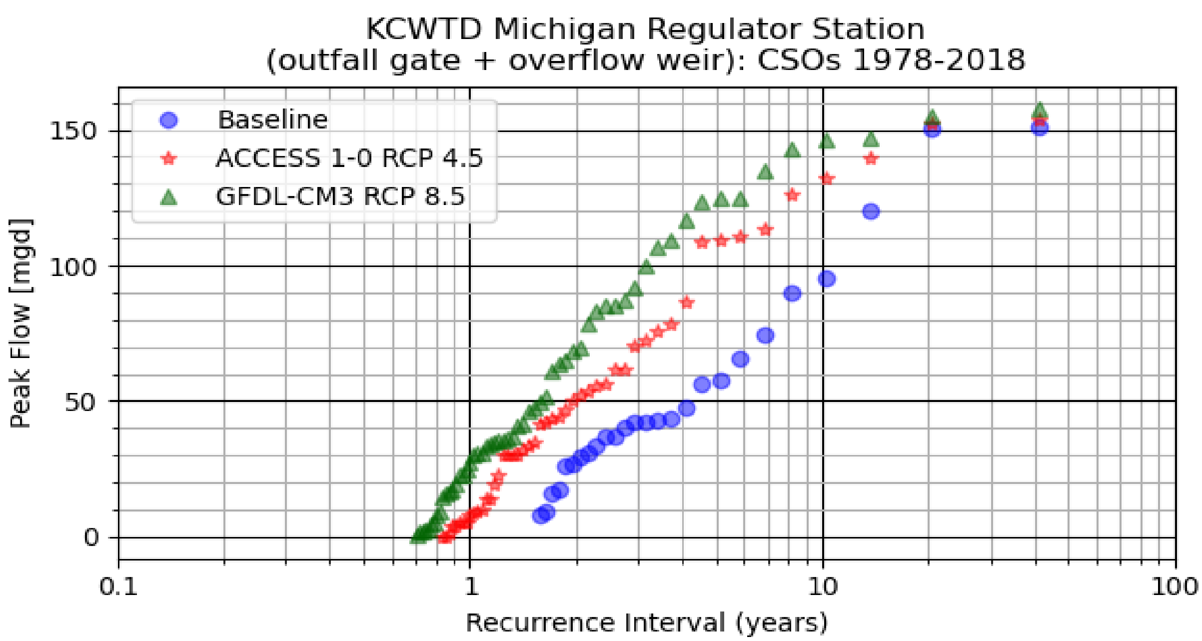

Figure 57. Peak untreated CSO flowrate recurrence interval for S. Michigan St. Regulator Station (with Georgetown WWTS complete) under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

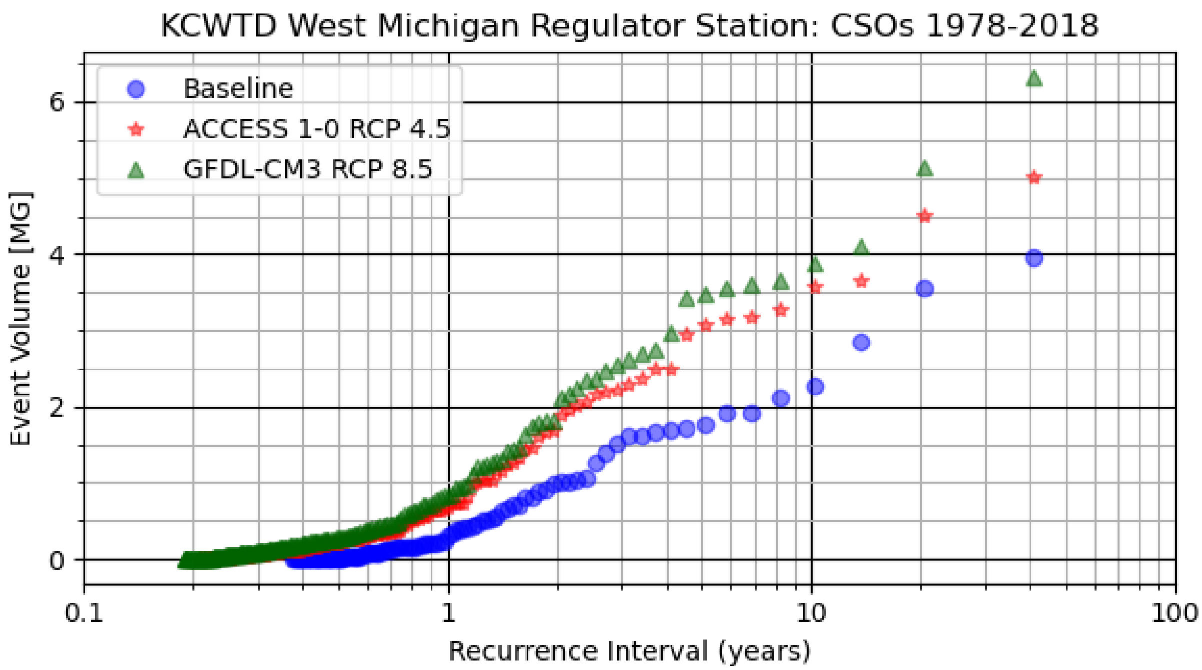

Figure 58. CSO volume recurrence Interval for W. Michigan Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

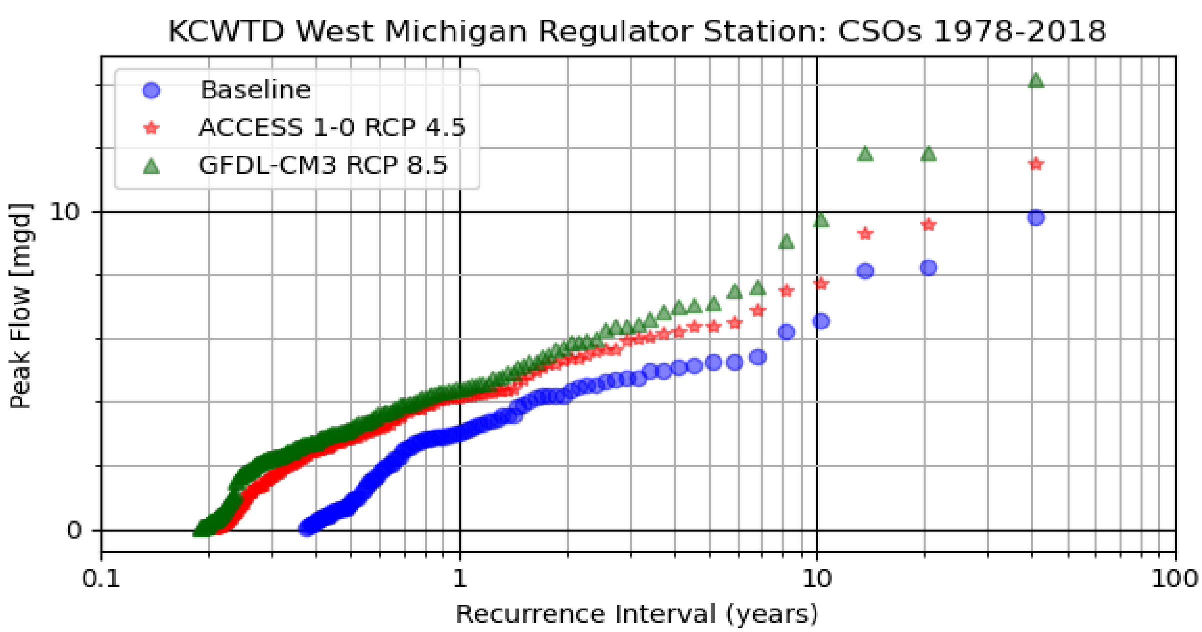

Figure 59. Peak untreated CSO flowrate recurrence interval for W. Michigan Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

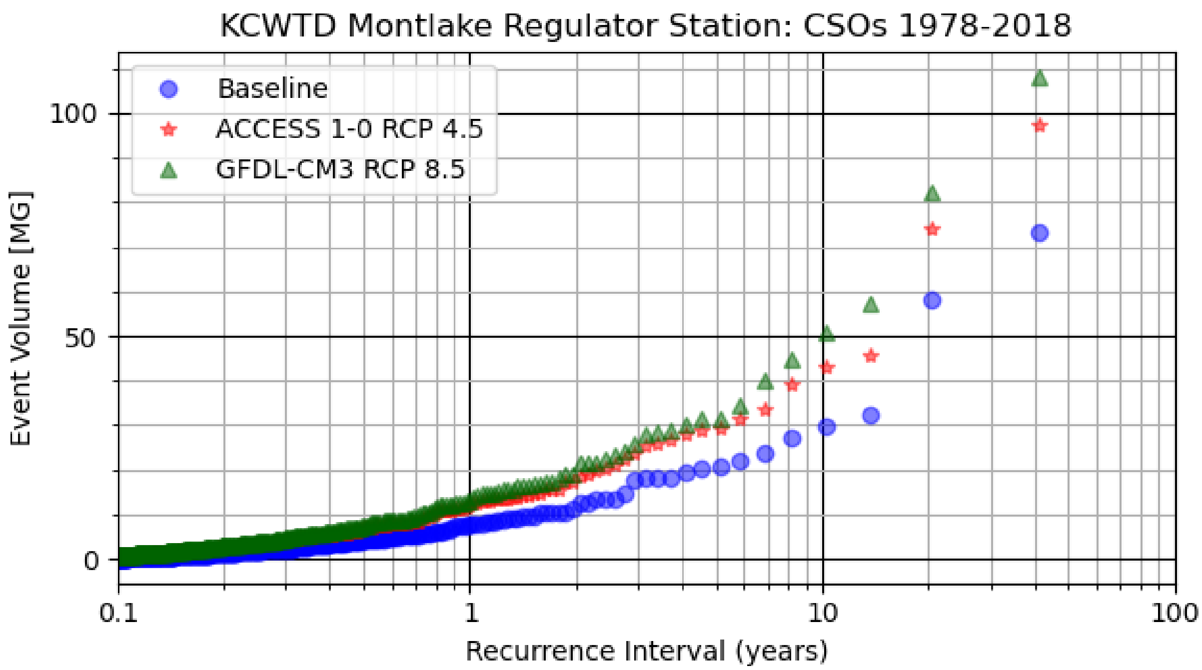

Figure 60. CSO volume recurrence Interval for Montlake Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

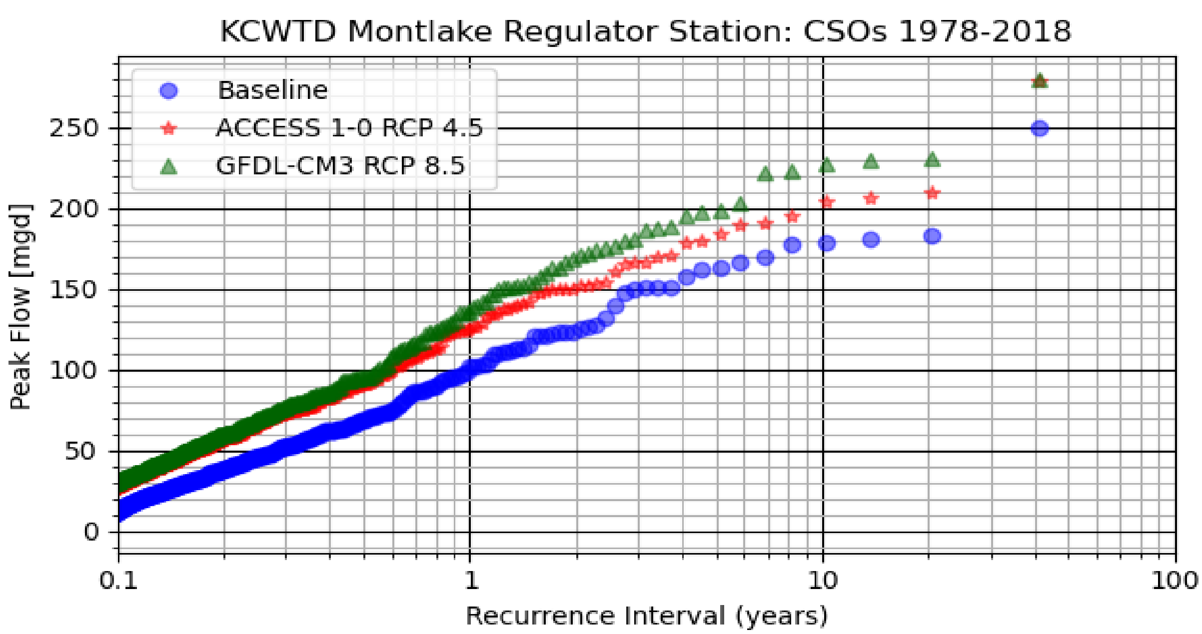

Figure 61. Peak untreated CSO flowrate recurrence interval for Montlake Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

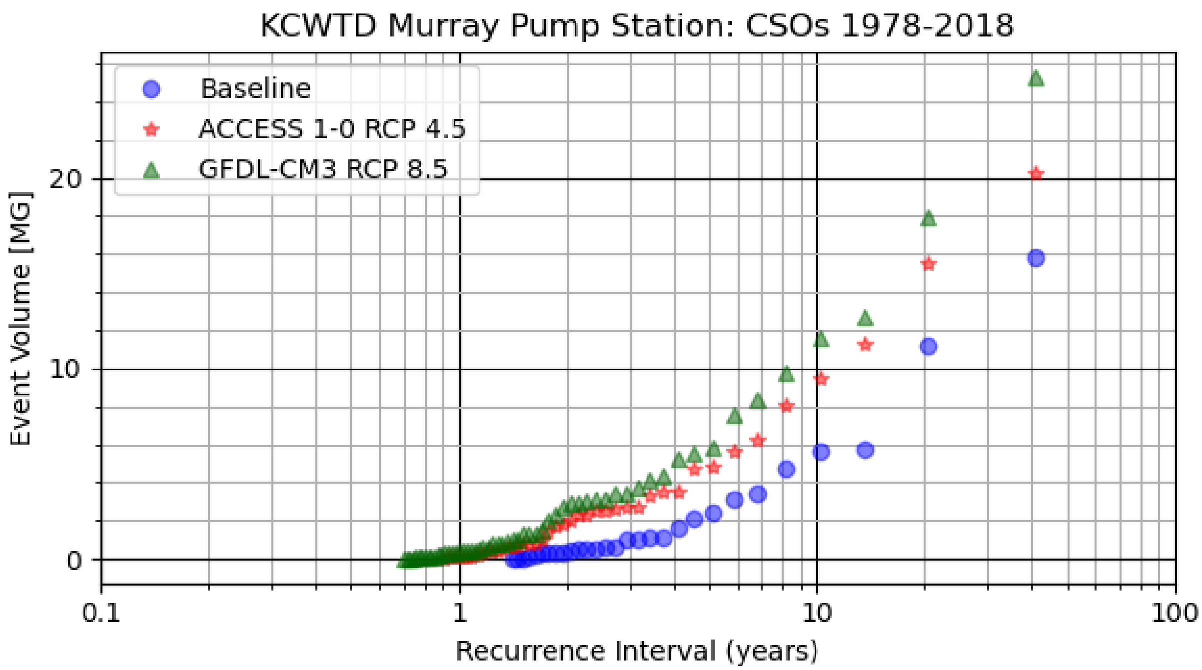

Figure 62. CSO volume recurrence Interval for Murray Ave. Pump Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

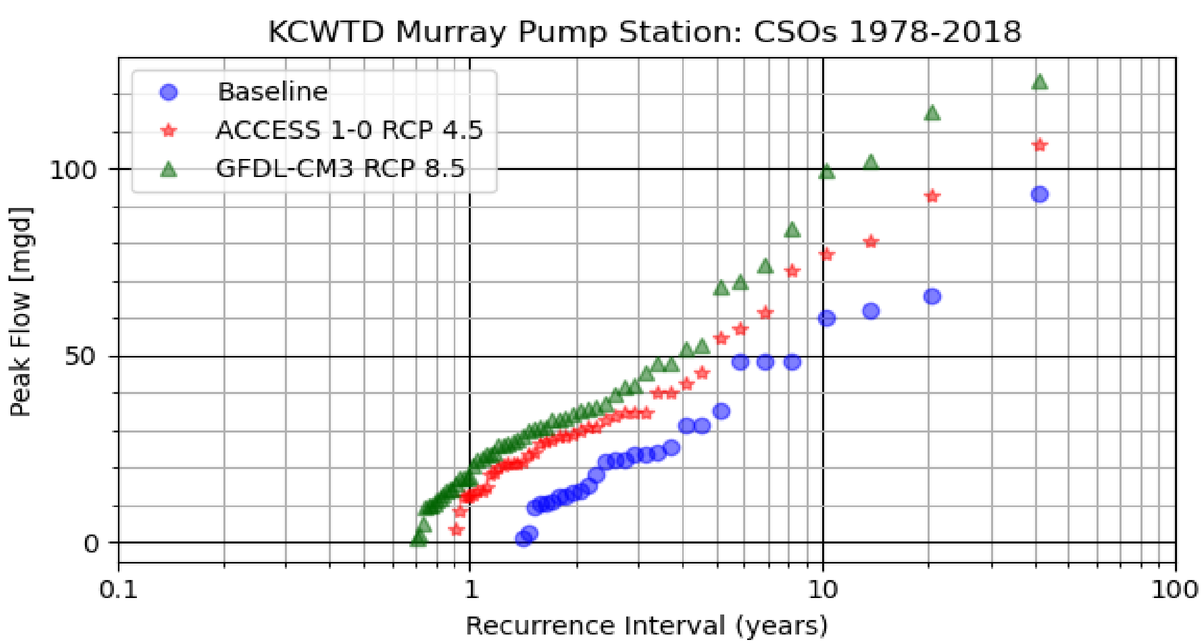

Figure 63. Peak untreated CSO flowrate recurrence interval for Murray Ave. Pump Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

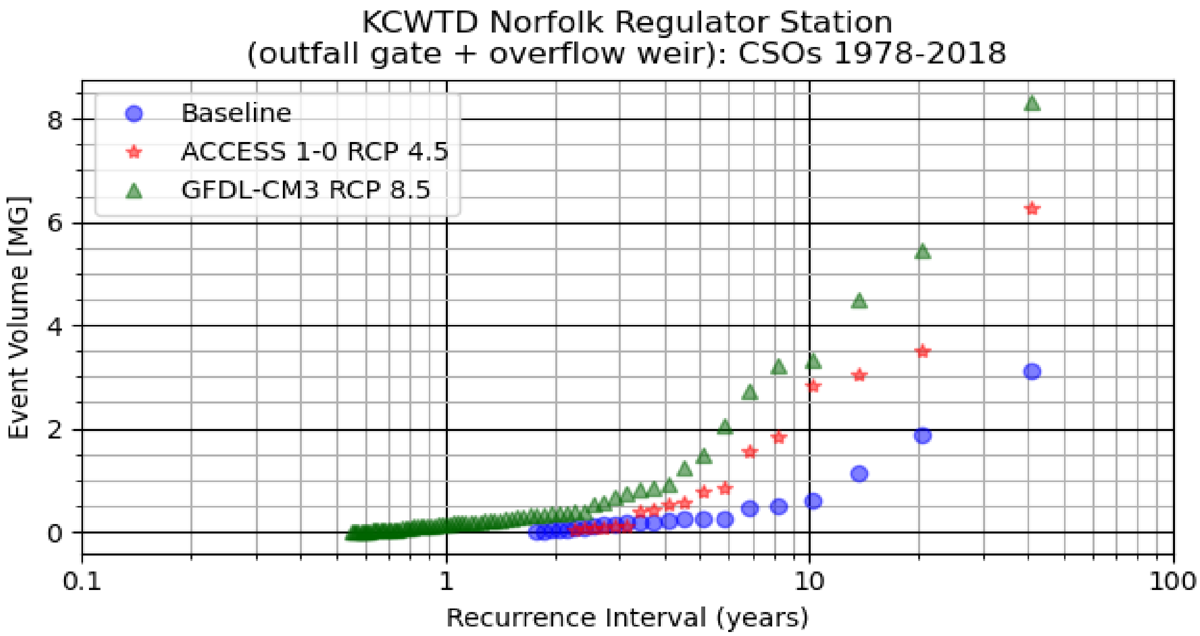

Figure 64. CSO volume recurrence Interval for Norfolk Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

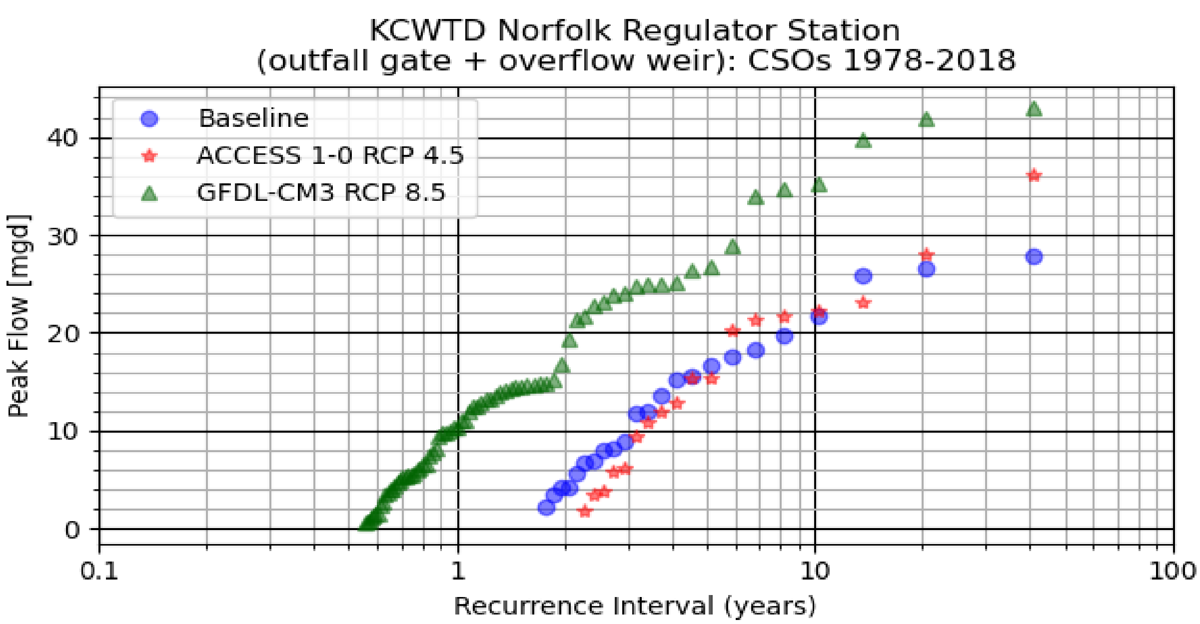

Figure 65. Peak untreated CSO flowrate recurrence interval for Norfolk Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

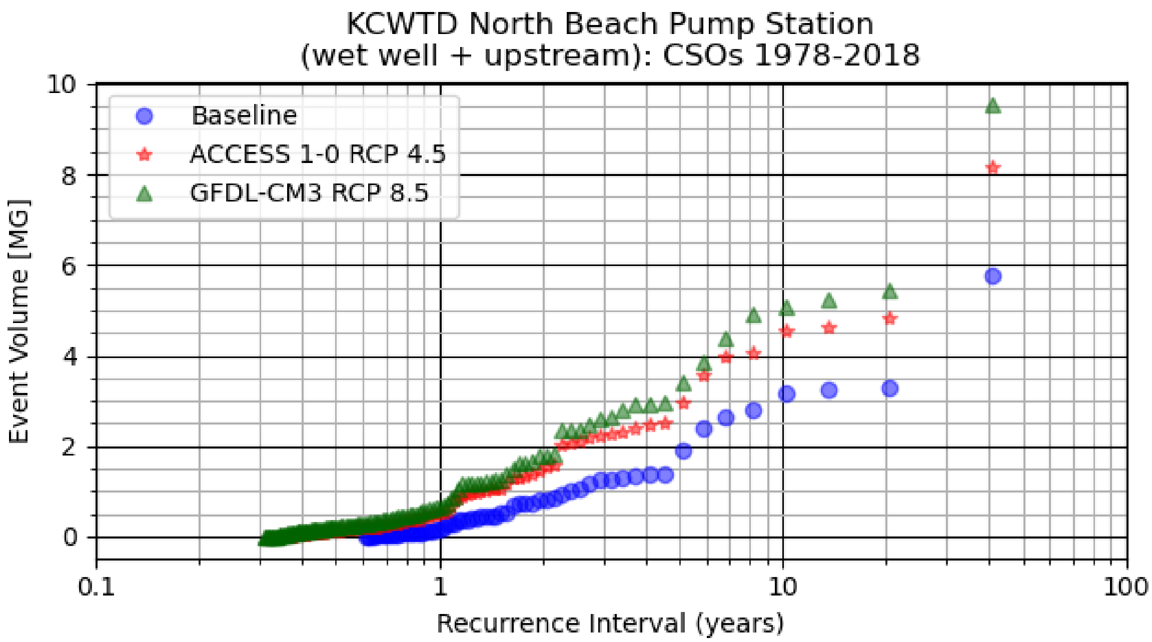

Figure 66. CSO volume recurrence interval for North Beach Pump Station (after CSO project was complete) under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

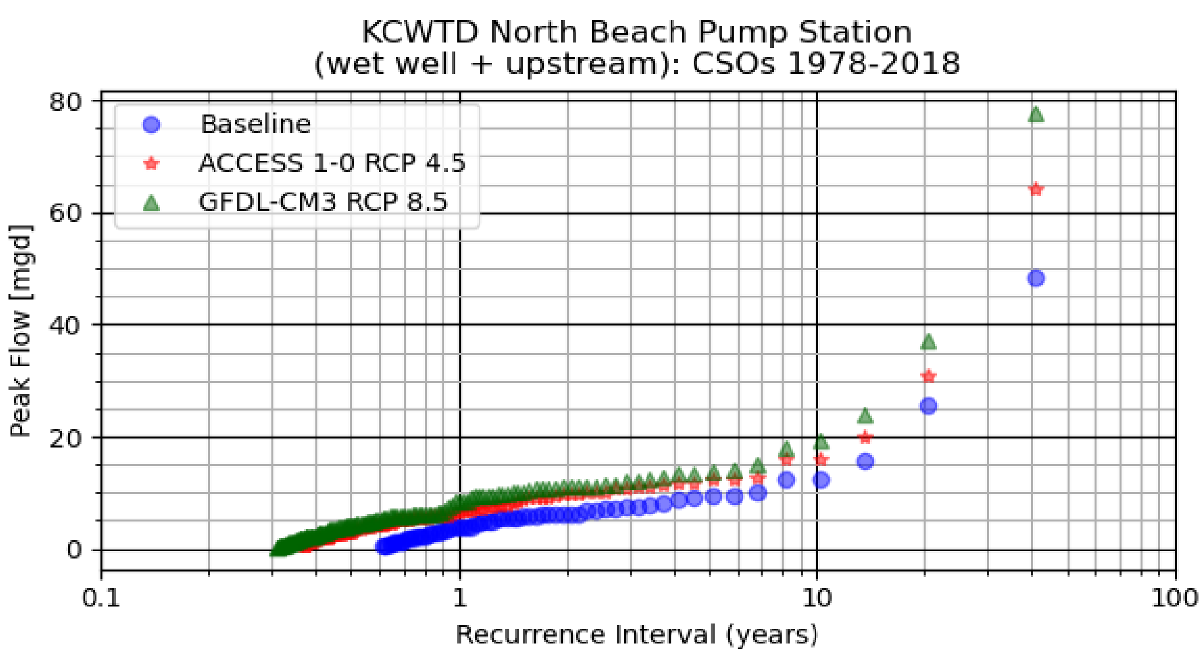

Figure 67. Peak untreated CSO flowrate recurrence interval for North Beach Pump Station (after CSO project was finished) under Baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

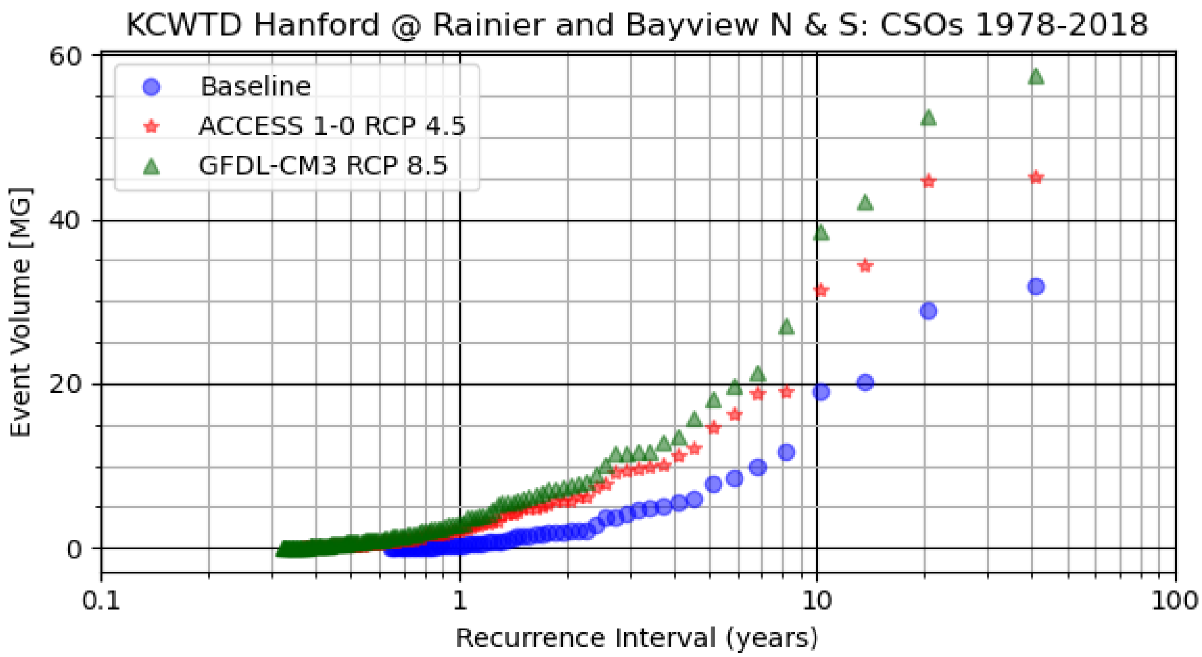

Figure 68. CSO volume recurrence interval for Rainier Valley Storage Facility (after project completion) under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

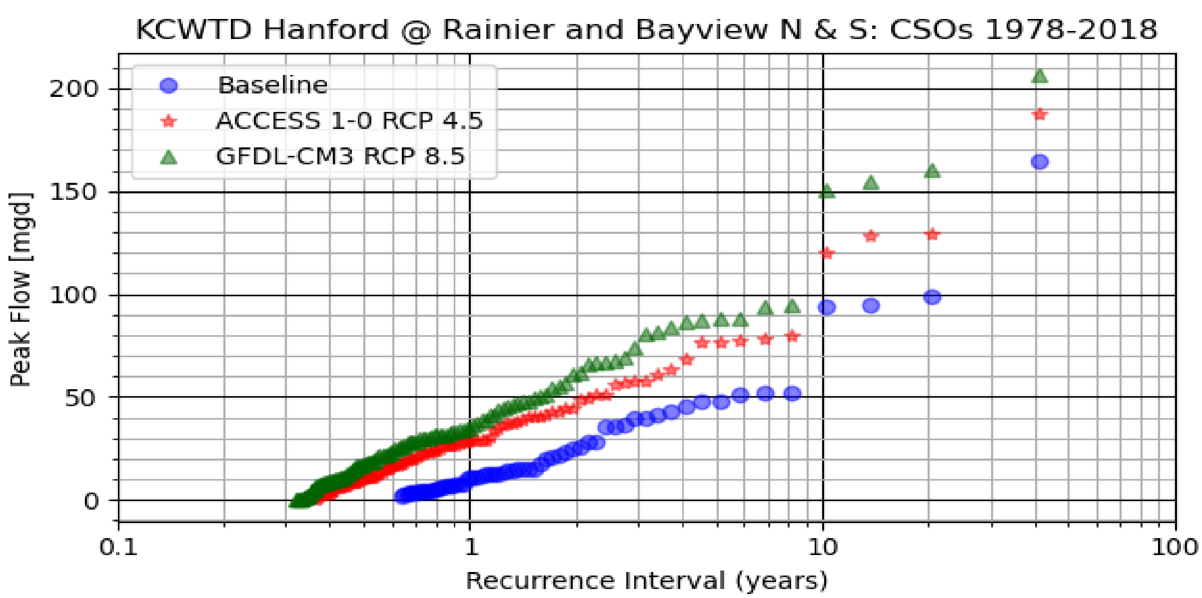

Figure 69. Peak untreated CSO flowrate recurrence interval for Rainier Valley Storage Facility (after project completion) under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

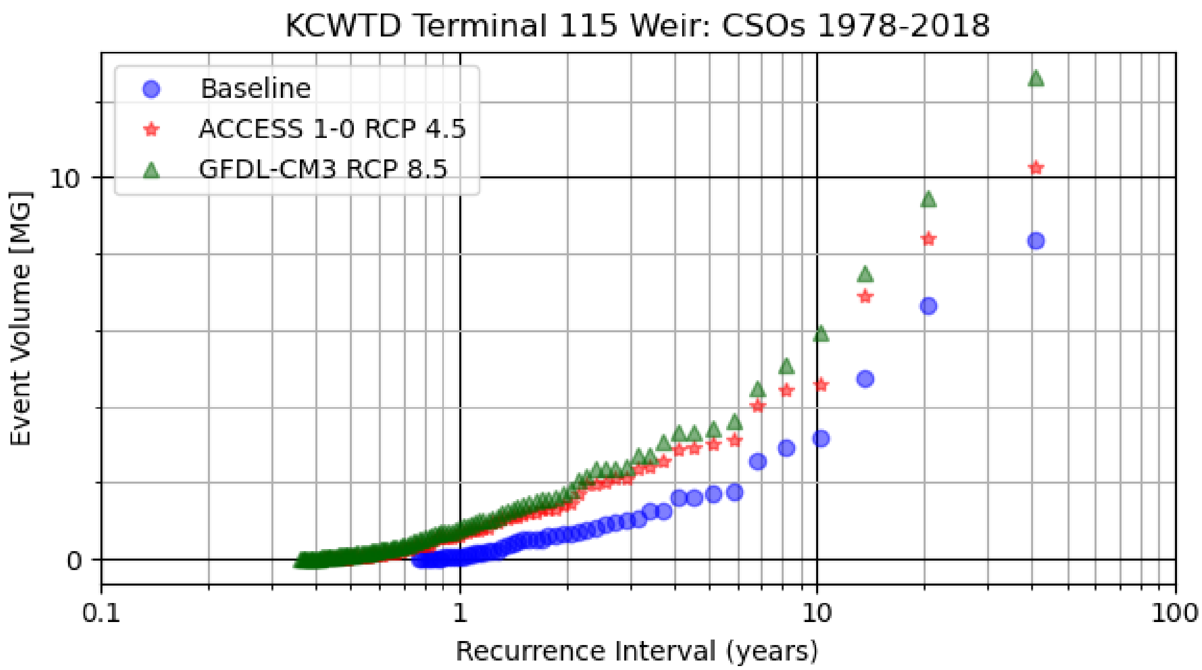

Figure 70. CSO volume recurrence Interval for Terminal 115 Weir under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

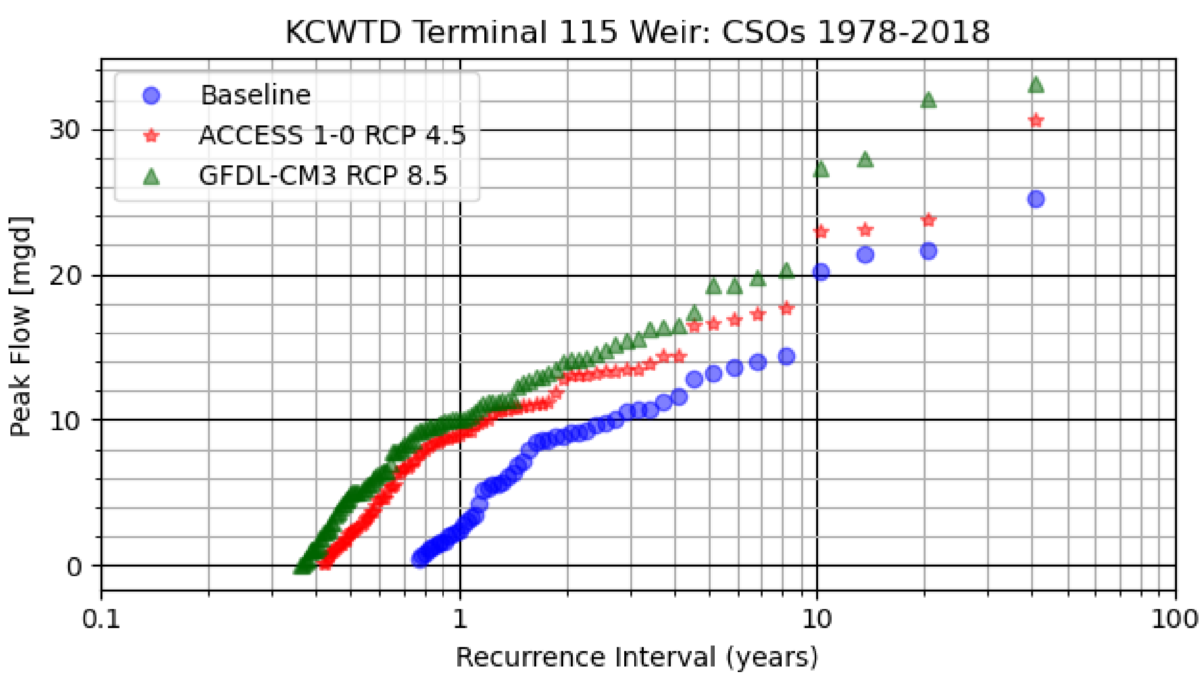

Figure 71. Peak untreated CSO flowrate recurrence interval for Terminal 115 Weir under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

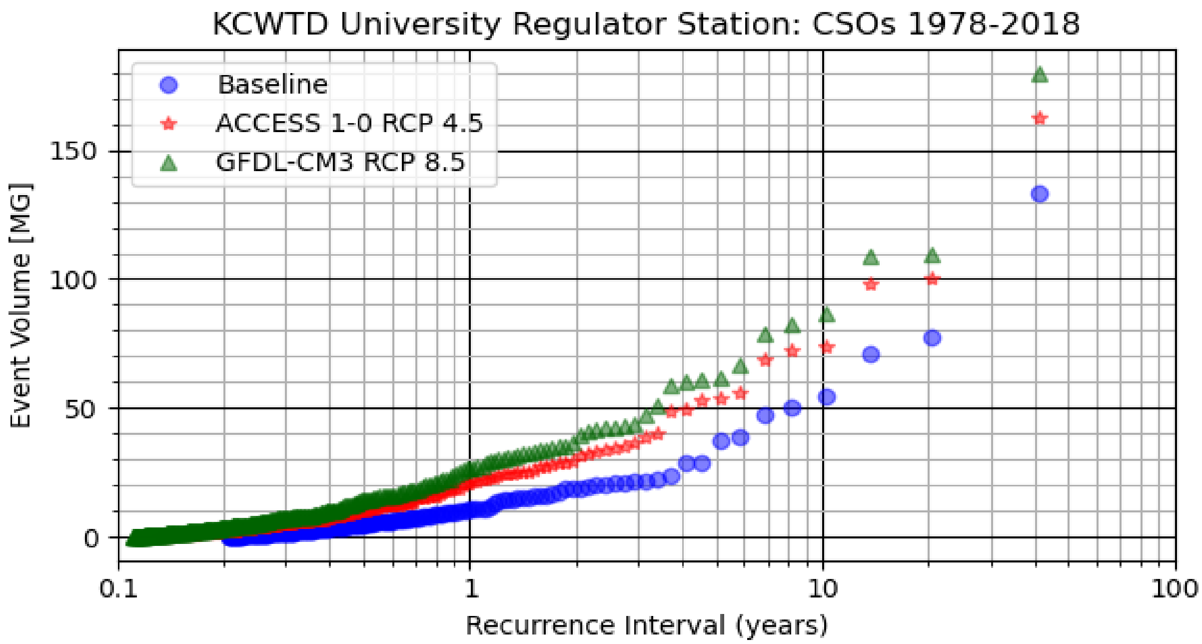

Figure 72. CSO volume recurrence Interval for University Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)

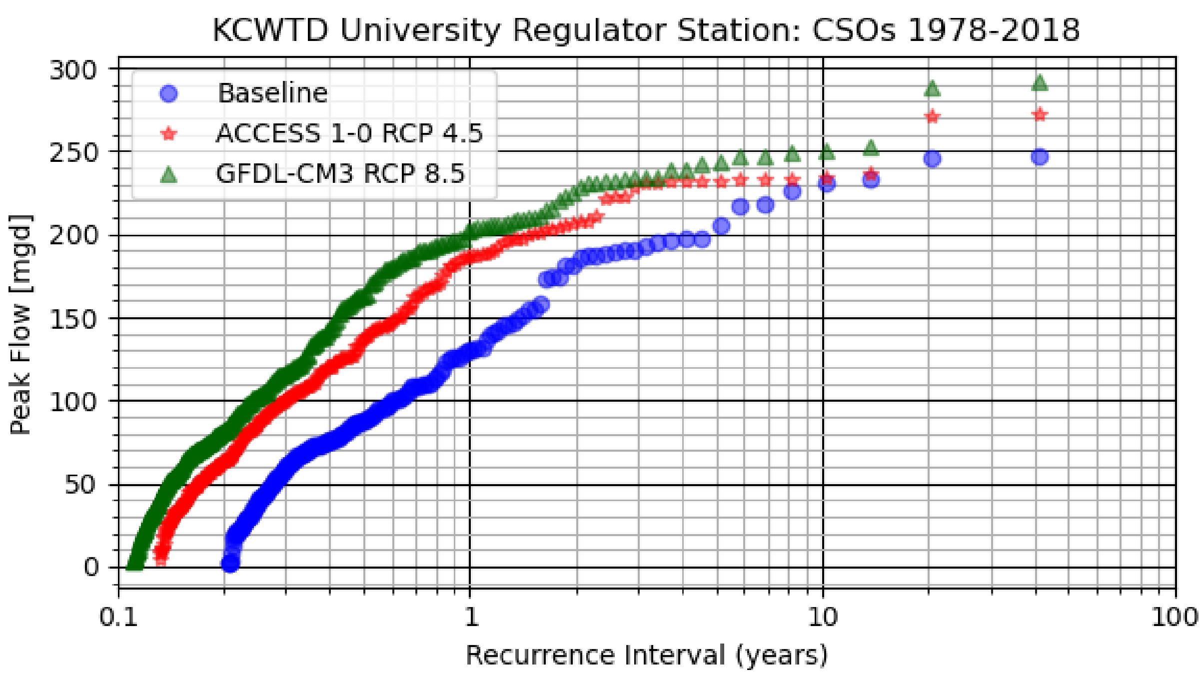

Figure 73. Peak untreated CSO flowrate recurrence interval for University Regulator Station under baseline (historical) and two-year 2085 climate change scenarios (ACCESS 1-0/4.5 and GFDL-CM3/8.5)