MEMORANDUM

Date: April 25, 2022
To: Andrea McNamara Doyle, Office of Chehalis Basin
From: Adam Hill, PE, and Heather Page Anchor QEA, LLC
Re: Updated Future Climate Projections for Estimating Frequency of Chehalis River Flood and Low Streamflow Events and Flood Retention Expandable (FRE) Operations

Executive Summary

This memorandum documents the preparation of flooding and other streamflow estimates under existing conditions and future climate conditions to support technical studies for the Chehalis Basin Strategy efforts. It is intended to supplement the "Chehalis Basin Climate Change Flows and Flooding Results" (Anchor QEA and WSE 2019) memorandum.

The updated estimates in this memorandum represent revised future climate conditions that are now available to analyze how predicted changes in the frequency of peak flood flows, winter non-peak flows, and summer low-flows in the mid- and late-century may affect the basin's natural and built environment. These updated estimates can help inform the Aquatic Species Restoration Plan, the Community Flood Assistance and Resilience Program, the Local Actions Non Dam Alternative Steering Group's work, the proposed Flood Retention Expandable (FRE) facility, and other technical studies that require estimates of streamflow and resulting hydraulic conditions under climate change, by providing baseline technical study information for the Chehalis Basin Strategy.

Revised streamflow estimates under climate change conditions were developed using climate change projections from University of Washington Climate Impacts Group (CIG) models. CIG updated climate change projections in February 2021 for use in the Chehalis Basin Board's planning as part of the Local Actions Program (CIG 2021). Using this information, streamflow estimates for the high-end climate conditions were then developed in 2021 and early 2022 to support technical studies associated with the National and State Environmental Policy Act (NEPA and SEPA) Final Environmental Impact Statements (EISs; WSE 2022). These estimates consider mid-century and late-century scenarios averaged from multiple climate models, as well as mid-century and late-century high-end climate conditions using updated CIG climate projections.

Key Results

Using these revised future climate conditions projections, a catastrophic flood[1] is now estimated to occur at a 10-year to 50-year recurrence interval, depending on the future climate scenario used. For example, using the mid-century averaged or 12% increase future climate scenario, the recurrence interval for catastrophic floods is estimated at 50 years. When the late-century averaged or 26% increase future climate scenario is used, a 30-year recurrence interval is expected for catastrophic floods. Using the mid-century high-end and late-century high-end (49% and 66% increase) future climate scenarios, catastrophic floods are predicted to occur on a 10- to 15-year recurrence interval.

Table 1
Estimated Peak and Low Streamflow Changes Due to Climate Change

CLIMATE CHANGE SCENARIO	PEAK FLOW INCREASE[1]	NON-PEAK WINTER FLOW INCREASE (NOVEMBER TO APRIL)[1]	SUMMER FLOW DECREASE (MAY TO OCTOBER)[1]
Mid-century averaged	12%	3%	-11%
Mid-century high-end	37% (FRE Location) 49% (Grand Mound)	9%	-22%
Late-century averaged	26%	3%	-16%
Late-century high-end	50% (FRE Location) 66% (Grand Mound)	11%	-30%

1 Relative to Existing Conditions, which for modeling purposes is the period from Water Years 1929 to 2010 (refer to Table 7 in this memorandum)

One example of how these updated estimates are being used is in preparation of the SEPA Final EIS for the proposed FRE facility. To that end, this memorandum also documents revised estimated operational frequencies for the FRE facility under future climate change conditions. Streamflow analyses were completed for the FRE location and the Grand Mound gage, the two relevant locations for determining FRE operations based on the project location. Factors were developed for increasing peak flows, summer flows, and non-peak winter flows; these changes to existing flows are summarized in Table 1. These changes were applied to existing flows to create estimated streamflows for the four climate change scenarios that will be included in the SEPA Final EIS.[2]

---

[1] "Catastrophic flood" is defined as a flood that historically had a 1% chance of occurring in any given year (often referred to as the "100-year flood").

[2] Specific scenarios addressed in this memorandum include existing conditions, the "mid-century averaged" climate change scenario, the "mid-century high-end" climate change scenario, the "late-century averaged" climate change scenario, and the "late-century high-end" climate change scenario.

Results from the climate change streamflow analyses were used to analyze estimated FRE facility operations in climate change scenarios for the 30-year modeling period of record (Water Years 1989 to 2018). Results from the estimated FRE facility operation frequency for the period of record for current conditions and the climate change scenarios are summarized in Table 2.

Table 2
Range of Probabilities of Occurrence for Estimated FRE Facility Operation Frequency

SCENARIO	ESTIMATED ANNUAL EXCEEDANCE PROBABILITY OF 38,800 CFS FLOW	ESTIMATED RANGE OF ANNUAL EXCEEDANCE PROBABILITY OF 38,800 CFS FLOW	ESTIMATED RECURRENCE INTERVAL (YEARS)	ESTIMATED RANGE OF RECURRENCE INTERVAL (YEARS)
Existing Conditions	0.144	0.124 to 0.224	7	4 to 9
Mid-century averaged (12% Peak Flow Increase at Grand Mound)	0.289	0.186 to 0.302	3.5	3 to 6
Mid-century high-end (49% Peak Flow Increase at Grand Mound)	0.448	0.414 to 0.559	2.2	1.7 to 2.5
26% Peak Flow Increase at Grand Mound	0.349	0.269 to 0.399	2.9	2 to 4
66% Peak Flow Increase at Grand Mound	0.566	0.517 to 0.665	1.8	1.5 to 2

Notes: CFS = cubic feet per second
Grand Mound peak flow increases are used as that location is the trigger point for FRE operation.
Range is between 5% and 95% confidence limits of HEC-SSP analysis.

Streamflow Under Climate Change Conditions

Estimates of streamflow under climate change conditions were developed in the "Chehalis Basin Climate Change Flows and Flooding Results" (Anchor QEA and WSE 2019) memorandum, the Climate Impacts Group "Extreme Precipitation Projections" memorandum (Mauger 2021), and the "Mid-Century High End Climate Change Hydraulic Modeling Scenario" memorandum (WSE 2022). The Mauger 2021 memorandum examined potential increases in extreme precipitation events under the high greenhouse gas emission scenario (Representative Concentration Pathway 8.5) as well as potential streamflow increases from hydrologic modeling of a single climate model projection, while the Watershed Science & Engineering 2022 memorandum analyzed how mid-century and late-century high-end flow changes related to each other. These three documents are provided as attachments to this memorandum.

Factor for Increasing Peak Flows

The factors applied to increasing peak flows are described in previous memoranda (Anchor QEA and WSE 2019; Mauger 2021). In terms of the mid-century high-end and late-century high-end climate change scenarios, the increase in peak flows relevant to the FRE facility was estimated using information provided in Table 1 of the Mauger 2021 memorandum and Table 1 of the WSE 2022 memorandum. Table 3 provides the peak flow increases recommended for the climate change scenarios.

Table 3
Estimated Peak Flow Increases Due to Climate Change

CLIMATE CHANGE SCENARIO	PEAK FLOW INCREASE[1]	SOURCE
Mid-century averaged	12%	Anchor QEA and WSE 2019
Mid-century high-end	37% (FRE Location)[2] 49% (Grand Mound)	WSE 2022
Late-century averaged	26%	Anchor QEA and WSE 2019
Late-century high-end	50% (FRE Location)[2] 66% (Grand Mound)	Mauger 2021

Note:
1. Relative to Existing Conditions, which for modeling purposes is the period from Water Years 1929 to 2010 (refer to Table 7 in this memorandum)
2. Streamflow not explicitly provided for FRE location; estimate generated from differences between precipitation at FRE location and near Doty.

Seasonal Flow Adjustment

Analyses performed for peak flows were also applied to streamflow outside of peak flow periods. As in previous iterations (Anchor QEA and WSE 2019), streamflow data from 15 sites analyzed in the “Chehalis River Basin Hydrologic Modeling” technical memorandum (WSE 2019) were analyzed to determine the change in average monthly flows. Additional methodology details are included in the Anchor QEA and WSE 2019 memorandum. The methodology used in determining the mid-century flow adjustment factors were applied to determine the spatially variable factors. The methodology included determining a single flow increase or decrease using the average of flow changes across the 15 sites. The results of the analysis are that flows would increase from November to April and decrease from May to October under climate change scenarios. Table 4 lists the adjustments to flow determined using that method. Application of these factors is described on the following two pages, including additional winter flow adjustments.

Table 4
Flow Adjustment Factors Due to Climate Change

CLIMATE CHANGE SCENARIO	PERIOD	FLOW CHANGE
Mid-century averaged	November to April (winter; high flow)	4%
	May to October (summer; low flow)	-11%
Mid-century high-end	November to April (winter; high flow)	13%
	May to October (summer; low flow)	-22%
Late-century averaged	November to April (winter; high flow)	5%
	May to October (summer; low flow)	-16%
Late-century high-end	November to April (winter; high flow)	17%
	May to October (summer; low flow)	-30%

Flow Records Used to Develop Climate Change

As noted in previous memoranda (WSE 2019; Anchor QEA and WSE 2019), streamflow projections generated by hydrologic modeling was not used for this analysis due to large differences compared to historical flows. Instead, the adjustments to streamflow shown in Tables 3 and 4 were applied to relevant historical flows from active U.S. Geological Survey (USGS) gages. Table 5 provides the USGS gages and type of data available and used in the analysis.

Table 5
Gages and Data Used in Flow Record Development

GAGE NAME	GAGE NO.	DATA USED
Chehalis River near Doty (Doty gage)	12020000	Hourly flow; daily flow
Chehalis River near Grand Mound (Grand Mound gage)	12027500	Hourly flow; daily flow

Source: USGS 2019

Development of Flows Under Climate Change Conditions

Both hourly and daily flows under future climate change scenarios were developed for use in other technical studies as part of the Chehalis Basin Strategy. To maintain consistency through all flow data development, data from a single period of record, from October 1988 to September 2018 (Water Years 1989 to 2018), were used. This 30-year period of record was chosen because it is the longest coincident period of record available at the gages used in this analysis. This methodology is the same as what was applied in the Anchor QEA and WSE 2019 memorandum. Flows under future climate change conditions were estimated for the summer and winter periods listed in Table 4.

Summer Flows Under Climate Change Conditions

The summer flow adjustments provided in Table 4 were applied directly to the gage data for the May to October time period in each year to develop summer climate change flows. This methodology is the same as what was applied in the Anchor QEA and WSE 2019 memorandum.

Winter Flows Under Climate Change Conditions

Two adjustments to winter flows were required; high flow events during winter were adjusted using the peak flow adjustments provided in Table 3, while flows outside of high flow periods were adjusted to achieve the winter flow increases provided in Table 4. Winter flow adjustments were continuous such that either the peak flow adjustment or the non-peak winter flow adjustment was applied; no step functions between peak flows and flows outside high flow periods were developed.

Application of Peak Flow Adjustments

As the peak flow adjustments provided in Table 3 are greater than the winter flow adjustments provided in Table 4, the period that peak flow increases would occur must be defined. This definition was established in the Anchor QEA and WSE 2019 memorandum, where it was assumed that flows above the 1% exceedance value would have the peak flow adjustments applied. Table 6 lists the existing 1% exceedance flows established for the Doty and Grand Mound gages.

Table 6
Existing 1% Exceedance Flows

GAGE NAME	1% EXCEEDANCE FLOW (CUBIC FEET PER SECOND)
Doty gage	4,830 (hourly flow); 4,690 (daily flow)
Grand Mound gage	20,500 (hourly flow); 20,100 (daily flow)

Source: Anchor QEA and WSE 2019

During storms with flows exceeding the thresholds listed in Table 6, the flows were multiplied by the peak flow factors in Table 3 to estimate flows under climate change conditions. This methodology is the same as what was applied in the Anchor QEA and WSE 2019 memorandum.

Application of Winter Flow Adjustments

Adjustments to the remainder of winter flows were performed by first calculating the volume of flow in events above the 1% exceedance threshold and multiplying flows in the remainder of winter by factors less than shown in Table 3, until the total flow volume over the winter period approximately equaled the factors in Table 4. This winter flow adjustment factor was previously established as 3% in the mid-century and late-century averaged climate change scenarios (Anchor QEA and WSE 2019) and was found to be 9% in the mid-century high-end climate change scenario and 11% in the late-century high-end climate change scenario.

Streamflow Record Under Climate Change Conditions

Streamflow records for the climate change scenarios were prepared for the gages listed in Table 5 using the adjustments described previously. Streamflow data are not included in this memorandum because of their size; the data are available upon request. To illustrate the change in flow, streamflow under climate change conditions for each gage listed in Table 5 was plotted against the historical streamflow records for Water Years 1996, 2009, and 2011. Those years contain a range of flow conditions; climate change flows based upon those years were used in previous analyses (Anchor QEA and WSE 2019). Figures 1 to 3 illustrate the change in average daily flow for the Doty gage in Water Years 1996, 2009, and 2011, and Figures 4 to 6 illustrate the change in average daily flow for the Grand Mound gage for the same water years.

Figure 1
Climate Change Flow Comparison – Doty Gage (Water Year 1996)

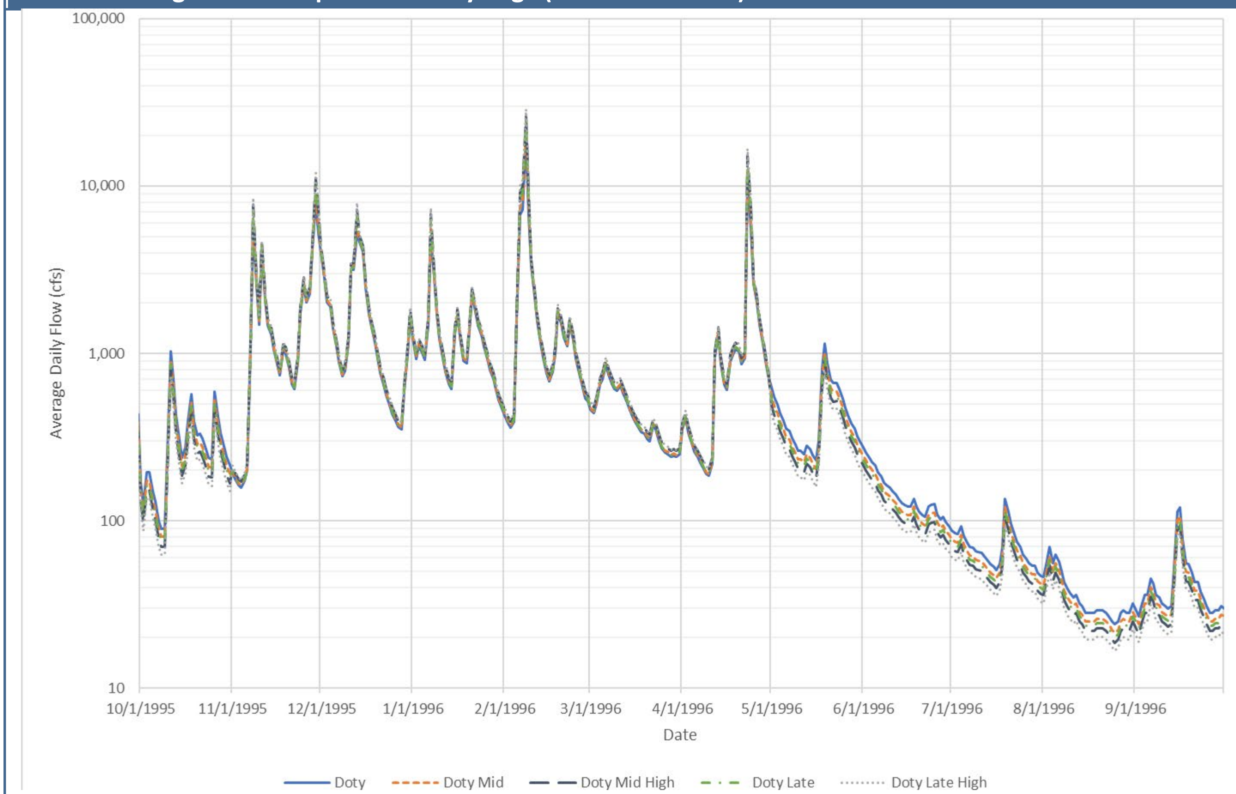


Figure 2
Climate Change Flow Comparison – Doty Gage (Water Year 2009)

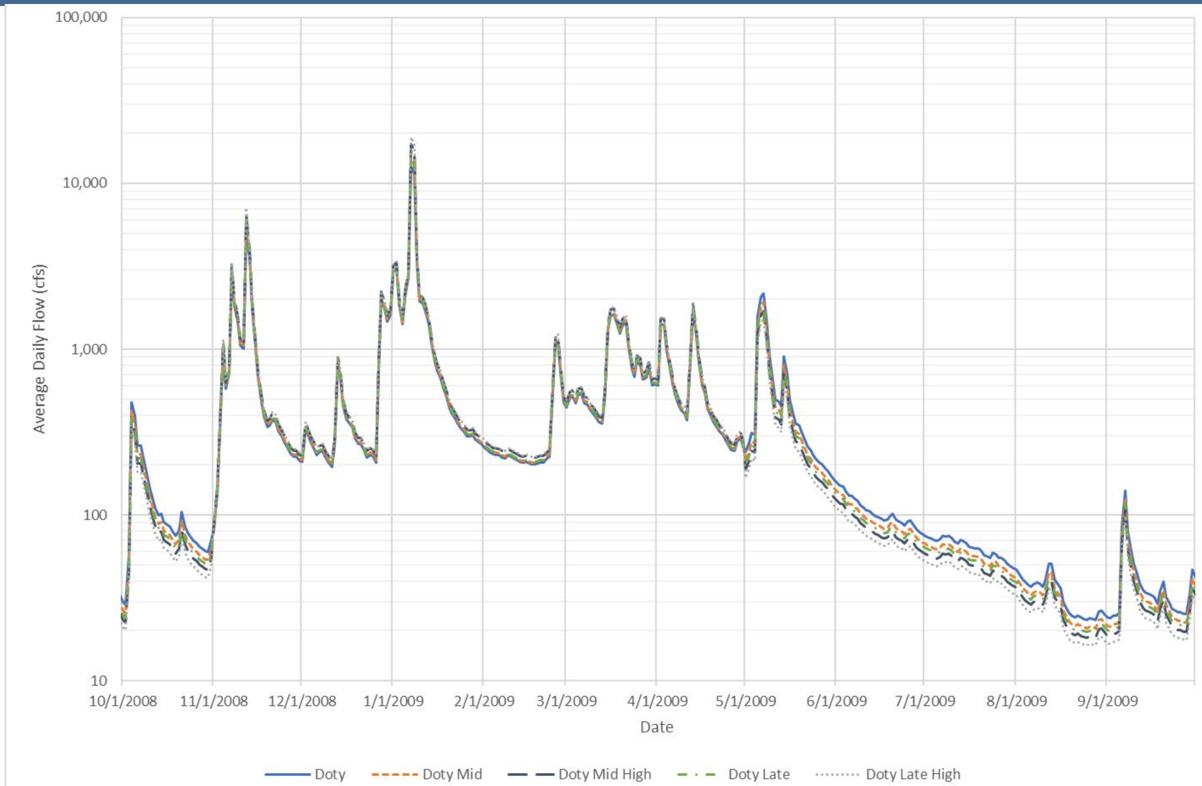


Figure 3
Climate Change Flow Comparison – Doty Gage (Water Year 2011)

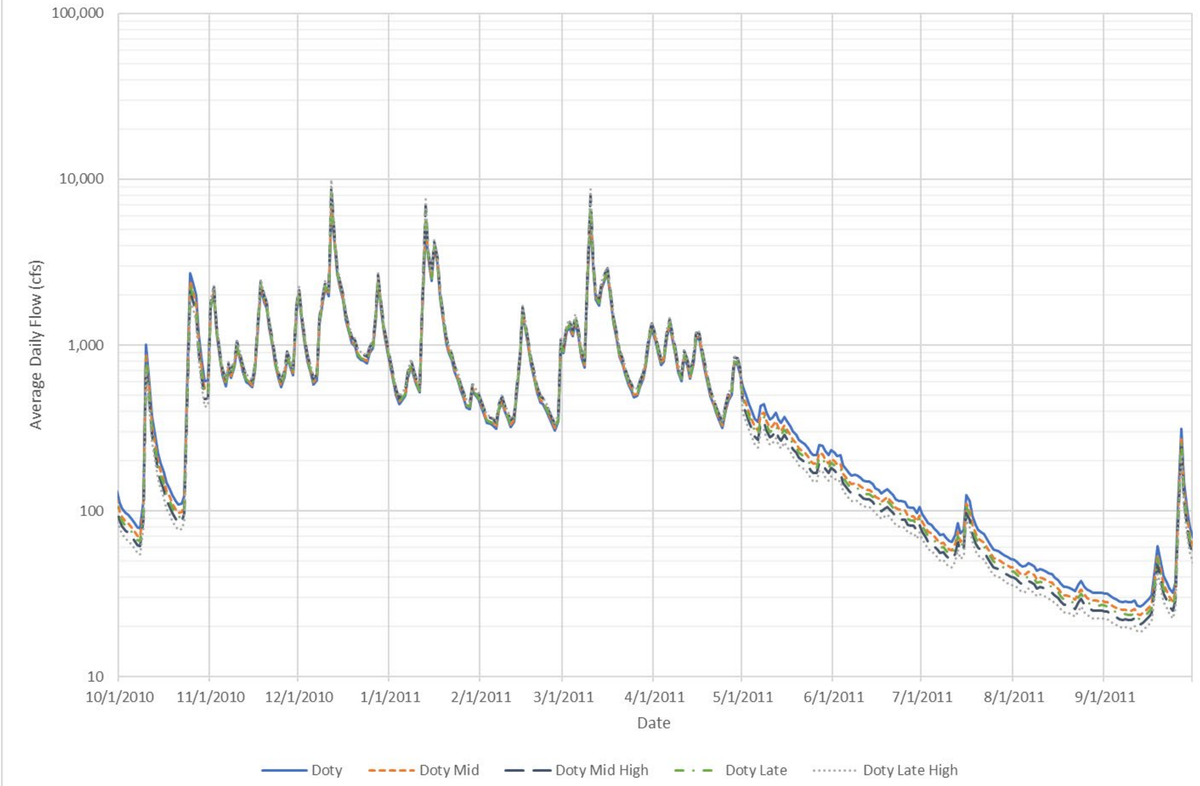


Figure 4
Climate Change Flow Comparison – Grand Mound Gage (Water Year 1996)

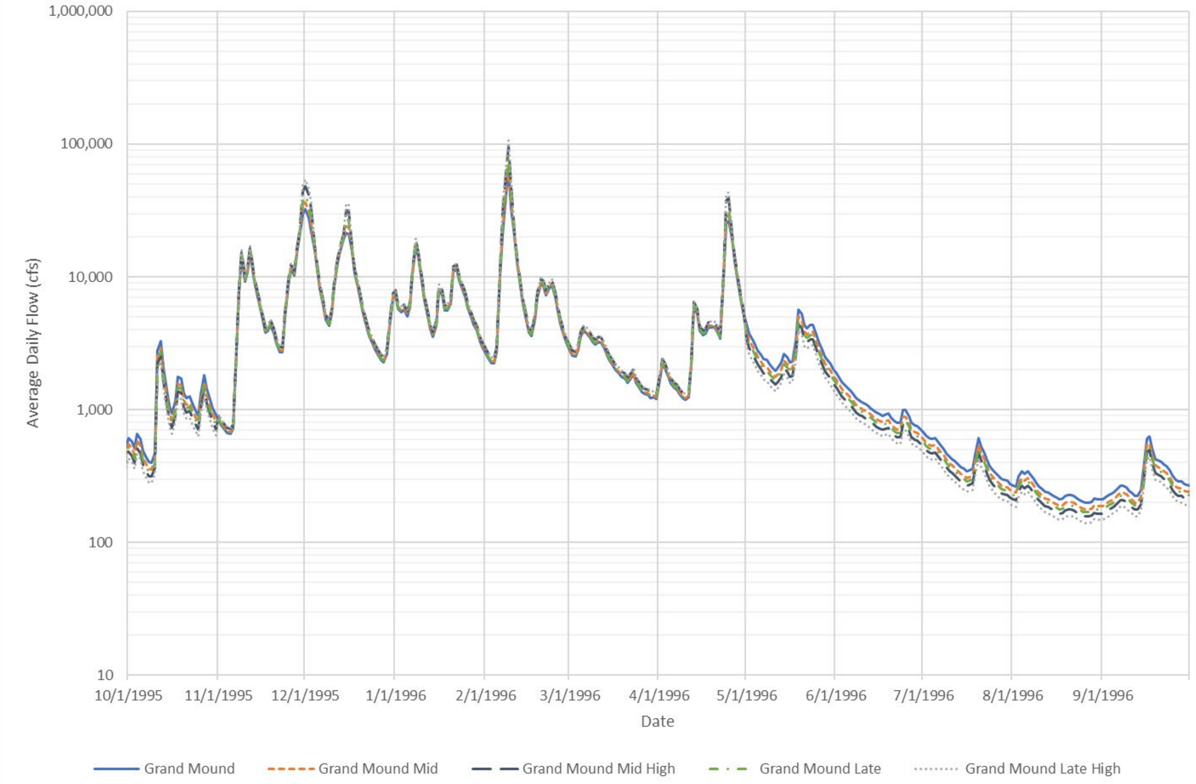


Figure 5
Climate Change Flow Comparison – Grand Mound Gage (Water Year 2009)

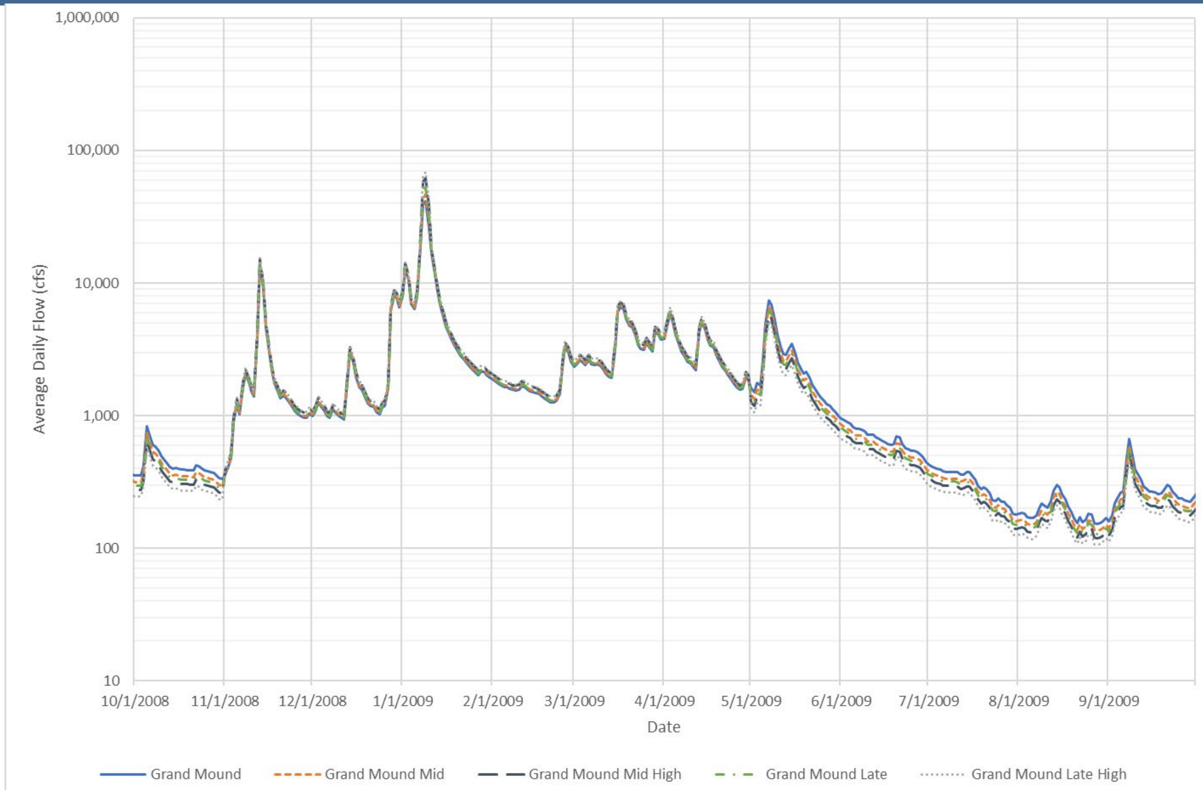
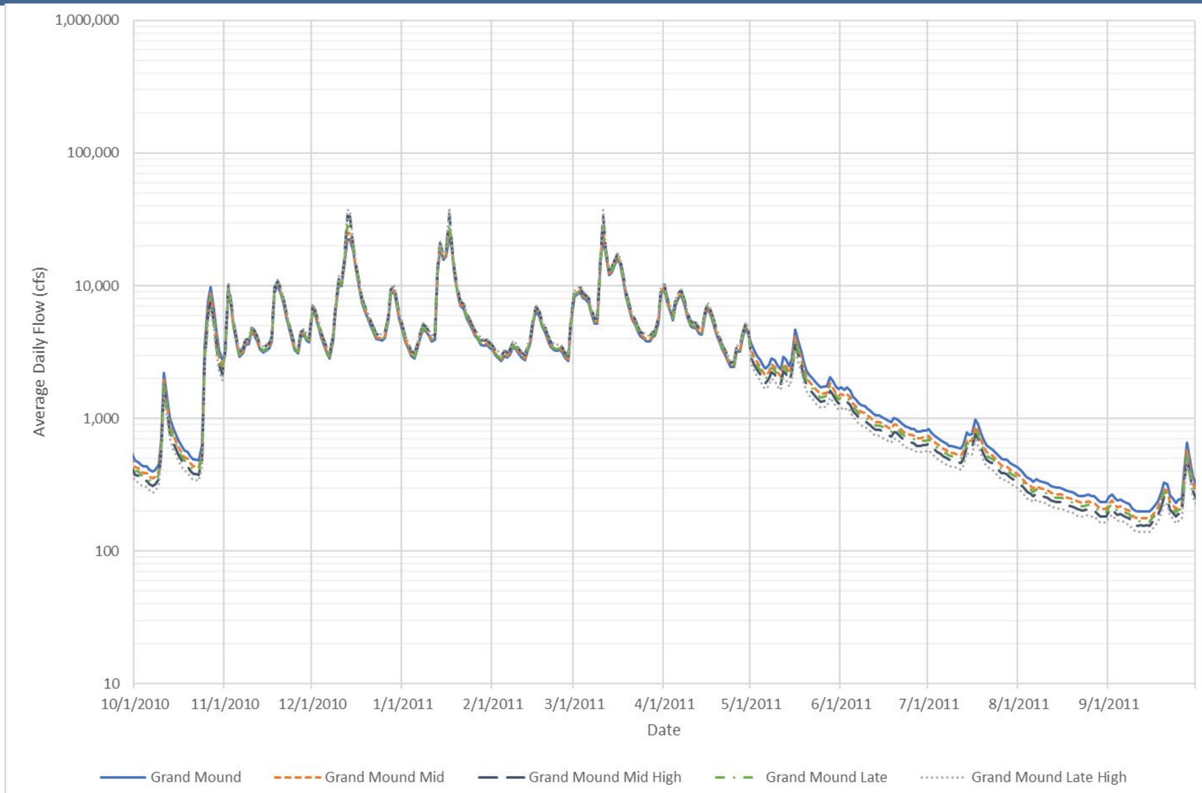


Figure 6
Climate Change Flow Comparison – Grand Mound Gage (Water Year 2011)



FRE Facility Operation Frequency

Using the FRE facility operations threshold of 38,800 cfs at the Grand Mound gage, the frequency of operations were estimated. The *Operations Plan for Flood Retention Facilities* (Anchor QEA 2017) referred to the operations threshold as being about a 7-year recurrence interval peak flow (15% probability of occurrence in any single year). For Chehalis Basin Strategy studies, flood frequency discharges at the Grand Mound gage were established in the *Chehalis Basin Ecosystem Restoration General Investigation Study Baseline Hydrology and Hydraulic Modeling* report (West Consultants 2014). Statistical hydrology was reviewed in the "Re-evaluation of Statistical Hydrology and Design Storm Selection for the Chehalis River Basin" technical memorandum. It was recommended that design flood events established in the West Consultants report be used with minor adjustments to Doty gage events (Watershed Science & Engineering 2014). West Consultants analyzed a period of record from 1929 to 2010 using techniques from Bulletin 17B (U.S. Geological Survey 1981) with a weighted skew, a regional skew of 0.04, a regional skew mean squared error of 0.302, and computed expected probability curves.

For this memorandum, a statistical analysis of the period of record from 1929 to 2010 was performed to be consistent with the West Consultants analysis. The annual peak flows at the Grand Mound gage were ranked by magnitude and the exceedance probability calculated. The recurrence interval is defined as the inverse of probability. Table 7 summarizes the calculations. As shown in Table 7, the FRE facility operation threshold of 38,800 cfs is very close to an event of 38,700 cfs that has an annual exceedance probability of 14.5%. This is equivalent to a 7-year recurrence interval event. Based on this information, FRE facility operation is expected to be at a 7-year recurrence interval for existing conditions.

Table 7
Ranked Peak Annual Discharges – Grand Mound Gage – Existing Conditions

WATER YEAR	ANNUAL PEAK FLOW (CFS)	RANK	ANNUAL EXCEEDANCE PROBABILITY (PERCENT)	RECURRENCE INTERVAL (YEAR)
2008	79,100	1	0.0120	83.0
1996	74,800	2	0.0241	41.5
1990	68,700	3	0.0361	27.7
1987	51,600	4	0.0482	20.8
2009	50,700	5	0.0602	16.6
1972	49,200	6	0.0723	13.8
1938	48,400	7	0.0843	11.9
1991	48,000	8	0.0964	10.4
1934	45,700	9	0.1084	9.2
1976	44,800	10	0.1205	8.3
1971	40,800	11	0.1325	7.5
FRE Facility Operating Threshold	***38,800***			
1997	38,700	12	0.1446	6.9
1951	38,000	13	0.1566	6.4
1935	38,000	14	0.1687	5.9
2006	37,900	15	0.1807	5.5
1974	37,400	16	0.1928	5.2
1999	36,500	17	0.2048	4.9
1978	36,500	18	0.2169	4.6
1949	36,500	19	0.2289	4.4
1936	36,300	20	0.2410	4.2
1995	35,900	21	0.2530	4.0
1964	35,700	22	0.2651	3.8
1956	35,100	23	0.2771	3.6
1954	34,700	24	0.2892	3.5
1967	34,400	25	0.3012	3.3
2007	32,700	26	0.3133	3.2
1986	32,100	27	0.3253	3.1
2002	31,900	28	0.3373	3.0
2000	31,000	29	0.3494	2.9
1963	29,800	30	0.3614	2.8

WATER YEAR	ANNUAL PEAK FLOW (CFS)	RANK	ANNUAL EXCEEDANCE PROBABILITY (PERCENT)	RECURRENCE INTERVAL (YEAR)
1982	27,300	31	0.3735	2.7
1961	27,000	32	0.3855	2.6
1945	27,000	33	0.3976	2.5
1975	26,900	34	0.4096	2.4
1942	26,900	35	0.4217	2.4
1950	26,300	36	0.4337	2.3
1965	26,200	37	0.4458	2.2
1983	25,600	38	0.4578	2.2
1933	24,900	39	0.4699	2.1
1968	24,800	40	0.4819	2.1
1939	24,800	41	0.4940	2.0
1960	24,700	42	0.5060	2.0
1937	24,300	43	0.5181	1.9
1947	24,200	44	0.5301	1.9
1981	24,000	45	0.5422	1.8
1932	23,500	46	0.5542	1.8
1970	23,300	47	0.5663	1.8
2003	23,100	48	0.5783	1.7
1946	23,100	49	0.5904	1.7
1940	22,700	50	0.6024	1.7
1959	22,500	51	0.6145	1.6
1973	21,900	52	0.6265	1.6
1966	21,900	53	0.6386	1.6
1998	21,400	54	0.6506	1.5
1957	20,900	55	0.6627	1.5
2005	20,700	56	0.6747	1.5
1953	20,500	57	0.6867	1.5
2004	20,400	58	0.6988	1.4
1943	20,200	59	0.7108	1.4
1948	20,000	60	0.7229	1.4
1992	19,600	61	0.7349	1.4
2010	19,400	62	0.7470	1.3
1931	19,400	63	0.7590	1.3
1984	19,200	64	0.7711	1.3
1980	19,000	65	0.7831	1.3
1952	18,800	66	0.7952	1.3
1941	18,800	67	0.8072	1.2
1958	18,500	68	0.8193	1.2
1979	18,300	69	0.8313	1.2
1955	18,100	70	0.8434	1.2
1985	18,000	71	0.8554	1.2

WATER YEAR	ANNUAL PEAK FLOW (CFS)	RANK	ANNUAL EXCEEDANCE PROBABILITY (PERCENT)	RECURRENCE INTERVAL (YEAR)
1969	17,500	72	0.8675	1.2
1988	16,400	73	0.8795	1.1
1944	16,400	74	0.8916	1.1
1962	15,900	75	0.9036	1.1
1977	15,200	76	0.9157	1.1
1989	14,400	77	0.9277	1.1
1929	13,700	78	0.9398	1.1
1994	13,100	79	0.9518	1.1
1930	12,200	80	0.9639	1.0
1993	10,400	81	0.9759	1.0
2001	5,750	82	0.9880	1.0

Source: West Consultants 2014

Catastrophic Flood Frequency

Catastrophic flood conditions were defined as a 100-year recurrence interval event at Grand Mound gage, or 75,100 cfs. This value was obtained from Watershed Science & Engineering analysis originally completed as part of the "Re-Evaluation of Statistical Hydrology and Design Storm Selection for the Chehalis River Basin" technical memorandum (Watershed Science & Engineering 2014).

Comparison to Previous Reports

These results are generally consistent with the estimated flood frequency discharges for the Grand Mound gage listed in the West Consultants report. Table 8 presents those results, which show the FRE facility operating threshold to be between a 5-year and 10-year recurrence interval event and the catastrophic flood to be near a 100-year recurrence interval event under existing conditions.

Table 8
Flood Frequency Discharges – Grand Mound Gage – Existing Conditions

RECURRENCE INTERVAL (YEARS)	ANNUAL EXCEEDANCE PROBABILITY	FLOW AT GRAND MOUND (CFS)
1.5	0.667	21,519
2	0.500	25,659
5	0.200	36,917
FRE Facility Operating Threshold		***38,800***
10	0.100	45,352
20	0.050	54,239
50	0.020	67,091
Catastrophic Flood		***75,100***
100	0.010	77,844

200	0.005	89,514
500	0.002	107,184

Source: West Consultants 2014

Estimated Operation Frequency – Future Climate Conditions

Several future climate condition scenarios have been developed for the Chehalis River Basin. As noted in the technical memorandum "Chehalis River Basin Hydrologic Modeling," simulation results indicated that future flood flows may increase by an average of 12 to 26 percent (Watershed Science & Engineering 2019). More recent analysis from Watershed Science & Engineering and the Climate Impacts Group suggests that future flood flows may increase by as much as 66% at the Grand Mound gage as noted in Table 1 of the "Chehalis Basin: Extreme Precipitation Projections" document (Mauger 2021).

FRE Facility Operation Frequency

To determine the estimated operation frequency under future climate conditions, annual peak flows for Grand Mound were increased by 12%, 26%, 49%, and 66% and were analyzed using the same procedure summarized in Table 7. The results are provided in Appendix A and summarized in Table 9.

Table 9
Probability of Occurrence Peak Annual Discharges – FRE Facility Operation – Future Conditions

FUTURE PEAK FLOW INCREASE	ESTIMATED ANNUAL EXCEEDANCE PROBABILITY OF 38,800 CFS FLOW	ESTIMATED RECURRENCE INTERVAL (YEARS)
12%	0.289	3.5
26%	0.349	2.9
49%	0.448	2.2
66%	0.566	1.8

The estimated annual exceedance probability for a 38,800 cfs peak flow under the 12% increase future climate scenario is around 29%, or between a 3-year and 4-year recurrence interval. The estimated annual exceedance probability for the 26% increase future climate scenario is about 35%, or around a 3-year recurrence interval. The estimated annual exceedance probability for the 49% increase future climate scenario is 45%, or slightly less often than a 2-year recurrence interval. The estimated annual exceedance probability for the 66% increase future climate scenario is 57%, or slightly more often than a 2-year recurrence interval.

Table 10 presents the entire range of estimated flood frequency discharges for various flow increases for future climate conditions at the Grand Mound gage. The flows were estimated by scaling the existing peak flows for each recurrence interval by the percentage increase in future peak flows.

Table 10
Flood Frequency Discharges – Grand Mound Gage – Future Climate Conditions

<table>
<tr><th rowspan="2">RECURRENCE INTERVAL (YEARS)</th><th rowspan="2">ANNUAL EXCEEDANCE PROBABILITY</th><th colspan="4">FLOW AT GRAND MOUND (CFS)</th></tr>
<tr><th>12% INCREASE</th><th>26% INCREASE</th><th>49% INCREASE</th><th>66% INCREASE</th></tr>
<tr><td>1.5</td><td>0.667</td><td>24,189</td><td>27,213</td><td>32,175</td><td>35,853</td></tr>
<tr><td colspan="2">FRE Facility Operating Threshold (66% Increase)</td><td></td><td></td><td></td><td>38,800</td></tr>
<tr><td>2</td><td>0.500</td><td>28,738</td><td>32,330</td><td>38,227</td><td>42,597</td></tr>
<tr><td colspan="2">FRE Facility Operating Threshold (12% and 26% Increase)</td><td colspan="3">38,800</td><td></td></tr>
<tr><td>5</td><td>0.200</td><td>41,347</td><td>46,515</td><td>55,006</td><td>61,290</td></tr>
<tr><td>10</td><td>0.100</td><td>50,794</td><td>57,143</td><td>67,580</td><td>75,297</td></tr>
<tr><td>20</td><td>0.050</td><td>60,748</td><td>68,342</td><td>80,830</td><td>90,056</td></tr>
<tr><td>50</td><td>0.020</td><td>75,142</td><td>84,535</td><td>99,993</td><td>111,399</td></tr>
<tr><td>100</td><td>0.010</td><td>87,185</td><td>98,083</td><td>116,029</td><td>129,256</td></tr>
<tr><td>200</td><td>0.005</td><td>100,435</td><td>112,989</td><td>133,673</td><td>148,902</td></tr>
<tr><td>500</td><td>0.002</td><td>120,046</td><td>135,052</td><td>159,793</td><td>177,984</td></tr>
</table>

Note: Flows increased as described by Watershed Science & Engineering 2019 and Mauger 2021 and analyzed using methodology described in West Consultants 2014.

Note that recurrence intervals can change with additional data and with future conditions; recurrence intervals will be different if the analysis used data up to the current period of record, or if different methods were used in determining the flood frequency. This also assumes the operational threshold of 38,800 cfs will remain the same. The threshold could change as flood damage reduction measures are implemented or in response to environmental issues.

HEC-SSP Analysis (Catastrophic Flood)

HEC-SSP was used to duplicate results developed in the West Consultants report and to produce graphics that illustrate the recurrence intervals of existing and future peak flow events. This analysis was used to estimate recurrence intervals for the catastrophic flood for future peak flow events and was also used to corroborate the estimated operation frequency and give a range of annual exceedance probabilities and recurrence intervals between the 5% and 95% confidence limits. Inputs to HEC-SSP were obtained from Appendix C of the West Consultants report. The West Consultants results were duplicated by using a Bulletin 17B analysis (U.S. Geological Survey 1981) with a weighted skew, a regional skew of 0.04, a regional skew mean squared error of 0.302, computed expected probability curves, and a period of record from 1929 to 2010. Table 11 provides the estimated probability for catastrophic flood conditions for future peak flow events. Figure 7 shows a plot of the HEC-SSP analysis for existing peak flows, while Figures 8 through 11 plot future conditions. Table 12 provides the range of estimated annual exceedance probabilities and estimated recurrence intervals between the 5% and 95%

confidence limits for existing conditions and the future peak flow increase conditions for FRE facility operation.

Table 11
Probability of Occurrence Peak Annual Discharges – Catastrophic Flood – Future Conditions

FUTURE PEAK FLOW INCREASE	ESTIMATED ANNUAL EXCEEDANCE PROBABILITY OF 75,100 CFS FLOW	ESTIMATED RECURRENCE INTERVAL (YEARS)
12%	0.020	50.0
26%	0.034	29.7
49%	0.067	14.9
66%	0.101	9.9

Figure 7
Flood Frequency Discharges – Grand Mound Gage – Existing Conditions

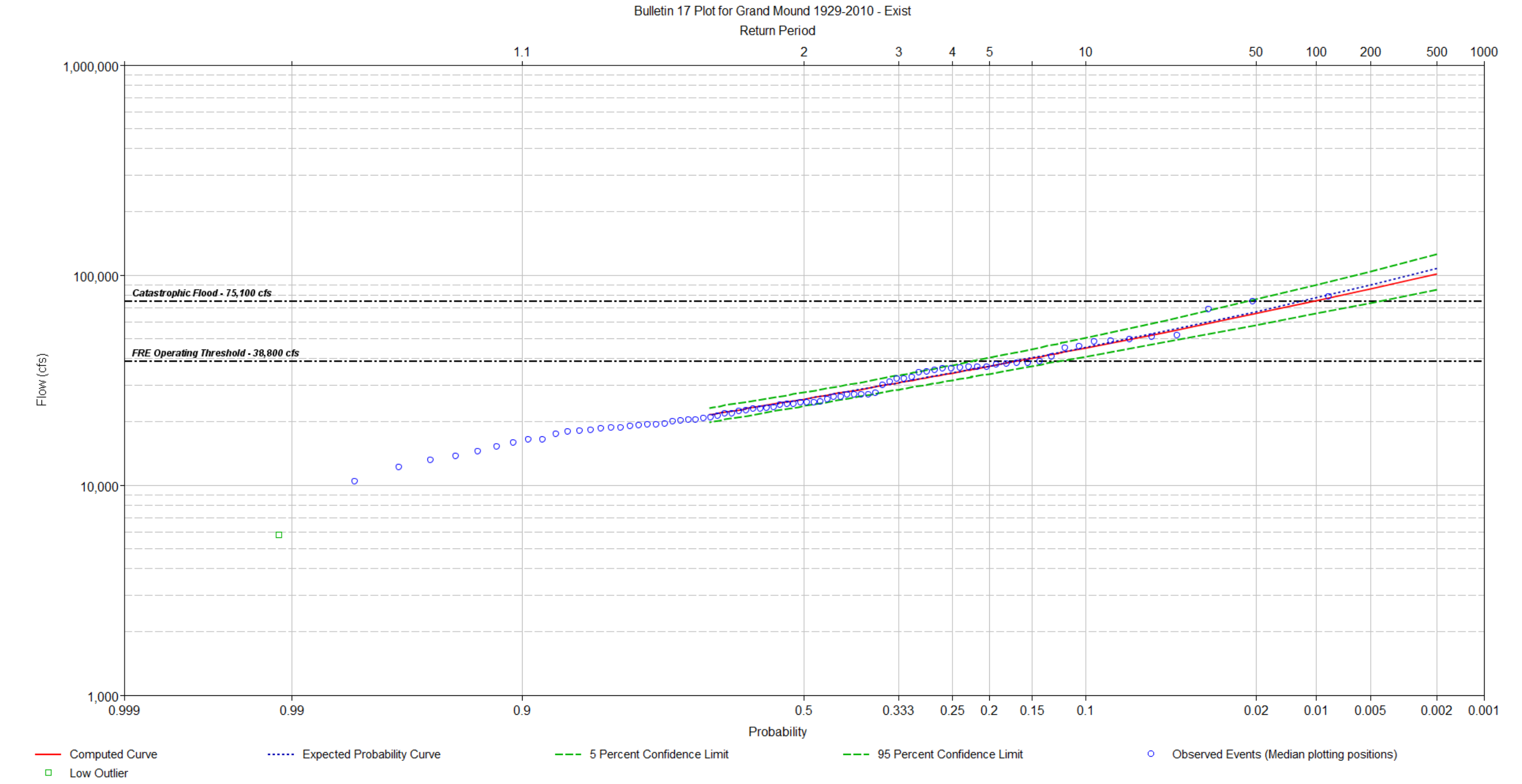


Figure 8
Flood Frequency Discharges – Grand Mound Gage – Future Climate Conditions – 12% Increase Scenario

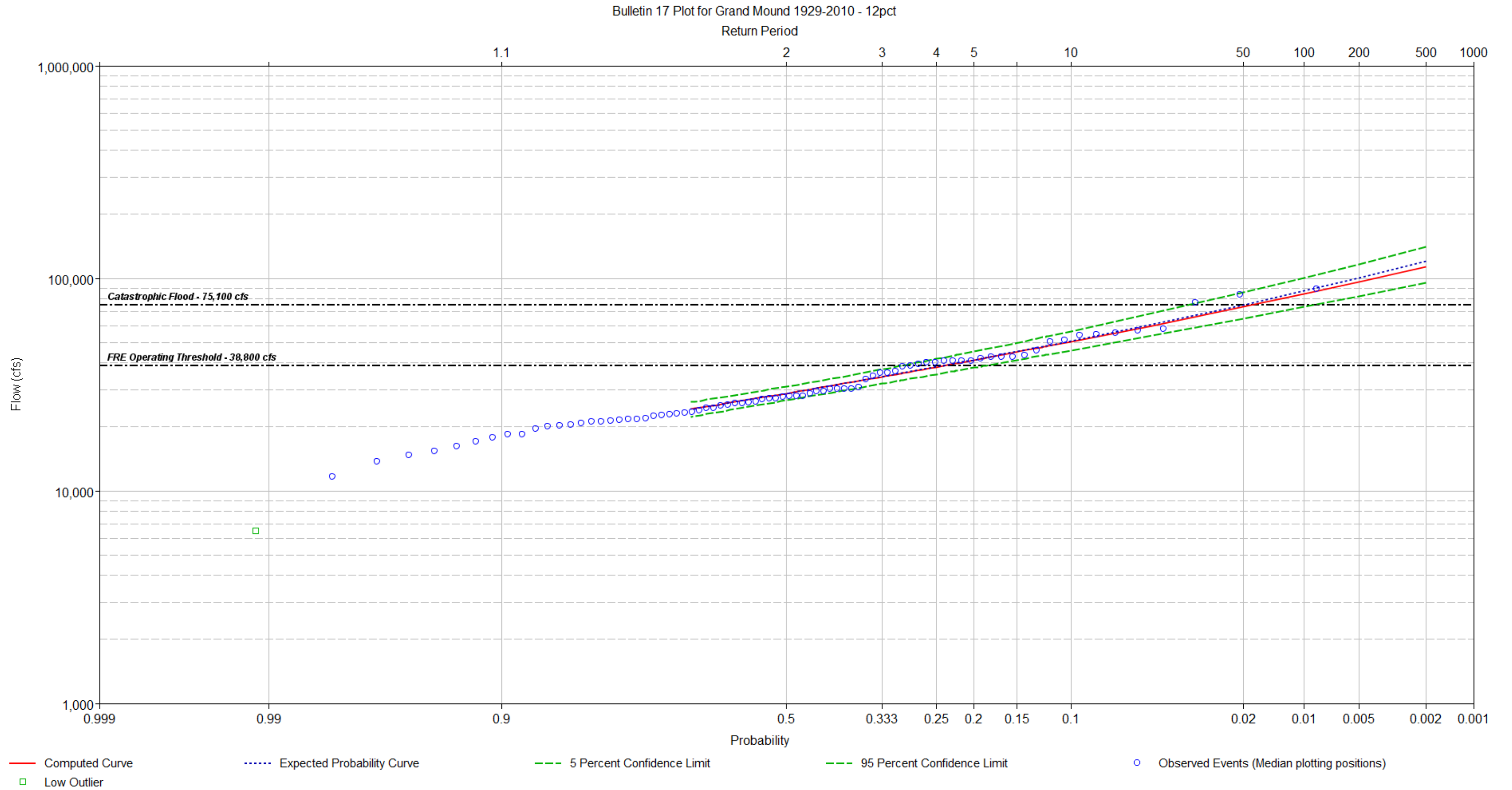


Figure 9

Flood Frequency Discharges – Grand Mound Gage – Future Climate Conditions – 26% Increase Scenario

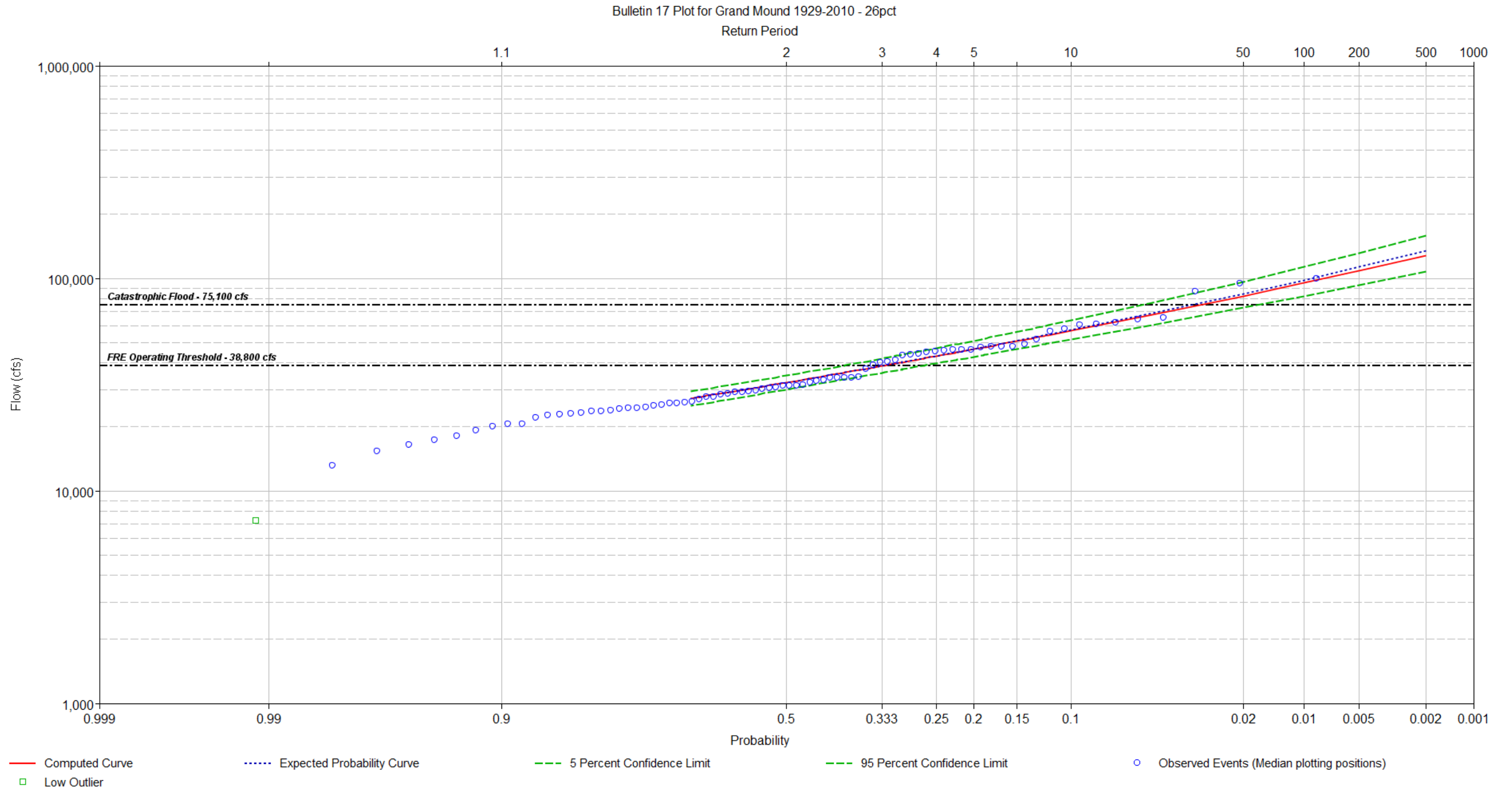


Figure 10
Flood Frequency Discharges – Grand Mound Gage – Future Climate Conditions – 49% Increase Scenario

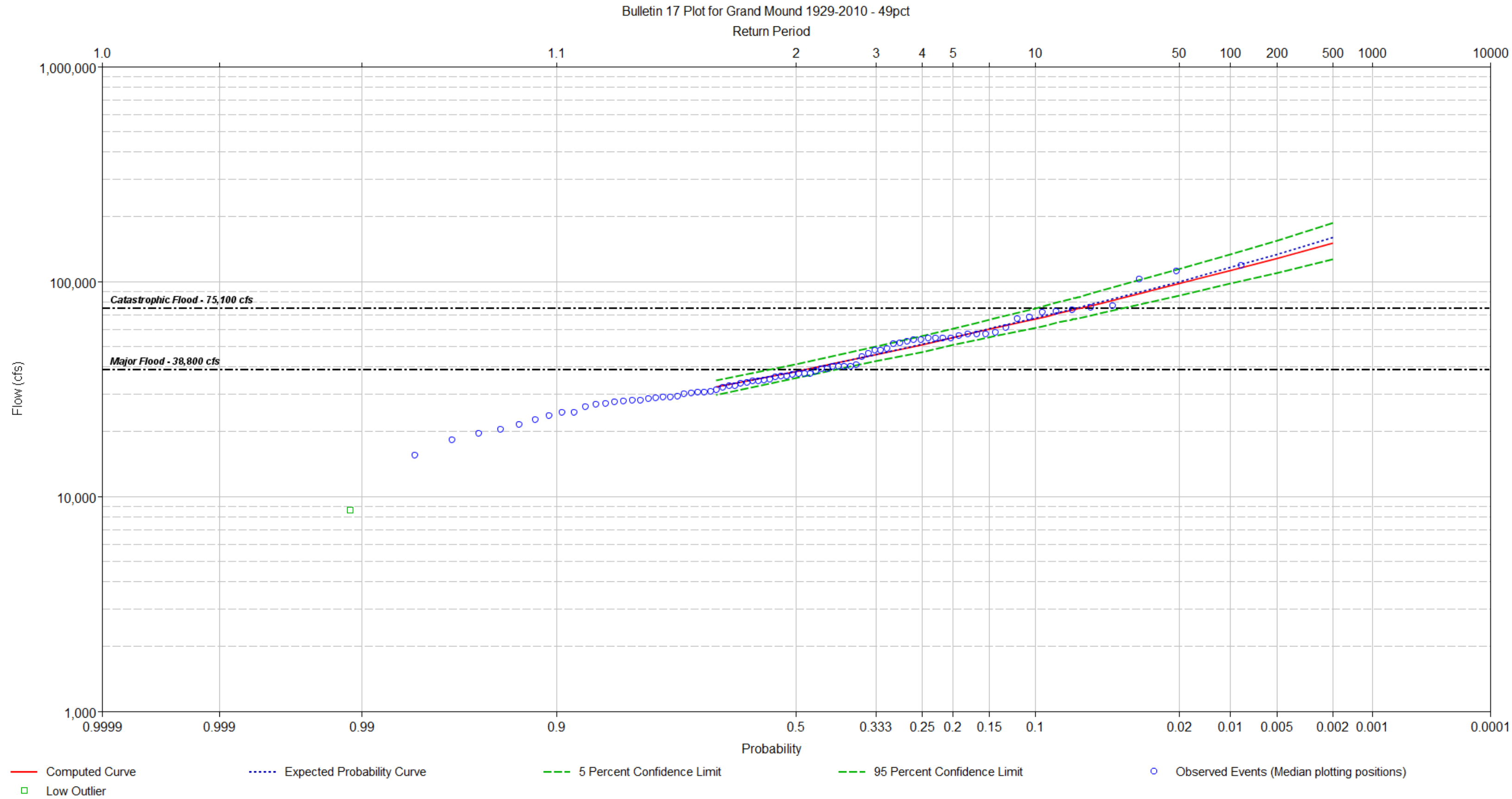


Figure 11
Flood Frequency Discharges – Grand Mound Gage – Future Climate Conditions – 66% Increase Scenario

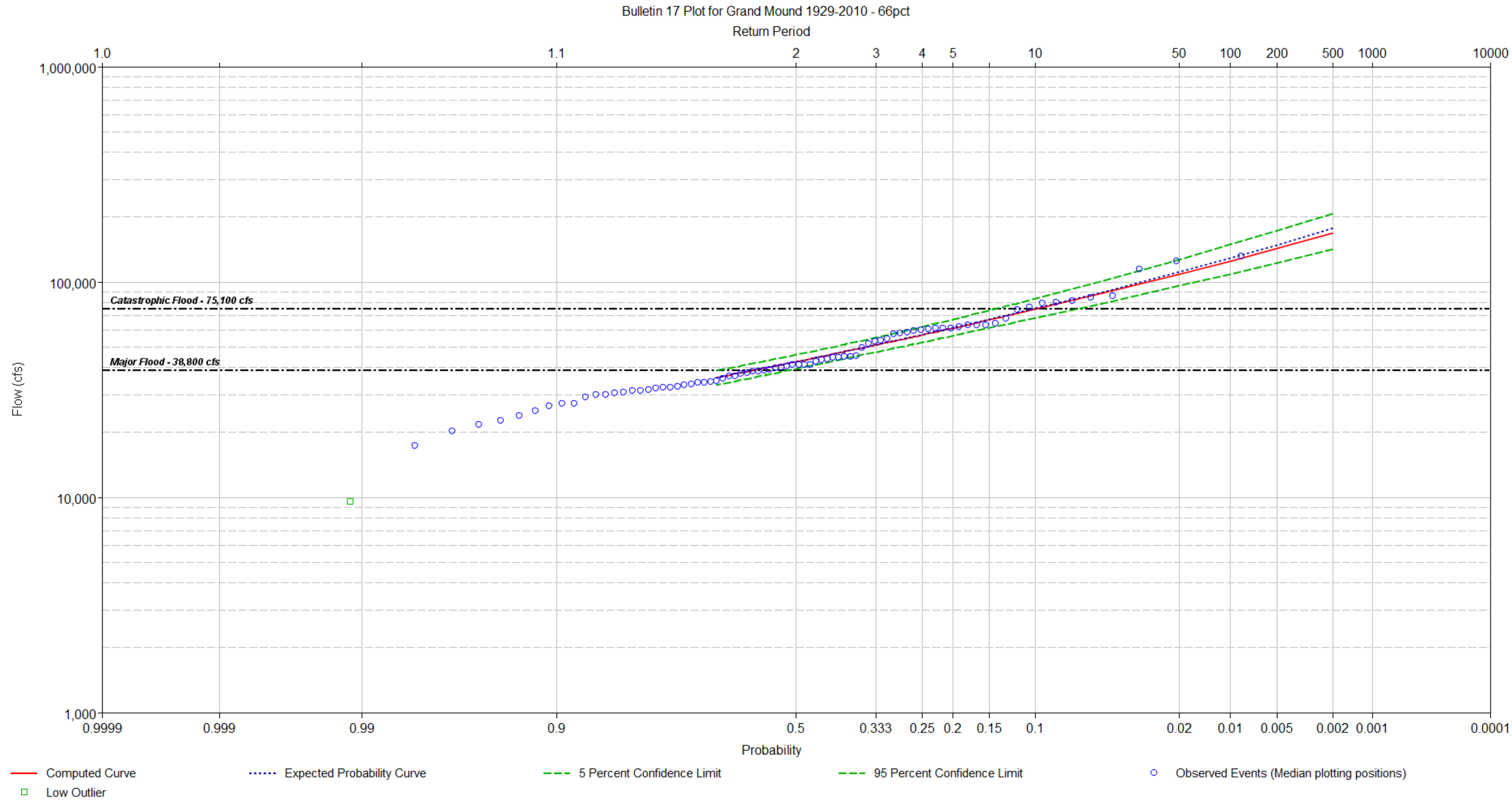


Table 12
Range of Probabilities of Occurrence for Estimated FRE Facility Operation Frequency

SCENARIO	ESTIMATED RANGE OF ANNUAL EXCEEDANCE PROBABILITY OF 38,800 CFS FLOW	ESTIMATED RANGE OF RECURRENCE INTERVAL (YEARS)
Existing Conditions	0.124 to 0.224	4 to 9
12% Peak Flow Increase	0.186 to 0.302	3 to 6
26% Peak Flow Increase	0.269 to 0.399	2 to 4
49% Peak Flow Increase	0.414 to 0.559	1.7 to 2.5
66% Peak Flow Increase	0.517 to 0.665	1.5 to 2

Note: Range is between 5% and 95% confidence limits of HEC-SSP analysis.

Summary

For future climate conditions, a catastrophic flood is estimated to occur at a 50-year recurrence interval for the mid-century averaged or 12% increase future climate scenario, at a 30-year recurrence interval for the late-century averaged or 26% increase future climate scenario, at a 15-year recurrence interval for the mid-century high-end or 49% increase future climate scenario, and at a 10-year recurrence interval for the late-century high-end or 66% increase future climate scenario.

Operations frequency estimates for the FRE facility for existing conditions and future climate scenarios were developed. The FRE facility operation would be activated when the peak flow at the Grand Mound gage is predicted to be 38,800 cfs or higher. A catastrophic flood occurs when the peak flow at the Grand Mound gage is 75,100 cfs or higher. HEC-SSP was used to duplicate previously established flood frequency estimates for the Grand Mound gage.

For existing conditions, FRE facility operation is estimated to occur at a 7-year recurrence interval with an estimated range of recurrence intervals from 4 to 9 years, and a catastrophic flood is estimated to occur at a 100-year recurrence interval.

For future climate conditions, FRE facility operation is estimated to occur at a 3.5-year recurrence interval for the 12% increase future climate scenario, at a 2.9-year recurrence interval for the 26% increase future climate scenario, a 2.2-year recurrence interval for the 49% increase future climate scenario, and a 1.8-year recurrence interval for the 66% increase future climate scenario. The estimated range of recurrence intervals for future climate conditions is from 3 to 6 years for the 12% increase future climate scenario, from 2 to 4 years for the 26% increase future climate scenario, from 1.7 to 2.5 years for the 49% increase future climate scenario, and from 1.5 to 2 years for the 66% increase future climate scenario.

The statistical analyses contained in this document used a period of record and methodology consistent with previous studies. The results can vary some as more data is added to the period of record.

References

Anchor QEA and WSE (Anchor QEA, LLC, and Watershed Science & Engineering), 2019. "Chehalis Basin Climate Change Flows and Flooding Results." Chehalis Basin Strategy: Reducing Flood Damage and Restoring Aquatic Species Habitat. Memorandum to Andrea McNamara Doyle and Chrissy Bailey, Office of Chehalis Basin. May 6, 2019.

Anchor QEA (Anchor QEA, LLC), 2017. *Operations Plan for Flood Retention Facilities*. Chehalis Basin Strategy: Reducing Flood Damage and Restoring Aquatic Species Habitat. June 2017.

Mauger, G., 2021. "Chehalis Basin: Extreme Precipitation Projections." Climate Impacts Group, University of Washington. February 4, 2021.

U.S. Geological Survey, 1981. "Guidelines for Determining Flood Flow Frequency." Bulletin #17B of the Hydrology Subcommittee. Revised September 1981.

Watershed Science & Engineering, 2022. Memorandum to Ann Costanza, Anchor QEA: "Mid-Century High End Climate Change Hydraulic Modeling Scenario." February 9, 2022.

Watershed Science & Engineering, 2019. Memorandum to: Bob Montgomery, Anchor QEA, LLC. Regarding: Chehalis River Basin Hydrologic Modeling. Chehalis Basin Strategy: Reducing Flood Damage and Restoring Aquatic Species Habitat. February 28, 2019.

Watershed Science & Engineering, 2014. Memorandum to: H&H Technical Committee. Regarding: Re-Evaluation of Statistical Hydrology and Design Storm Selection for the Chehalis River Basin. Chehalis Basin Strategy: Reducing Flood Damage and Restoring Aquatic Species Habitat. January 31, 2014.

West Consultants, 2014. *Chehalis Basin Ecosystem Restoration General Investigation Study Baseline Hydrology and Hydraulics Modeling*. Prepared for U.S. Army Corps of Engineers Seattle District. January 2014.

APPENDIX A
DATA TABLES

Table A-1

Ranked Peak Annual Discharges – Grand Mound Gage – Future Conditions with 12% Increase

WATER YEAR	ANNUAL PEAK FLOW – 12% INCREASE (CFS)	RANK	ANNUAL EXCEEDANCE PROBABILITY (PERCENT)	RECURRENCE INTERVAL (YEAR)
2008	88,600	1	0.0120	83.0
1996	83,800	2	0.0241	41.5
1990	76,900	3	0.0361	27.7
Catastrophic Flood Level	***75,100***			
1987	57,800	4	0.0482	20.8
2009	56,800	5	0.0602	16.6
1972	55,100	6	0.0723	13.8
1938	54,200	7	0.0843	11.9
1991	53,800	8	0.0964	10.4
1934	51,200	9	0.1084	9.2
1976	50,200	10	0.1205	8.3
1971	45,700	11	0.1325	7.5
1997	43,300	12	0.1446	6.9
1935	42,600	13	0.1566	6.4
1951	42,600	14	0.1687	5.9
2006	42,400	15	0.1807	5.5
1974	41,900	16	0.1928	5.2
1949	40,900	17	0.2048	4.9
1978	40,900	18	0.2169	4.6
1999	40,900	19	0.2289	4.4
1936	40,700	20	0.2410	4.2
1995	40,200	21	0.2530	4.0
1964	40,000	22	0.2651	3.8
1956	39,300	23	0.2771	3.6
1954	38,900	24	0.2892	3.5
Major Flood Level	***38,800***			
1967	38,500	25	0.3012	3.3
2007	36,600	26	0.3133	3.2
1986	36,000	27	0.3253	3.1
2002	35,700	28	0.3373	3.0
2000	34,700	29	0.3494	2.9
1963	33,400	30	0.3614	2.8

WATER YEAR	ANNUAL PEAK FLOW – 12% INCREASE (CFS)	RANK	ANNUAL EXCEEDANCE PROBABILITY (PERCENT)	RECURRENCE INTERVAL (YEAR)
1982	30,600	31	0.3735	2.7
1945	30,200	32	0.3855	2.6
1961	30,200	33	0.3976	2.5
1942	30,100	34	0.4096	2.4
1975	30,100	35	0.4217	2.4
1950	29,500	36	0.4337	2.3
1965	29,300	37	0.4458	2.2
1983	28,700	38	0.4578	2.2
1933	27,900	39	0.4699	2.1
1939	27,800	40	0.4819	2.1
1968	27,800	41	0.4940	2.0
1960	27,700	42	0.5060	2.0
1937	27,200	43	0.5181	1.9
1947	27,100	44	0.5301	1.9
1981	26,900	45	0.5422	1.8
1932	26,300	46	0.5542	1.8
1970	26,100	47	0.5663	1.8
1946	25,900	48	0.5783	1.7
2003	25,900	49	0.5904	1.7
1940	25,400	50	0.6024	1.7
1959	25,200	51	0.6145	1.6
1966	24,500	52	0.6265	1.6
1973	24,500	53	0.6386	1.6
1998	24,000	54	0.6506	1.5
1957	23,400	55	0.6627	1.5
2005	23,200	56	0.6747	1.5
1953	23,000	57	0.6867	1.5
2004	22,800	58	0.6988	1.4
1943	22,600	59	0.7108	1.4
1948	22,400	60	0.7229	1.4
1992	22,000	61	0.7349	1.4
1931	21,700	62	0.7470	1.3
2010	21,700	63	0.7590	1.3
1984	21,500	64	0.7711	1.3
1980	21,300	65	0.7831	1.3
1941	21,100	66	0.7952	1.3
1952	21,100	67	0.8072	1.2
1958	20,700	68	0.8193	1.2
1979	20,500	69	0.8313	1.2
1955	20,300	70	0.8434	1.2
1985	20,200	71	0.8554	1.2
1969	19,600	72	0.8675	1.2

WATER YEAR	ANNUAL PEAK FLOW – 12% INCREASE (CFS)	RANK	ANNUAL EXCEEDANCE PROBABILITY (PERCENT)	RECURRENCE INTERVAL (YEAR)
1944	18,400	73	0.8795	1.1
1988	18,400	74	0.8916	1.1
1962	17,800	75	0.9036	1.1
1977	17,000	76	0.9157	1.1
1989	16,100	77	0.9277	1.1
1929	15,300	78	0.9398	1.1
1994	14,700	79	0.9518	1.1
1930	13,700	80	0.9639	1.0
1993	11,600	81	0.9759	1.0
2001	6,400	82	0.9880	1.0

Table A-2
Ranked Peak Annual Discharges – Grand Mound Gage – Future Conditions with 26% Increase

WATER YEAR	ANNUAL PEAK FLOW – 26% INCREASE (CFS)	RANK	ANNUAL EXCEEDANCE PROBABILITY (PERCENT)	RECURRENCE INTERVAL (YEAR)
2008	99,700	1	0.0120	83.0
1996	94,200	2	0.0241	41.5
1990	86,600	3	0.0361	27.7
Catastrophic Flood Level	***75,100***			
1987	65,000	4	0.0482	20.8
2009	63,900	5	0.0602	16.6
1972	62,000	6	0.0723	13.8
1938	61,000	7	0.0843	11.9
1991	60,500	8	0.0964	10.4
1934	57,600	9	0.1084	9.2
1976	56,400	10	0.1205	8.3
1971	51,400	11	0.1325	7.5
1997	48,800	12	0.1446	6.9
1935	47,900	13	0.1566	6.4
1951	47,900	14	0.1687	5.9
2006	47,800	15	0.1807	5.5
1974	47,100	16	0.1928	5.2
1949	46,000	17	0.2048	4.9
1978	46,000	18	0.2169	4.6
1999	46,000	19	0.2289	4.4
1936	45,700	20	0.2410	4.2
1995	45,200	21	0.2530	4.0
1964	45,000	22	0.2651	3.8
1956	44,200	23	0.2771	3.6
1954	43,700	24	0.2892	3.5
1967	43,300	25	0.3012	3.3
2007	41,200	26	0.3133	3.2
1986	40,400	27	0.3253	3.1
2002	40,200	28	0.3373	3.0
2000	39,100	29	0.3494	2.9
Major Flood Level	***38,800***			
1963	37,500	30	0.3614	2.8
1982	34,400	31	0.3735	2.7
1945	34,000	32	0.3855	2.6
1961	34,000	33	0.3976	2.5
1942	33,900	34	0.4096	2.4
1975	33,900	35	0.4217	2.4
1950	33,100	36	0.4337	2.3
1965	33,000	37	0.4458	2.2

WATER YEAR	ANNUAL PEAK FLOW – 26% INCREASE (CFS)	RANK	ANNUAL EXCEEDANCE PROBABILITY (PERCENT)	RECURRENCE INTERVAL (YEAR)
1983	32,300	38	0.4578	2.2
1933	31,400	39	0.4699	2.1
1939	31,200	40	0.4819	2.1
1968	31,200	41	0.4940	2.0
1960	31,100	42	0.5060	2.0
1937	30,600	43	0.5181	1.9
1947	30,500	44	0.5301	1.9
1981	30,200	45	0.5422	1.8
1932	29,600	46	0.5542	1.8
1970	29,400	47	0.5663	1.8
1946	29,100	48	0.5783	1.7
2003	29,100	49	0.5904	1.7
1940	28,600	50	0.6024	1.7
1959	28,400	51	0.6145	1.6
1966	27,600	52	0.6265	1.6
1973	27,600	53	0.6386	1.6
1998	27,000	54	0.6506	1.5
1957	26,300	55	0.6627	1.5
2005	26,100	56	0.6747	1.5
1953	25,800	57	0.6867	1.5
2004	25,700	58	0.6988	1.4
1943	25,500	59	0.7108	1.4
1948	25,200	60	0.7229	1.4
1992	24,700	61	0.7349	1.4
1931	24,400	62	0.7470	1.3
2010	24,400	63	0.7590	1.3
1984	24,200	64	0.7711	1.3
1980	23,900	65	0.7831	1.3
1941	23,700	66	0.7952	1.3
1952	23,700	67	0.8072	1.2
1958	23,300	68	0.8193	1.2
1979	23,100	69	0.8313	1.2
1955	22,800	70	0.8434	1.2
1985	22,700	71	0.8554	1.2
1969	22,100	72	0.8675	1.2
1944	20,700	73	0.8795	1.1
1988	20,700	74	0.8916	1.1
1962	20,000	75	0.9036	1.1
1977	19,200	76	0.9157	1.1
1989	18,100	77	0.9277	1.1
1929	17,300	78	0.9398	1.1
1994	16,500	79	0.9518	1.1

WATER YEAR	ANNUAL PEAK FLOW – 26% INCREASE (CFS)	RANK	ANNUAL EXCEEDANCE PROBABILITY (PERCENT)	RECURRENCE INTERVAL (YEAR)
1930	15,400	80	0.9639	1.0
1993	13,100	81	0.9759	1.0
2001	7,200	82	0.9880	1.0

Table A-3
Ranked Peak Annual Discharges – Grand Mound Gage – Future Conditions with 49% Increase

WATER YEAR	ANNUAL PEAK FLOW – 66% INCREASE (CFS)	RANK	ANNUAL EXCEEDANCE PROBABILITY (PERCENT)	RECURRENCE INTERVAL (YEAR)
2008	117,900	1	0.0120	83.0
1996	111,500	2	0.0241	41.5
1990	102,400	3	0.0361	27.7
1987	76,900	4	0.0482	20.8
2009	75,500	5	0.0602	16.6
Catastrophic Flood Level	***75,100***			
1972	73,300	6	0.0723	13.8
1938	72,100	7	0.0843	11.9
1991	71,500	8	0.0964	10.4
1934	68,100	9	0.1084	9.2
1976	66,800	10	0.1205	8.3
1971	60,800	11	0.1325	7.5
1997	57,700	12	0.1446	6.9
1935	56,600	13	0.1566	6.4
1951	56,600	14	0.1687	5.9
2006	56,500	15	0.1807	5.5
1974	55,700	16	0.1928	5.2
1949	54,400	17	0.2048	4.9
1978	54,400	18	0.2169	4.6
1999	54,400	19	0.2289	4.4
1936	54,100	20	0.2410	4.2
1995	53,500	21	0.2530	4.0
1964	53,200	22	0.2651	3.8
1956	52,300	23	0.2771	3.6
1954	51,700	24	0.2892	3.5
1967	51,300	25	0.3012	3.3
2007	48,700	26	0.3133	3.2
1986	47,800	27	0.3253	3.1
2002	47,500	28	0.3373	3.0
2000	46,200	29	0.3494	2.9
1963	44,400	30	0.3614	2.8
1982	40,700	31	0.3735	2.7
1945	40,200	32	0.3855	2.6
1961	40,200	33	0.3976	2.5
1942	40,100	34	0.4096	2.4
1975	40,100	35	0.4217	2.4
1950	39,200	36	0.4337	2.3
1965	39,000	37	0.4458	2.2
Major Flood Level	***38,800***			

WATER YEAR	ANNUAL PEAK FLOW – 66% INCREASE (CFS)	RANK	ANNUAL EXCEEDANCE PROBABILITY (PERCENT)	RECURRENCE INTERVAL (YEAR)
1983	38,100	38	0.4578	2.2
1933	37,100	39	0.4699	2.1
1939	37,000	40	0.4819	2.1
1968	37,000	41	0.4940	2.0
1960	36,800	42	0.5060	2.0
1937	36,200	43	0.5181	1.9
1947	36,100	44	0.5301	1.9
1981	35,800	45	0.5422	1.8
1932	35,000	46	0.5542	1.8
1970	34,700	47	0.5663	1.8
1946	34,400	48	0.5783	1.7
2003	34,400	49	0.5904	1.7
1940	33,800	50	0.6024	1.7
1959	33,500	51	0.6145	1.6
1966	32,600	52	0.6265	1.6
1973	32,600	53	0.6386	1.6
1998	31,900	54	0.6506	1.5
1957	31,100	55	0.6627	1.5
2005	30,800	56	0.6747	1.5
1953	30,500	57	0.6867	1.5
2004	30,400	58	0.6988	1.4
1943	30,100	59	0.7108	1.4
1948	29,800	60	0.7229	1.4
1992	29,200	61	0.7349	1.4
1931	28,900	62	0.7470	1.3
2010	28,900	63	0.7590	1.3
1984	28,600	64	0.7711	1.3
1980	28,300	65	0.7831	1.3
1941	28,000	66	0.7952	1.3
1952	28,000	67	0.8072	1.2
1958	27,600	68	0.8193	1.2
1979	27,300	69	0.8313	1.2
1955	27,000	70	0.8434	1.2
1985	26,800	71	0.8554	1.2
1969	26,100	72	0.8675	1.2
1944	24,400	73	0.8795	1.1
1988	24,400	74	0.8916	1.1
1962	23,700	75	0.9036	1.1
1977	22,600	76	0.9157	1.1
1989	21,500	77	0.9277	1.1
1929	20,400	78	0.9398	1.1
1994	19,500	79	0.9518	1.1

WATER YEAR	ANNUAL PEAK FLOW – 66% INCREASE (CFS)	RANK	ANNUAL EXCEEDANCE PROBABILITY (PERCENT)	RECURRENCE INTERVAL (YEAR)
1930	18,200	80	0.9639	1.0
1993	15,500	81	0.9759	1.0
2001	8,600	82	0.9880	1.0

Table A-4
Ranked Peak Annual Discharges – Grand Mound Gage – Future Conditions with 66% Increase

WATER YEAR	ANNUAL PEAK FLOW – 66% INCREASE (CFS)	RANK	ANNUAL EXCEEDANCE PROBABILITY (PERCENT)	RECURRENCE INTERVAL (YEAR)
2008	131,300	1	0.0120	83.0
1996	124,200	2	0.0241	41.5
1990	114,000	3	0.0361	27.7
1987	85,700	4	0.0482	20.8
2009	84,200	5	0.0602	16.6
1972	81,700	6	0.0723	13.8
1938	80,300	7	0.0843	11.9
1991	79,700	8	0.0964	10.4
1934	75,900	9	0.1084	9.2
Catastrophic Flood Level	***75,100***			
1976	74,400	10	0.1205	8.3
1971	67,700	11	0.1325	7.5
1997	64,200	12	0.1446	6.9
1935	63,100	13	0.1566	6.4
1951	63,100	14	0.1687	5.9
2006	62,900	15	0.1807	5.5
1974	62,100	16	0.1928	5.2
1949	60,600	17	0.2048	4.9
1978	60,600	18	0.2169	4.6
1999	60,600	19	0.2289	4.4
1936	60,300	20	0.2410	4.2
1995	59,600	21	0.2530	4.0
1964	59,300	22	0.2651	3.8
1956	58,300	23	0.2771	3.6
1954	57,600	24	0.2892	3.5
1967	57,100	25	0.3012	3.3
2007	54,300	26	0.3133	3.2
1986	53,300	27	0.3253	3.1
2002	53,000	28	0.3373	3.0
2000	51,500	29	0.3494	2.9
1963	49,500	30	0.3614	2.8
1982	45,300	31	0.3735	2.7
1945	44,800	32	0.3855	2.6
1961	44,800	33	0.3976	2.5
1942	44,700	34	0.4096	2.4
1975	44,700	35	0.4217	2.4
1950	43,700	36	0.4337	2.3
1965	43,500	37	0.4458	2.2
1983	42,500	38	0.4578	2.2

WATER YEAR	ANNUAL PEAK FLOW – 66% INCREASE (CFS)	RANK	ANNUAL EXCEEDANCE PROBABILITY (PERCENT)	RECURRENCE INTERVAL (YEAR)
1933	41,300	39	0.4699	2.1
1939	41,200	40	0.4819	2.1
1968	41,200	41	0.4940	2.0
1960	41,000	42	0.5060	2.0
1937	40,300	43	0.5181	1.9
1947	40,200	44	0.5301	1.9
1981	39,800	45	0.5422	1.8
1932	39,000	46	0.5542	1.8
Major Flood Level	***38,800***			
1970	38,700	47	0.5663	1.8
1946	38,300	48	0.5783	1.7
2003	38,300	49	0.5904	1.7
1940	37,700	50	0.6024	1.7
1959	37,400	51	0.6145	1.6
1966	36,400	52	0.6265	1.6
1973	36,400	53	0.6386	1.6
1998	35,500	54	0.6506	1.5
1957	34,700	55	0.6627	1.5
2005	34,400	56	0.6747	1.5
1953	34,000	57	0.6867	1.5
2004	33,900	58	0.6988	1.4
1943	33,500	59	0.7108	1.4
1948	33,200	60	0.7229	1.4
1992	32,500	61	0.7349	1.4
1931	32,200	62	0.7470	1.3
2010	32,200	63	0.7590	1.3
1984	31,900	64	0.7711	1.3
1980	31,500	65	0.7831	1.3
1941	31,200	66	0.7952	1.3
1952	31,200	67	0.8072	1.2
1958	30,700	68	0.8193	1.2
1979	30,400	69	0.8313	1.2
1955	30,000	70	0.8434	1.2
1985	29,900	71	0.8554	1.2
1969	29,100	72	0.8675	1.2
1944	27,200	73	0.8795	1.1
1988	27,200	74	0.8916	1.1
1962	26,400	75	0.9036	1.1
1977	25,200	76	0.9157	1.1
1989	23,900	77	0.9277	1.1
1929	22,700	78	0.9398	1.1
1994	21,700	79	0.9518	1.1

WATER YEAR	ANNUAL PEAK FLOW – 66% INCREASE (CFS)	RANK	ANNUAL EXCEEDANCE PROBABILITY (PERCENT)	RECURRENCE INTERVAL (YEAR)
1930	20,300	80	0.9639	1.0
1993	17,300	81	0.9759	1.0
2001	9,500	82	0.9880	1.0

ATTACHMENTS

1. Chehalis Basin Climate Change Flows and Flooding Results" (Anchor QEA and WSE 2019)
2. Extreme Precipitation Projections (Mauger 2021)
3. Mid-Century High End Climate Change Hydraulic Modeling Scenario"(WSE 2022)

ATTACHMENTS

1. Chehalis Basin Climate Change Flows and Flooding Results" (Anchor QEA and WSE 2019)
2. Extreme Precipitation Projections (Mauger 2021)
3. Mid-Century High End Climate Change Hydraulic Modeling Scenario"(WSE 2022)

MEMORANDUM

Date: May 6, 2019
To: Andrea McNamara Doyle and Chrissy Bailey, Office of Chehalis Basin
From: Adam Hill, PE, Anchor QEA; Larry Karpack, PE, Watershed Science and Engineering
Cc: Heather Page, Anchor QEA
Re: Chehalis River Basin Climate Change Flows and Flooding Results

Purpose

This memorandum documents the preparation of streamflow and flooding estimates under future climate change conditions. The streamflow estimates use the information contained in the Chehalis River Basin Hydrologic Modeling (WSE 2019a) technical memorandum combined with U.S. Geological Survey (USGS) flow records to develop flows under future climate change conditions. The flows were input to the 2D model developed for the Chehalis River Basin Existing Conditions RiverFlow2D Model Development and Calibration (WSE 2019b) technical memorandum to estimate flooding conditions under future climate change conditions.

The results of these analyses will be used for other technical studies that require estimates of streamflow and resulting hydraulic conditions under climate change, providing baseline technical study information for the Chehalis Basin Strategy.

Streamflow Under Climate Change Conditions

Factor for Increasing Peak Flows

The factors applied to increasing peak flows were developed using results from the Chehalis River Basin Hydrologic Modeling technical memorandum (WSE 2019a). Table 1 provides the peak flow increases recommended by Watershed Science and Engineering (WSE) for climate change conditions for mid-century conditions (2016 to 2060) and late-century conditions (2055 to 2099).

Table 1
Peak Flow Increases Due to Climate Change

CLIMATE CHANGE SCENARIO	PEAK FLOW INCREASE	RATIONALE
Mid-century	12%	Average of RCP 4.5 and RCP 8.5 average peak flow mid-century increase (15 sites)
Late-century	26%	RCP 8.5 average peak flow late-century increase (15 sites)

Notes:
Source: WSE 2019a
RCP: Representative Concentration Pathway

Seasonal Flow Adjustment

Analyses performed for peak flows were also applied to streamflow outside of peak flow periods. Streamflows from the same 15 sites analyzed in Chehalis River Basin Hydrologic Modeling technical memorandum (WSE 2019a) were analyzed to determine the change in average monthly flows throughout the modeling period of record. It was projected that flows increase from November to April and decrease from May to October.

To simplify the development of flows under climate change conditions, a single flow increase or decrease was determined for those 6-month periods for mid-century and late-century flow conditions using the average of flow changes across the 15 sites. Table 2 lists the adjustments to flow determined using that method.

Table 2
Flow Adjustment Factors Due to Climate Change

CLIMATE CHANGE SCENARIO	PERIOD	FLOW CHANGE
Mid-century	November to April (Winter; high flow)	4%
	May to October (Summer; low flow)	-11%
Late-century	November to April (Winter; high flow)	5%
	May to October (Summer; low flow)	-16%

Flow Records Used to Develop Climate Change

Streamflow generated by hydrologic modeling was not used in this analysis because the hydrologic model, "does a good job of replicating flow frequency results at some locations and recurrence intervals, and it does poorly at other locations" (WSE 2019a). To avoid bias in estimating streamflow under climate change for particular locations or gages, the adjustments to streamflow basin-wide, as shown in Tables 1 and 2, were applied to historical flows from active USGS gages. Table 3 provides a list of USGS gages and the type of data available and used in the analysis.

Table 3
Gages and Data Used in Flow Record Development

GAGE NAME	GAGE NO.	DATA USED
Chehalis River near Doty (Doty gage)	12020000	Hourly flow; Daily flow
Chehalis River near Grand Mound (Grand Mound gage)	12027500	Hourly flow; Daily flow
Chehalis River near Porter (Porter gage)	12031000	Daily flow
South Fork Chehalis River near Wildwood (South Fork gage)	12020800	Daily flow
Newaukum River near Chehalis (Newaukum gage)	12025000	Daily flow
Skookumchuck River near Bucoda (Skookumchuck gage)	12026400	Daily flow
Satsop River near Satsop (Satsop gage)	12035000	Daily flow
Wynoochee River above Black Creek near Montesano (Wynoochee gage)	12037400	Daily flow

Source: USGS 2019

Development of Flows Under Climate Change Conditions

Both hourly and daily flows under future climate change conditions were developed, depending on the gage analyzed and the technical study requirements the flows are being used for. To maintain consistency through all flow data development, data from a single period of record were used in flow development, from October 1988 to September 2018 (Water Years 1989 to 2018). This 30-year period of record was chosen because it is the period of record available for the hourly data at Doty gage (the shortest hourly period of record of gages used).

The summer flow adjustments were applied directly to the gage data to develop climate change flows.

Because the winter flow adjustments also include peak flow events, the flow change outside of peak flow events was reduced to balance the total volume of flow for winter. To determine that factor, the period that peak flow increases (Table 1) would occur was first defined. The period was assumed to be when the flow was above the 1% flow exceedance value for the period of record used (water years 1989 to 2018). Table 4 lists the 1% exceedance flows for the gages used in the climate change analyses.

Table 4
One-Percent Exceedance Flows

GAGE NAME	1% EXCEEDANCE FLOW (CUBIC FEET PER SECOND)
Doty gage	4,830 (Hourly flow); 4,690 (Daily flow)
Grand Mound gage	20,500 (Hourly flow); 20,100 (Daily flow)
Porter gage	25,840
South Fork gage	1,570
Newaukum gage	3,660
Skookumchuck gage	2,520
Satsop gage	15,040
Wynoochee gage	8,950

During storms with flows exceeding the thresholds listed in Table 4, the flows were multiplied by the factors in Table 1. The volume of flow in those events was calculated and the remainder of winter flows multiplied by factors until the total volume of winter flow agreed with the factors in Table 2. This non-peak factor was found to be 3% in both mid-century and late-century climate change conditions.

Although different thresholds were used for hourly and daily data for Doty and Grand Mound gages to maintain consistency in the flow calculations, the difference was minor, and a single factor of 3% was used for all non-peak flow adjustments.

A streamflow record for mid-century and late-century conditions was prepared for each gage listed in Table 3 using the adjustments described above. Streamflow data are not included in this memorandum because of their size; the data was provided to Office of Chehalis Basin in spreadsheet format. To illustrate the change in flow, streamflow under climate change conditions for each gage listed in Table 3 was plotted against the historical streamflow records for 1996, 2009, and 2011. Those years contain a range of flow conditions, and the climate change flows based upon those years were used in EDT modeling. The plots are provided in Appendix A. Also included in Appendix A are the estimated change in flow during 10-year and 100-year flood events. The development of 10-year and 100-year hydrographs for current conditions are described in the Statistical Hydrology technical memorandum (WSE 2014). Peak flow adjustments from Table 1 were made to those hydrographs to estimate climate change conditions for those events.

Hydraulic Analyses

Hydraulic Model Used

A RiverFlow2D model was developed to model the hydraulics of the Chehalis River from River Mile 108 to the Porter gage at River Mile 33. Full details of the work completed are described in the WSE technical memorandum (WSE 2019b).

Climate Change Conditions

To evaluate climate change conditions, flows in the RiverFlow2D model were updated using the 10-year and 100-year events for mid-century and late-century periods shown in Figures A-25 and A-26. Tables 5 (mid-century) and 6 (late-century) show the water surface elevations at 21 locations along the Chehalis River from the RiverFlow2D model results.

Comprehensive water level data are not included in this memorandum because of their size; the data along with GIS maps of floodplain boundaries and depth of flooding were provided to Office of Chehalis Basin.

Table 5
RiverFlow2D Modeled Water Surface Elevation Results, Mid-Century Conditions

LOCATION	10-YEAR ELEVATION (FEET)	100-YEAR ELEVATION (FEET)
Near Doty	312.9	321.1
Curtis Store (on South Fork Chehalis River)	229.9	233.0
Downstream of South Fork Chehalis River	215.3	221.3
Near Adna	195.8	198.5
Labree Road Bridge (on Newaukum River)	205.7	206.3
Newaukum Confluence	183.3	186.4
Dillenbaugh Creek at I-5	182.5	186.6
South End of Airport Riverward of Levee	178.5	182.5
South End of Airport Landward of Levee	Dry	181.6
North End of Airport Riverward of Levee	175.3	180.9
North End of Airport Landward of Levee	Dry	181.6
Mellen Street Bridge	172.6	177.8
Mellen Street East of I-5	173.0	177.5

LOCATION	10-YEAR ELEVATION (FEET)	100-YEAR ELEVATION (FEET)
Skookumchuck Confluence	171.0	176.3
Upstream of Galvin Road	163.9	168.5
Grand Mound (Prather Road Bridge)	144.5	147.1
Near Rochester	121.9	124.8
Anderson Road	108.9	111.1
Black River Confluence	91.6	95.2
Sickman Ford Bridge	79.8	83.5
Porter Creek Road Bridge	51.2	54.2

Table 6

RiverFlow2D Modeled Water Surface Elevation Results, Late-Century Conditions

LOCATION	10-YEAR ELEVATION (FEET)	100-YEAR ELEVATION (FEET)
Near Doty	314.3	323.0
Curtis Store (on South Fork Chehalis River)	230.3	234.4
Downstream of South Fork Chehalis River	216.3	222.7
Near Adna	196.4	198.9
Labree Road Bridge (on Newaukum River)	205.9	206.5
Newaukum Confluence	183.8	186.9
Dillenbaugh Creek at I-5	183.5	187.1
South End of Airport Riverward of Levee	179.3	183.4
South End of Airport Landward of Levee	Dry	183.2
North End of Airport Riverward of Levee	176.4	182.3
North End of Airport Landward of Levee	162.9	182.4
Mellen Street Bridge	173.9	178.9
Mellen Street East of I-5	173.8	179.3
Skookumchuck Confluence	172.3	177.6
Upstream of Galvin Road	164.9	169.7
Grand Mound (Prather Road Bridge)	145.0	147.9
Near Rochester	122.5	125.7
Anderson Road	109.4	111.7
Black River Confluence	92.3	96.2
Sickman Ford Bridge	80.5	84.6
Porter Creek Road Bridge	51.8	55.3

References

USGS (U.S. Geological Survey), 2019. *NWIS Site Information for Washington: Site Inventory*. Accessed March 14, 2019. Available at https://waterdata.usgs.gov/wa/nwis/inventory/.

WSE (Watershed Science and Engineering), 2019a. Memorandum to: Robert Montgomery, Anchor QEA, LLC. Regarding: Chehalis River Basin Hydrologic Modeling. February 28, 2019.

WSE, 2019b. Memorandum to: Robert Montgomery, Anchor QEA, LLC. Regarding: Chehalis River Basin Existing Conditions RiverFlow2D Model Development and Calibration*.* February 28, 2019.

WSE, 2014. Memorandum to: Robert Montgomery, Anchor QEA, LLC. Regarding: Chehalis Basin Strategy: Reducing Flood Damage and Enhancing Aquatic Species – Re-Evaluation of Statistical Hydrology and Design Storm Selection for the Chehalis River Basin*.* January 31, 2014.

Appendix A
Climate Change Flow Data Plots

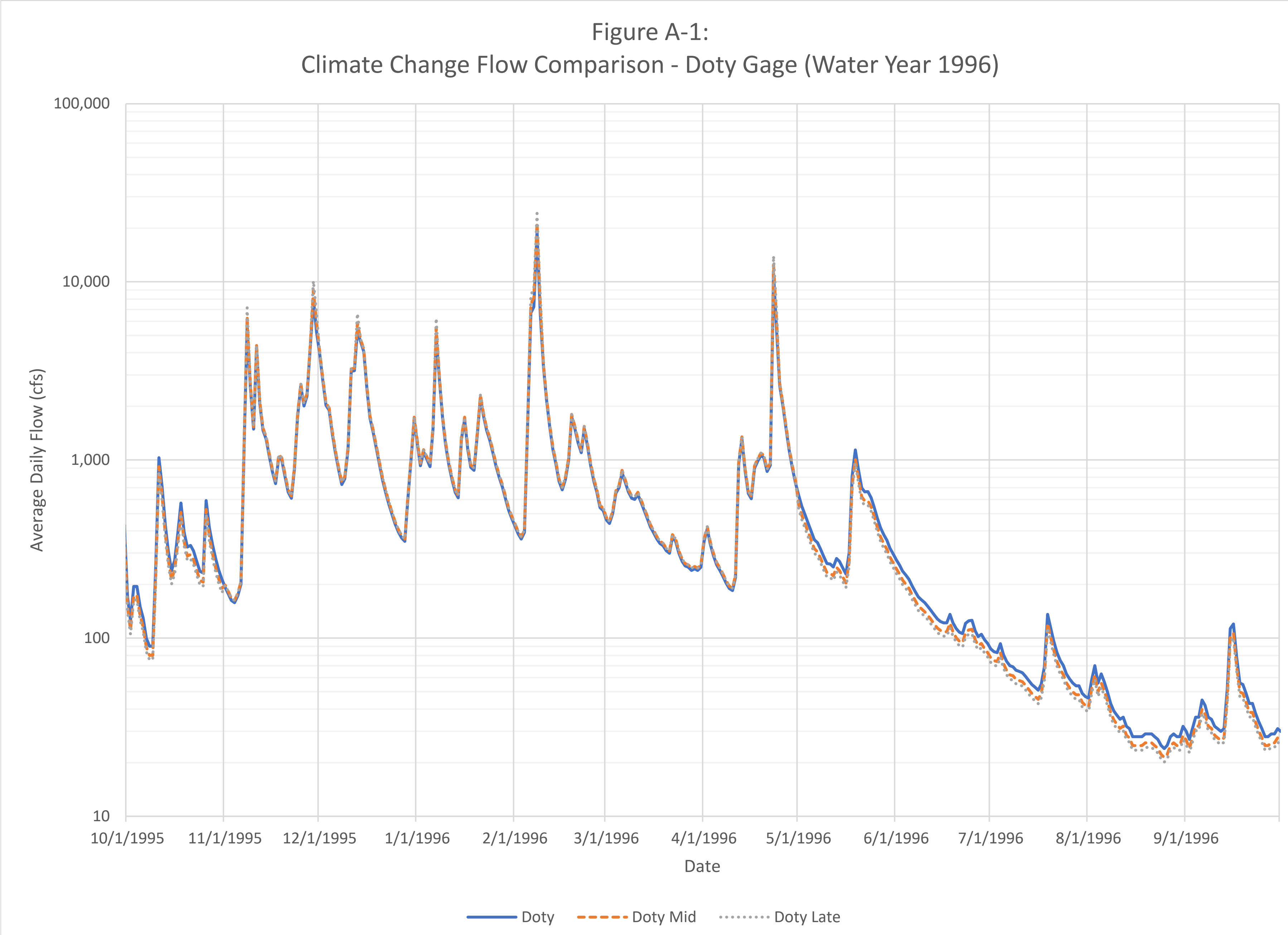


Figure A-1:
Climate Change Flow Comparison - Doty Gage (Water Year 1996)
100,000
10,000
1,000
100
10
Average Daily Flow (cfs)
10/1/1995
11/1/1995
12/1/1995
1/1/1996
2/1/1996
3/1/1996
4/1/1996
5/1/1996
6/1/1996
7/1/1996
8/1/1996
9/1/1996
Date
Doty
Doty Mid
Doty Late

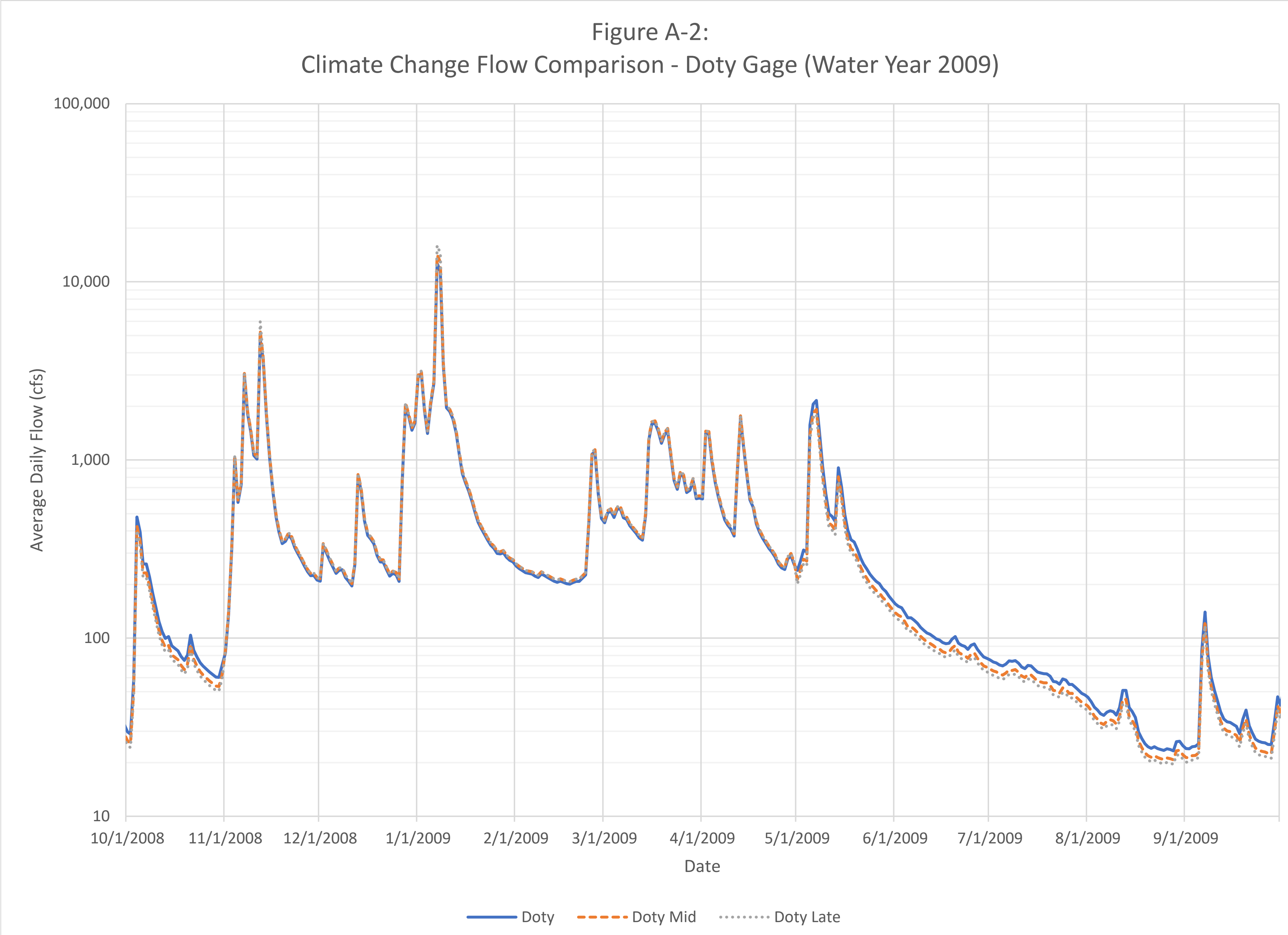


Figure A-2:
Climate Change Flow Comparison - Doty Gage (Water Year 2009)
100,000
10,000
1,000
100
10
Average Daily Flow (cfs)
10/1/2008
11/1/2008
12/1/2008
1/1/2009
2/1/2009
3/1/2009
4/1/2009
5/1/2009
6/1/2009
7/1/2009
8/1/2009
9/1/2009
Date
Doty
Doty Mid
Doty Late

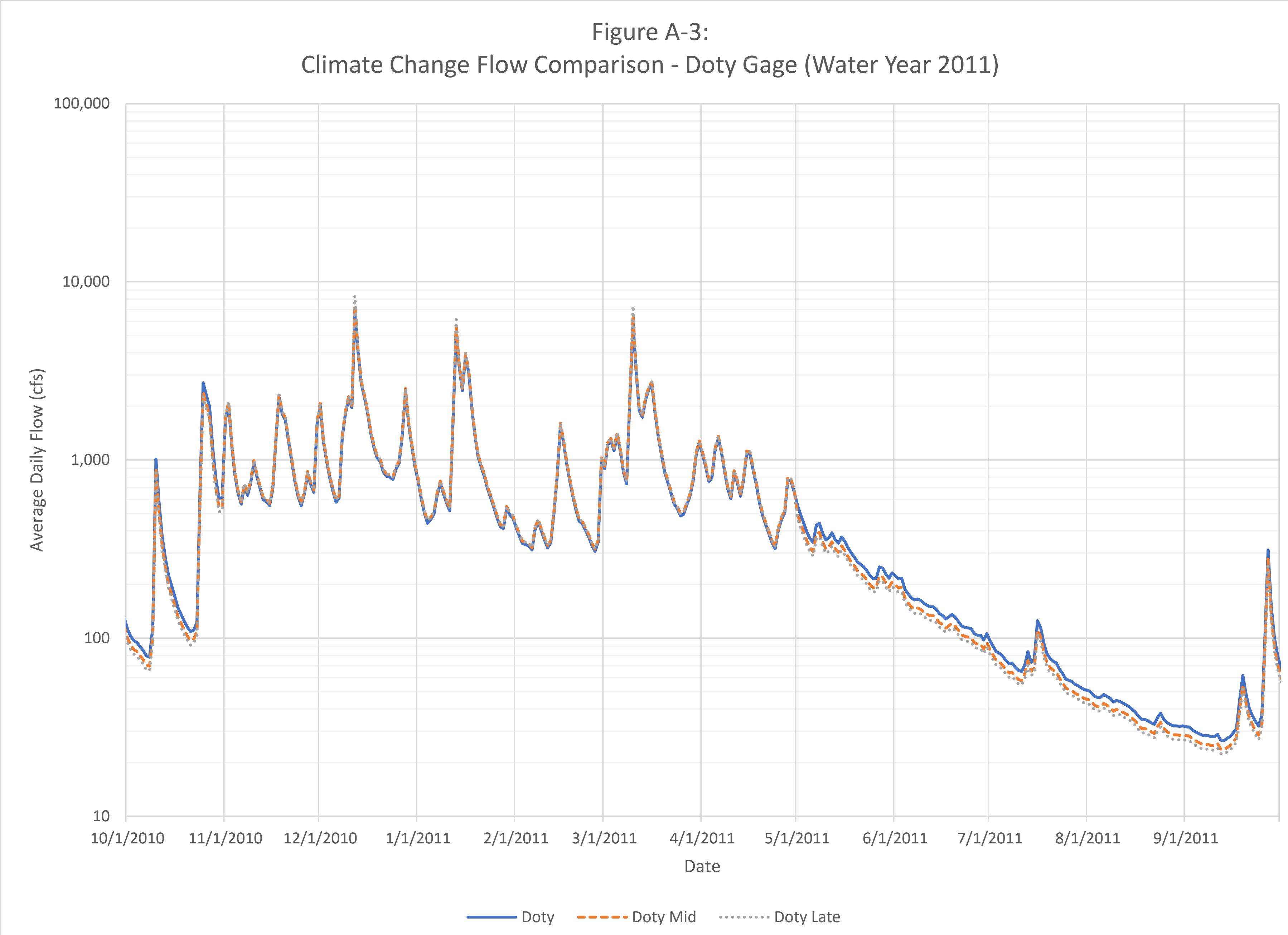


Figure A-3:
Climate Change Flow Comparison - Doty Gage (Water Year 2011)
100,000
10,000
1,000
100
10
Average Daily Flow (cfs)
10/1/2010
11/1/2010
12/1/2010
1/1/2011
2/1/2011
3/1/2011
4/1/2011
5/1/2011
6/1/2011
7/1/2011
8/1/2011
9/1/2011
Date
Doty
Doty Mid
Doty Late

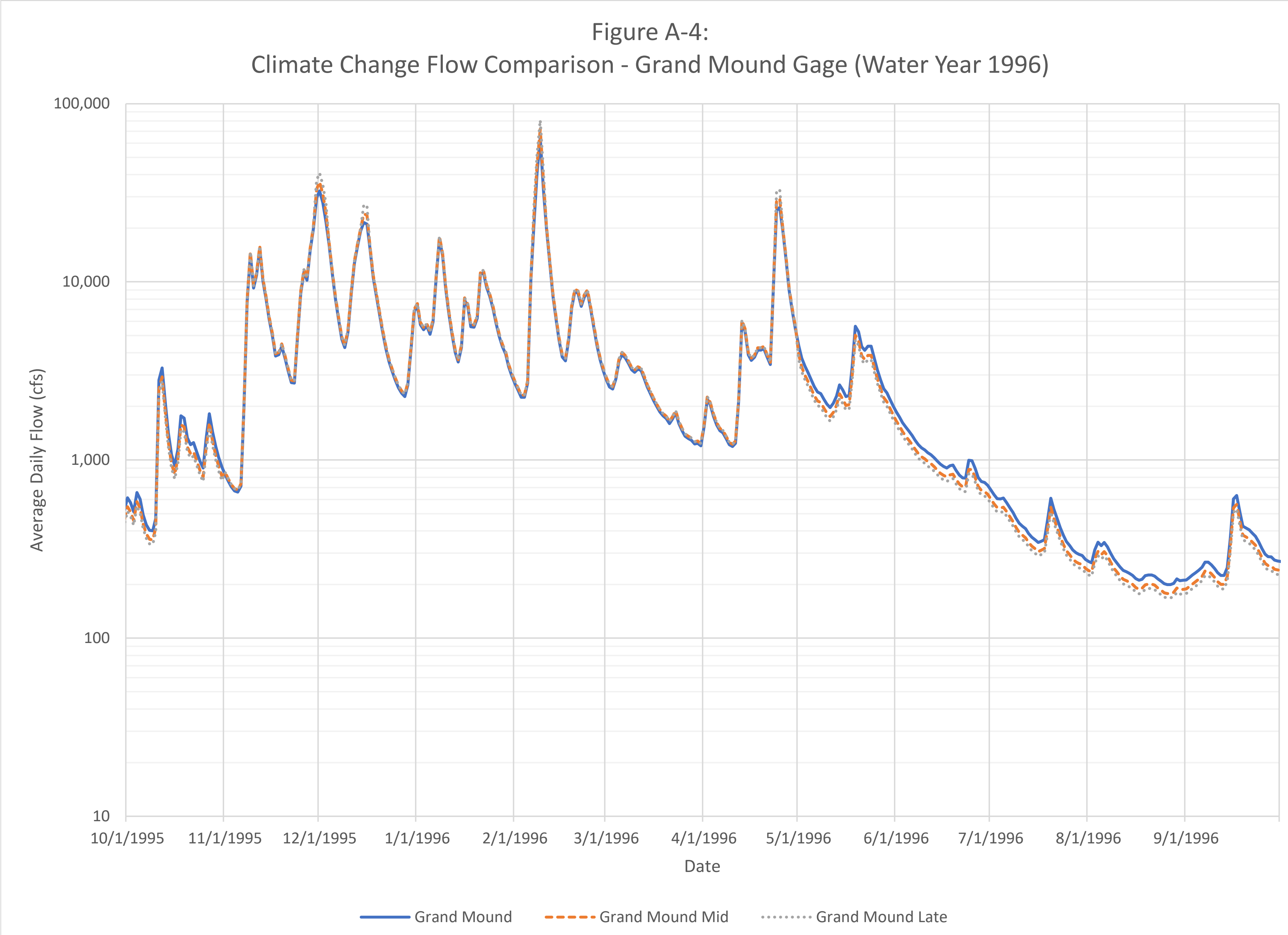


Figure A-4:
Climate Change Flow Comparison - Grand Mound Gage (Water Year 1996)
100,000
10,000
1,000
100
10
Average Daily Flow (cfs)
10/1/1995
11/1/1995
12/1/1995
1/1/1996
2/1/1996
3/1/1996
4/1/1996
5/1/1996
6/1/1996
7/1/1996
8/1/1996
9/1/1996
Date
Grand Mound
Grand Mound Mid
Grand Mound Late

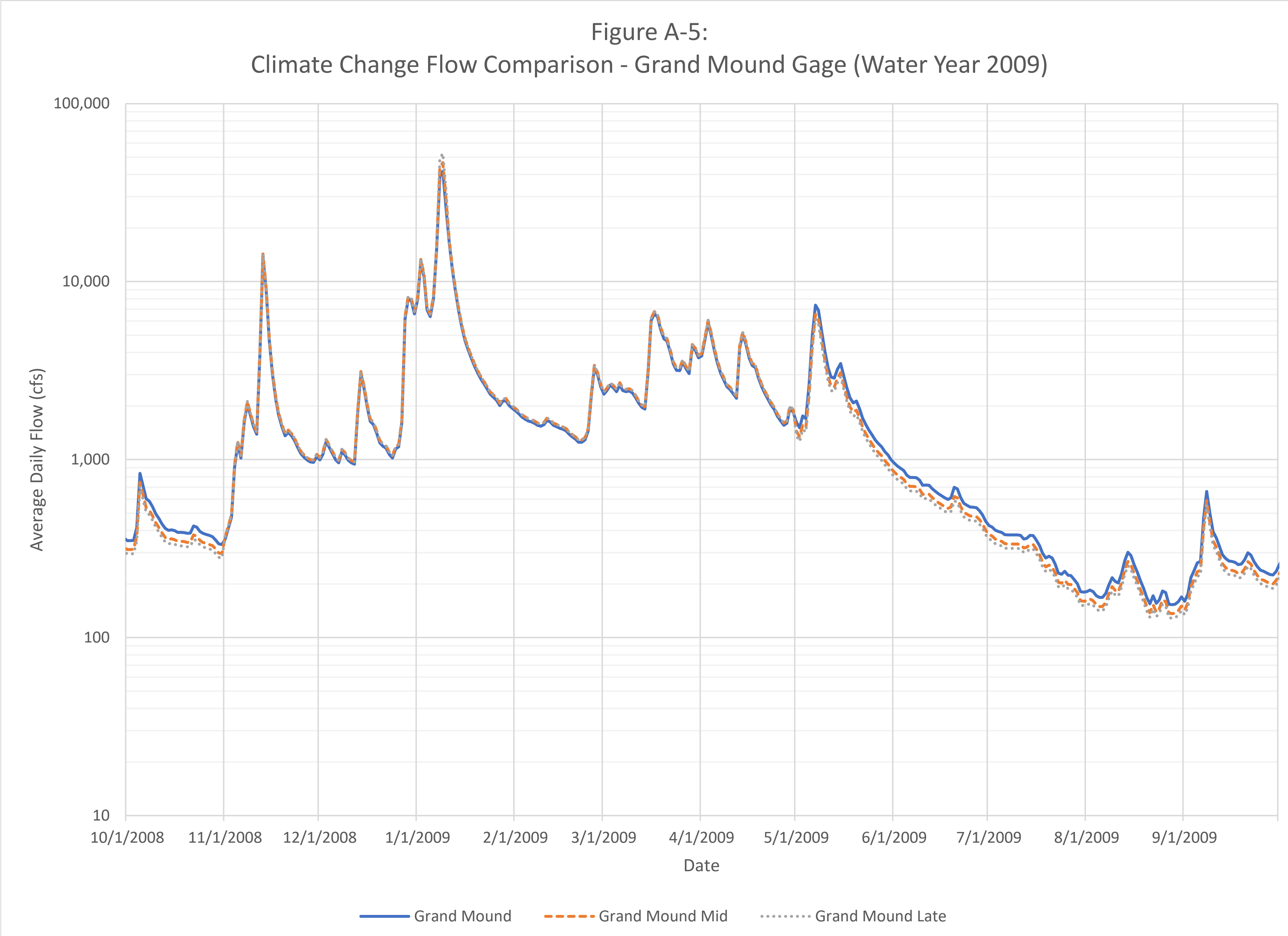


Figure A-5:
Climate Change Flow Comparison - Grand Mound Gage (Water Year 2009)
100,000
10,000
1,000
100
10
Average Daily Flow (cfs)
10/1/2008
11/1/2008
12/1/2008
1/1/2009
2/1/2009
3/1/2009
4/1/2009
5/1/2009
6/1/2009
7/1/2009
8/1/2009
9/1/2009
Date
Grand Mound
Grand Mound Mid
Grand Mound Late

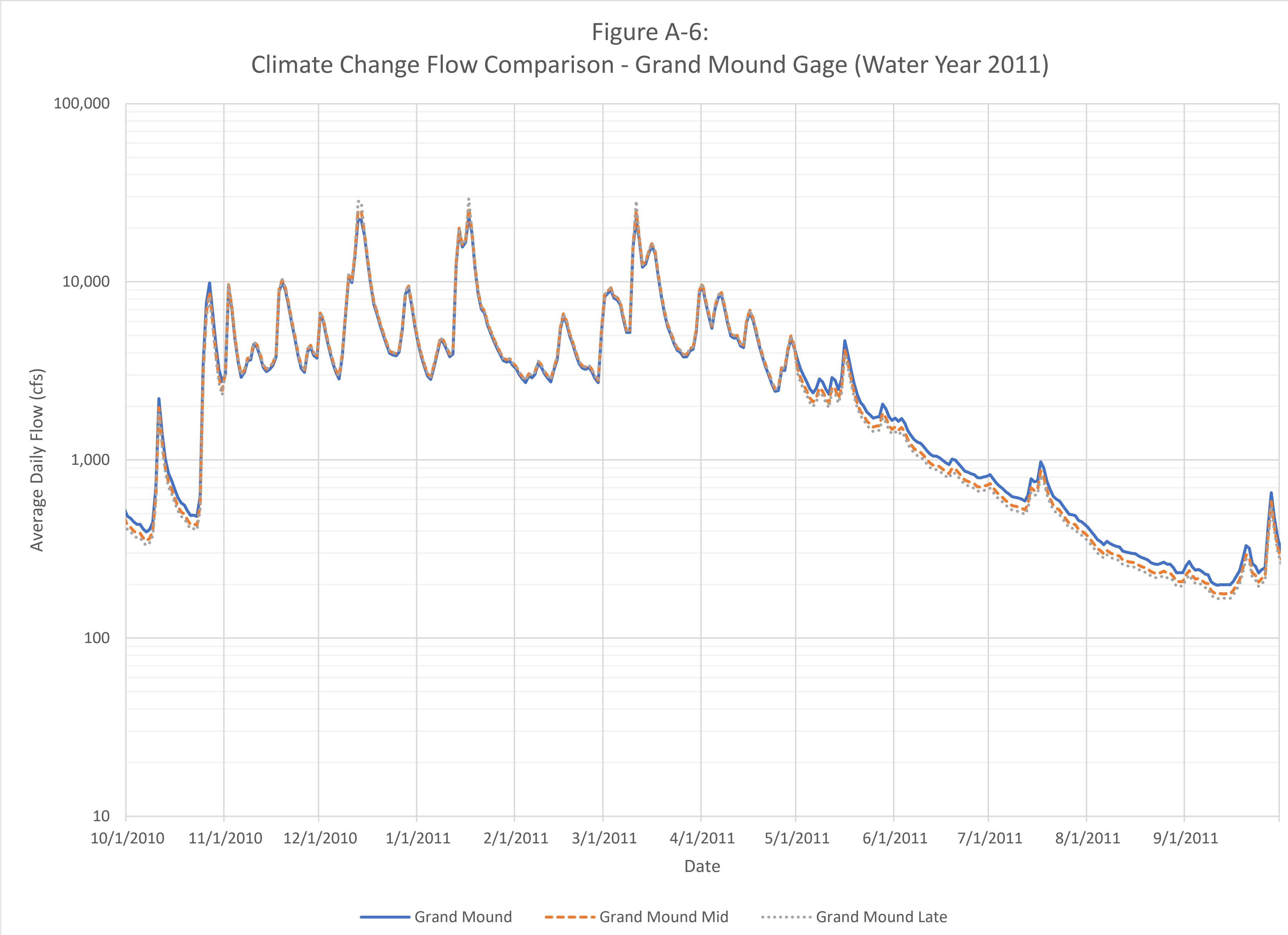


Figure A-6:
Climate Change Flow Comparison - Grand Mound Gage (Water Year 2011)
100,000
10,000
1,000
100
10
Average Daily Flow (cfs)
10/1/2010
11/1/2010
12/1/2010
1/1/2011
2/1/2011
3/1/2011
4/1/2011
5/1/2011
6/1/2011
7/1/2011
8/1/2011
9/1/2011
Date
Grand Mound
Grand Mound Mid
Grand Mound Late

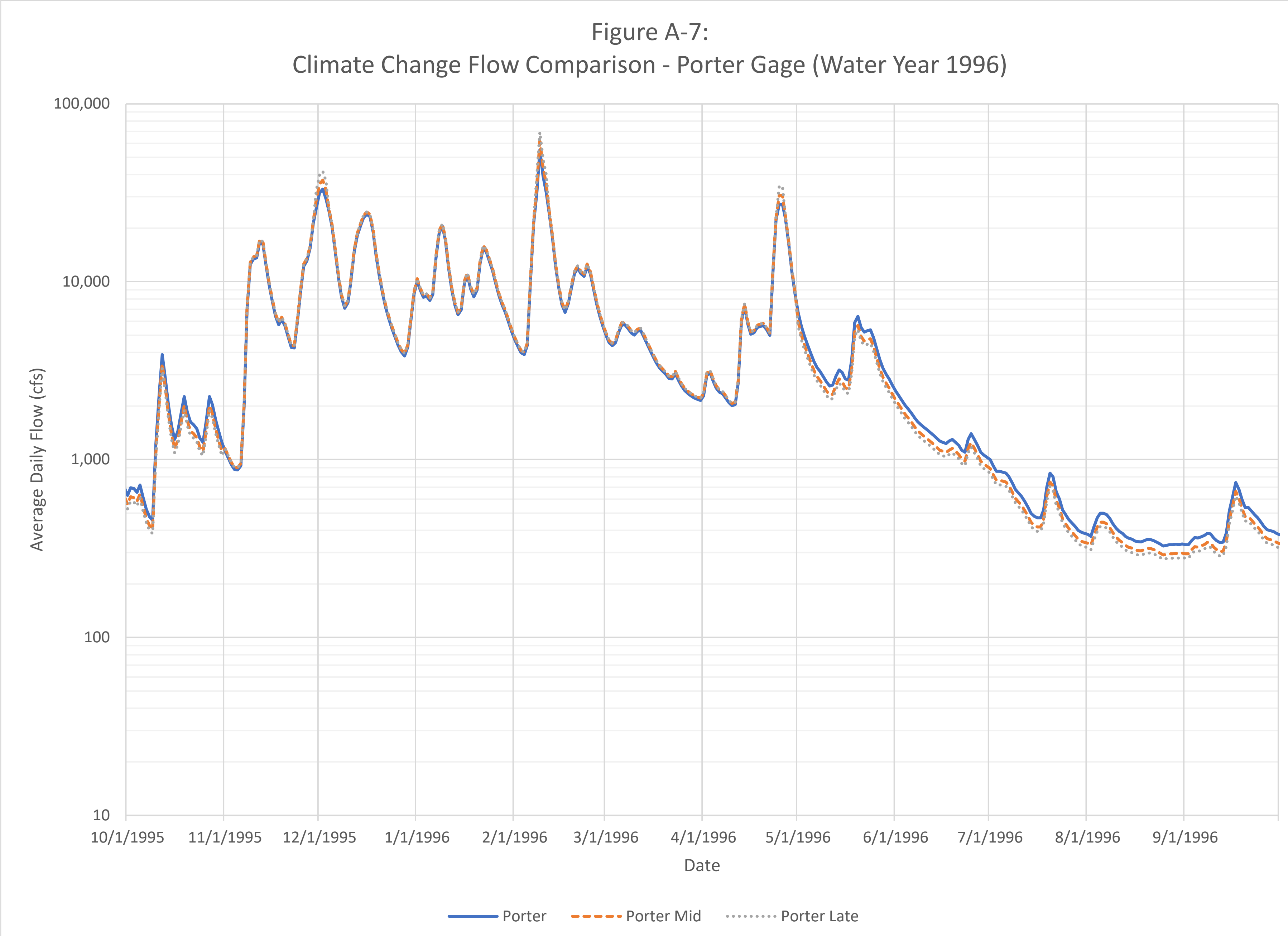


Figure A-7:
Climate Change Flow Comparison - Porter Gage (Water Year 1996)
100,000
10,000
1,000
100
10
Average Daily Flow (cfs)
10/1/1995
11/1/1995
12/1/1995
1/1/1996
2/1/1996
3/1/1996
4/1/1996
5/1/1996
6/1/1996
7/1/1996
8/1/1996
9/1/1996
Date
Porter
Porter Mid
Porter Late

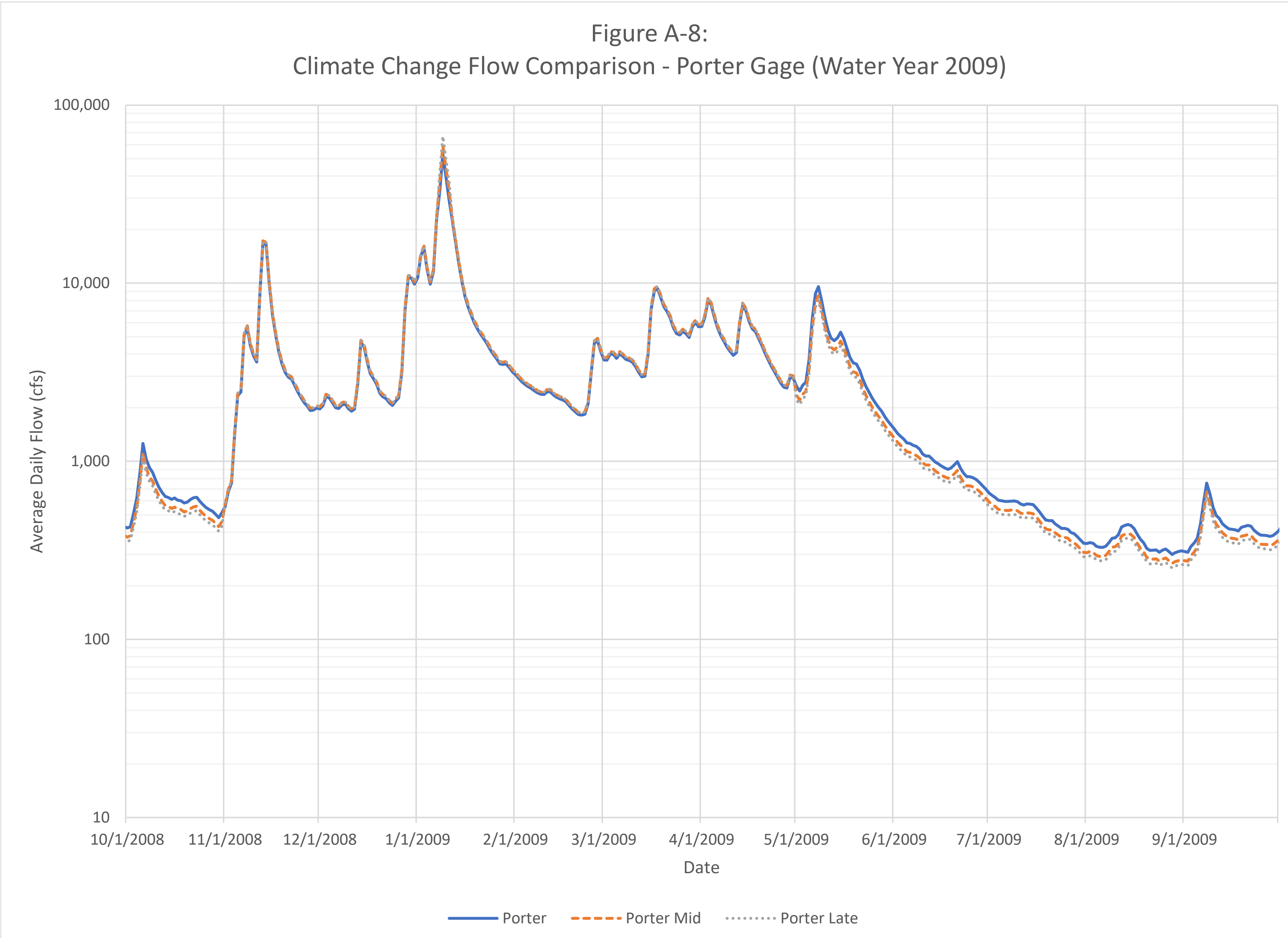


Figure A-8:
Climate Change Flow Comparison - Porter Gage (Water Year 2009)
100,000
10,000
1,000
100
10
Average Daily Flow (cfs)
10/1/2008
11/1/2008
12/1/2008
1/1/2009
2/1/2009
3/1/2009
4/1/2009
5/1/2009
6/1/2009
7/1/2009
8/1/2009
9/1/2009
Date
Porter
Porter Mid
Porter Late

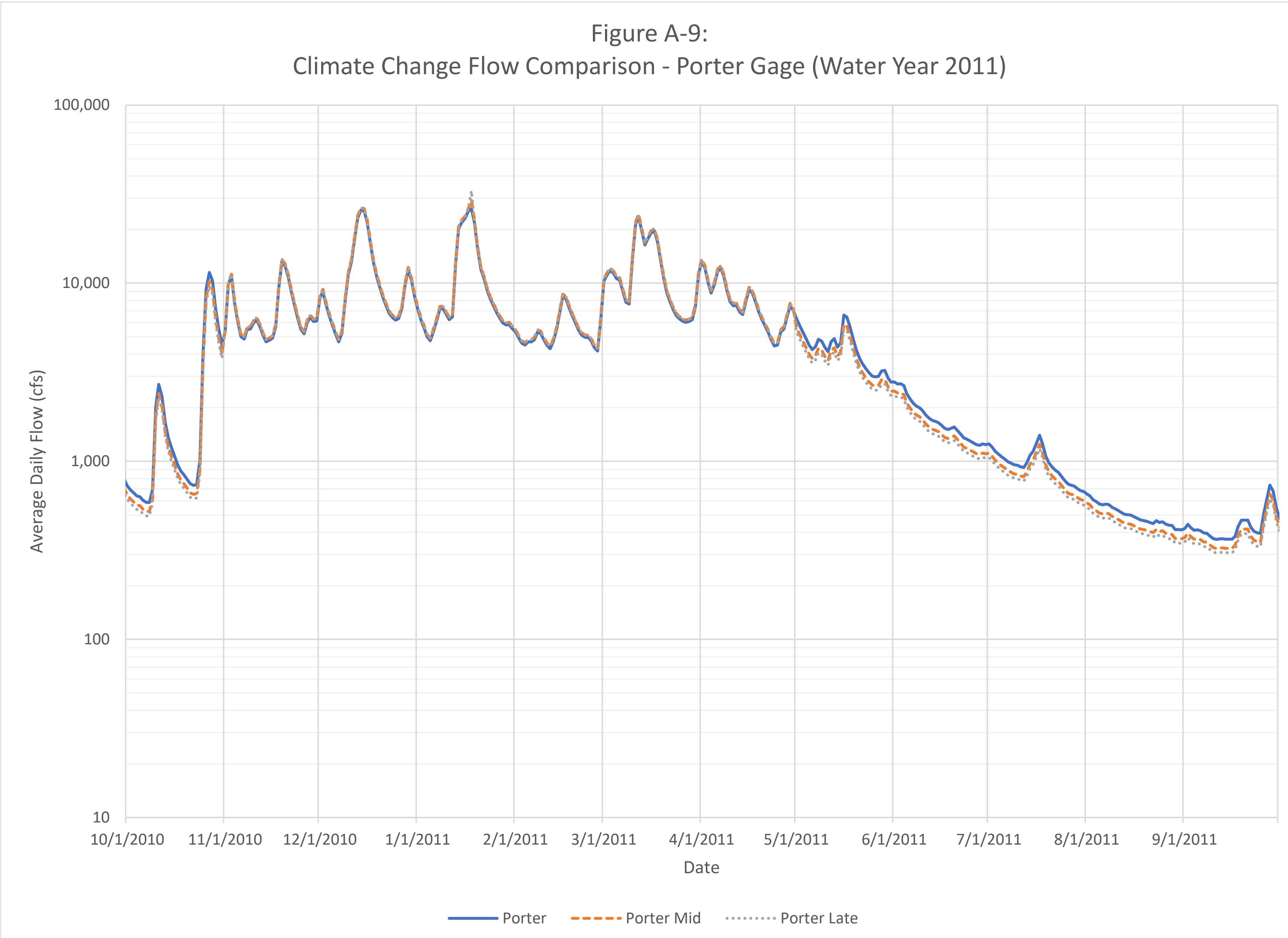


Figure A-9:
Climate Change Flow Comparison - Porter Gage (Water Year 2011)
Average Daily Flow (cfs)
100,000
10,000
1,000
100
10
10/1/2010
11/1/2010
12/1/2010
1/1/2011
2/1/2011
3/1/2011
4/1/2011
5/1/2011
6/1/2011
7/1/2011
8/1/2011
9/1/2011
Date
Porter
Porter Mid
Porter Late

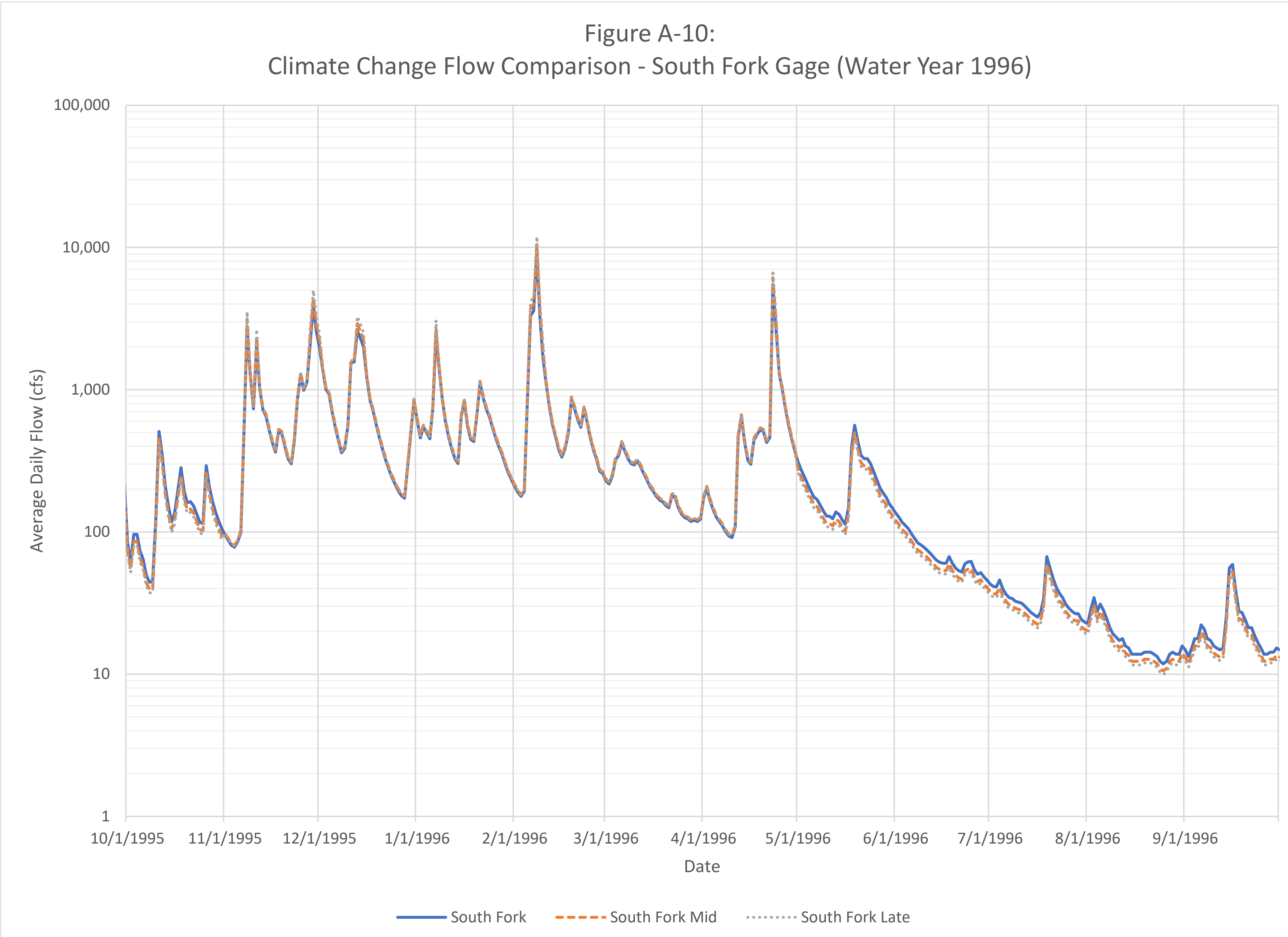
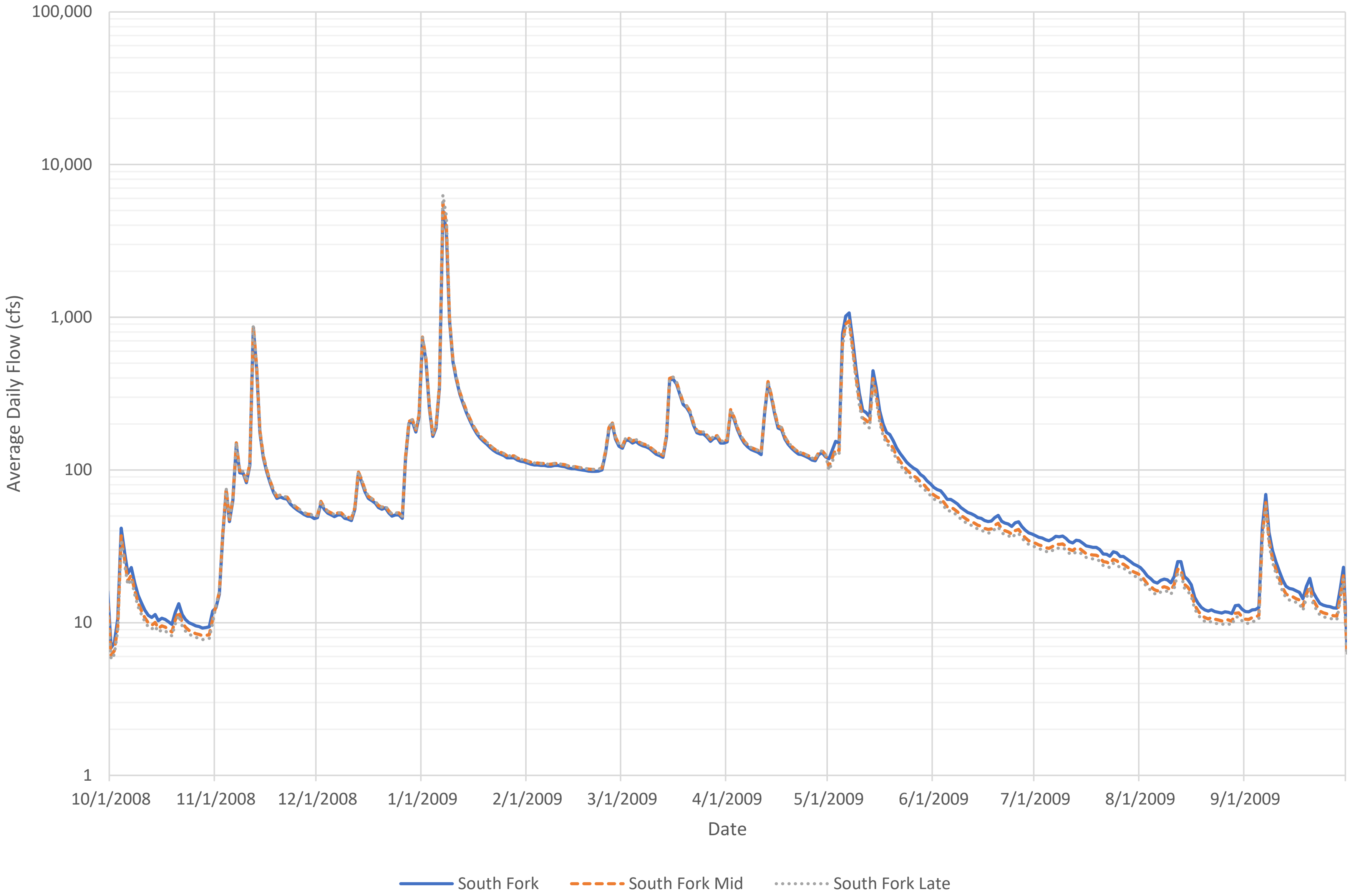


Figure A-10:
Climate Change Flow Comparison - South Fork Gage (Water Year 1996)
100,000
10,000
1,000
100
10
1
Average Daily Flow (cfs)
10/1/1995
11/1/1995
12/1/1995
1/1/1996
2/1/1996
3/1/1996
4/1/1996
5/1/1996
6/1/1996
7/1/1996
8/1/1996
9/1/1996
Date
South Fork
South Fork Mid
South Fork Late

Figure A-11:
Climate Change Flow Comparison - South Fork Gage (Water Year 2009)



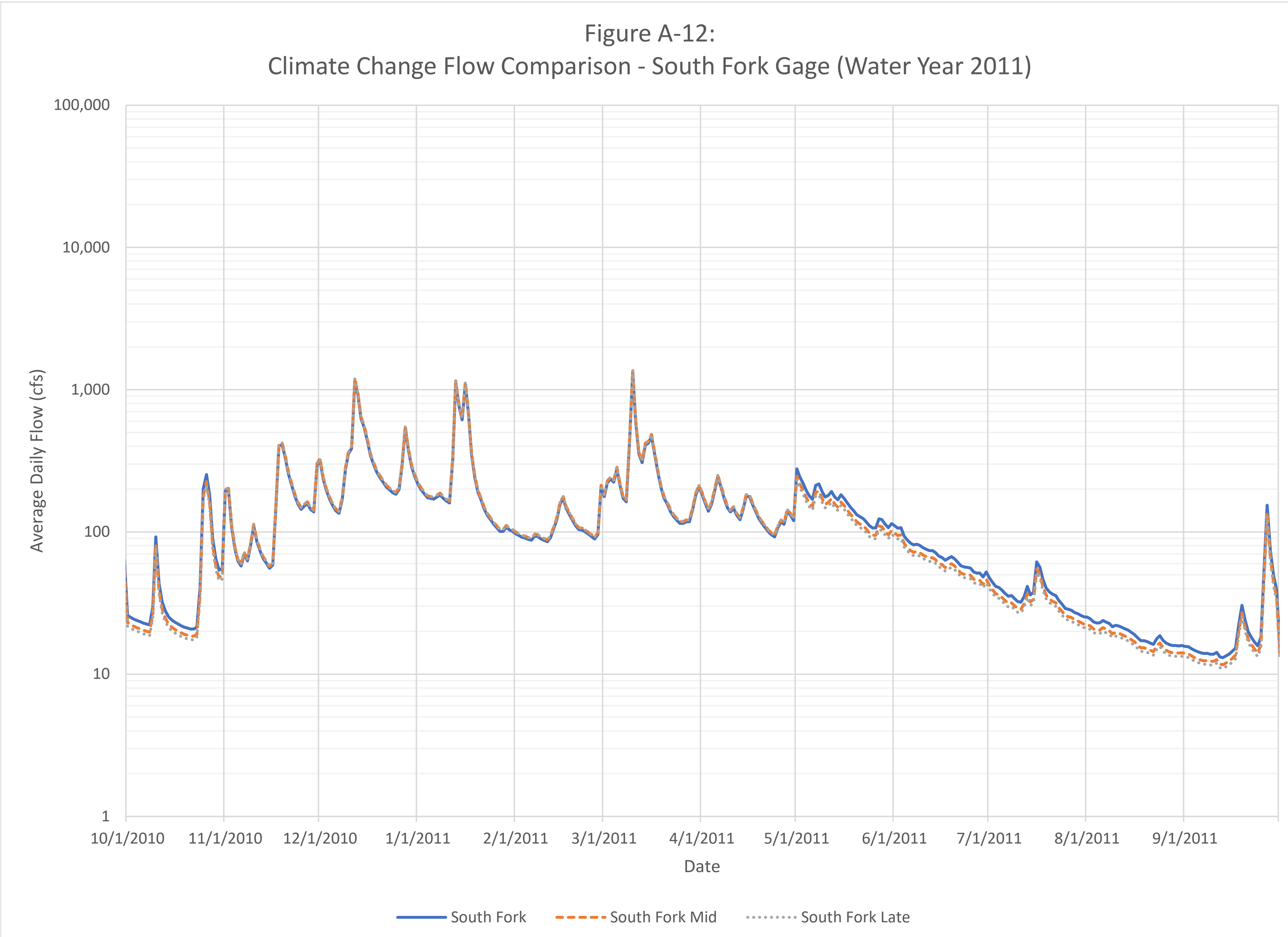


Figure A-12:
Climate Change Flow Comparison - South Fork Gage (Water Year 2011)
100,000
10,000
1,000
100
10
1
Average Daily Flow (cfs)
10/1/2010
11/1/2010
12/1/2010
1/1/2011
2/1/2011
3/1/2011
4/1/2011
5/1/2011
6/1/2011
7/1/2011
8/1/2011
9/1/2011
Date
South Fork
South Fork Mid
South Fork Late

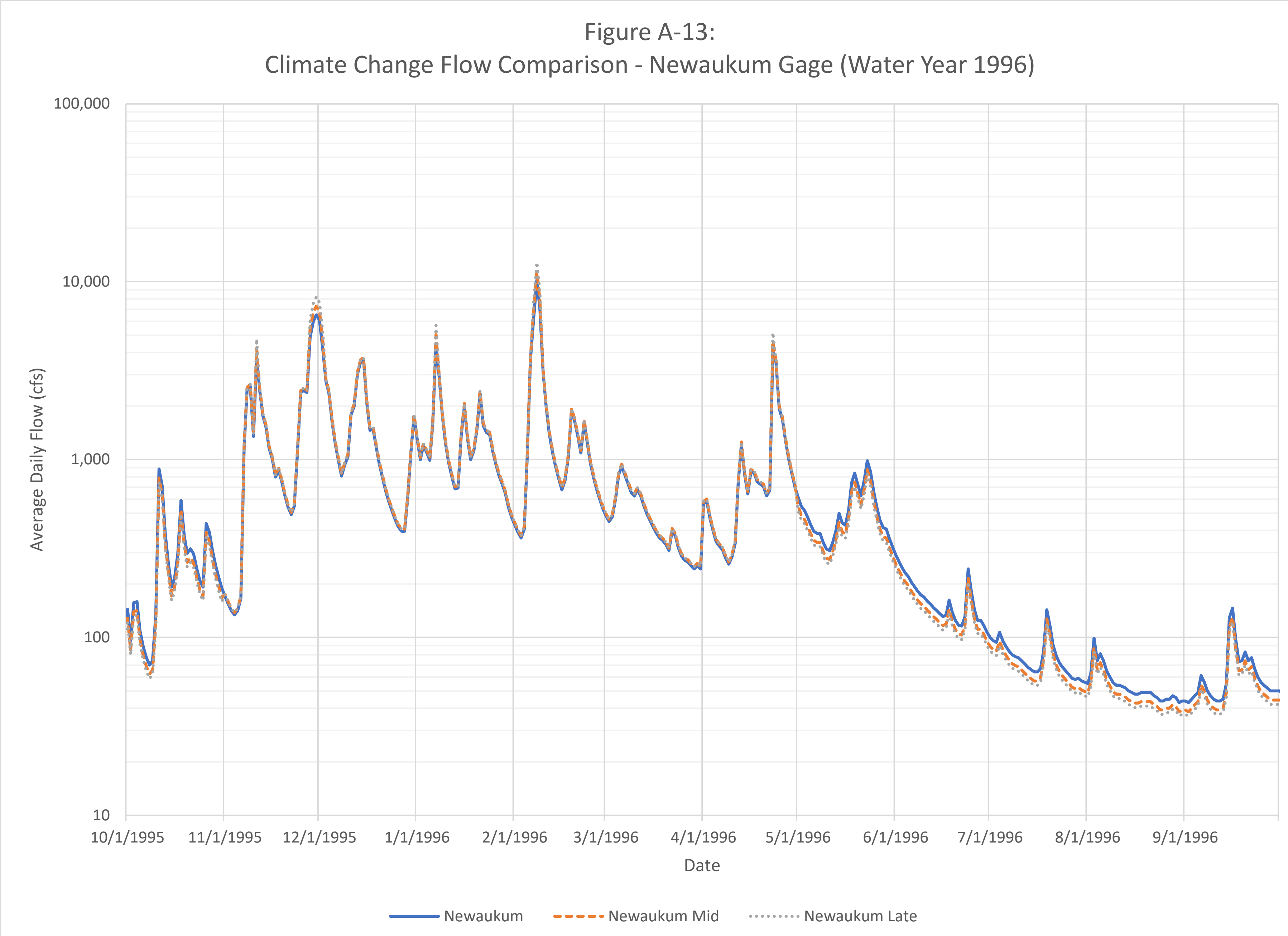


Figure A-13:
Climate Change Flow Comparison - Newaukum Gage (Water Year 1996)
100,000
10,000
1,000
100
10
Average Daily Flow (cfs)
10/1/1995
11/1/1995
12/1/1995
1/1/1996
2/1/1996
3/1/1996
4/1/1996
5/1/1996
6/1/1996
7/1/1996
8/1/1996
9/1/1996
Date
Newaukum
Newaukum Mid
Newaukum Late

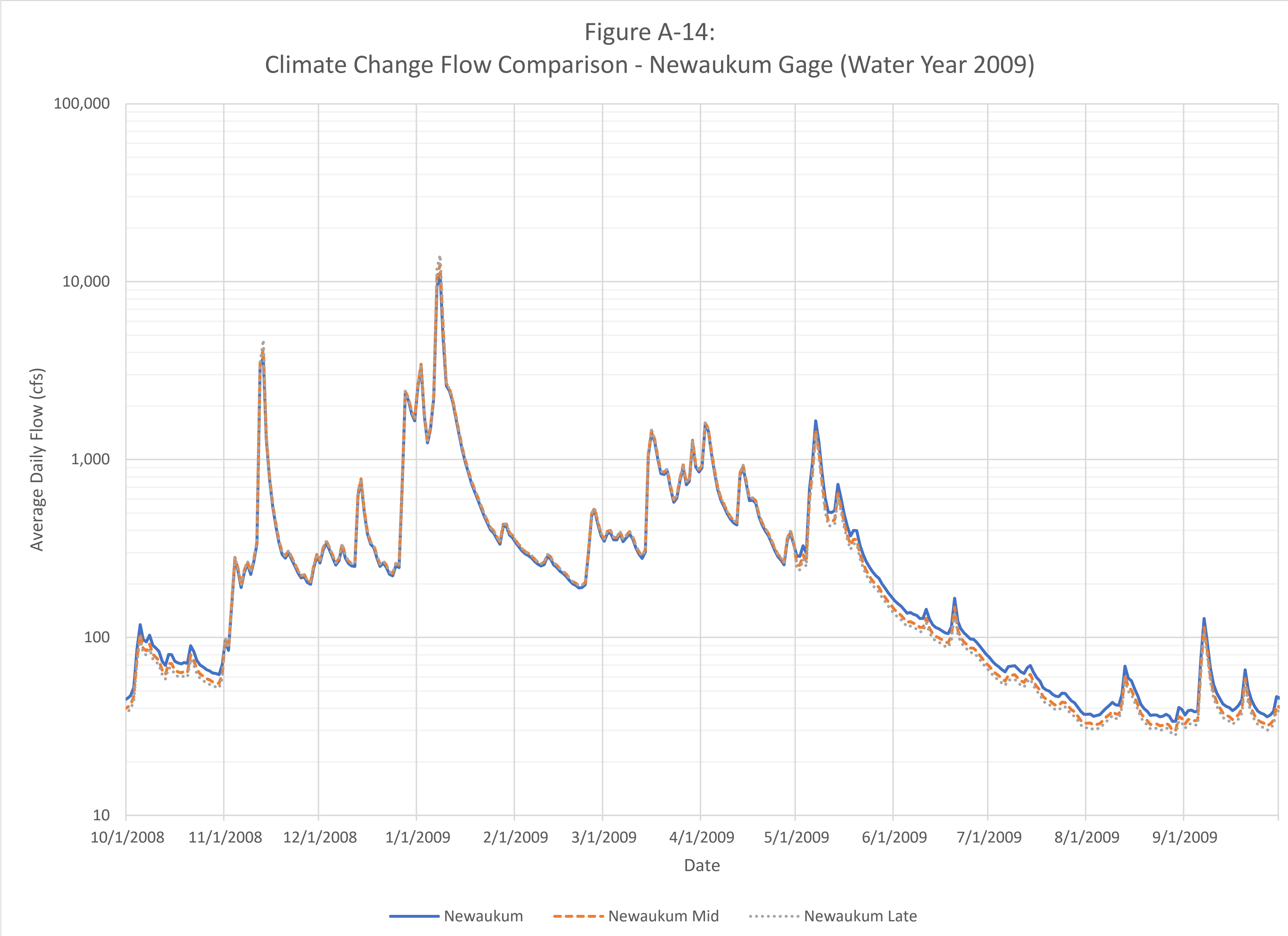


Figure A-14:
Climate Change Flow Comparison - Newaukum Gage (Water Year 2009)
100,000
10,000
1,000
100
10
Average Daily Flow (cfs)
10/1/2008
11/1/2008
12/1/2008
1/1/2009
2/1/2009
3/1/2009
4/1/2009
5/1/2009
6/1/2009
7/1/2009
8/1/2009
9/1/2009
Date
Newaukum
Newaukum Mid
Newaukum Late

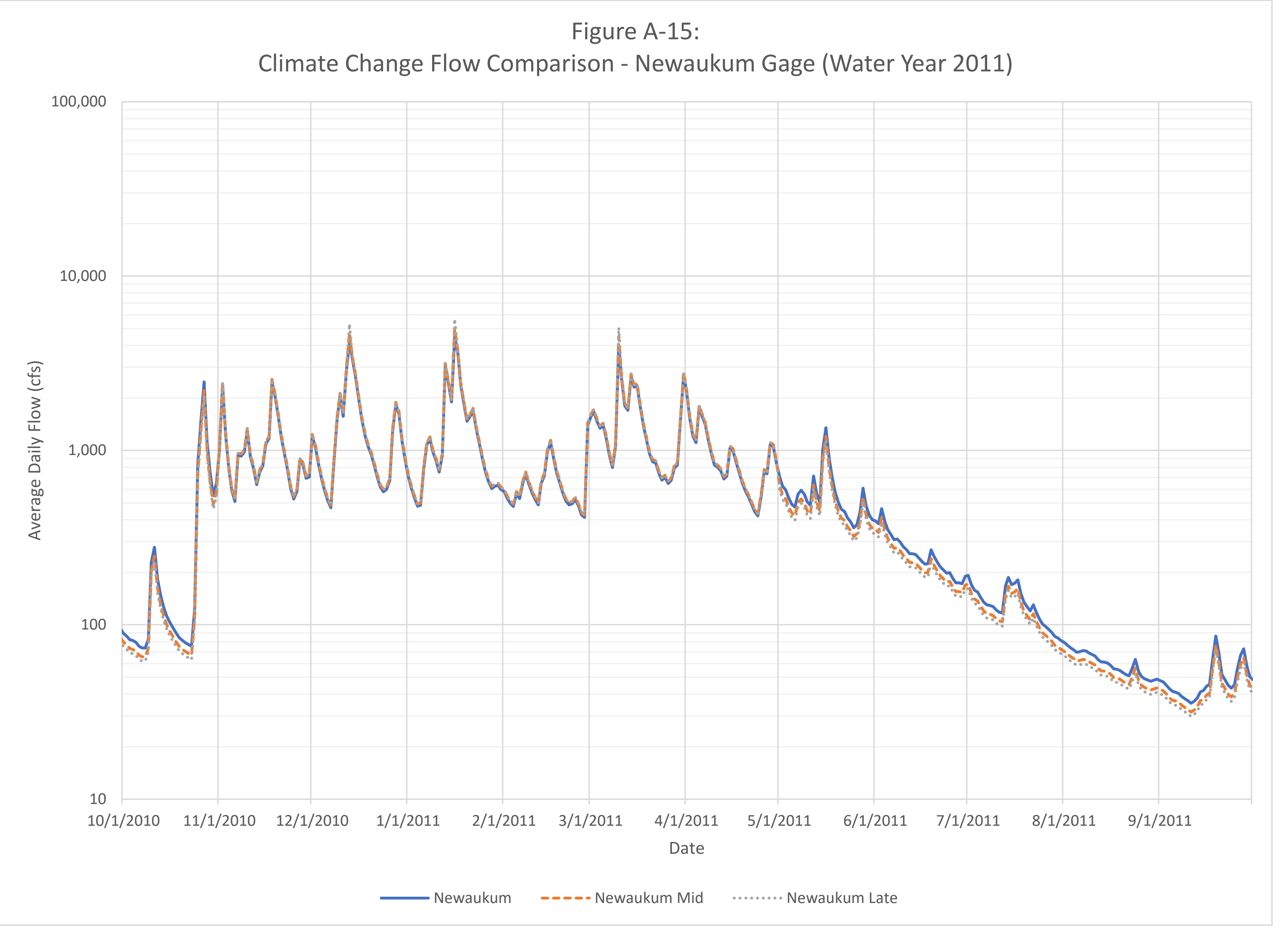


Figure A-15:
Climate Change Flow Comparison - Newaukum Gage (Water Year 2011)
100,000
10,000
1,000
100
10
Average Daily Flow (cfs)
10/1/2010
11/1/2010
12/1/2010
1/1/2011
2/1/2011
3/1/2011
4/1/2011
5/1/2011
6/1/2011
7/1/2011
8/1/2011
9/1/2011
Date
Newaukum
Newaukum Mid
Newaukum Late

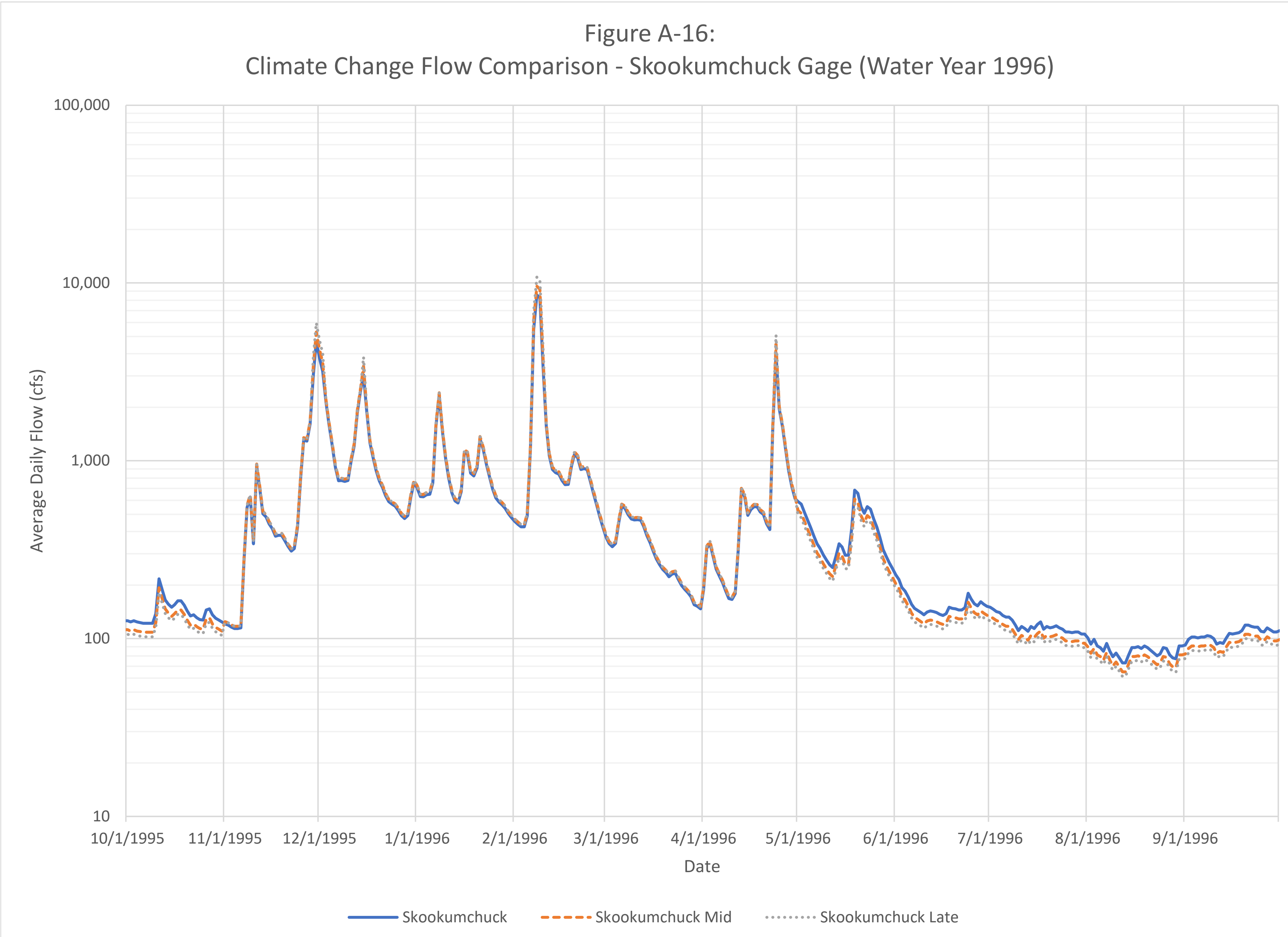
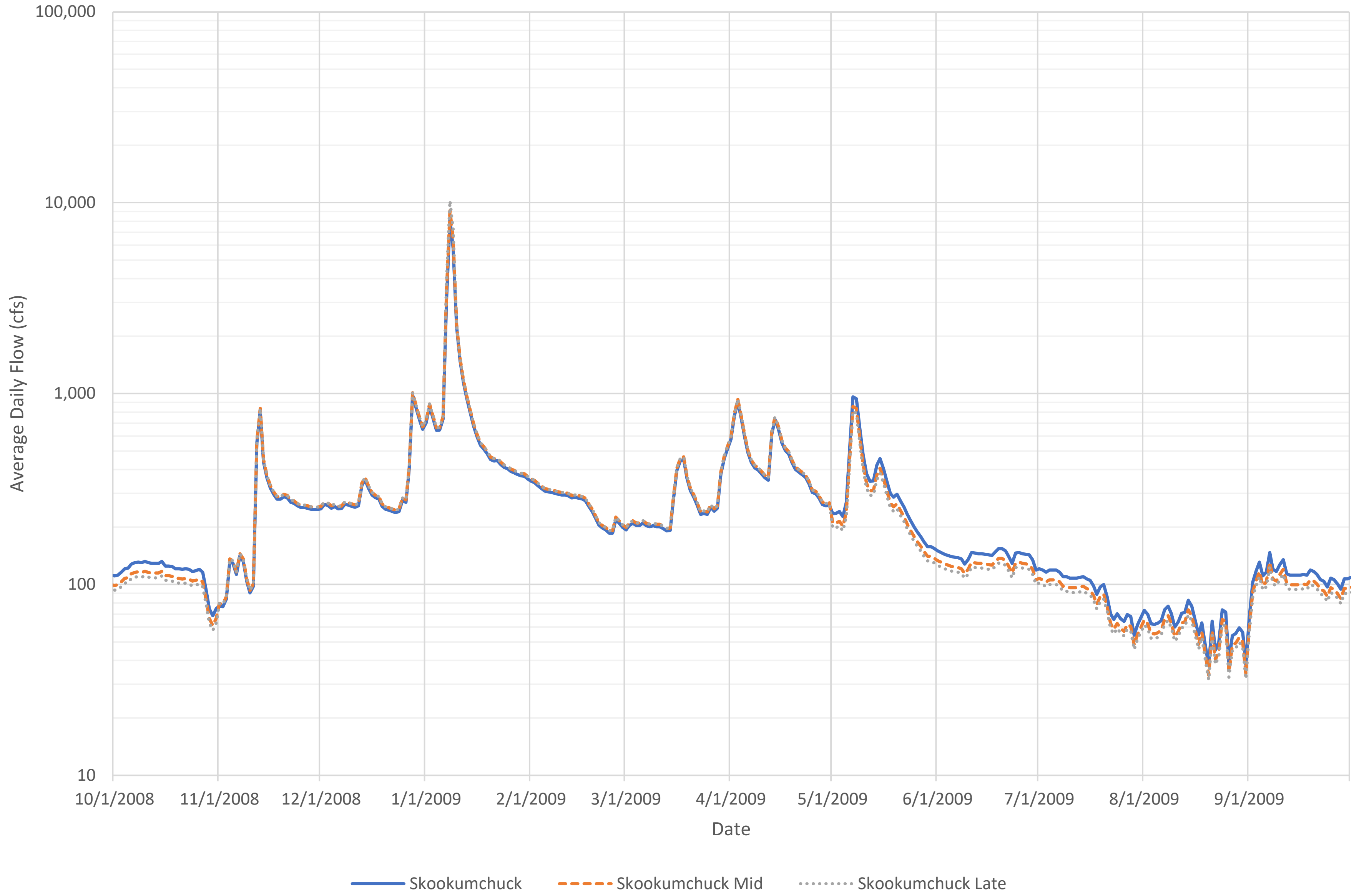


Figure A-16:
Climate Change Flow Comparison - Skookumchuck Gage (Water Year 1996)
100,000
10,000
1,000
100
10
Average Daily Flow (cfs)
10/1/1995
11/1/1995
12/1/1995
1/1/1996
2/1/1996
3/1/1996
4/1/1996
5/1/1996
6/1/1996
7/1/1996
8/1/1996
9/1/1996
Date
Skookumchuck
Skookumchuck Mid
Skookumchuck Late

Figure A-17:
Climate Change Flow Comparison - Skookumchuck Gage (Water Year 2009)



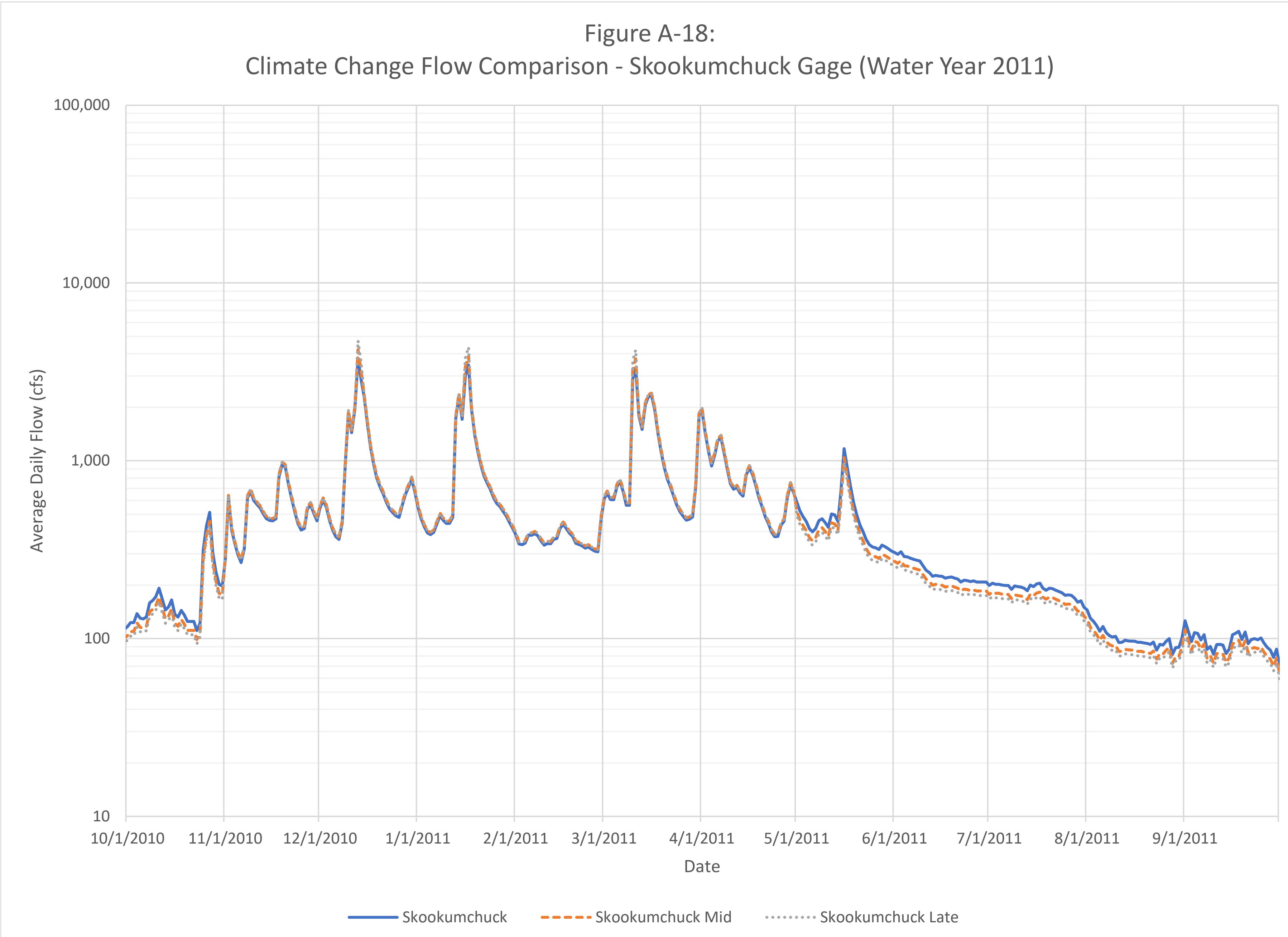


Figure A-18:
Climate Change Flow Comparison - Skookumchuck Gage (Water Year 2011)
100,000
10,000
1,000
100
10
Average Daily Flow (cfs)
10/1/2010
11/1/2010
12/1/2010
1/1/2011
2/1/2011
3/1/2011
4/1/2011
5/1/2011
6/1/2011
7/1/2011
8/1/2011
9/1/2011
Date
Skookumchuck
Skookumchuck Mid
Skookumchuck Late

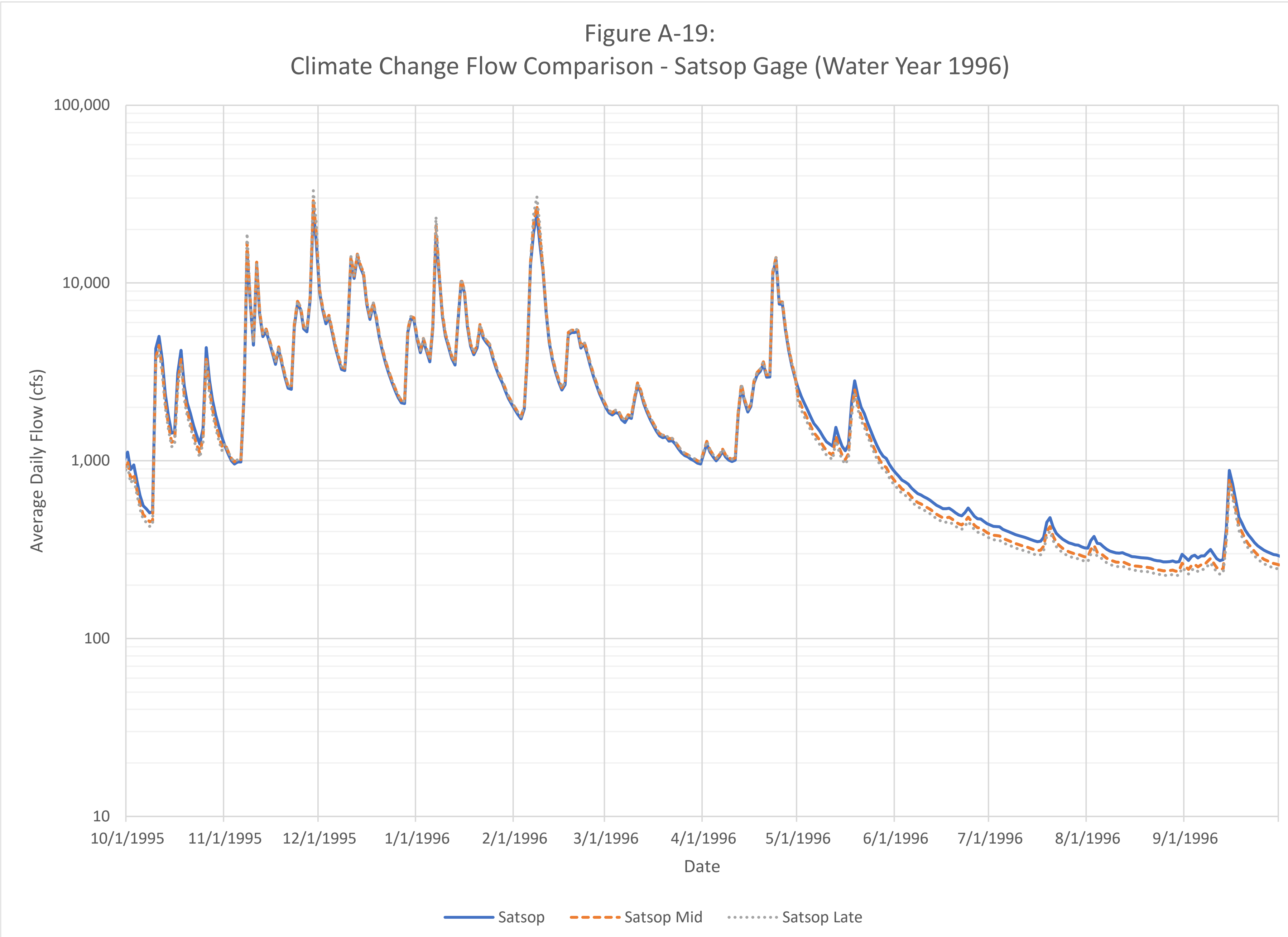


Figure A-19:
Climate Change Flow Comparison - Satsop Gage (Water Year 1996)
100,000
10,000
1,000
100
10
Average Daily Flow (cfs)
10/1/1995
11/1/1995
12/1/1995
1/1/1996
2/1/1996
3/1/1996
4/1/1996
5/1/1996
6/1/1996
7/1/1996
8/1/1996
9/1/1996
Date
Satsop
Satsop Mid
Satsop Late

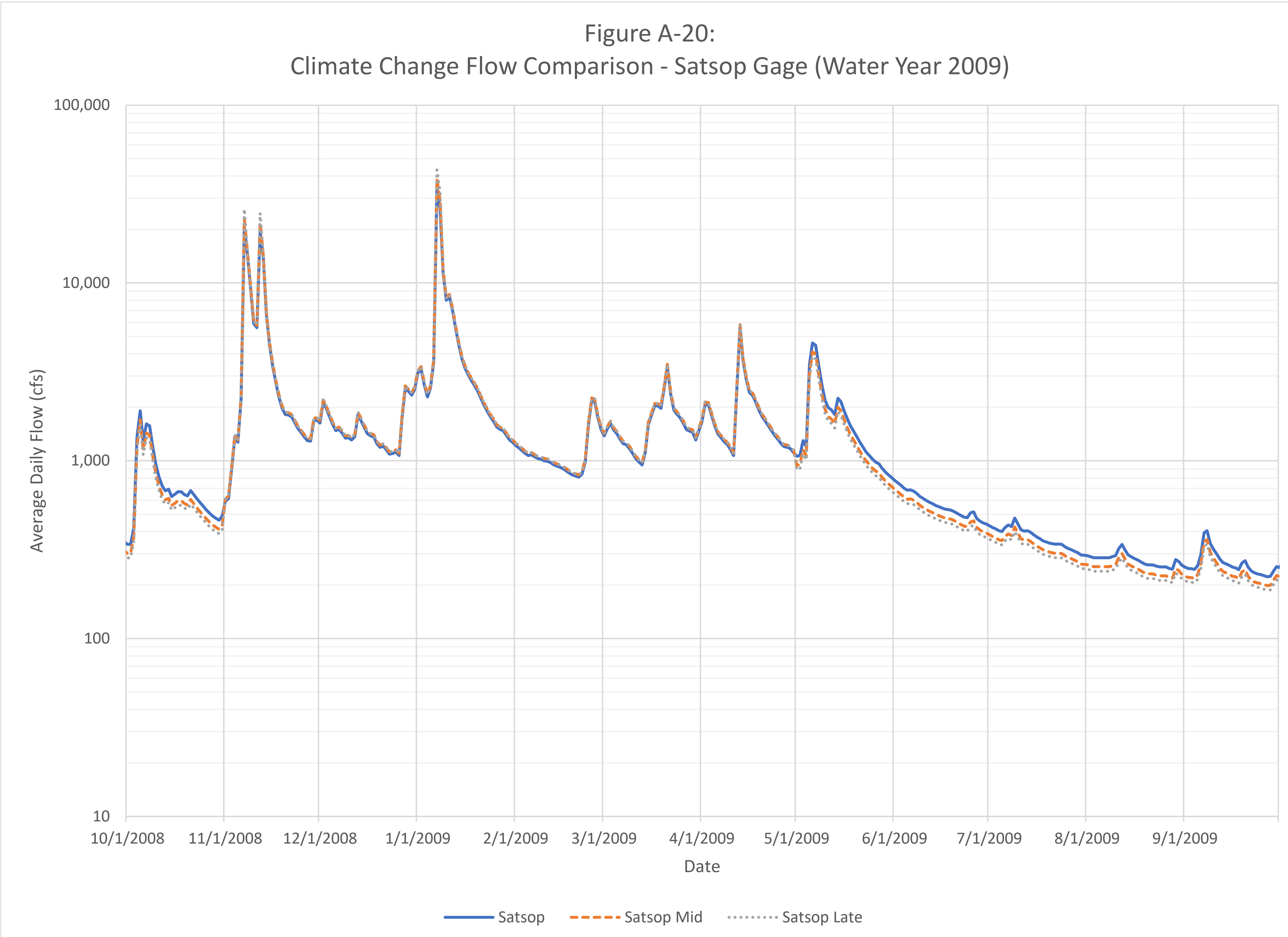
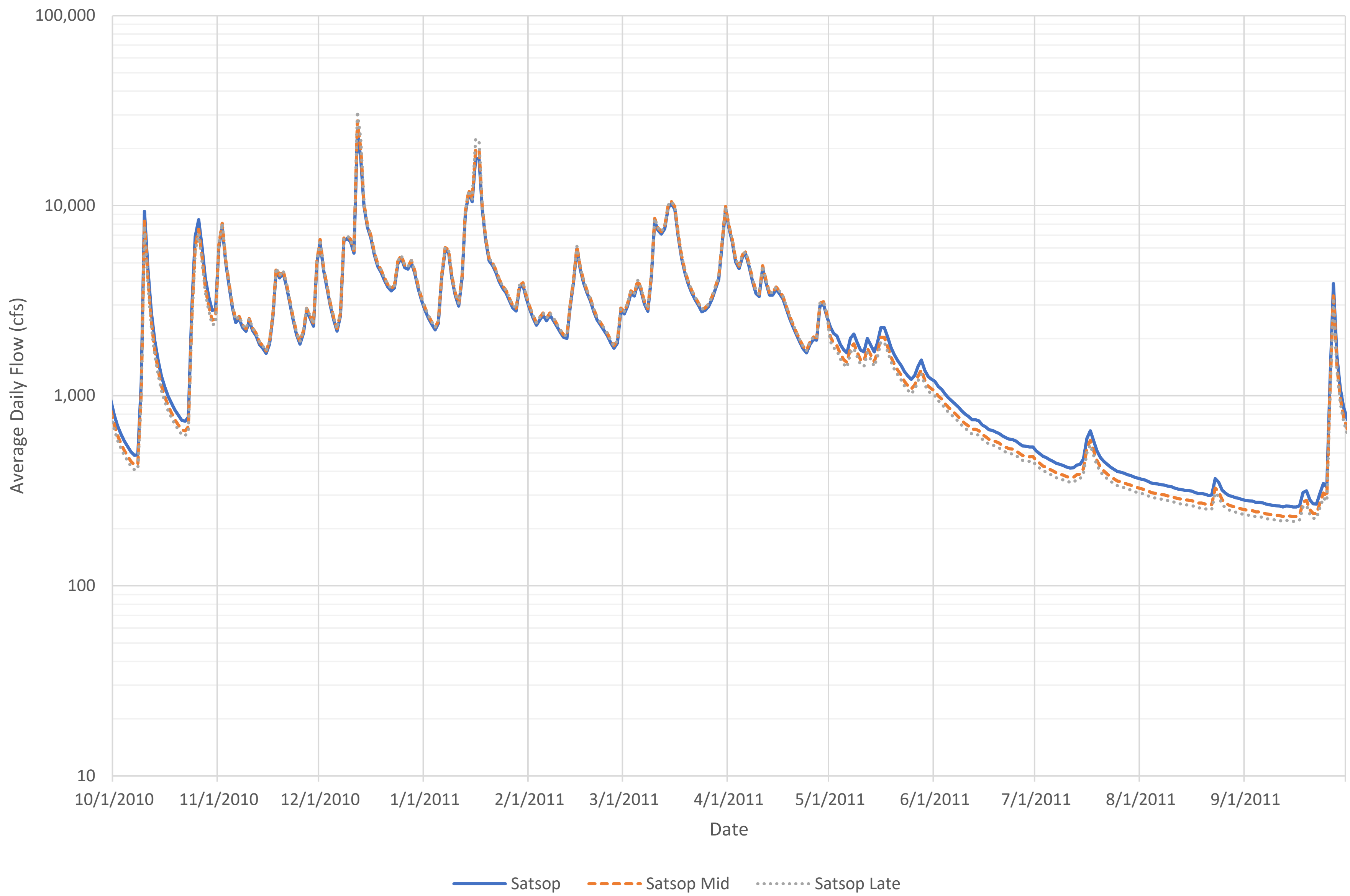


Figure A-20:
Climate Change Flow Comparison - Satsop Gage (Water Year 2009)
100,000
10,000
1,000
100
10
Average Daily Flow (cfs)
10/1/2008
11/1/2008
12/1/2008
1/1/2009
2/1/2009
3/1/2009
4/1/2009
5/1/2009
6/1/2009
7/1/2009
8/1/2009
9/1/2009
Date
Satsop
Satsop Mid
Satsop Late

Figure A-21:
Climate Change Flow Comparison - Satsop Gage (Water Year 2011)



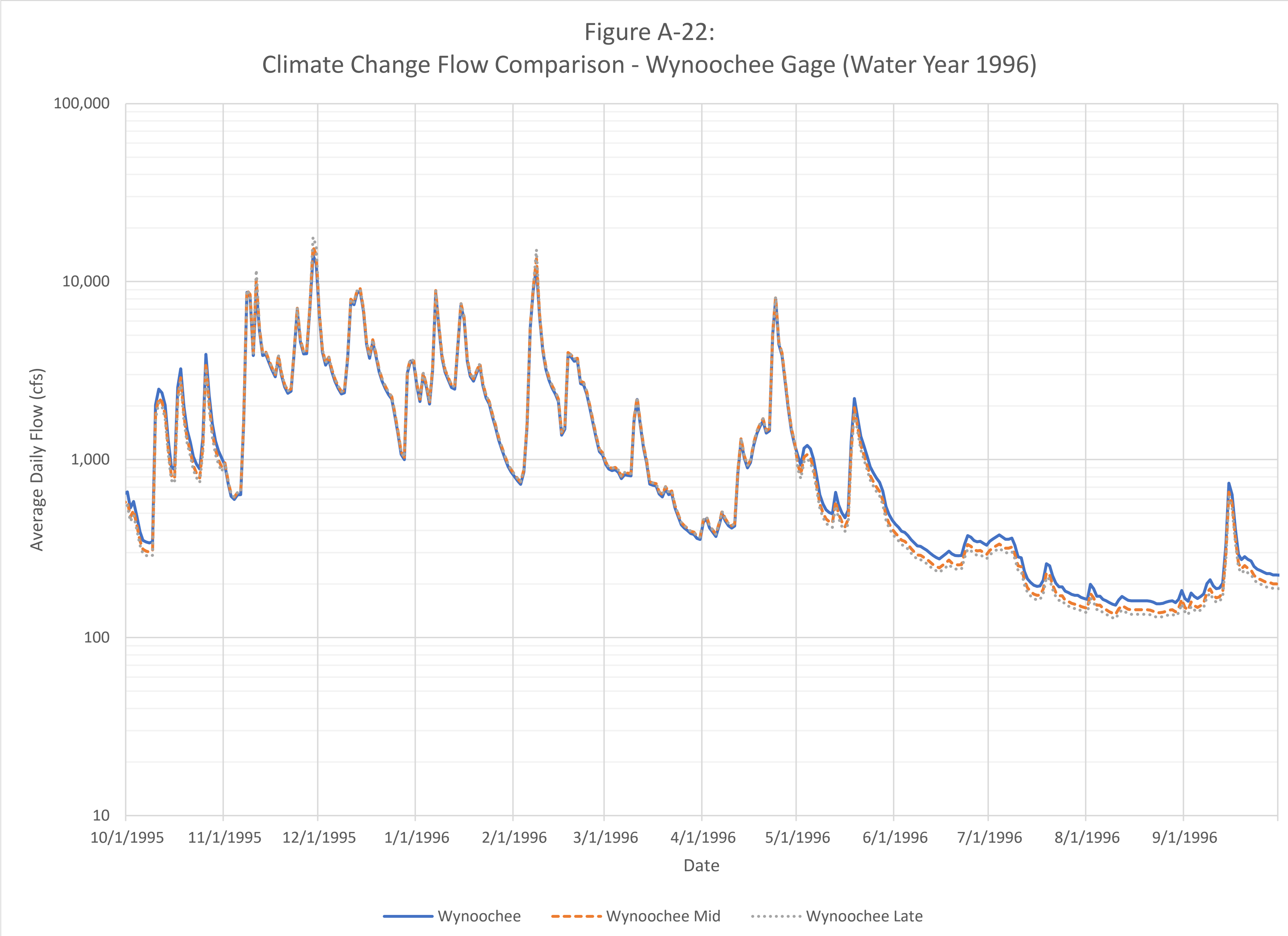


Figure A-22:
Climate Change Flow Comparison - Wynoochee Gage (Water Year 1996)
100,000
10,000
1,000
100
10
Average Daily Flow (cfs)
10/1/1995
11/1/1995
12/1/1995
1/1/1996
2/1/1996
3/1/1996
4/1/1996
5/1/1996
6/1/1996
7/1/1996
8/1/1996
9/1/1996
Date
Wynoochee
Wynoochee Mid
Wynoochee Late

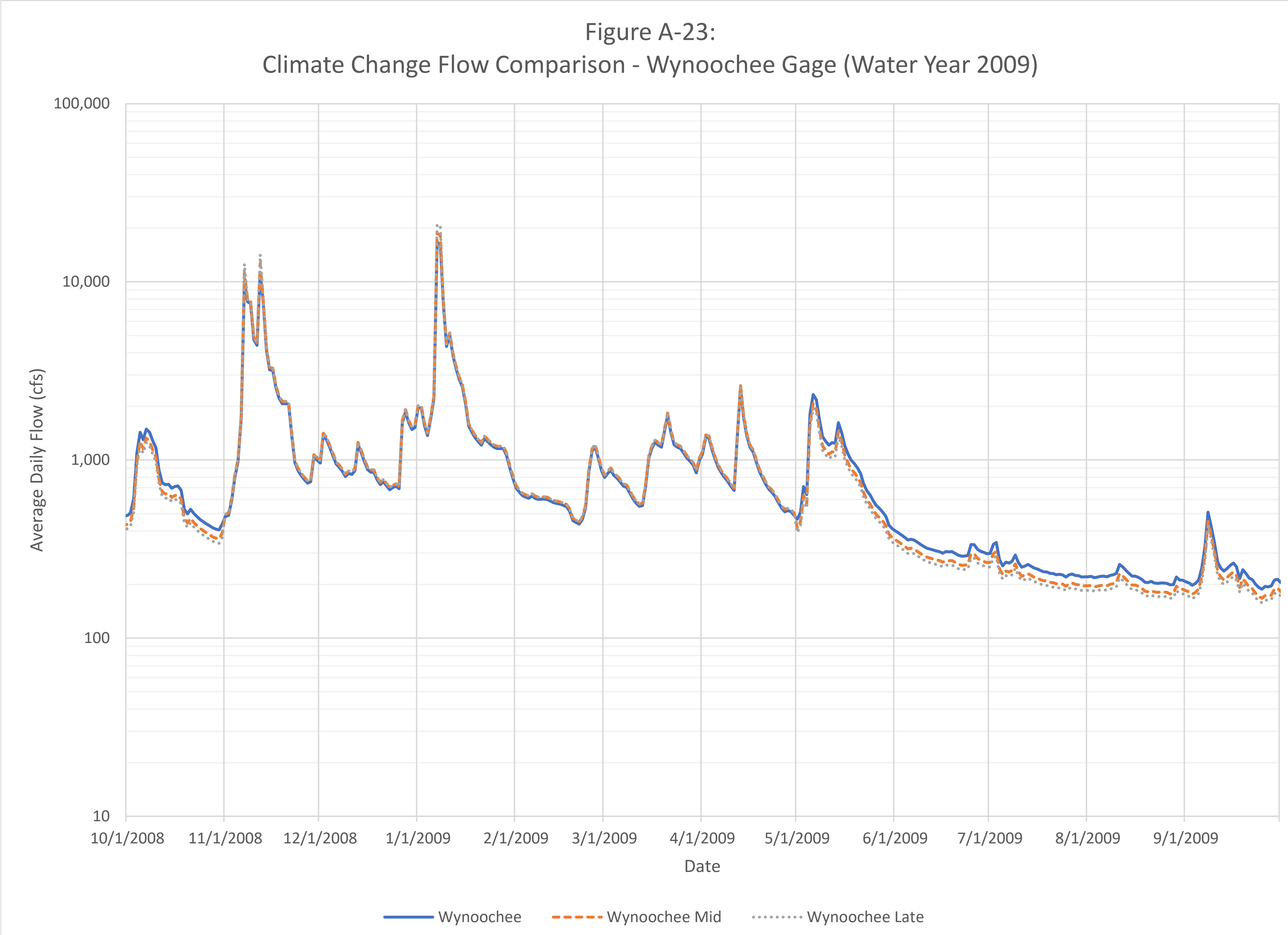


Figure A-23:
Climate Change Flow Comparison - Wynoochee Gage (Water Year 2009)
100,000
10,000
1,000
100
10
Average Daily Flow (cfs)
10/1/2008
11/1/2008
12/1/2008
1/1/2009
2/1/2009
3/1/2009
4/1/2009
5/1/2009
6/1/2009
7/1/2009
8/1/2009
9/1/2009
Date
Wynoochee
Wynoochee Mid
Wynoochee Late

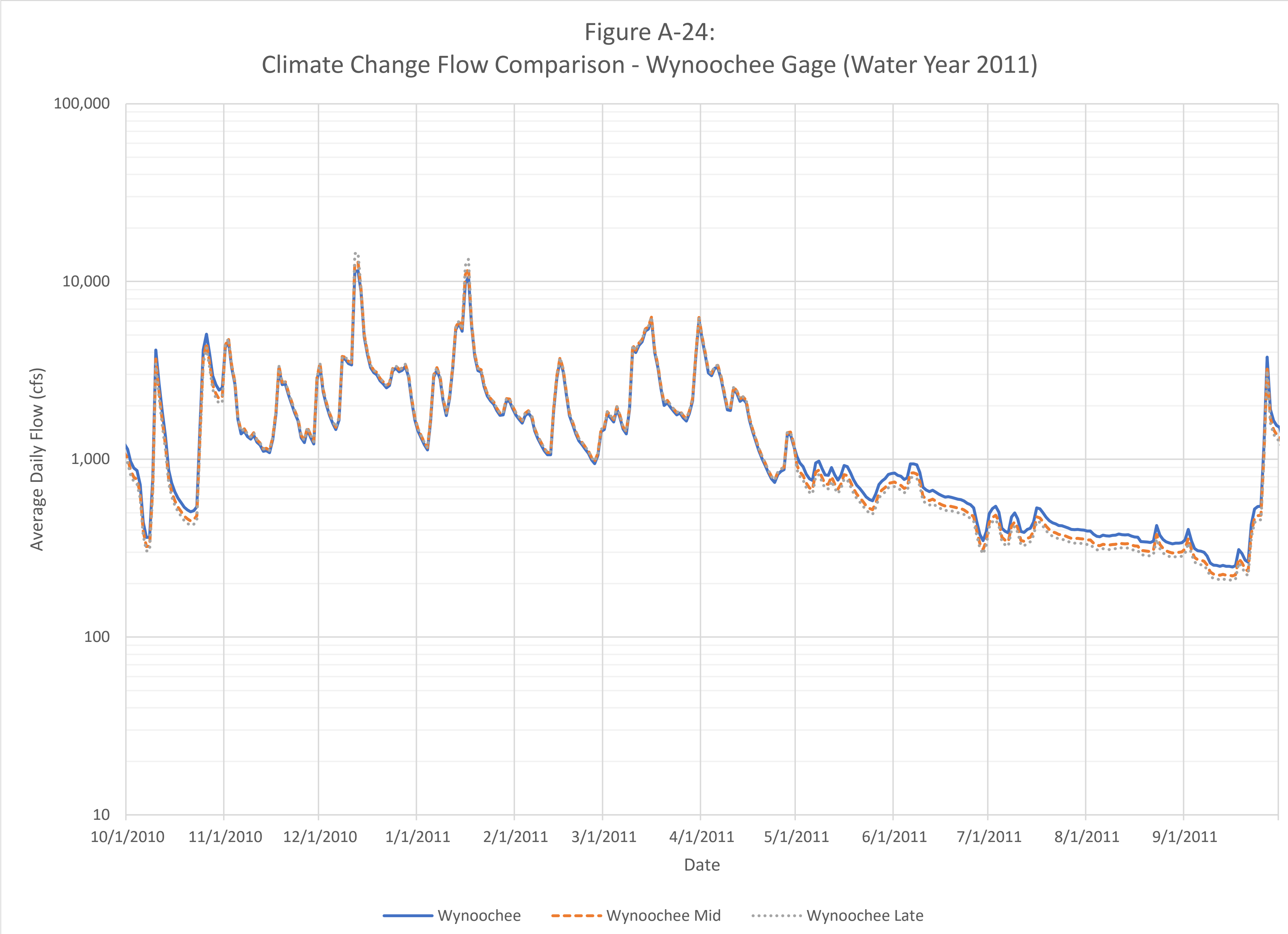


Figure A-24:
Climate Change Flow Comparison - Wynoochee Gage (Water Year 2011)
100,000
10,000
1,000
100
10
Average Daily Flow (cfs)
10/1/2010
11/1/2010
12/1/2010
1/1/2011
2/1/2011
3/1/2011
4/1/2011
5/1/2011
6/1/2011
7/1/2011
8/1/2011
9/1/2011
Date
Wynoochee
Wynoochee Mid
Wynoochee Late

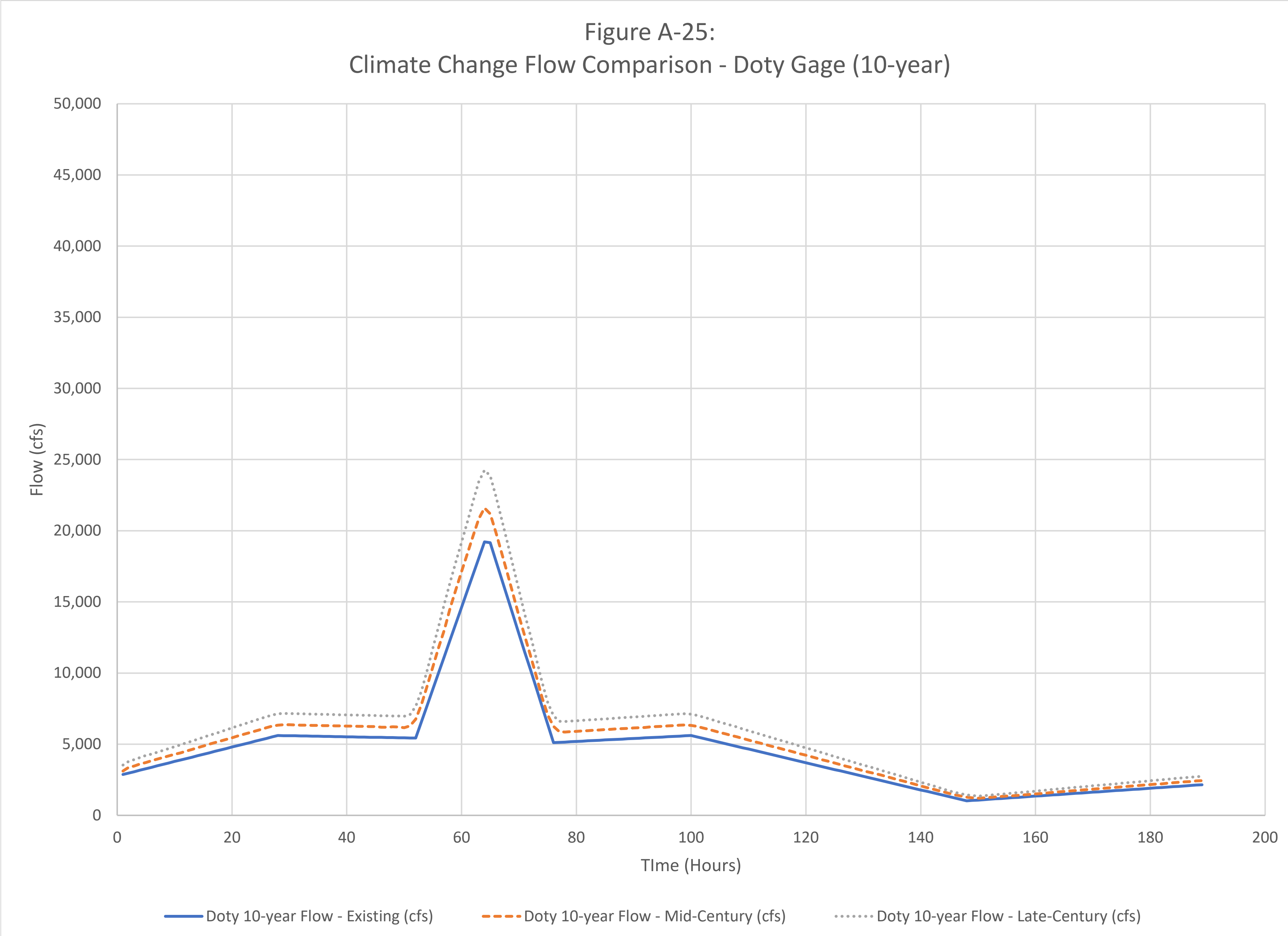


Figure A-25:
Climate Change Flow Comparison - Doty Gage (10-year)
Flow (cfs)
50,000
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
0
20
40
60
80
100
120
140
160
180
200
TIme (Hours)
Doty 10-year Flow - Existing (cfs)
Doty 10-year Flow - Mid-Century (cfs)
Doty 10-year Flow - Late-Century (cfs)

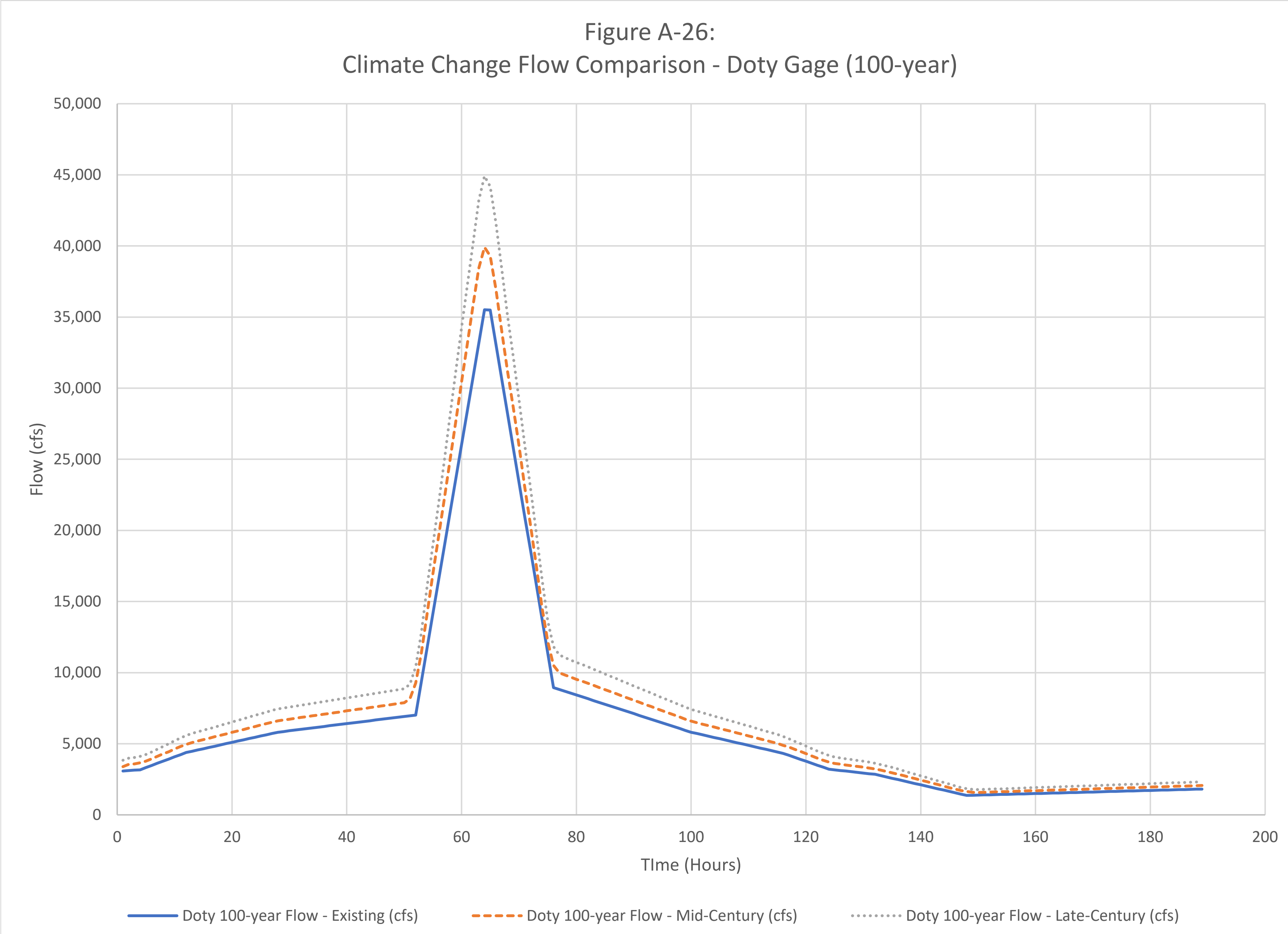


Figure A-26:
Climate Change Flow Comparison - Doty Gage (100-year)
50,000
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
Flow (cfs)
0
20
40
60
80
100
120
140
160
180
200
TIme (Hours)
Doty 100-year Flow - Existing (cfs)
Doty 100-year Flow - Mid-Century (cfs)
Doty 100-year Flow - Late-Century (cfs)

February 4th, 2021

Chehalis Basin: Extreme Precipitation Projections

Guillaume Mauger, Climate Impacts Group, UW

PURPOSE

The purpose of this technical memo is to characterize the spatial distribution of projected increases in extreme precipitation in the Chehalis basin for use in the Chehalis Basin Board's planning as part of the Local Actions Program (LAP). The spatial distribution characterization provided in this memo responds to the Technical Advisory Group's (TAG) request for refined model assumptions that could be used to estimate a reasonable upper range of predicted increases in late-century flood flows throughout the Chehalis Basin for preliminary planning purposes. The TAG's request, in turn, was generated by the Chehalis Basin Board's desire to understand how a 50 percent increase in flood flows in 2080 would differ from the 26 percent increase assumed in the draft SEPA EIS for the proposed flood retention facility/airport levee improvement project.

BACKGROUND

Precipitation projections were obtained from the recent ensemble of simulations developed by Cliff Mass in UW's Atmospheric Sciences department (projections are described in Mauger and Won, 2019 and Lorente-Plazas et al., 2018). These simulations were implemented at an hourly time step, at a spatial resolution of 12 km, spanning the years 1970-2099. Projections were developed for the following 12 global climate models (GCMs), all driven by the high-end RCP 8.5 greenhouse gas scenario (Taylor et al., 2012; Van Vuuren et al., 2011): ACCESS1-0, ACCESS1-3, bcc-csm1-1, CanESM2, CCSM4, CSIRO-Mk3-6-0, FGOALS-g2, GFDL-CM3, GISS-E2-H, MIROC5, MRI-CGCM3, and NorESM1-M.

Since all projections are based on the same greenhouse gas scenario, the results presented here do not reflect uncertainties in future greenhouse gas emissions. As such, the range among projections described below provides an estimate of the model uncertainty, related to physical process understanding and model accuracy.

CLIMATE IMPACTS GROUP

APPROACH

We analyzed projections for three durations (6-hr, 12-hr, and 24-hr) and four return intervals (2-, 10-, 25-, and 100-year events). Following the approach used in the draft SEPA EIS, projected changes are assessed by evaluating the percent change for 2016-2060 (“mid-century”) and 2055-2099 (“late-century”) relative to 1970-2015 (“historical”).

Precipitation statistics are summarized for the entire Chehalis Basin as well as the following sub-basins or mainstem river locations:

- Upper Chehalis River at proposed dam location
- Upper Chehalis River at Doty
- Elk Creek
- South Fork Chehalis River
- Chehalis River Near Adna
- North Fork Newaukum River
- South Fork Newaukum River
- Mainstem Newaukum River
- Skookumchuck River at Dam
- Skookumchuck River at Mouth
- Lincoln Creek
- Chehalis River at Grand Mound
- Scatter Creek
- Black River
- Chehalis River at Porter
- Satsop River
- Chehalis River at Satsop River
- Wynoochee River
- Chehalis River below Wishkah River
- Wishkah River
- Hoquiam River
- Humptulips River

Finally, we compare projected changes in precipitation to projected changes in streamflow based on hydrologic modeling of the GFDL-CM3 climate model projection, developed by Watershed Science & Engineering (WSE, 2019).

RESULTS

Results for all models, time periods, durations, and return intervals are summarized in a spreadsheet that accompanies this technical memo. Our analysis of the results indicates that there is no systematic difference between the results for different precipitation durations. As a result, this memo focuses on the average change across all durations.

Although there does appear to be a systematic increase in the projected change in precipitation at higher return intervals (e.g., the change in the 100-year precipitation is generally greater than the change in the 2-year precipitation), we chose to also average over all return intervals for two reasons: First, changes in streamflow extremes are heavily influenced by antecedent conditions, which means that changes in the 100-year precipitation may not be a reliable predictor of changes in the 100-year flow. This is supported by the comparison with the hydrologic modeling results shown in Table 1 and Figure 1 which show greater variability than the precipitation statistics. Second, the statistics of the 100-year precipitation are extrapolations and are subject to far greater uncertainty than those for more frequent events (e.g., 2-year), and are therefore less reliable.

All projections analyzed show a similar spatial pattern of change, in which changes in upper basin tributaries (e.g., Skookumchuck) are larger than changes in the lower basin tributaries (e.g., Wishkah). Within the upper basin, projected increases are somewhat lower for the Chehalis River above Doty, South Fork Chehalis River, and Newaukum River than for the Skookumchuck River or Scatter Creek. Elk Creek and Lincoln Creek show slightly higher projected increases.

Table 1. Projected change, averaged over both durations and return intervals, for each site. Results are shown for the average and maximum among the 12 climate model projections, as well as for the GFDL model, which was the focus of the 2019 flood study used in the draft SEPA EIS. A final column shows the streamflow projections obtained from WSE for comparison; these are also based on the GFDL model. All changes are expressed as a percent change for late-century (2055-2099) relative to historical (1970-2015).

	Precipitation			Streamflow
	Avg. of all 12 Models	Max. of all 12 Models	GFDL	GFDL
CHEHALIS AT DAM	+19%	+46%	+42%	
CHEHALIS NEAR DOTY	+20%	+49%	+46%	+53%
ELK CREEK	+24%	+67%	+58%	
SF CHEHALIS	+19%	+46%	+42%	+42%
CHEHALIS AT ADNA	+21%	+54%	+49%	
NF NEWAUKUM AT SF	+23%	+51%	+48%	+76%
SF NEWAUKUM AT NF	+22%	+53%	+50%	+56%
NEWAUKUM RIVER	+23%	+51%	+48%	+71%
SKOOKUMCHUCK AT DAM	+21%	+58%	+57%	+53%
SKOOKUMCHUCK AT MOUTH	+24%	+59%	+55%	+69%
LINCOLN CREEK	+28%	+63%	+54%	
CHEHALIS AT GRAND MOUND	+23%	+54%	+50%	+66%
SCATTER CREEK	+26%	+60%	+55%	
BLACK RIVER	+26%	+56%	+47%	
CHEHALIS AT PORTER	+24%	+54%	+48%	+65%
SATSOP RIVER	+20%	+41%	+29%	+41%
CHEHALIS AT SATSOP	+23%	+49%	+43%	+55%
WYNOOCHEE	+19%	+41%	+27%	+19%
CHEHALIS US WISHKAH	+23%	+47%	+42%	+49%
WISHKAH RIVER	+18%	+40%	+27%	
HOQUIAM RIVER	+18%	+37%	+27%	
HUMPTULIPS	+19%	+38%	+25%	+18%
CHEHALIS ENTIRE BASIN	+22%	+43%	+38%	

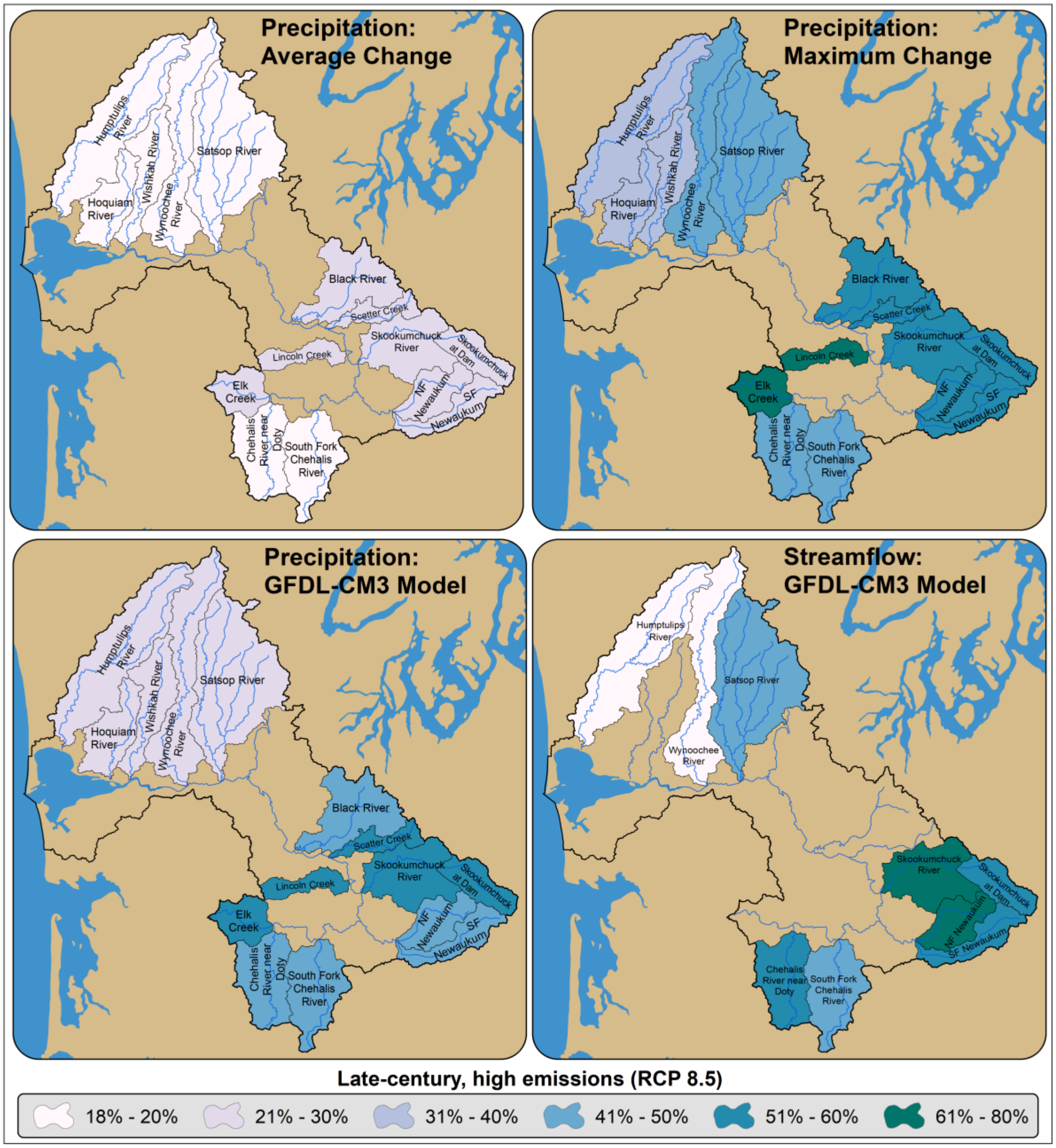


Figure 1. Projected change, averaged over both durations and return intervals, for each site. Only upstream basins are included so as to focus on differences among source watersheds. Results are shown for the average (top left) and maximum (top right) among the 12 climate model projections, as well as for the GFDL model (bottom left), which was the focus of the 2019 flood study used in the draft SEPA EIS. A final map shows the streamflow projections obtained from WSE for comparison (bottom right); these are also based on the GFDL model. All changes are expressed as a percent change for late-century (2055-2099) relative to historical (1970-2015)

CONCLUSIONS

We analyzed precipitation projections from the new ensemble of regional climate model projections produced by UW's Cliff Mass. These are based on the same methods used to develop the projections for the Draft SEPA EIS, and were chosen because research indicates regional climate models are needed to accurately estimate changes in heavy rainfall events.

The results of our analysis show that there are distinct variations in projected precipitation increases across the Chehalis basin and that the differences are relatively consistent among all of the climate models evaluated. This suggests that spatially distributed scaling factors should be used to characterize future flows across the Chehalis basin, as opposed to a single uniform scaling factor across all basins.

We recommend basing the spatially distributed scaling factors on the maximum change projected among the 12 climate models, after averaging over return intervals and durations (Figure 2). We note that the averaging reduces the potential for anomalies in these projections, while using the maximum projection among all of the models ensures that a high-end future flow scenario is considered. Results using these high-end scalars can be considered as a complement to the results with the 26% scaling, as used for the draft SEPA DEIS. The 26% increase is comparable to the average projection among the 12 models evaluated here (Figure 1, top left).

The primary argument against using the maximum increase from the 12-models is that it could exaggerate the change on the mainstem Chehalis River by aggregating the maximum projections on all tributaries. We nonetheless recommend using the 12-model maximum because (a) the results are not very different from those for the GFDL model, and (b) using the maximum ensures that a high-end projection is considered for each sub-basin, whereas the same would not be true if using the GFDL projection alone.

Due to the spatial resolution of the regional climate model, smaller basins were not evaluated in this analysis. We recommend applying scalars to these basins as shown in Figure 2. These were developed based on the spatial distribution shown in Table 1 and Figure 1 above.

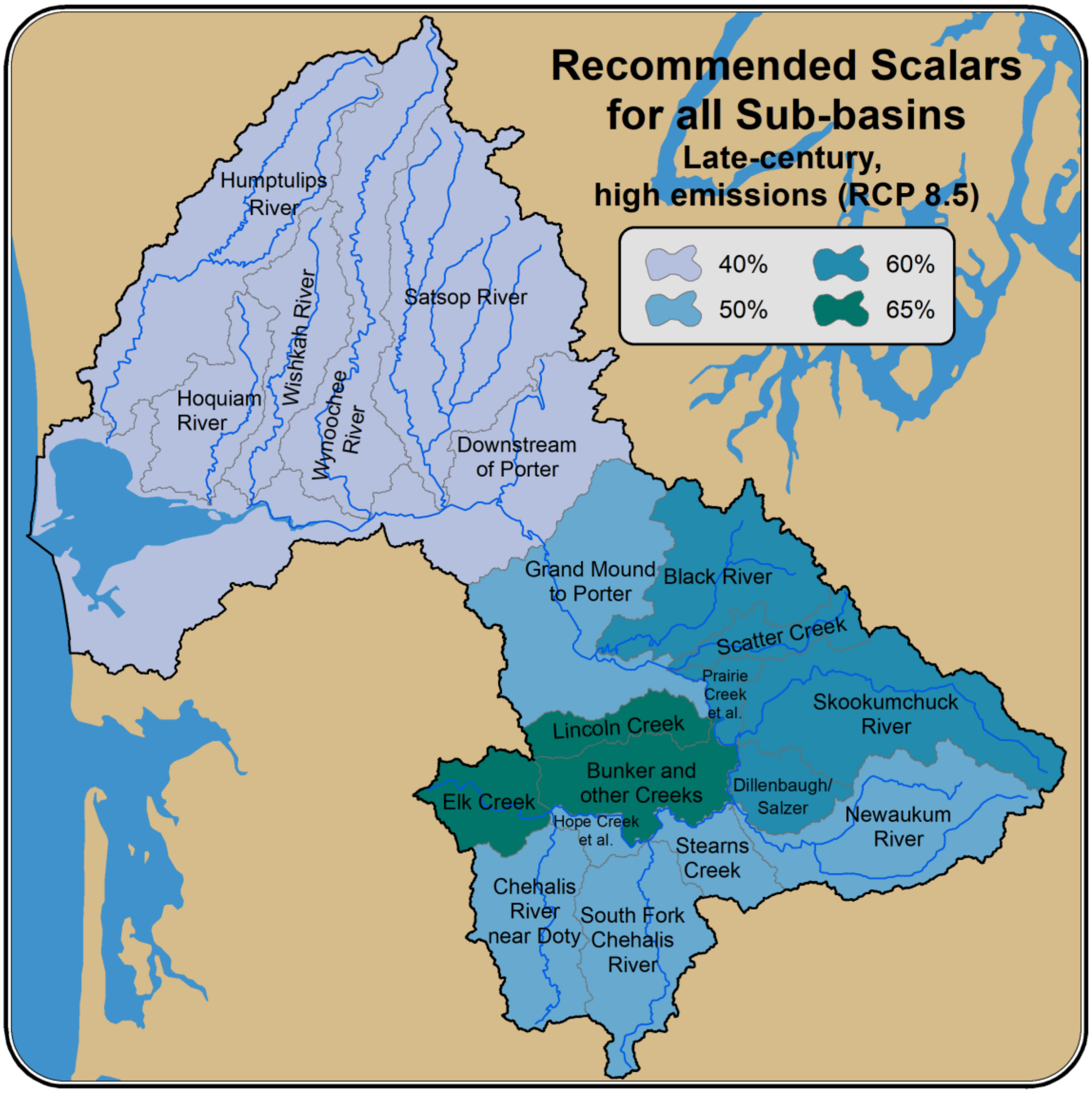


Figure 2. Recommended spatial distribution of scalars representing the high-end projected changes in precipitation for the Chehalis basin. As in Figure 1, all changes are expressed as a percent change for late-century (2055-2099) relative to historical (1970-2015).

REFERENCES

Lorente-Plazas, R., Mitchell, T. P., Mauger, G., & Salathé Jr, E. P. (2018). Local enhancement of extreme precipitation during atmospheric rivers as simulated in a regional climate model. Journal of Hydrometeorology, 19(9), 1429-1446. https://doi.org/10.1175/JHM-D-17-0246.1

Mauger, G.S., J.S. Won, 2019. Expanding the ensemble of precipitation projections for King County. Report prepared for the King County Department of Natural Resources. Climate Impacts Group, University of Washington, Seattle. https://cig.uw.edu/publications/expanding-the-ensemble-of-precipitation-projections-for-king-county/

Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society, 93(4), 485-498. https://doi.org/10.1175/BAMS-D-11-00094.1

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., ... & Rose, S. K. (2011). The representative concentration pathways: an overview. Climatic change, 109(1-2), 5. https://link.springer.com/article/10.1007/s10584-011-0148-z

WSE, 2019. Chehalis River Basin Hydrologic Modeling – Technical Memorandum prepared by WSE for Anchor QEA dated 2/28/2019. Seattle, Washington. Available from: https://chehalisbasinstrategy.com/wp-content/uploads/2019/04/20190228_Memo_Chehalis_Chehalis-River-Basin-Hydrologic-Modeling.pdf

DRAFT MEMORANDUM

Date: February 9, 2022
To: Ann Costanza, Anchor QEA
From: Larry Karpack, Watershed Science and Engineering
cc: Adam Hill and Heather Page, Anchor QEA
Re: Mid-Century High End Climate Change Hydraulic Modeling Scenario

Numerical modeling was conducted to provide data for evaluation of hydraulic conditions in the Chehalis River basin corresponding to a mid-century (2016-2060) high end climate change scenario. The mid-century hydraulic simulations were performed using the same RiverFlow2D model previously used to evaluate conditions under existing hydrology (1970-2015) and late century (2055-2099) climate change scenarios (WSE, 2019). Hydrologic data for the mid-century high end climate scenario were developed by scaling the existing condition hydrologic inputs in a similar manner to what was done for the late-century high end climate scenario (Mauger, 2021).

Analyses of precipitation frequency and flow frequency statistics for the mid-century scenario were completed and compared to existing and late-century conditions. Table 1 shows the projected changes in precipitation and flow frequency statistics for the mid-century high end climate scenario. Table 2, adapted from Mauger 2021, shows the corresponding results for the late-century high end climate scenario. As shown in Table 1 the mid-century high end climate scenario predicts an average increase in precipitation of 37% compared to existing precipitation quantiles, when considering all sub-basins and the maximum of all global climate models (GCMs), or 35% increase when considering only the GFDL GCM. These results compare to the previously estimated late-century high end climate scenario increases of 50% for all GCMs and 44% for GFDL. From the hydrologic model simulations, using the GFDL GCM meteorological inputs, the mid-century high end flow increases averaged 30% at mid-century, versus 52% at late century. Differences between precipitation frequency results and flow frequency results, particularly at the mid-century, are attributed to several factors, including “noise” in the mid-century data among the different GCMs and non-linearities in the rainfall-runoff response.

The spatial distribution of precipitation and streamflow changes seen in the mid-century high end climate scenario results are somewhat different from the previously reported late-century results, and there is less spatial coherence for the mid-century scenario. Discussions with CIG indicate that this lack of coherence is likely a result of noise in the mid-century frequency results among the various GCMs, with this noise being less pronounced in the late century results. Because the mid-century results do not show a well-defined and consistent spatial pattern across the different metrics evaluated, the spatial pattern for mid-century analyses was taken to be the same as the late century pattern. Therefore, only the magnitude of the scalars were changed between the late-century and mid-century scenarios; all were changed by the ratio of the mid-century to late-century flow change across all basins for the GFDL scenario (29.9/52.4 or 0.57). Thus, the mid-century high end climate scenario hydrologic inputs were developed by scaling the historical inputs by 57% of the late century high end projected increases. The resulting scalars are shown in Figure 1.

The RiverFlow2D hydraulic model was configured using hydrologic inputs developed as described above. Runs were made for the mid-century high end 10-year and 100-year flood events for the No Action and with Project conditions. Results of these runs, in the form of spatially referenced water surface elevations, flow depths, and flow velocities were provided for use in other analyses.

References

Mauger, G.S., 2021, Chehalis Basin: Extreme Precipitation Projections, Memorandum prepared for the Office of the Chehalis Basin, Climate Impacts Group, University of Washington, Seattle, February 4, 2021.

WSE, 2019. Chehalis River Existing Conditions RiverFlow2D Model Development and Calibration. Technical Memorandum to Bob Montgomery, Anchor QEA, LLC, February 28, 2019.

Table 1
Mid-century (2016-2060) projected change, averaged over both durations and recurrence intervals, for each site. Results are shown for the average and maximum among the 12 global climate model projections, as well as for the GFDL model alone, which was the focus of the 2019 hydrologic modeling used in the draft SEPA EIS. A final column shows the streamflow projections based on the DHSVM simulations of the GFDL GCM (WSE, 2019). All projections are expressed as a percent change for mid-century (2016-2060) relative to historical (1970-2015) conditions.

	PRECIPITATION			FLOW
	AVERAGE OF ALL 12 MODELS	MAXIMUM OF ALL 12 MODELS	GFDL	GFDL
CHEHALIS AT DAM	7	29	24	
CHEHALIS NEAR DOTY	8	35	30	+22
ELK CREEK	9	51	48	
SF CHEHALIS	6	31	26	+19
CHEHALIS AT ADNA	8	40	37	
NF NEWAUKUM AT SF	8	31	30	+44
SF NEWAUKUM AT NF	7	25	24	+24
NEWAUKUM RIVER	8	29	29	+37
SKOOKUMCHUCK AT DAM	7	36	36	+25
SKOOKUMCHUCK AT MOUTH	11	49	49	+44
LINCOLN CREEK	13	58	58	
CHEHALIS AT GRAND MOUND	9	41	41	+47
SCATTER CREEK	14	59	59	
BLACK RIVER	13	49	49	
CHEHALIS AT PORTER	10	42	42	+43
SATSOP RIVER	8	27	23	+27
CHEHALIS AT SATSOP	10	37	37	+35
WYNOOCHEE	8	23	20	+8
CHEHALIS US WISHKAH	9	35	35	+32
WISHKAH RIVER	8	27	22	
HOQUIAM RIVER	10	30	25	
HUMPTULIPS	8	22	19	+12
CHEHALIS ENTIRE BASIN	10	33	32	
Basinwide Average	9	37	35	+29.9

Table 2 (excerpted from Mauger, 2021).
Late-century (2055-2099) projected change, averaged over both durations and recurrence intervals, for each site. Results are shown for the average and maximum among the 12 global climate model projections, as well as for the GFDL model alone, which was the focus of the 2019 hydrologic modeling used in the draft SEPA EIS. A final column shows the streamflow projections based on the DHSVM simulations of the GFDL GCM (WSE, 2019). All projections are expressed as a percent change for late-century (2055-2099) relative to historical (1970-2015) conditions.

	PRECIPITATION			FLOW
	AVERAGE OF ALL 12 MODELS	MAXIMUM OF ALL 12 MODELS	GFDL	GFDL
CHEHALIS AT DAM	19	46	42	
CHEHALIS NEAR DOTY	20	49	46	+53
ELK CREEK	24	67	58	
SF CHEHALIS	19	46	42	+42
CHEHALIS AT ADNA	21	54	49	
NF NEWAUKUM AT SF	23	51	48	+76
SF NEWAUKUM AT NF	22	53	50	+56
NEWAUKUM RIVER	23	51	48	+71
SKOOKUMCHUCK AT DAM	21	58	57	+53
SKOOKUMCHUCK AT MOUTH	24	59	55	+69
LINCOLN CREEK	28	63	54	
CHEHALIS AT GRAND MOUND	23	54	50	+66
SCATTER CREEK	26	60	55	
BLACK RIVER	26	56	47	
CHEHALIS AT PORTER	24	54	48	+65
SATSOP RIVER	20	41	29	+41
CHEHALIS AT SATSOP	23	49	43	+55
WYNOOCHEE	19	41	27	+19
CHEHALIS US WISHKAH	23	47	42	+49
WISHKAH RIVER	18	40	27	
HOQUIAM RIVER	18	37	27	
HUMPTULIPS	19	38	25	+18
CHEHALIS ENTIRE BASIN	22	43	38	
Basinwide Average	22	50	44	+52.4

Figure 1
Recommended spatial distribution of scalars representing the mid-century high-end projected changes in precipitation and streamflow for the Chehalis basin. All changes are expressed as a percent increase for mid-century (2016-2060) relative to historical (1970-2015) conditions.