**US Army Corps
of Engineers**
Portland District

# Willamette Basin Review Feasibility Study

# APPENDIX K

# Discussion of Climate Change Impact
on Future Regulation

**September 2019**

# Appendix K
# Willamette Basin Review – Discussion of Climate Change Impact on Future Regulation

This appendix documents the climate change impact analysis for the Willamette Basin Review (WBR). Several studies and reports were reviewed and the overall effect on flows in the basin is summarized here. The impact assessment for the WBR is qualitative, with a generalized estimate for the average decrease in the volume of unregulated flow passing Salem. This estimate is used to approximate the increase in the amount of stored water that would be needed for supplemental fish and wildlife flows to cover the decreasing mainstem flows, with an estimated range.

The U.S. Army Corps of Engineers (USACE) has specific guidance regarding climate impact assessments for inland hydrology, according to the Engineering and Construction Bulletin (ECB), No. 2016-25. This required USACE assessment is included in this appendix. Note, the ECB was revised and re-issued as ECB No. 2018-14 in September 2018. The analysis in this appendix was developed and completed prior to the revised ECB and therefore follows the guidelines in place at the time of analysis, i.e., ECB No. 2016-25.

# Contents

# 1  Introduction

The assessment of climate change impacts is required per USACE guidance in Engineering and Construction Bulletin (ECB) 2016-25. This appendix documents the qualitative effects of climate change on flows in the region and estimates the impact of those flow changes on stored water needs to support supplemental flows for fish and wildlife. The projected, increases in municipal and industrial demand due to climate change are documented in Appendix A and increases in agricultural irrigation demand due to climate change are documented in Appendix B.

The impacts to the region that will be presented here are:

- A qualitative summary of the expected trends in precipitation and temperatures in the region, based on reviews of several published studies.
- A single representative location in the Willamette Basin, the Willamette River at Salem, was chosen to display climate change streamflow results from the Climate Impacts Group, a University of Washington study completed in 2010. The study contains estimated, climate changed streamflows derived using a variety of calculation methodologies for three estimated time horizons (2020, 2040, and 2080) for many locations throughout the Columbia Basin.
- A separate section is devoted to the required steps outlined in ECB 2016-25, where the online USACE tools for the Pacific Northwest were used to assess climate impacts and watershed vulnerability.

The projected, estimated change in stored water needed to support supplemental flows for fish and wildlife (BiOp minimum flow) was approximated as follows:

- Median, unregulated, monthly flows are computed based on six, daily representative climate changed, future streamflow records. These daily streamflow records represent six time horizon-emission scenario realizations of projected, future streamflow. The projected, daily streamflow records are produced by averaging the results from an ensemble of GCMs (10 GCMs for emission scenario A1B and 9 GCMs for emission scenario B1).
- Ensemble averages (average from all climate models) of the unregulated flow at Salem for three, future time horizons and for two different emissions scenarios from the Climate Impact Study were used to determine the decreased conservation season total flow volume at Salem. The 95% and 5% monthly flows projected using the climate models at Salem for both emissions scenarios are plotted to show the spread of the dataset resulting from using a low versus more moderate projection of future, greenhouse gas emissions. The values also represent the spread of the projected, future streamflows over the three time horizons considered.
- The decreased water volume is assumed to be related to the amount of extra stored water that the reservoirs would need to release to meet BiOp minimum mainstem flow targets in the future.

The expected climate trends in the region are summarized in Section 2, with an emphasis on describing trends at each of the thirteen USACE reservoirs in the Willamette Basin. The Climate Impacts Group

unregulated Salem streamflow results are presented in Section 3, where the Salem flow data is presented as an average of an ensemble of global circulation model based predictions of climate changed hydrology with some general estimates made for the decrease in water volume passing Salem that can be expected in the future due to climate change. This can be used as an estimate for how much additional stored water would be needed to achieve the BiOp minimum Salem flow targets in the future. Section 4 contains the assessments required by ECB 2016-25. A brief summary is given in Section 5.

# 2 Summary of Previously Published, Detailed Climate Assessments for the Pacific Northwest

To date, the most comprehensive study of climate change in the Pacific Northwest is the "Pacific Northwest (PNW) Hydroclimate Scenarios Project (2860)", which is also referred to as the Columbia Basin Climate Change Scenarios Project, or simply as the Climate Impacts Group analysis. In this report, the study will be referenced as the Climate Impacts Group analysis, which is the term used on the study website. The final report and results from the study can be found on the project website: http://warm.atmos.washington.edu/2860. The Climate Impacts Group analysis provides for a comprehensive database of statistically downscaled climate and hydrologic projections for the Pacific Northwest, implemented at a daily temporal resolution and a spatial resolution of $1/16^{th}$ degree (~30 square km). Climate projections, derived from the CMIP3 global model archive include results from the ten best performing global circulation models, three different statistical downscaling approaches and two emission scenarios. Results include summary statistics for nearly 300 streamflow locations in the Columbia River Basin and coastal drainages.

Datasets generated as part of the Climate Impacts Group study were used by the Oregon Climate Change Research Institute (OCCRI) to write a report for the USACE Portland District, titled "Historical Trends and Future Projections of Climate and Streamflow in the Willamette Valley and Rogue River Basins."

In 2010, researchers from Portland State University (PSU) published a report titled "Climate Change and Freshwater Resources in Oregon", which is a statewide climate impact assessment. This report consists of a compilation of existing studies and original research.

Another study in the basin that should be noted is the Willamette Water 2100 (WW2100) study, which is an Oregon State University project targeted at identifying the interactions of humans, hydrology, and ecology on water supply in the Willamette Basin. The climate models used in WW2100 generate daily temperature, precipitation, and other variables from 2010 to 2100, based on a suite of Global Circulation Model (GCM) outputs. Data from this study is not referenced in great detail within this appendix because results focus on the impacts associated with changes in socioeconomic factors such as population and economic growth, as well as changes in agricultural practices like irrigation. The WW2100 assessment also includes detailed biophysical models simulating effects of climate change on forests and the incidence of forest fires. The WW2100 study is addressed in greater detail in Appendix B. The streamflow data used to generate the WW2100 results is not as readily available as the data produced by the Climate Impacts Group.

### *Highlights from the OCCRI Report*

Highlights from the OCCRI report are summarized in this section by reservoir. The Climate Impacts Group analysis, the source of the data used by the OCCRI, was based on two emissions scenarios (A1B and B1), one applied using ten Global Circulation Models (GCMs) and one applied with nine GCMs. The GCMs used were those models whose $20^{th}$ century simulations had the smallest bias in temperature and precipitation and that simulate the most realistic annual cycle of these parameters. A hybrid delta

approach (combined traditional delta methods and bias correction and statistical downscaling) was used for the hydrologic analysis. The Variable Infiltration Capacity (VIC) model of the Columbia River Basin (of which the Willamette Basin is a part) is used to convert meteorological inputs produced by the GCMs into a hydrologic response. The VIC model simulations were for three climate change scenarios: for the 2020s (30 year average centered on 2025), 2040s (30 year average centered on 2045), and 2080s (30 year average centered on 2085). The emissions scenarios and CGMs used were:

GCMs applied using Emissions Scenario A1B: CCSM3, CGCM3.1(T47), CNRM-CM3, ECHAM5/MPI-OM, ECHO-G, UKMO-HadCM3, UKMO-HadGEM1, IPSL-CM4, MIROC3.2(medres), and PCM.

GCMs applied using Emissions Scenario B1: CCSM3, CGCM3.1 (T47), CNRM_CM3, ECHAM5/MPI-OM, ECHO-G, UKMO-HadCM3, IPSL-CM4, MIROC3.2 (medres), and PCM.

The OCCRI report describes general climate projections for 2030-2059 as having higher regional minimum and the maximum temperatures, meaning that both winters and summers will be warmer, with a greater increase in summer temperatures than winter temperatures. This trend is described as having a high degree of confidence, since all the GCM models reviewed had the same result. The amount of precipitation, however, varied among the various GCM models by both season and by the sign of the change (increases or decreases in precipitation). Regardless of the precipitation changes, the models show that the warming temperatures decrease the amount of the snow water equivalent (SWE) as a proportion of the cumulative precipitation (P) in the Willamette Basin. Sub-basins, such as the North Santiam, that historically receive the most snow will have significant declines in the projected winter ratio of SWE/P.  The more southern sub-basins, such as the Middle Willamette, are projected to receive little or no snow in the future. The models that did show projected increases in winter precipitation also showed less snow accumulation, which affects the streamflows in each sub-basin.

The combination of the increasing temperatures with the precipitation changes results in a set of streamflow projections that, on average, have higher wintertime flows and lower summertime flows. The magnitude of these changes varies by each sub-basin's sensitivity to the loss of accumulated snow. The OCCRI report summarizes these results by USACE reservoir groups (See Figure 2.1 for reservoir locations within the basin).

In the OCCRI report, Hills Creek, Cougar, and Detroit projects are considered to have high streamflow sensitivity, largely due to their high elevations. These projects are described as exhibiting a projected increase in mean flow during the period December through March in 18 of the 19 future climate scenarios, with all 19 scenarios showing a projected decrease in mean flow for May through September.

Cottage Grove, Dorena, and Fern Ridge projects are considered to have low streamflow sensitivity, because snow accumulation and melt have a small influence on the hydrograph shape. These projects are described as exhibiting a trend toward increasing winter flows transitioning towards a trend in decreasing flow somewhere around April. There is small variability in this trend across the results produced by the 19 GCM based simulations.
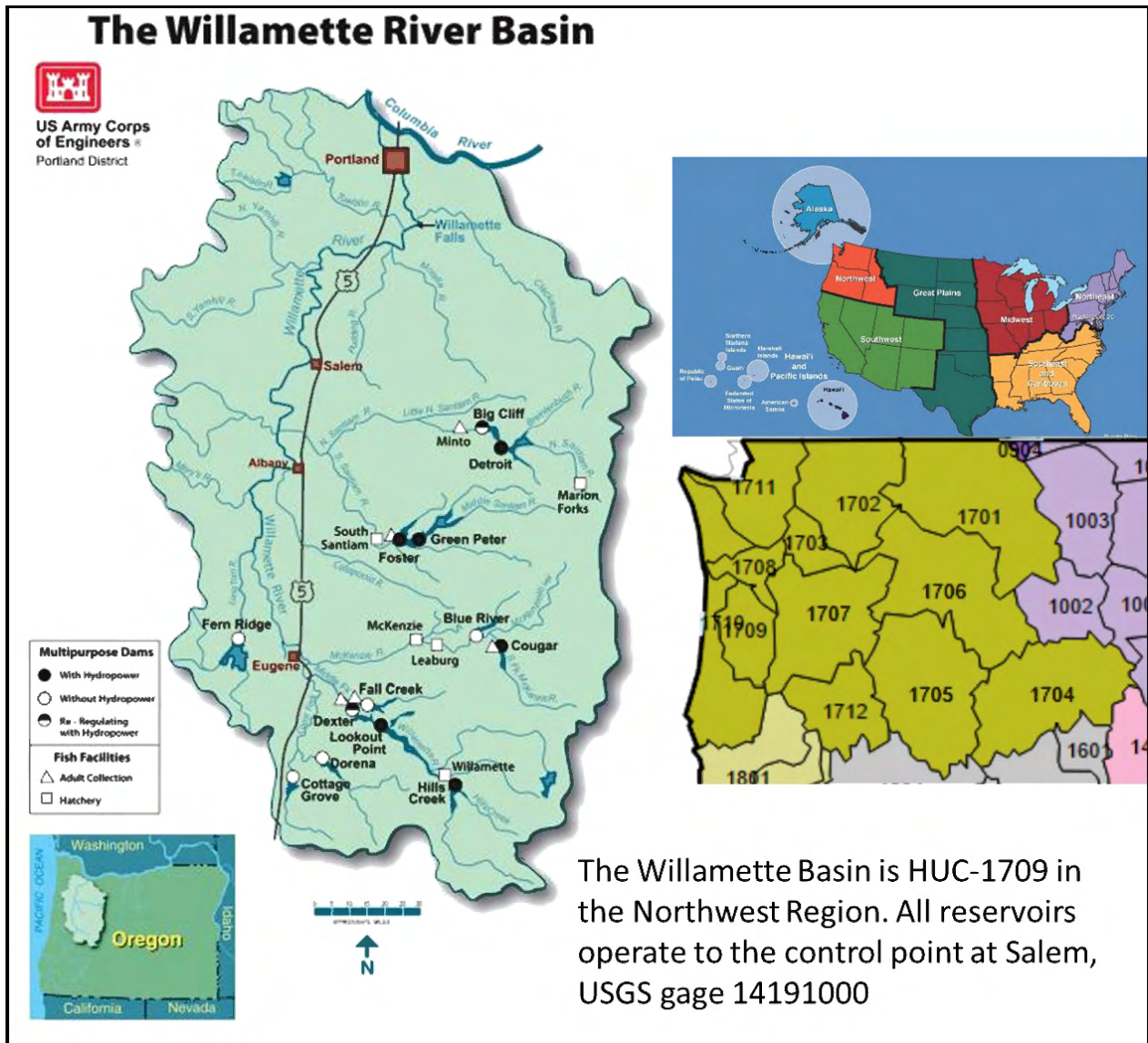
*Figure 2.1 The Willamette Basin and the thirteen USACE dams. (HUC 1709.)*

Lookout Point and Fall Creek projects are described as having moderate-to-high streamflow sensitivity; the contributing area above these reservoirs is governed less by snowpack than by variability in total precipitation. These projects are described as exhibiting a projected increase in mean flow during the period December through March in the majority of the 19 future climate scenarios. All 19 future scenarios show decreasing summer flows.

The Blue River project is considered to have a moderate-to-high streamflow sensitivity in the OCCRI report as well, with overall results similar to those described above for Lookout Point and Fall Creek, but this project's results were described separately in the OCCRI report because the project is a little more sensitive to melting snowpack due to its higher elevation and because the number of scenarios showing wintertime increasing flows is slightly different.

The OCCRI report describes Green Peter and Foster projects as having low-to-moderate streamflow sensitivity. Slightly more than half of the future scenarios show increasing winter flow volumes, but all scenarios show decreasing summer flows.

The OCCRI report does not provide any specific summary information for the Willamette River at Salem. The Willamette River at Salem is an important downstream location used for reservoir modeling and management. USACE projects in the basin work together to provide flood damage reduction at Salem, along with other control points in the basin, and all the projects provide supplemental storage during the summer months to help maintain BiOp required minimum flow targets, including at Salem. The Salem site specific data files from the Climate Impacts Group were used to draw conclusions at Salem, as described in Section 3.

### *Highlights from the PSU Report*

The PSU report does not break down the Willamette sub-basin areas in as detailed a manner as the OCCRI report, as their purpose was a statewide climate impact assessment, but their overall conclusions about future climate scenarios are similar. The PSU report states "…many Oregon streams will experience higher winter flow and reduced summer flows as temperature rises and the variability of precipitation increases." This report also references the Climate Impacts Group study for the Willamette Basin results.

### *Summary of the Climate Assessments for the Willamette Basin*

The following points (synthesized from the OCCRI report, PSU Report and the data from the Climate Impacts Group analysis) summarize the trends in the expected climate change impacts at the thirteen USACE reservoirs in the Willamette Basin:

- Wintertime flows into the reservoirs trend higher than historical values, so reservoirs will still need to regulate for flood damage reduction.
- Summer inflows consistently show a decrease relative to historical inflows, across the full spectrum of models and scenarios. This means that the Willamette reservoirs may need to supply more water in future, whether for supplemental flows for fish and wildlife, agricultural irrigation, or municipal and industrial water supply.
- None of the research studies described in this section addressed the timing of the transition point between the higher winter flows and the lower summer flows in the future climate scenarios. This is due in part to the bias correction method, which uses historical data for downscaling, making the timing in the historical record implicitly embedded in the results. The likelihood of a Willamette reservoir refilling depends partly on the timing of spring flows, not just the inflow value, so it is difficult to determine how reservoir refill will be affected by the higher winter flows/lower summer flows.

# 3 Assessment of Unregulated Flows at Salem

One location of interest for this study is the Willamette River at Salem, which is an important location for reservoir regulation in the Willamette River Basin. The BiOp specifies minimum flow targets at Salem for April through October, and reservoir releases supplement the local flows passing through Salem. The term "local flow" here means all the water at Salem that did not pass through a USACE reservoir.

*Background: Climate Impacts Group Data*

Projected, climate changed streamflow data for the Willamette River at Salem was downloaded from the Climate Impacts Group website and analyzed by the Portland District. Three streamflow files for unregulated flows at Salem were pulled from the project website for future climate scenarios centered around 2020, 2040, and 2080. The website with the data files is:

http://warm.atmos.washington.edu/2860/products/sites/?site=4060

The three specific files pulled for Salem are the following:

- *mod_bias_adjusted_vic_streamflow_daily_hd_2020*
- *mod_bias_adjusted_vic_streamflow_daily_hd_2040*
- *mod_bias_adjusted_vic_streamflow_daily_hd_2080*

Each data file contains 10 CMIP3 records for an A1B emissions scenario and 9 CMIP3 records for a B1 emissions scenario. The two emission scenarios were chosen by the Climate Impact Group to represent medium (A1B) and low (B1) emissions. (See Section 2.2.1 of Chapter 4 of the CIG report.) The Climate Impact Group did not assess a high emissions scenario or state why one was not included.

The 10 records for the A1B scenario represent ten global circulation model (GCM) results, and the 9 records for the B1 scenario are the results produced using nine GCMs. These GCMs were chosen by the Climate Impact Group because their 20th century simulations have the smallest bias and most realistic annual cycle in temperature and precipitation (See Section 2.2.2 of Chapter 4 of the CIG report). It is felt that these 10 GCMs present a reasonable representation of the range of future climate change impacts on the Willamette Basin. It was necessary to down select from the larger ensemble of GCM results available to reduce computational demand.

Raw CMIP3 GCM temperature and precipitation data is available at a monthly timescale and is representative of a large-scale spatial extent (~200 sq. km resolution). Consequently, GCM outputs must be downscaled to a spatial (1/16 degree or ~30 sq. km) and temporal scale (daily) relevant to water resources planning. The streamflow projections analyzed for the Salem gage were developed using the Hybrid Delta Downscaling method and the unregulated Variable Infiltration Capacity (VIC) macro-scale hydrologic model. The hybrid delta (HD) downscaling technique has been developed specifically for this region and it combines some of the strengths associated with both the traditional delta method and the Bias Correction and Statistical Downscaling (BCSD) approach for downscaling GCM outputs to a finer spatial and temporal scale (see Chapter 8 of the Climate Impacts Group report for these details). The VIC

model was calibrated by sub-watersheds on a monthly timestep to available unregulated streamflow data, where the Willamette calibration period was 1975-1989 with an N-S model efficiency of 0.89 and an $R^2$ of 0.93.

The three Salem files for 2020, 2040, and 2080 each contain 19 scenarios (10 GCM models run for A1B and 9 GCM models run for B1) in the files, which makes for 19 time series records, and each time series record consists of 91 water years of daily average streamflows at Salem. All of the time series in the files run from 01 October 1915 to 30 September 2006, with the dates corresponding to the historical flow used for the bias correction downscaling method. Each time series represents 91 water years of statistically downscaled, daily temperature/precipitation inputs, translated into a hydrologic response using the VIC model. Note that each series contains only 90 full calendar year records. For this analysis data was analyzed by calendar year to capture monthly variation in flow and to assess April through October cumulative water volumes. Consequently, only 90 complete years of record are available to support analysis at this temporal resolution.

A close look at any of the time series in the three files confirms that the timing of flows in the future time series is the same as timing of the historical flows. This is a consequence of the hybrid delta downscaling technique applied, where both the inter-annual and inter-decadal climate variability, as well as the inter-arrival time and duration of droughts and floods is patterned after historic observations. Figure 3.1 shows a very short time window (late November 1964 to early February 1965, chosen because the late December 1964 flood event is the largest in the historical record) for six different time series, two from each future period. (Note that this year is just an indication of the seasonal/sub-monthly timing pattern applied and is not representative of the time stamp actually tied to the data being displayed.) The GCMs chosen for this plot are the Echo and Miroc. Note that all six time series in the figure have the same timing of the peak at Salem, and also the same peak timing for other smaller events in the time period plotted. The peaks shown in the figure are centered on the historical flood event in late 1964 because the historical record is used in the process of downscaling the raw, gridded temperature/precipitation GCM data into a spatial and temporal scale relevant to water resources planning.
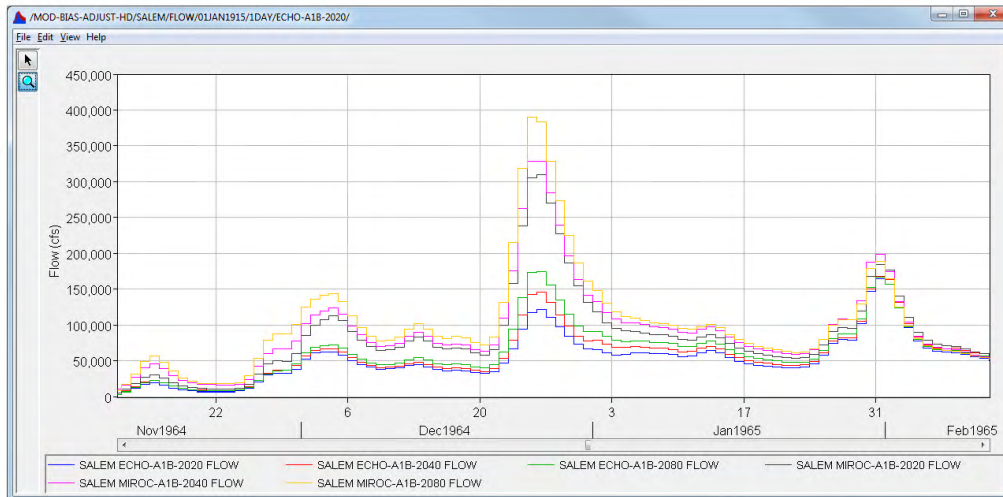
***Figure 3.1 Example of timing of bias adjusted flows for a short window around the 1964 flood event, using two specific GCMs (Echo and Miroc) for all three future periods, plotted using HEC-DSSVue. Note that the dates displayed correspond to the historical record used to bias correct and downscale GCM data.***

This is not a flaw in the climate impact study, but an explanation for why projected changes in refill timing cannot be obtained from the results. It is important to understand that the climate impact study provides estimates on the magnitudes of the flows in the future, not the dates on which those flows might occur.

### *Data Analysis: Computation of Daily Ensemble Average Monthly Value*

The daily ensemble average value was calculated for all ten of the A1B scenarios for 2020 and for all nine of the B1 scenarios for 2020, and then repeated for 2040 and 2080, to obtain six ensemble average time series records of daily unregulated flow values at Salem. To illustrate the methodology used to obtain the ensemble averages, Figure 3.2 shows a flow chart of the steps involved in the calculation of the ensemble average process for the ten A1B emission scenario time series for the 2020 projection. The ten green boxes in the center of the figure represent the ten Global Climate Models (GCMs) used with the A1B emission scenario, which are from the file *mod_bias_adjusted_vic_streamflow_daily_hd_2020*, and the ensemble average of these ten time series records, represented by the blue box, were calculated by the Portland District for this WBR climate impact report. The ensemble average is a single 91-water year record of daily flows at Salem, where each daily value is the average of the ensemble of the GCMs used for the A1B emission scenario.
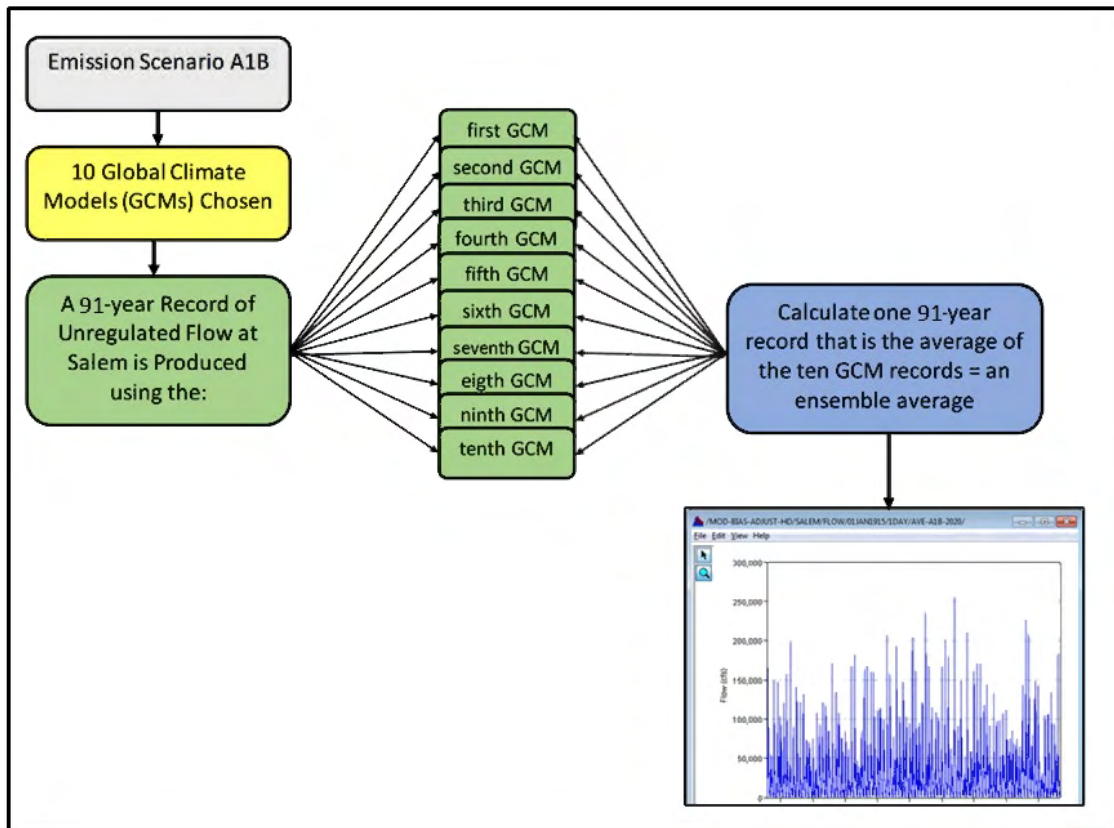
***Figure 3.2 Flow chart showing steps to obtain the 91-year record of the ensemble average (daily values) for emission scenario A1B for 2020. The ensemble average daily values are used for water volume calculations shown later in this section.***

The ensemble averages were calculated for all three time horizons (2020, 2040, and 2080) for both emissions scenarios, and these plots are shown in Figure 3.3. Each graph in the figure contains 91 water years of time series records of daily Salem flows (~91 * 365 data points), which are now average values across the ensemble of GCMs used for each emission scenario. A single year is shown for all six ensemble averages in the bottom graph of the figure. (As mentioned for Figure 3.1, the year displayed is an indication of the seasonal/sub-monthly timing pattern applied and is not representative of the time stamp actually tied to the data being displayed.) This emphasis on the ensemble average values containing daily records is provided because monthly values will be presented in all the following graphs, and all the monthly values presented are calculated from the daily ensemble averages shown in Figure 3.3.
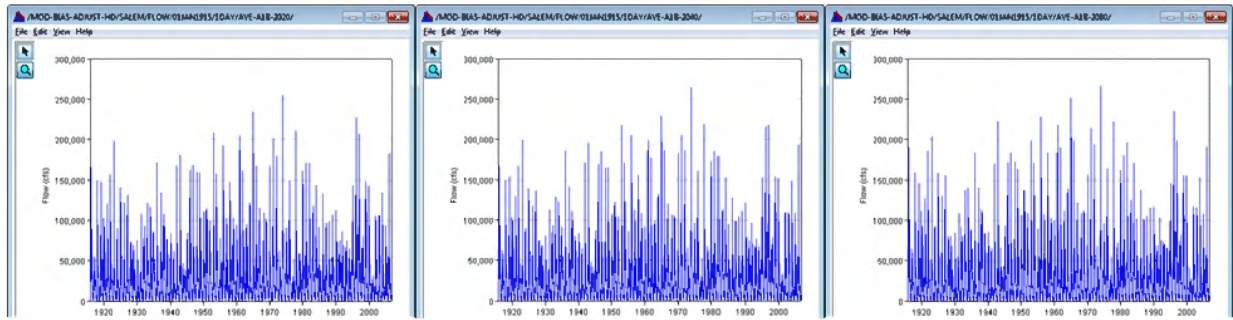
Ensemble Average of the
10 A1B Scenarios for 2020

Ensemble Average of the
10 A1B Scenarios for 2040

Ensemble Average of the
10 A1B Scenarios for 2080
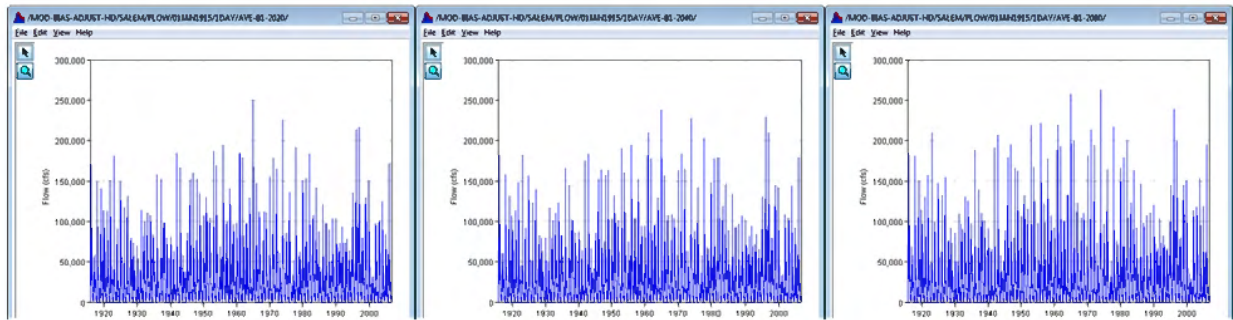
Ensemble Average of the
9 B1 Scenarios for 2020

Ensemble Average of the
9 B1 Scenarios for 2040

Ensemble Average of the
9 B1 Scenarios for 2080
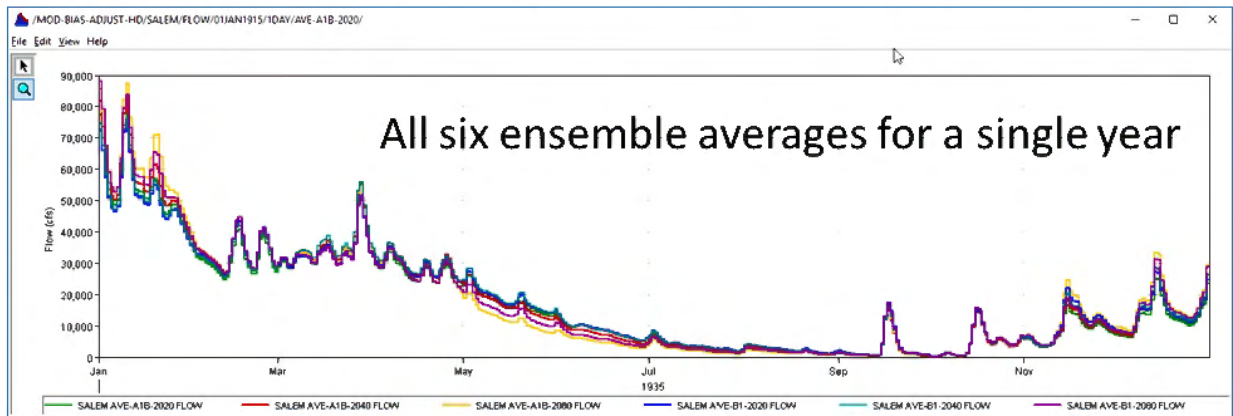
**Figure 3.3 Ensemble average (daily value) plots for both emission scenarios for 2020, 2040, and 2080, plotted using HEC-DSSVue. (Note date range is 01 Oct 1915 to 30 Sep 2006 for each ensemble.) Lower graphs shows just 1935 year data for all six ensemble averages. Note that the dates displayed correspond to the historical record used to bias correct and downscale GCM data.**

In order to present the data in a more generalized way, these ensemble daily average values are used to calculate the monthly 95%, 5%, and 50% (median) non-exceedance values. At a monthly time step, only 90 full calendar years of data are available. Figure 3.4 is a schematic illustration of obtaining the monthly median values of the ensemble averages. For example, for the month of January and the A1B scenario for 2020: use all 31 days of January values for all years to calculate one median value (median of 31 * 90 January values). The January values represent the median January flow based on the representative, projected, 90 year daily flow record produced by averaging the GCM model traces for the emissions

scenario at a daily time step. Using the same method for all twelve months, the median monthly values for the ensemble average of the A1B 2020 time series is shown at the right of Figure 3.4.
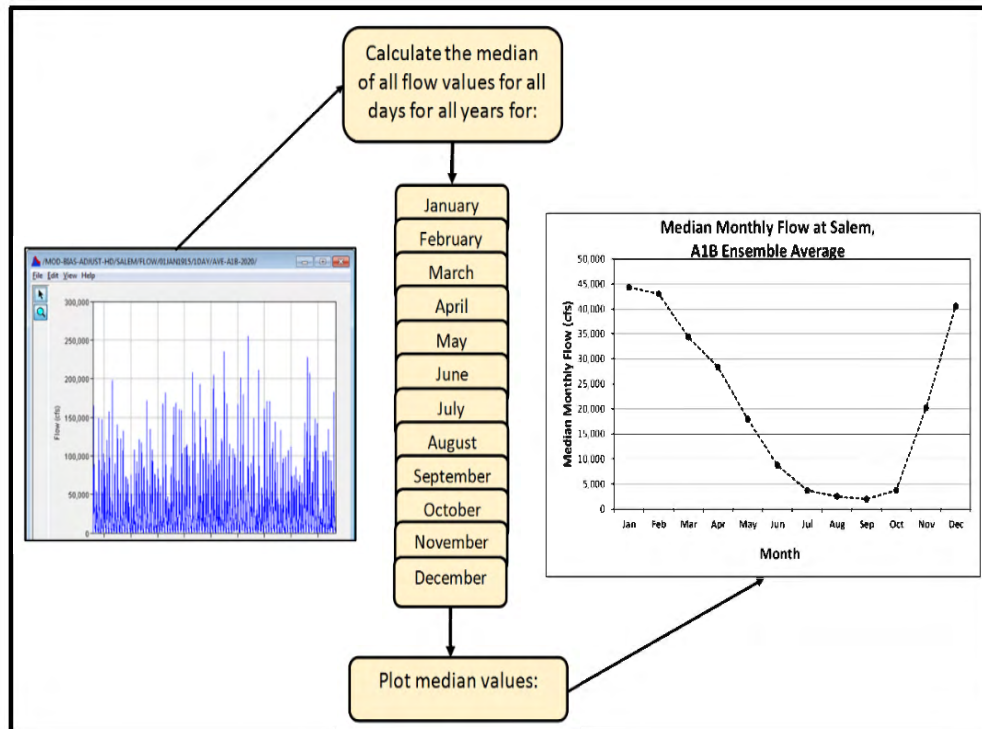


*Figure 3.4 Schematic showing steps to obtain the median monthly flow, obtained from the ensemble average daily values, at Salem for the 90-year record of the ensemble average of emission scenario A1B for 2020.*

The methodology just described for obtaining the median monthly flows from the ensemble average daily values is applied to all six ensemble averages and plotted in Figure 3.5. The top graph in Figure 3.5 is for the A1B emissions scenario and the bottom graph is for the B1 emissions scenario. The 2020 projected future median monthly flow is shown in black, the 2040 in blue, and the 2080 in red. Results are shown only for the conservation season, April through October, since that is the data that is relevant to this reallocation study.

The monthly 95% and 5% non-exceedance values for all six ensemble averages are computed using the same methodology as described above for the median values. These results are shown in Figure 3.6 for each ensemble average using the same color scheme as Figure 3.5. The plots are for the conservation season, with the median values from Figure 3.5 included for reference. Note that the scale is expanded to include the higher 95% October values. (Remember that the 95% value for A1B 2020 is the 95th percentile flow computed from the daily ensemble average, so April values are based on 30 * 90 data points for each ensemble average.) Therefore, Figure 3.6 demonstrates the spread of the daily ensemble average values for each month in the six ensemble average time series.
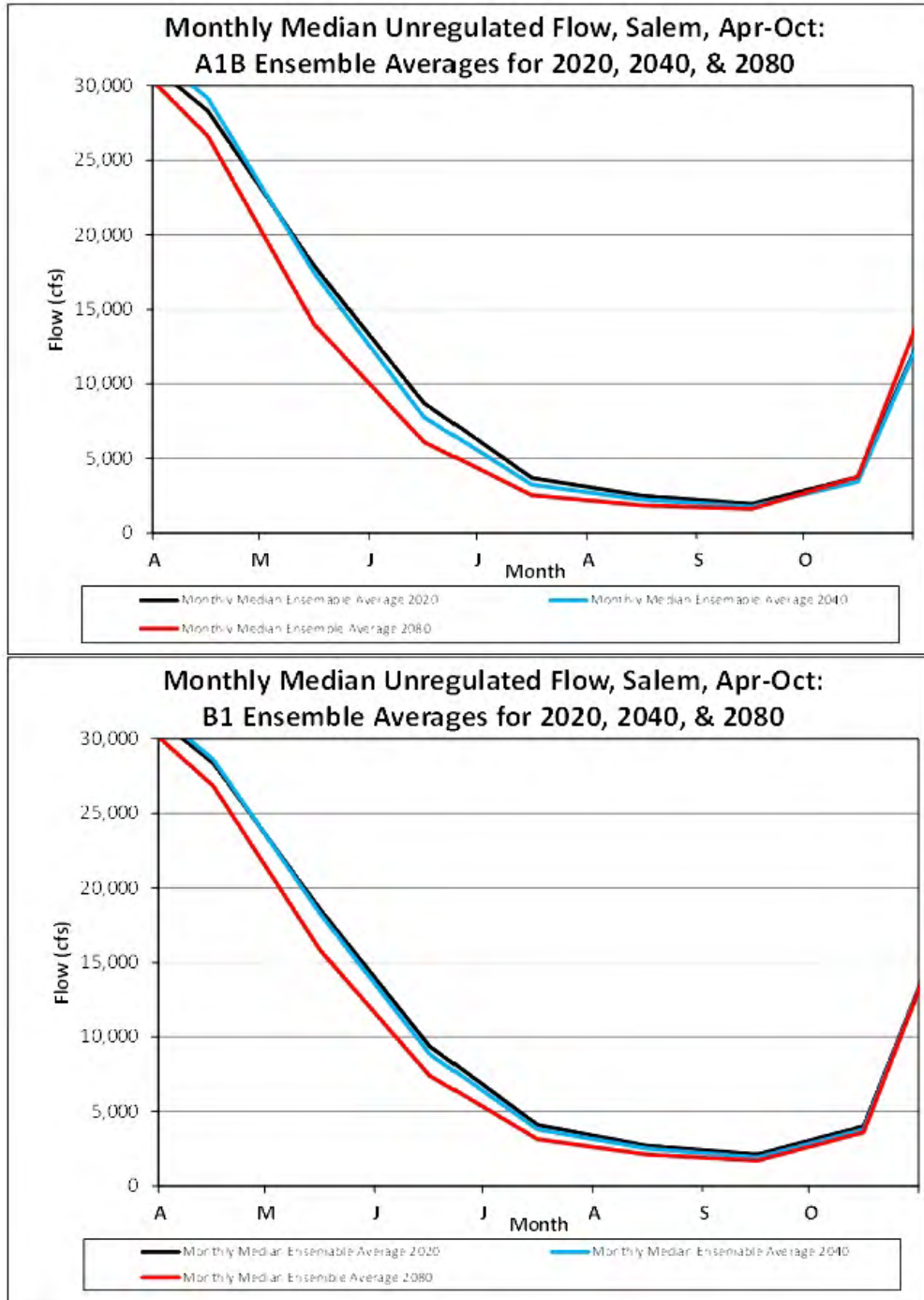
***Figure 3.5 Median monthly value of the ensemble average of unregulated streamflow at Salem for emission scenarios A1B and B1 for all three future time horizons, 2020, 2040, and 2080. The black lines are for 2020, blue for 2040, and red for 2080. Results are for the conservation season, April through October.***
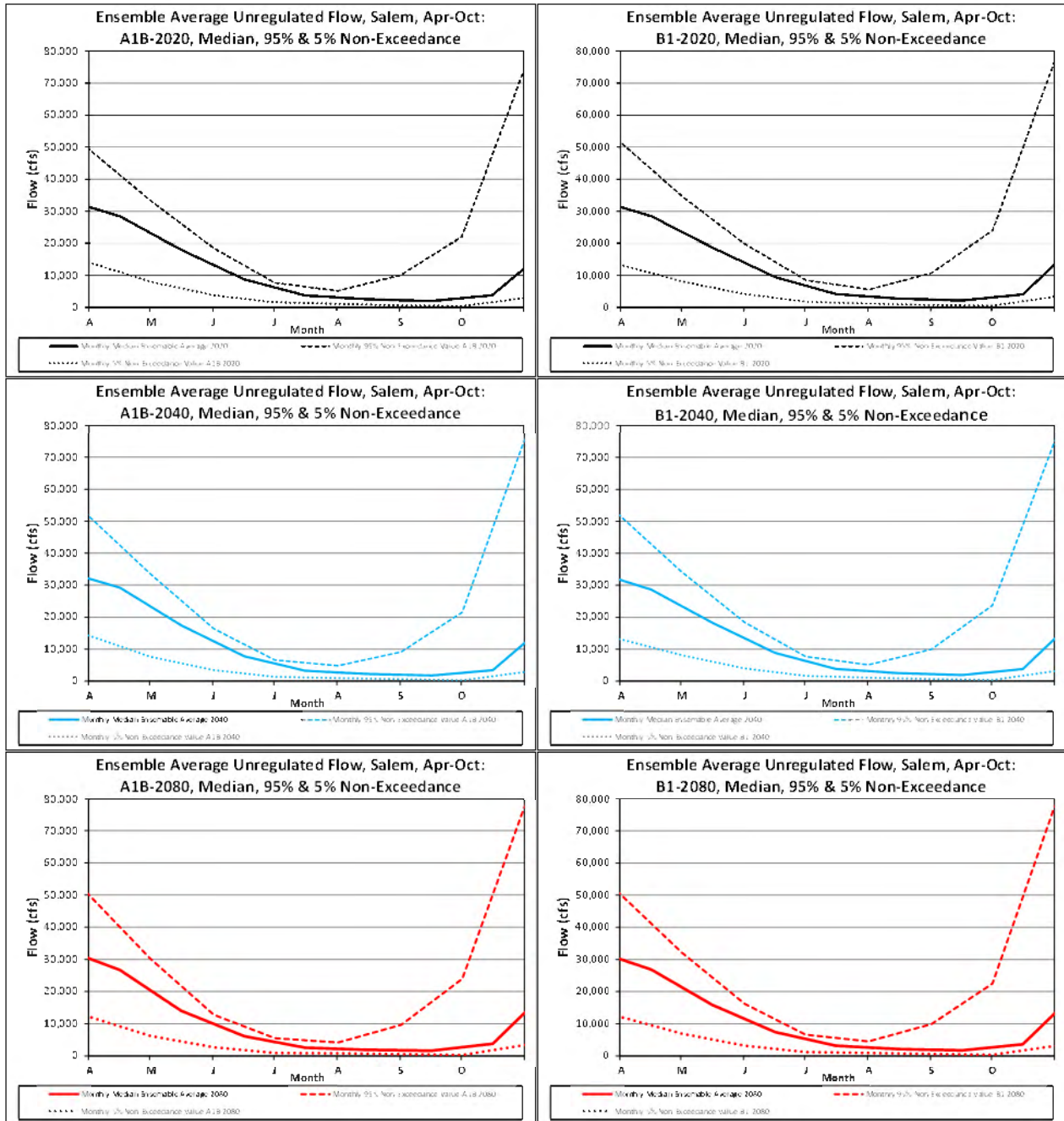
**Figure 3.6 Spread of ensemble average flows for the conservation season for both emissions scenarios and the three future projections. Left side graphs are for the A1B emissions scenario and right side graphs for the B1 emissions scenario, with the median values from Figure 3.5 plotted as solid lines, 95% non-exceedance values plotted in the dashed lines, and the 5% non-exceedance values plotted as the dotted lines. The 2020 time horizon values are black, 2040 are blue, and 2080 are red.**

*Data Analysis: April through October – Critical BiOp Volumes Assessed in Accordance to Appendix C Criteria*

In order to estimate the effects of climate changed flows in the region on the amount of stored water needed for supplemental flows for fish and wildlife, it is most useful to look at water volumes passing

through Salem in the conservation season: April through October. Using April through October water volumes is consistent with Appendix C (of this WBR study), which showed the calculated results for the amount of stored water needed for supplemental flows in the period of record analyzed. The GCM ensemble average, daily datasets (the six time series with daily unregulated flow values at Salem, representing the A1B and B1 emissions for the three time horizons) are converted to cumulative water volumes passing through Salem so that a comparison of results with Appendix C can be made. Each record has 90 annual values of April-October water volumes (note the first month in each record is October 1915, so there is not a full April to October cumulative volume for that year), obtained by summing the daily water volume passing Salem for all the days in the April to October time window on an annual basis. Each ensemble average then has 90 values that can be assessed for non-exceedance levels (5%, 10%, 25%, 50%, 75%, 90%, and 95%), along with maximum, minimum, and average values.

Results are broken down by non-exceedance values to facilitate an assessment of changes in available storage volume for drier, moderate, and wetter flow years. This characterization is necessary in order to be consistent with now available storage is assessed within Appendix C. Minimum, maximum, and average values are displayed to provide an overview of the inter-annual variability in volume and the overall change in available storage for each time horizon-emission scenario combination. Figure 3.7 on the following page displays the results of these computations for each of the six ensemble average time horizon-emission scenario combinations. (Note that the total conservation storage capacity of the WVP is 1.59 MAF, and these projects regulate less than half of the water upstream of Salem, Oregon. Furthermore, the primary function of the WVP dams is flood risk management, not water supply, and there is no carry over storage between water years.)

In Appendix C, the volume of water available from the various reservoirs are broken out for each year: the water volume components related to the BiOp targets were the stored water released to meet BiOp needs, the inflow passed without being stored to meet BiOp needs, and any shortages in meeting BiOp needs; additional water volume components broken out were inflow passed and stored water released for reasons other than meeting BiOp needs (municipal and Industrial water supply, as well as agricultural irrigation).

It is important to understand that the water volumes computed in Appendix C were based on the current reservoir regulation operations using the 2010 modified flow dataset, created from observed records from 1928 to 2008 (the Period of Record, POR), to determine the spread of expected requirements for stored water to supplement flows to achieve the BiOp flow targets. The data in Appendix C does not reproduce historic or observed regulated flows, so none of the calculations represent how often BiOp flow targets were actually met – the analysis was a tool to obtain an estimated amount of conservation storage to be reallocated specifically for fish and wildlife. The estimated range of increase in this water volume under climate change is required by the WBR study, since both agricultural irrigation and municipal and industrial water supply needs included estimated increases from climate change. The remainder of this section documents how the six ensemble averages were used to estimate the range of additional supplement water volume needed for fish and wildlife.

## Total Conservation Season (Apr-Oct) Flow Volume at Salem (in MAF)

| Emission Scenario: A1B | | | Time Horizon: 2020 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Total Water Volume Passing Salem for April - October (MAF)** | | | | | | | | | |
| | Min | Max | Average | P5 | P10 | P25 | P50 | P75 | P90 | P95 |
| Apr-Oct | 1.62 | 9.69 | 4.50 | 2.23 | 2.71 | 3.31 | 4.28 | 5.41 | 6.68 | 7.34 |

| Emission Scenario: A1B | | | Time Horizon: 2040 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Total Water Volume Passing Salem for April - October (MAF)** | | | | | | | | | |
| | Min | Max | Average | P5 | P10 | P25 | P50 | P75 | P90 | P95 |
| Apr-Oct | 1.51 | 9.83 | 4.40 | 2.21 | 2.66 | 3.25 | 4.18 | 5.24 | 6.64 | 7.13 |

| Emission Scenario: A1B | | | Time Horizon: 2080 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Total Water Volume Passing Salem for April - October (MAF)** | | | | | | | | | |
| | Min | Max | Average | P5 | P10 | P25 | P50 | P75 | P90 | P95 |
| Apr-Oct | 1.29 | 8.94 | 3.93 | 1.85 | 2.23 | 2.79 | 3.74 | 4.80 | 6.07 | 6.73 |

| Emission Scenario: B1 | | | Time Horizon: 2020 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Total Water Volume Passing Salem for April - October (MAF)** | | | | | | | | | |
| | Min | Max | Average | P5 | P10 | P25 | P50 | P75 | P90 | P95 |
| Apr-Oct | 1.56 | 10.62 | 4.70 | 2.30 | 2.79 | 3.47 | 4.45 | 5.62 | 7.06 | 7.80 |

| Emission Scenario: B1 | | | Time Horizon: 2040 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Total Water Volume Passing Salem for April - October (MAF)** | | | | | | | | | |
| | Min | Max | Average | P5 | P10 | P25 | P50 | P75 | P90 | P95 |
| Apr-Oct | 1.51 | 9.88 | 4.59 | 2.27 | 2.73 | 3.37 | 4.38 | 5.47 | 6.87 | 7.67 |

| Emission Scenario: B1 | | | Time Horizon: 2080 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Total Water Volume Passing Salem for April - October (MAF)** | | | | | | | | | |
| | Min | Max | Average | P5 | P10 | P25 | P50 | P75 | P90 | P95 |
| Apr-Oct | 1.37 | 9.50 | 4.17 | 2.01 | 2.34 | 2.93 | 3.96 | 5.06 | 6.38 | 7.07 |

*Figure 3.7 Spread of April-October unregulated water volume passing through Salem from the six ensemble averages (A1B for 2020, 2040, 2080 and B1 for 2020, 2040, and 2080).*

Estimates of the supplemental water volume from Appendix C depended on whether the year was wet or dry. The BiOp provides a classification of water year type based on the total amount of storage in the reservoirs during a ten day window each May. The breakdown of water year types in the Appendix C ResSim analysis and their frequency of occurrence are: Abundant = 44 years, Adequate = 14 years, Insufficient = 11 years, and Deficit = 11 years. The Deficit years are the driest, while the Abundant years include normal to very wet years. Figure 17.1 in Appendix C (WBR report) has a bar graph of the water volume components calculated, sorted from low to high based on the total volume needed to meet BiOp targets. The years from the Period of Record are also labeled by the water year type classification. That graph illustrates that Abundant years needed the least amount of stored water for supplemental flows. Deficit years had a high need, but since they also had large shortages in meeting flow targets, the amounts of stored water released in Deficit years to supplement flows were not the largest volumes calculated. In other words, in dry years, there isn't enough water in the system anyway to meet the flow targets (reservoir refill is very low in Deficit years).

Figure 17.3 in Appendix C documents that 23 years in the POR had no stored water available at the end of the conservation season, and the remainder of the years in the POR had stored water remaining. This means that 29% of the years in the POR were too dry to support the BiOp minimum targets in full, even with supplemental stored water, but 71% of water years were wet enough that stored water could supplement enough volume to meet the target minimums. In order to make an estimate of the increase in stored water needed to supplement flows in a climate changed future, it is assumed that the likelihood of having a year too dry to have enough storage would be at least 29%. On the wetter end of the spectrum, Figure 17.3 in Appendix C indicates there are 19 years in the POR with more than 500 KAF (thousand acre-feet) of stored water remaining in the reservoirs at the end of the conservation season, and another 22 years with between 250 and 500 KAF of stored water remaining after the conservation season. These

These generalizations are important to keep in mind while determining the estimated range of additional stored water needs for supplemental flows under changing climate conditions, because the system currently cannot guarantee enough stored water to meet BiOp targets based on the observed flow records of 1928 to 2008. The best estimate of future increases in the stored water needed to supplement flows should come from the middle ranges of the flow dataset, so that the driest years are excluded since there is not enough water anyway and the wettest years are excluded because they use a much smaller amount of stored water. In order to make this estimate, the increase in stored water needs will be made by looking at the reductions in the conservation season volumes of water for the percentile ranges shown in Figure 3.7.

### General Conclusions

The data displayed in Figure 3.7 for each of the six ensemble averages has several important factors to highlight.

- There is a lot of variability in the water volumes at Salem from year to year. This is indicated by the difference between the minimum and maximum for all six time horizon-emission scenarios considered (2020, 2040, and 2080 for both A1B and B1). The spread between the minimum/maximum shows the variation between water years, from the driest to the wettest years. This is consistent with the variation demonstrated within the unregulated, historic record.
- Since each time horizon-emission scenario is calculated from all the GCMs applied for a given emissions scenario, the data in Figure 3.7 does not fully represent the uncertainty (spread) associated with the GCM outputs. It only represents variation in volume resulting from the future time period being considered and the emission scenario being applied.
- The changes in the values for each emissions scenario with the different time horizons displays an overall trend in decreasing total water volumes at Salem projected for the conservation season (Apr-Oct). This is the most important factor to highlight, because it distills the fundamental property of the projected, future streamflows – the total amount of water passing through Salem is expected to decline over time.

- As anticipated, the medium projected greenhouse gas emissions (A1B) scenario, indicates a more significant decrease in flow volume for the conservation season than the low emissions (B1) scenario.

The third point above is the outcome that is most relevant to the project's required estimate of changing supplemental flow needs – a trend of increasing need for supplemental flows.

### Quantification of Future Supplemental Flow Needs

The data from Figure 3.7 for the 5% to 95% non-exceedance levels is used to obtain differences for each emissions scenario for the different time horizons, and these differences are shown in Figure 3.8. The A1B scenario shows two sets of differences, which are the difference for 2040 minus 2020 values, and the difference for 2080 minus 2040 values, although that forty year difference is divided by two in order to get a change over an equivalent period of time (20 years) as the first set of differences. The B1 scenario has the same difference computations made. The negative value means the later time horizon value is less than the earlier time horizon value, and note all values in Figure 3.8 are negative.

**Change in April-October Water Volume (MAF) at Salem**

| Emission Scenario: A1B | change per 20 years, 2040 minus 2020 values | | | | | | |
|---|---|---|---|---|---|---|---|
| | P5 | P10 | P25 | P50 | P75 | P90 | P95 |
| Apr-Oct | -0.02 | -0.06 | -0.06 | -0.10 | -0.17 | -0.03 | -0.21 |

| Emission Scenario: A1B | change per 20 years, half of 2080 minus 2040 values | | | | | | |
|---|---|---|---|---|---|---|---|
| | P5 | P10 | P25 | P50 | P75 | P90 | P95 |
| Apr-Oct | -0.18 | -0.22 | -0.23 | -0.22 | -0.22 | -0.29 | -0.20 |

| Emission Scenario: B1 | change per 20 years, 2040 minus 2020 values | | | | | | |
|---|---|---|---|---|---|---|---|
| | P5 | P10 | P25 | P50 | P75 | P90 | P95 |
| Apr-Oct | -0.03 | -0.06 | -0.10 | -0.07 | -0.16 | -0.19 | -0.13 |

| Emission Scenario: B1 | change per 20 years, half of 2080 minus 2040 values | | | | | | |
|---|---|---|---|---|---|---|---|
| | P5 | P10 | P25 | P50 | P75 | P90 | P95 |
| Apr-Oct | -0.13 | -0.19 | -0.22 | -0.21 | -0.20 | -0.25 | -0.30 |

Appendix C documented the following:

Drier Years ← → Wetter Years

More Supplemental Flow Needed   Less Supplemental Flow Needed

Shortages in meeting BiOp targets   No Shortages in meeting BiOp targets
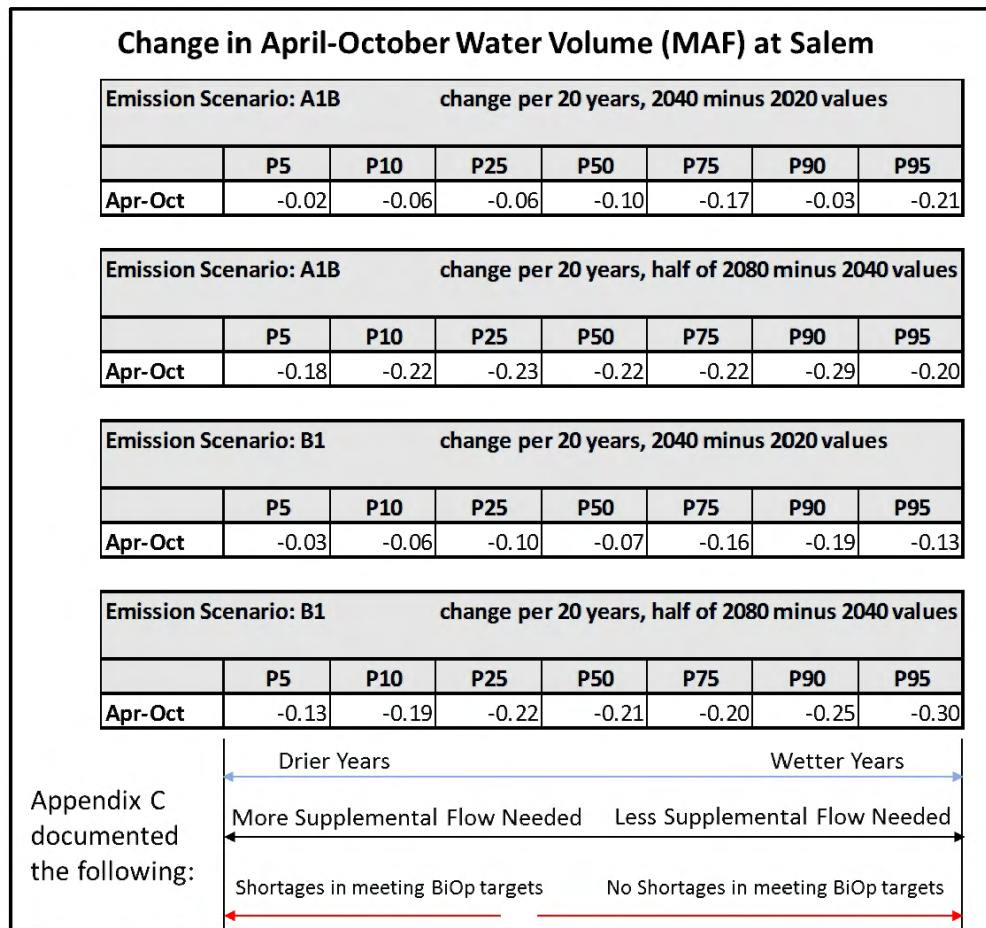
***Figure 3.8 Differences in the April-October water volume in MAF passing through Salem from the unregulated streamflows in the ensemble averages of Figure 3.5. Differences are computed for 20 year increments. The variable scale at the bottom of the figure is mean to be conceptual and generalized, based on the results from Appendix C of the WBR study.***

In order to use the incremental decreases in water volumes presented in Figure 3.8 to estimate an increase in supplemental flows needed, a few of the points from Appendix C will be repeated or emphasized here. Appendix C of the WBR study shows that even the wettest years require some supplemental flow to meet BiOp targets on the mainstem (because the unregulated summer flows are lower than the congressionally established mainstem minimums, based on old navigation requirements). The driest years needed the most supplemental storage but had shortages (were unable to meet BiOp targets) because there wasn't enough water available for the reservoirs to refill to their full conservation pool. This results in the driest years also showing lower levels of stored water released for supplemental flows. Figure 3.8 shows these three concepts (dry and wet years, more or less supplemental flows required, and shortage in meeting BiOp targets) as a variable scale below a tabulation of the water volume differences. The variable scale at the bottom of Figure 3.8 is not meant to suggest any specific water volume definition for dry or wet years or any specific volume for which targets are not met, but rather to show a conceptual generalization based on the results of Appendix C of the WBR study.

The data presented in Figure 3.8 can be studied to estimate a range of possible increases in supplemental flow needs to meet the BiOp targets in a projected, climate changed future. This estimate is required by the Willamette Basin Review study, not by the USACE guidance document EC Bulletin 2016-25. The WBR study provided an estimated increase in municipal and industrial demands due to climate change effects on streamflows (see Appendix A of the report), and an estimated increase in agricultural irrigation demand due to climate changes (see Appendix B of the report). An estimate of an increase need for supplemental flows for fish and wildlife due to climate change (i.e. an increase in stored water releases for meeting BiOp targets) is needed for the WBR study so that all three user allocation groups are treated equally.

To obtain an estimated range for an increase in stored water needed for supplemental flows, two key points from the data presented in Appendix C are summarized below with a corresponding assumption:

- The amount of supplemental flows needed in wetter years is less than the amount needed in drier years – assume that the P90 and P95 volume differences represent wetter years where the magnitude of the decreased flow volume at Salem is higher than the increase needed in supplemental flows (each acre-foot decrease in flow volume requires less than an acre-foot increase in supplemental flow needs). This is because wetter years have higher local inflows in all streams below the dams, so less supplemental flow from stored water is needed to reach the minimum flow target.
- In very dry years, reservoir refill levels are low and there is not enough water available to supplement flows to their minimum BiOp target levels – assume that the P5 and P10 volume differences represent the drier years where the magnitude of the decreased volume at Salem is lower than the increase needed in supplemental flows (each acre-foot decrease in flow volume requires more than an acre-foot increase in supplemental flow needs). This is because drier years have very low local inflows in all streams below the dams, so more supplemental flow from stored water is needed to reach the minimum flow target.

Based on the assumptions outlined above, the P25 to P75 flow volume changes will be assumed to represent a one to one comparison of the amount of additional supplemental stored water that would need to be released under projected, climate changed scenarios. The smallest increase between twenty year time horizons is 60 KAF (1 KAF = 1,000 acre=feet; the -0.06 value for P25 in the first A1B row), and the largest is 230 KAF (the -0.23 value for P25 in the second A1B row). The average of all volume differences for P25, P50, and P75 is -0.16 MAF, or an estimated 160 KAF increase in supplemental flows per 20 year increment.

This magnitude of projected, increased need in supplemental flow to satisfy BiOp target level has considerable uncertainty associated with it and should be used only in relative terms. This value is not to be considered a definitive approximation of what future water demand will be at Salem and should only be considered qualitatively during any decision making processes being conducted as part of this study and for any future studies. If there was a desire to quantitatively account for projected changes to water supply and demand due to climate change, the uncertainty associated with the stated value would have to better quantified and incorporated into such an assessment. Quantitatively accounting for the effects of climate change so that a numerical value can be incorporated within the decision making process (and consequently attempting to quantify uncertainty associated with GCM model outputs) is beyond the current scope of the Willamette River Basin Study.

### *Uncertainty Associated with Quantification of Future Supplemental Flow Needs*

There is a great deal of uncertainty associated with projecting an estimated 160 KAF increase in supplemental flows per 20 year increment into the future due to climate change. The uncertainty associated with this projection comes from the selected emission scenario, range of initial conditions used to prime the GCMs, the ability of a given GCM to replicate the physical drivers of future changes in climate, the techniques used to disaggregate GCM inputs into a temporal and spatial scale relevant to water resources planning, and uncertainty associated with the hydrologic model applied. This estimated volume increase in supplemental flow needed is provided only for discussion purposes, not for any proposed re-allocation of storage to accommodate climate change impacts.

The analysis and results presented thus far reveals some of the uncertainty associated with using projected, climate changed hydrology to generate quantitative conclusions concerning projected, future trends in hydrology. However, as noted previously since each time horizon-emission scenario is calculated from all the GCMs applied for a given emissions scenario, the data in Figure 3.7 does not fully represent the uncertainty (spread) associated with the GCM outputs. It only represents variation in volume resulting from the future time period being considered and the emission scenario being applied.

The uncertainties associated with applying the different GCMs themselves can be generally summarized in several ways using graphics already available, either on the Climate Impacts Groups website or from the OCCRI report.

The Climate Impacts Group Report includes summary graphics highlighting the spread of projections derived from the ten GCM models adopted for analysis (10 GCMs for A1B and 9 GCMs for B1). Figure 3.9 reveal the range of monthly average combined flow (monthly average total runoff depth) and monthly

average total actual evapotranspiration (average depth) produced by the various GCMS for Salem. The spread in monthly average projections derived from the 10 GCMs is indicated by the light red band. As can be seen from Figure 3.9 there is considerably more uncertainty surrounding projected flows than projected evapotranspiration. These graphics also reveal uncertainty associated with the emission scenario and time horizon being analyzed.
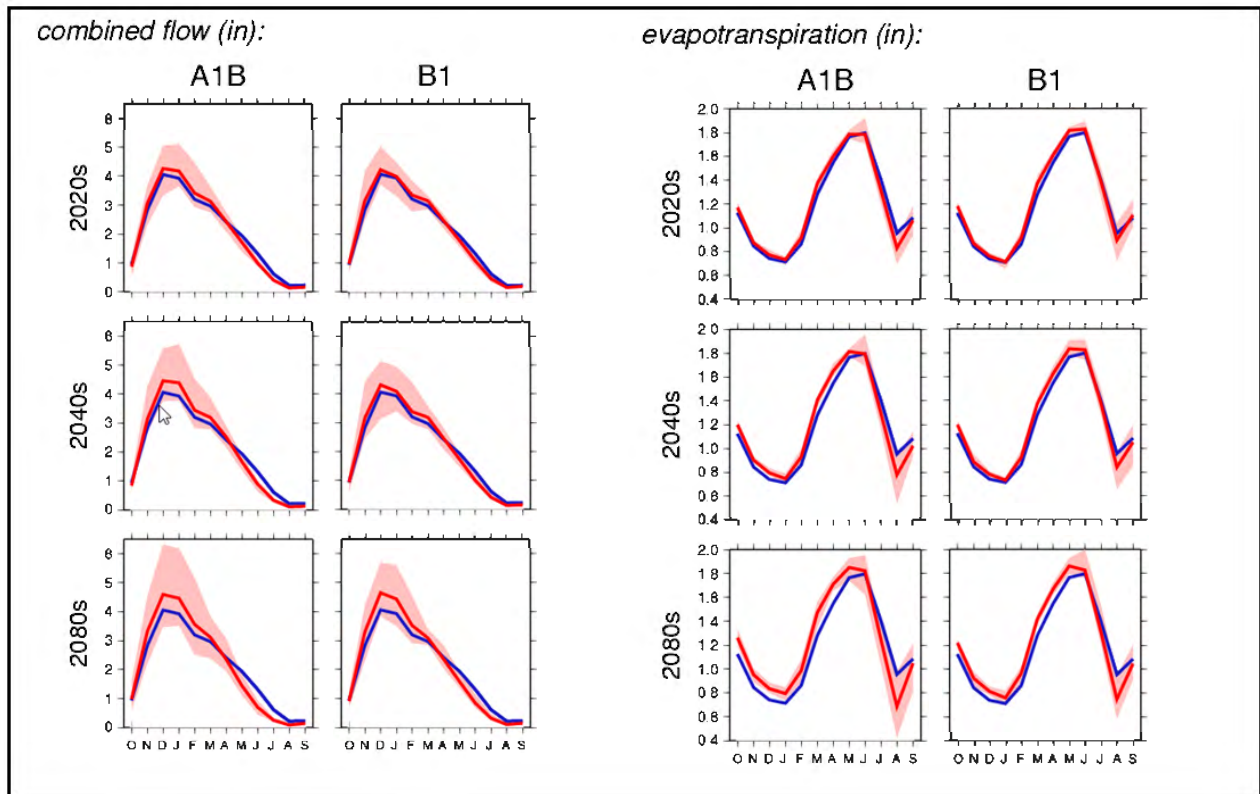


*Figure 3.9. These graphs from the Climate Impacts Group for the Willamette River at Salem illustrate the spread of the GCM model results for projected total runoff and evapotranspiration over the three time horizons and both emissions scenarios analyzed. The Blue line shows the simulated historical values, light red band shows the range of all hybrid delta scenarios for the future time period and emissions scenario and the dark red line shows the ensemble average for the future projections (Available at http://warm.atmos.washington.edu/2860/products/sites/?site=4060).*

Figure 3.10 is also from the Climate Impacts Group Report and presents another means of visualizing the range of results produced by using various GCM models run using two different emission scenarios and analyzed at different time horizons. The results in Figure 3.10 are for the Willamette River at Salem. This figure provides for a visualization of the spread in the 5%, 2%, and 1% annual exceedence probability (20, 50, and 100 year) daily flood statistic estimated using a Generalized Extreme Value (GEV) probability distribution and the spread in the 7Q10 low flow statistic estimate using the GEV probability distribution. The red circulates are indicative of the range of results produced by using different GCM models. This reveals the uncertainty associated with using GCM models to quantify changes in future flows due to climate change. These graphics also reveal uncertainty associated with the emission scenario and time horizon being analyzed.
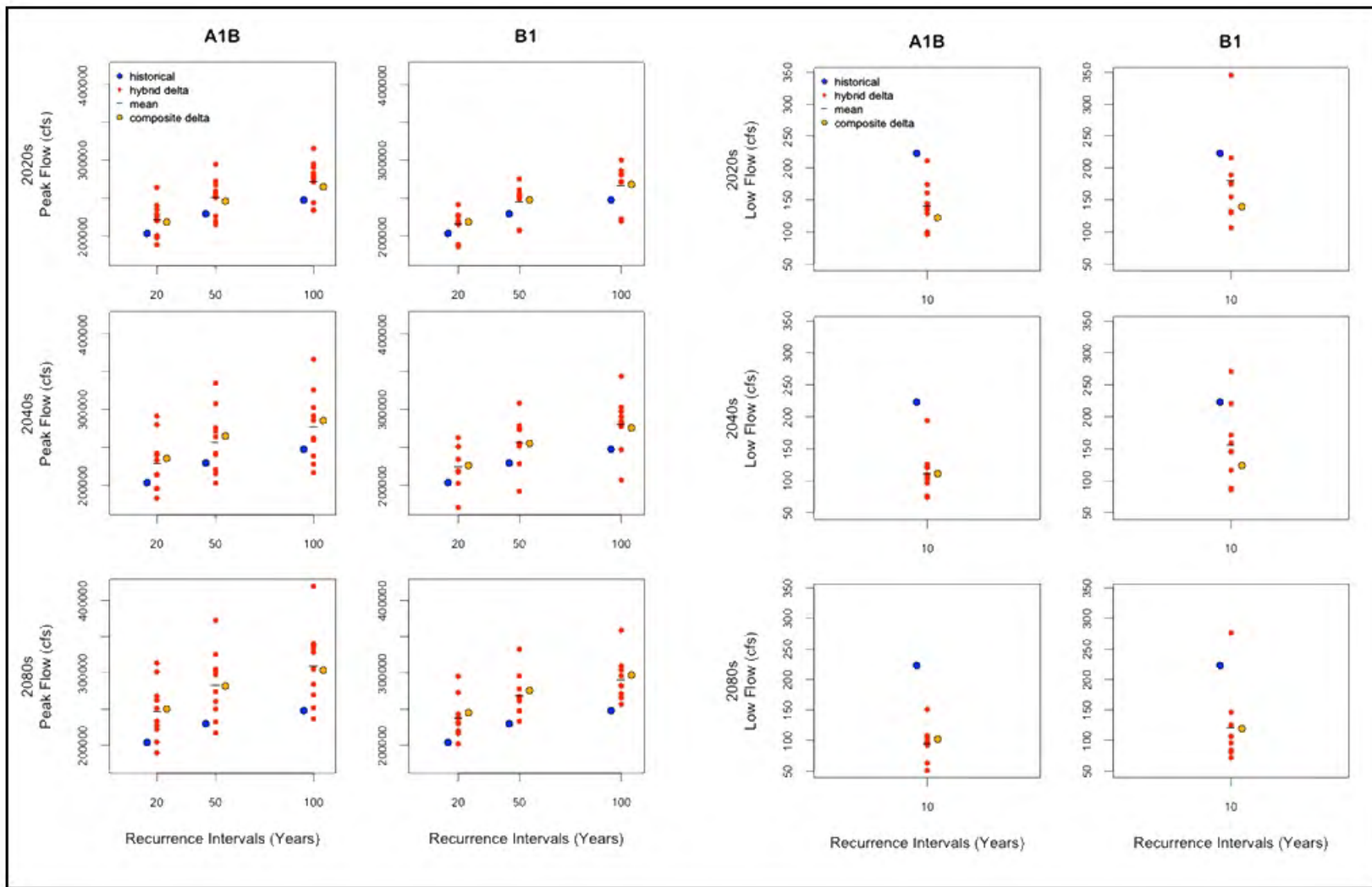
*Figure 3.10 These graphs from the Climate Impacts Group for the Willamette River at Salem illustrate the spread of the GCM model results for projected 5%, 2%, and 1% floods (20-year, 50-year, & 100-year), as well as 7Q10 low flow statics over the three time horizons and both emissions scenarios analyzed. The Blue circles shows the simulated historical values, red circles shows the range of all hybrid delta scenarios for the future time period and emissions scenario , the horizontal red line shows the ensemble average for the future projections and the orange circle shows the composite delta scenario (Available at http://warm.atmos.washington.edu/2860/products/sites/?site=4060).*

As mentioned in Section 2, the OCCRI report (prepared for the USACE Portland District CENWP) also used the data from the Climate Impacts Group, and that report contained some additional graphs which provide insight into the range of results produced using different GCMs to project future streamflows impacted by climate change. Figure 3.11 shows two graphs from that report for mean daily flow and mean monthly flow volume for the 2040 time horizon for both emissions scenarios for the Willamette River above the Falls at Oregon City, which is downstream of Salem. Both figures illustrate that the different GCMs produce a range of results. This spread is indicative of the uncertainty associated with using GCM based outputs to quantify projected, climate change impacted changes in flow magnitude.
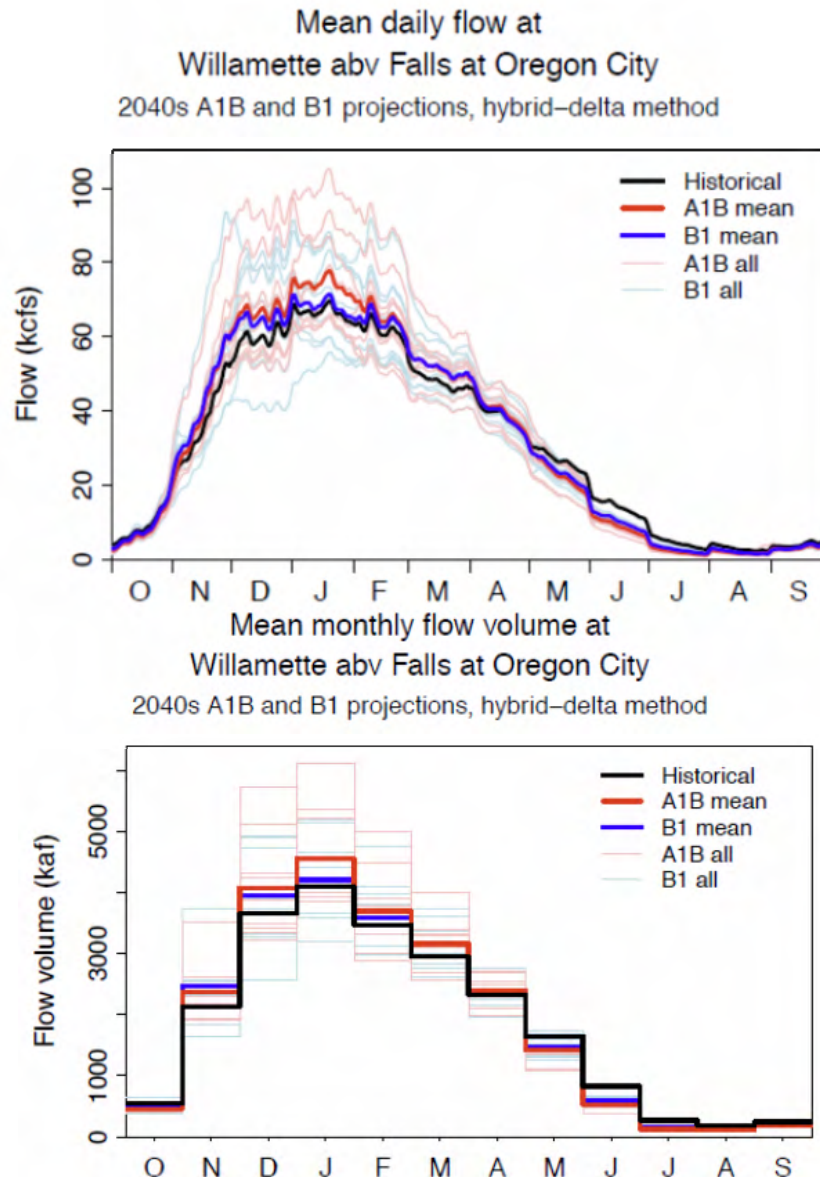


*Figure 3.11 Graphs from the OCCRI report showing the variability in GCMs for the 2040 time horizon and for both the A1B and B1 emissions scenarios for the Willamette River above the Falls at Oregon City. The top graph shows the mean daily flow for each day of the year and the bottom graph shows the mean monthly flow volume.*

# 4 Required Assessments Following ECB 2016-25

The U.S. Army Corps of Engineers requires a quantitative assessment for climate change impacts per ECB 2016-25. These requirements are for all hydrologic studies for inland watersheds. This assessment compliments the previous sections by providing a bigger picture of the impacts of climate change on the Pacific Northwest region and by highlighting the overall impacts to the study area.

The assessment in this section follows the flow chart from the guidance document. Note the assessment contains two phases, the first phase of which is a discussion of the relevant current climate and climate change, where the online assessment tools of the Corps are used to identify trends and slowly varying changes in observed flows, and the second phase for projected changes to the watershed hydrology and an assessment of the vulnerability of the watershed to climate change. A summary of the results derived as part of both phases of the climate change impact assessment is presented in this section.

### Phase I: Relevant Current Climate and Climate Change

*Climate in the Willamette Basin*. Climate in the Willamette Basin is primarily driven by proximity to the Pacific Ocean. The summers are warm and dry and winters are cool and wet in the heart of the valley, with extreme winter alpine conditions in the Cascades Mountain reaches on the eastern boundary of the valley. Most precipitation occurs between November and March, with spring snowmelt prolonging runoff into June or July (Willamette Master Manual, 2017, currently in draft version).

> *Temperatures*. Annual and diurnal temperature ranges are relatively small because the basin is largely dominated by maritime air from the Pacific Ocean. Mean air temperatures in the Willamette Valley (low elevations) range from about 40 deg F in January to 68 deg F in July. Mean mountain temperatures range from about 28 deg F in January to about 55 deg F in July. (See plate 3-7 from the Willamette Master Manual).

> *Precipitation*. Relatively high precipitation occurs in the Cascade Range, the eastern boundary of the Willamette Basin watershed, reaching 140 inches or more per year. Precipitation in the Willamette Valley is considerably less, varying from 35 to 50 inches per year. Most of the precipitation falling at low elevations occurs as rain. Roughly one-third of the precipitation falls as snow at the 4,000 foot elevation, and more than three-fourths falls at the 7,000 foot elevation. For the entire basin, the normal annual precipitation total is about 63 inches based on rain gage and snow depth data. Of this, 60 percent occurs during November through March. Based on stream flow data, the average annual runoff for the entire basin is about 47 inches. (See Plates 3-9 to 3-11, Willamette Master Manual).

*Observed Trends*. The USACE Climate Hydrology Assessment Tool (accessible at: https://maps.crrel.usace.army.mil/projects/rcc/portal.html) was used to examine observed streamflow trends on the Willamette River at Salem, Oregon (USGS gage 14191000). Salem is the most upstream, real-time, reservoir regulation control point on the mainstem that receives outflow from all thirteen Willamette Valley Project (WVP) USACE dams. Salem is a major control point used during flood risk management in the winter months and also the location where minimum flow targets are specified for

fish and wildlife by the BiOp for April through October. The drainage area for this gage is 7,280 square miles (65% of the 11,200 square miles that encompasses the whole Willamette River Basin). At the Salem gage daily discharge measurements became available in 1909. Annual peak streamflow records are available from 1893 to 2018, with three earlier data points of historical significance available for 1862, 1881, and 1890. The WVP total drainage areas (areas above all reservoirs) are 41.6% of the total Salem drainage area, and about half (51.4%) of the annual water volume passing through Salem has passed through at least one WVP dam.

The USACE WVP reservoirs provide about 1.6 MAF of flood storage space and were built with flood control as their primary purpose, however they are also operated for water supply (fish and wildlife, municipal & industrial, agricultural irrigation), hydropower, and recreation. The first USACE dam in the basin was completed in 1941 and the last was completed in 1969, with refill in 1970; so the flow data available at the USGS Salem gage has been influenced by reservoir operations since that time. Other effects on the Salem gage have been changing amounts of irrigation within the basin and increased urbanization, with a steady increase in population over the past fifty years, approximately doubling over this period.

It is important to note that the data series in the tool, which is from the USGS gage at Salem, is observed data, and the full record of peak flows from the gage included a mix of unregulated and regulated data. The data record up to 1940 represents homogenous, ***unregulated*** peak flows, since no USACE projects were in place during that time. The period of 1941 to 1969 is the period over which the thirteen dams, eleven of which are storage projects, were built – this period is not a homogeneous period due to the varying construction and first fill dates throughout the record. The period of 1970 to 2018 represents a homogenous period, with all dams operating, and so this portion of the record is representative of the homogenous, ***regulated*** peak flow.

The Climate Hydrology Assessment Tool has been developed to facilitate an evaluation of annual peak flows. In this watershed, peak flows occur in the winter months outside of the April through October conservation season (the conservation season is the critical season for this study for which storage re-allocation is being analyzed). Still, an assessment of peak flows is relevant since flood risk management is the primary purpose of the Willamette Valley Project (WVP). Figure 4.1 shows the results at Salem from this tool. Note that the Willamette Basin is HUC-4 number 1709. The figure shows a trend of decreasing annual peak instantaneous flow for 1893-2014; this portion of the period of record represents a mix of regulated and unregulated flows (top graph in Figure 4.1). The annual peaks for the *regulated* flow period (1970-2014) are shown in the bottom graph of Figure 4.1. The P-values for both graphs are shown on the graphs, the P-value is less than 0.0001 for the continuous (mixed unregulated and regulated) and 0.306325 for the regulated period. The typically adopted threshold for a statistically significant trend is a P-value less than 0.05. The decreasing trend in the top graph of Figure 4.1, for the full non-homogeneous record, likely reflects the impact of the WVP dams, which are operated for flood risk management. There is no significant trend in the data after the construction of the dams (lower graph of Figure 4.1, for 1970-2014).
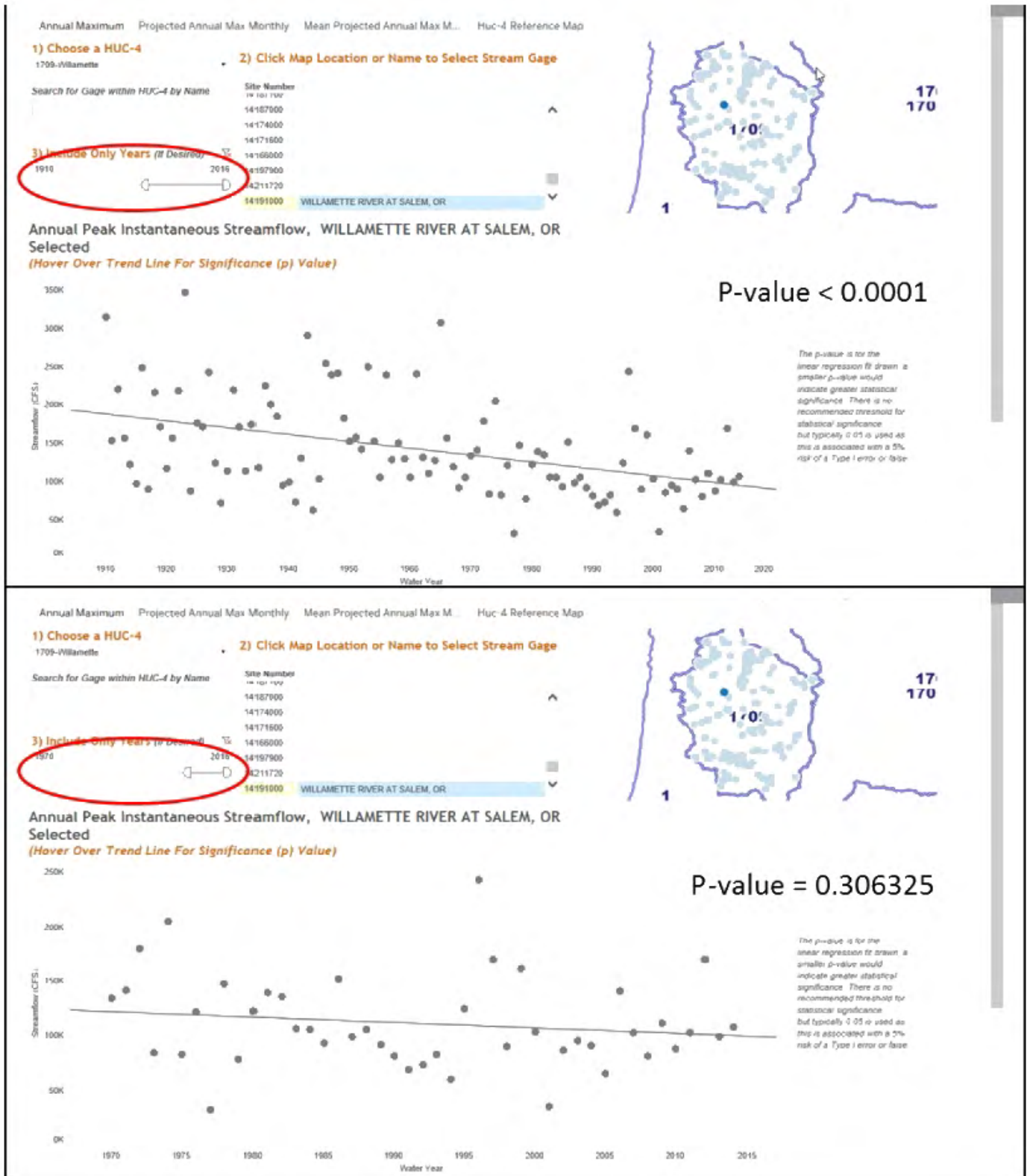
*Figure 4.1 Annual Peak Instantaneous Streamflow, Willamette River at Salem, Oregon. Top graph for full continuous record (1893-2014), bottom graph for regulated flow since last USACE dam in basin completed (1970-2014).*

Figures 4.2 through 4.4 show some trends and statistics for the record "SLM5M" from the 2010 Modified Flow dataset. The SLM5M record represents the **unregulated** flow at Salem as described in *Appendix D, Willamette Basin Review – Flow Dataset Used for ResSim Analyses*. The flow record contains daily average values for 1928-2008, and annual maximum and minimum values were pulled using HEC-DssVue and brought into Microsoft Excel for plotting and statistical analyses. The annual maximum value is relevant to flood risk management, but is not relevant to the WBR study. Trends in the annual minimum flow and the total conservation season volume are relevant to both water supply studies and estimates of increasing needs for supplemental flows on the mainstem to meet BiOp targets. Figure 4.2 shows the annual maximum values for the SLM5M record, and Figure 4.3 shows the annual minimum values of the record. Figure 4.4 is the total volume of water in the record for April through October of each year in the SLM5M record. The P-value associated with the linear trend analysis in the annual maximum peak flow data is 0.778, significantly higher than the generally accepted threshold for significance of 0.05, so there is no statistically significant trend in the unregulated annual maximum flows at Salem. The P-value associated with the linear trend analysis in the annual minimum flow data is 0.0066, which is below the generally accepted threshold for significance of 0.05, meaning there is evidence of a statistically significant decreasing trend in the annual minimum daily flows at Salem. The P-value associated with the linear trend analysis in the volume of water passing Salem for April through October is 0.44, significantly higher than the generally accepted threshold for significance of 0.05, so there is no statistically significant trend in the volume of water passing through Salem in April through October.
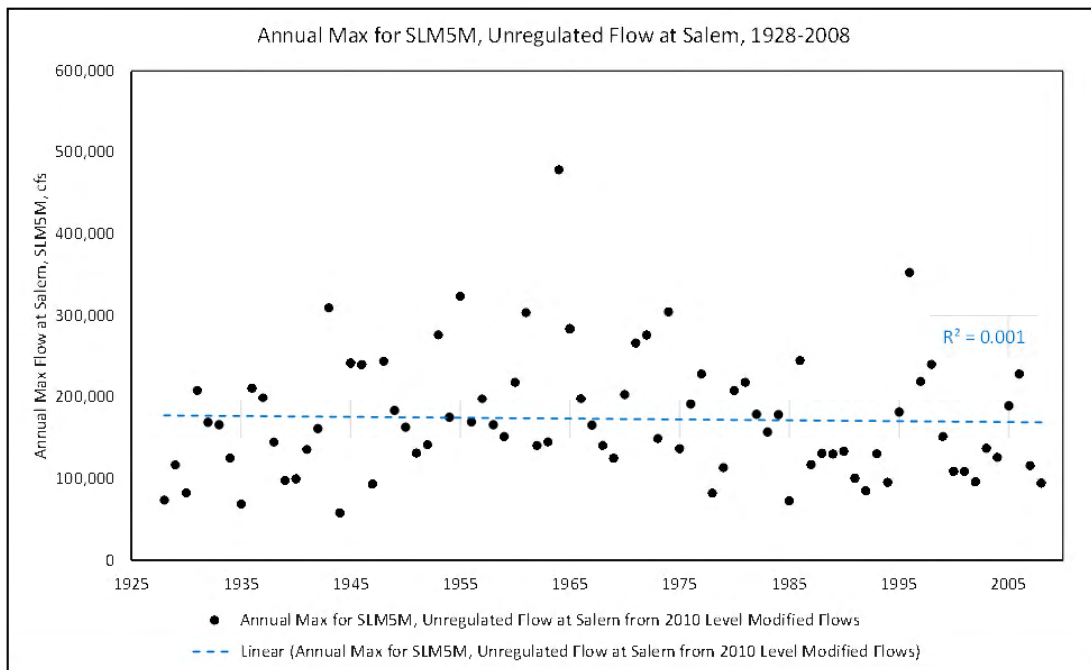


*Figure 4.2 Annual Maximum Daily unregulated Flows from the SLM5M record, Willamette River at Salem, from the 2010 Modified flow dataset. (See Appendix D for a full description of the Modified Flow dataset.) Note P-value is ~ 0.778>>0.05, $R^2$ = 0.001<<0.7*
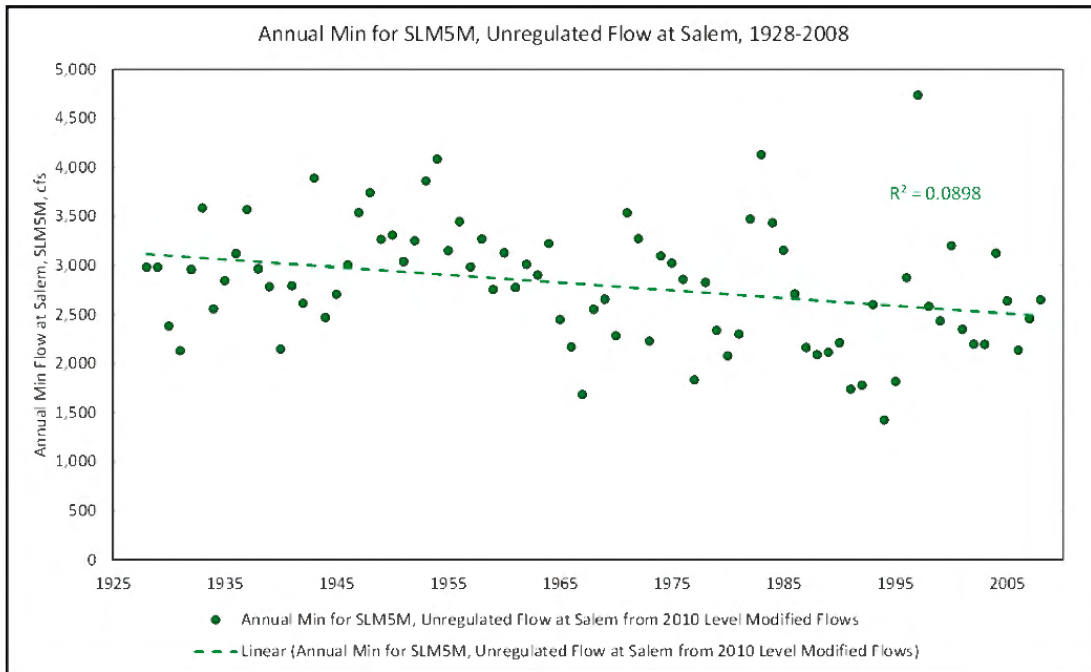
*Figure 4.3 Annual Minimum Daily unregulated Flows values from the SLM5M record, Willamette River at Salem, from the 2010 Modified flow dataset. (See Appendix D for a full description of the Modified Flow dataset.) Note P-value is ~ 0.0066, $R^2$ = 0.0898, with a negative slope to the trend line.*
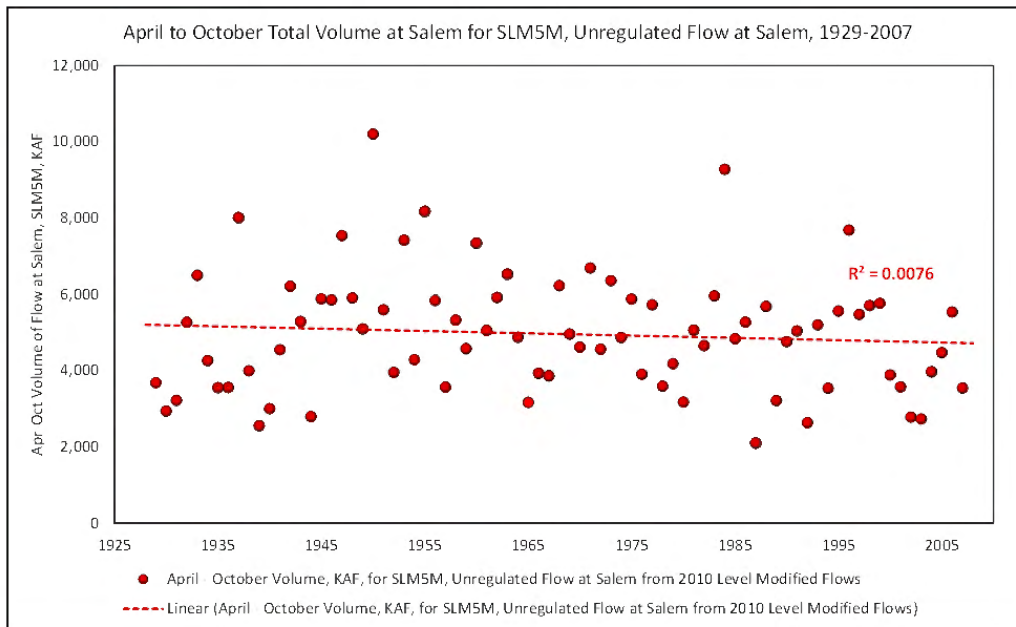


*Figure 4.4 Yearly water volume passing Salem from April through October, in KAF (1 KAF = 1,000 acre-feet), from the SLM5M record, Willamette River at Salem, from the 2010 Modified flow dataset. (See Appendix D for a full description of the Modified Flow dataset.) Note P-value is ~ 0.44>>0.05, $R^2$ = 0.0 76<<0.75*

*Observed Changes and Projected Trends in Hydrometerological Variables: Literature Synthesis.* A description of trends for temperature, precipitation, and hydrology is available in the report "Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions", Pacific

Northwest Region 17, 2015, with the key points highlighted in the top portion of Figure 4.5. This report was generated by the USACE and is a synthesis of a wide array of climate literature. Both observed and projected temperature data indicates that the region's temperatures are warming. There is some regional consensus indicating increasing trends in observed annual average precipitation. However, trends in projected, future precipitation do not provide a strong indication of how average annual precipitation will change in the future, although there are indications that the intensity and frequency of storms will increase. Projected hydrology changes, such as in streamflow, have a low consensus, with results varying with the location, climate models applied, and emissions scenarios chosen for a particular study. These trends are consistent with those that were described in more detail in Section 2 of this appendix.

---

**Observed Climate Trends**
*Temperature:*

*Key point: Increasing trends have been identified in the region's temperature data for the 20th century for average, minimum, and maximum temperatures. Some spatial variability is observed in the recent peer-reviewed literature related to mean annual temperature; however, there is a strong consensus that the region's coastal area has experienced an overall increase. A few studies note a slight decrease or no trend in the inland areas of the region, but the location of these decreasing trends (or no change) was not consistent amongst the literature presented.*

*Precipitation:*

*Key point: Overall, increasing trends have been identified in the Pacific Northwest Region's annual average precipitation data for the latter half of the 20th century, especially in the coastal areas. Note, there is only a moderate consensus across the literature for annual average precipitation trends and this increasing trend is variable depending upon location and season.*

*Hydrology:*

*Key point: A strong consensus of statistically significant decreasing trends have been identified in the region's streamflow and 1 April SWE data for the latter half of the 20th century.*

**Projected Climate Trends:**
*Temperature:*

*Key point: Strong consensus exists in the literature that maximum temperature extremes in the study region show an increasing trend over the next century. A moderate consensus was found supporting an increasing trend in annual average temperature and minimum temperature extremes.*

*Precipitation:*

*Key point: Strong consensus exists in the literature that the intensity and frequency of extreme storm events will increase in the future for the Pacific Northwest Region. Low consensus exists with respect to projected changes in total annual precipitation for the region. Future projected changes in annual average precipitation varied in magnitude (increasing or decreasing) depending upon location(s), season(s), climate model(s), and emissions scenario(s) considered in a particular study.*

*Hydrology:*

*Key point: Low consensus exists with respect to projected changes in hydrology for the region. Future projected changes in hydrologic parameters (e.g., runoff, streamflow, SWE) varied in magnitude (increasing or decreasing) depending upon location(s), climate model(s), and emissions scenario(s) considered in a particular study.*

---

***Figure 4.5 Key points copied from the "Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions", Pacific Northwest Region 17***

The USACE Nonstationarity Detection Tool (https://maps.crrel.usace.army.mil/apex/f?p=257:2:0::NO:::) (ETL-1100-2-3) is used to assess the observed, annual instantaneous peak streamflow dataset at Salem. Figure 4.6 shows the result from the nonstationarity detector tool and Figure 4.7 presents the monotonic trend analysis for Salem from the tool using the full period of record from 1893 to 2014. For the period of record analysis, Figure 4.6 shows some closely clustered nonstationarities in the mid-1960s (two red lines targeting mean and two blue lines targeting distribution) showing both consensus and robustness. Several other nonstationarities are flagged in the mid-1920s, early 1950s, and early 1980s. There is a gradual flux in the statistics between the 1950s and 1980s. This reflects the period when the reservoirs were coming on-line. There is a measureable decrease in the magnitude of the mean in 1970. These results are expected because the dams are primarily operating for flood risk management. For the whole period of record there is a statistically significant, decreasing monotonic trend. The USACE dams in the basin were completed by 1970, and Figure 4.8 shows the results from the detection tool for the relatively homogenous, regulated period of record since 1970.No nonstationarities were detected by the tool and there were no monotonic trends in the peak flow data collected between 1970 and 2014.

Although Salem is a focal point in the basin for both flood risk management and BiOp minimum flow targets, and it is the most upstream mainstem location on the Willamette River for which all reservoirs supply water, the nonstationarity detection tool was applied to two other locations in the basin, both representative of unregulated conditions. The purpose of looking at these two additional locations is to see if the lack of nonstationarities being detected at Salem post 1970 is a result of the impact of the reservoirs attenuating the signal associated with any nonstationarities potentially driven by land use/land cover changes, smaller watershed modifications, natural climate fluctuations or human driven climate change.  One location (USGS gage 14178000 NO SANTIAM R BLW BOULDER CRK, NR DETROIT, OR) is upstream of Detroit reservoir (the most northern project in the basin), and has a drainage area of 216 sq. miles, with peak streamflow data available from 1929 to 2016. The other location (USGS gage 14144800 MIDDLE FORK WILLAMETTE RIVER NR OAKRIDGE, OR) is upstream of Hills Creek reservoir (the most southern project in the basin), and has a drainage area of 264 sq. miles, with peak streamflow data available from 1959 to 2016. The tool results are shown in Figure 4.9 for the gage above Detroit and in Figure 4.10 for the gage upstream of Hills Creek. Neither location shows "strong" evidence of nonstationarity in their associated peak stream flow record. Neither location indicates a monotonic trend in the peak streamflow data.
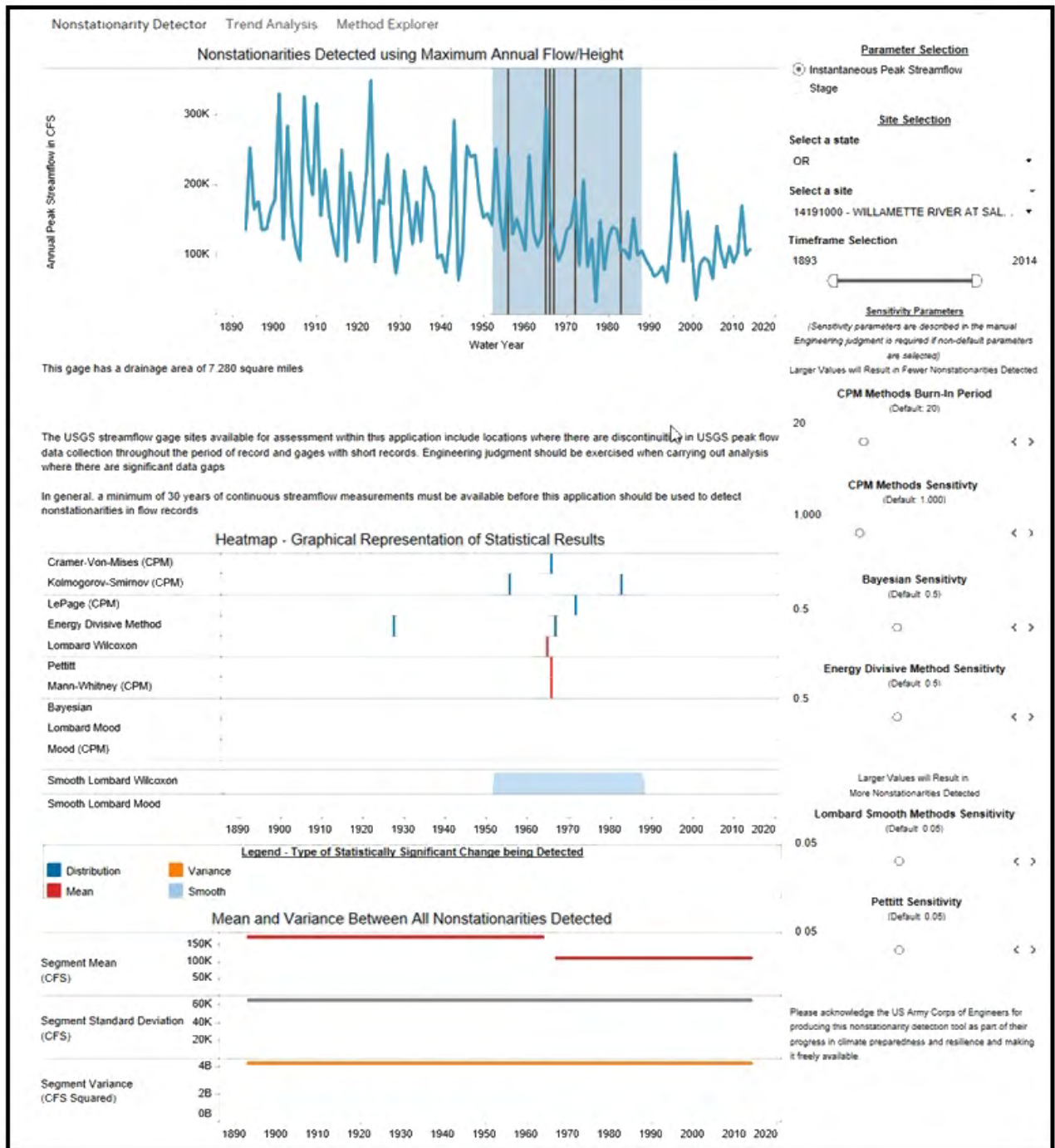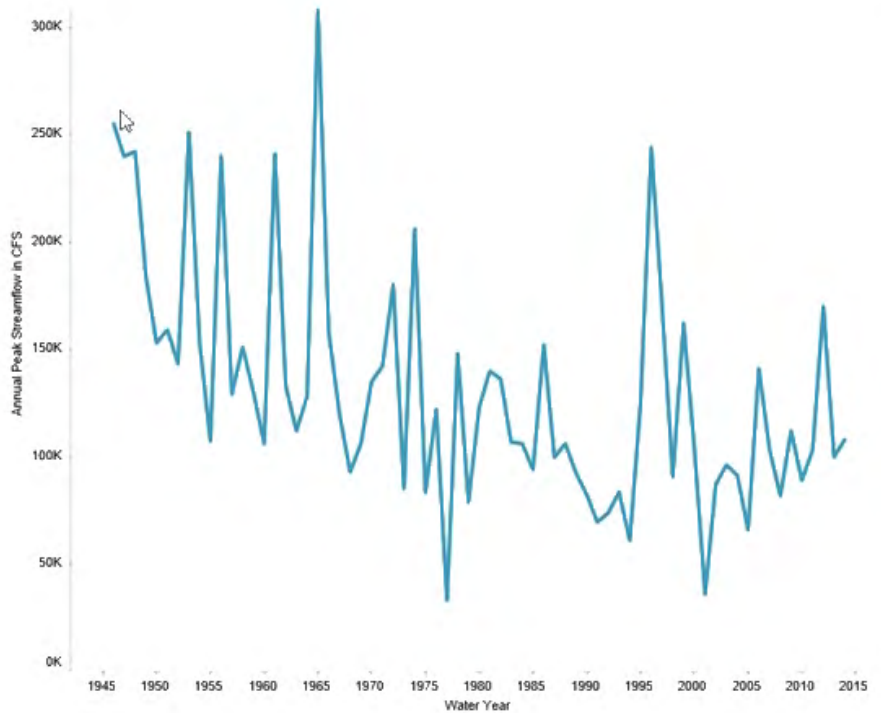
*Figure 4.6 Results from the Nonstationarity Detection Tool for the Willamette River at Salem. The full data record since 1893 was used, which included years before any dam construction and years after all dams were completed.*

**Monotonic Trend Analysis**

Is there a statistically significant trend?
**Yes,** using the Mann-Kendall Test at the .05 level of significance. The exact p-value for this test was less than 1e-3.
**Yes,** using the Spearman Rank Order Test at the .05 level of significance. The exact p-value for this test was less than 1e-3.

What type of trend was detected?
Using parametric statistical methods, **a negative trend** was detected
Using robust parametric statistical methods (Sen's Slope). **a negative trend** was detected.

Please acknowledge the US Army Corps of Engineers for producing this nonstationarity detection tool as part of their progress in climate preparedness and resilience and making it freely available

*Figure 4.7 Results from the Nonstationarity Detection Tool, Monotonic Trend Analysis, for the Willamette River at Salem. The full data record since 1893 was used, which included years before any dam construction and years after all dams were completed.*
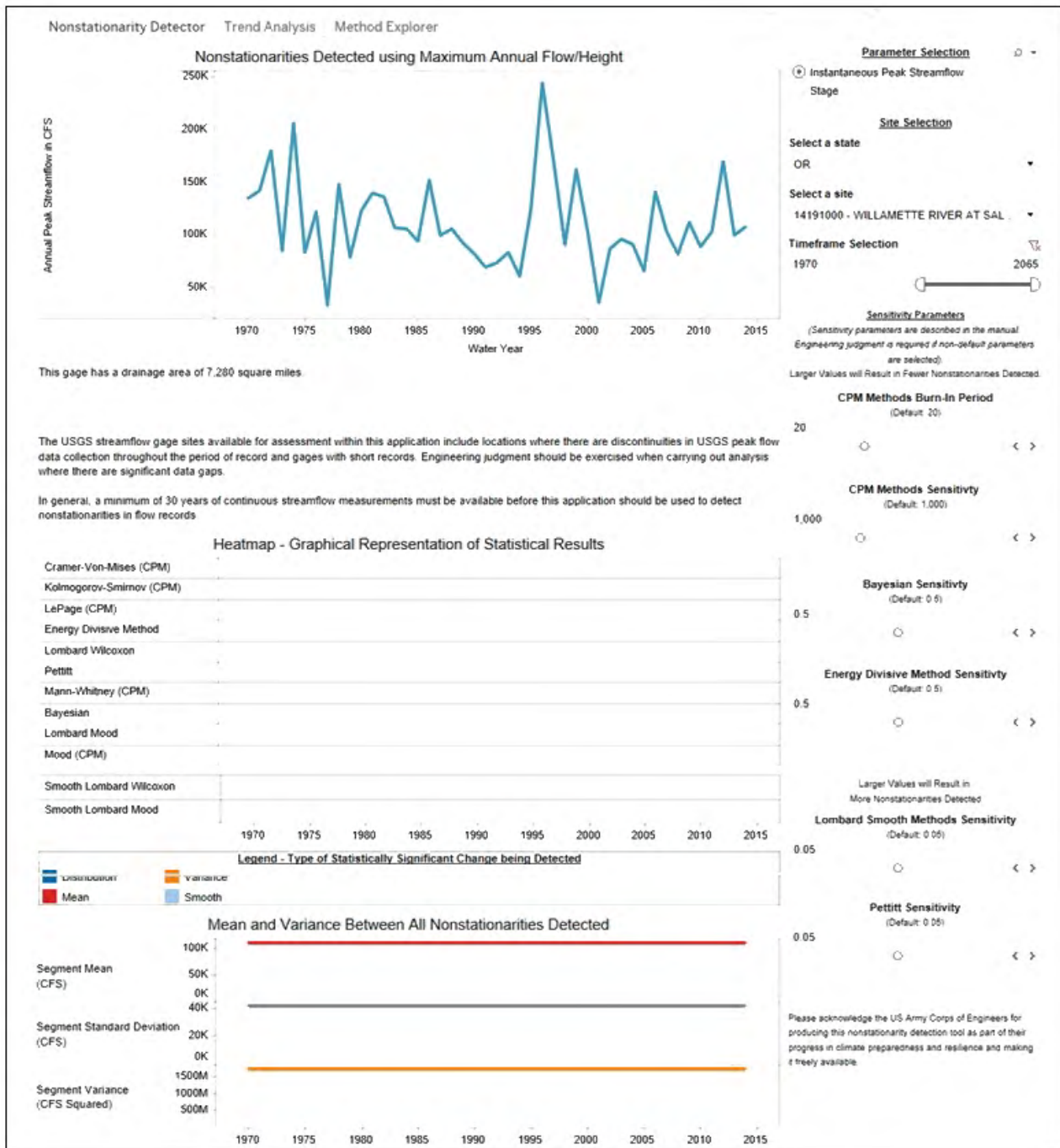
*Figure 4.8 Results from the Nonstationarity Detection Tool for the Willamette River at Salem, using the homogeneous period after all dams were completed, from 1970.*
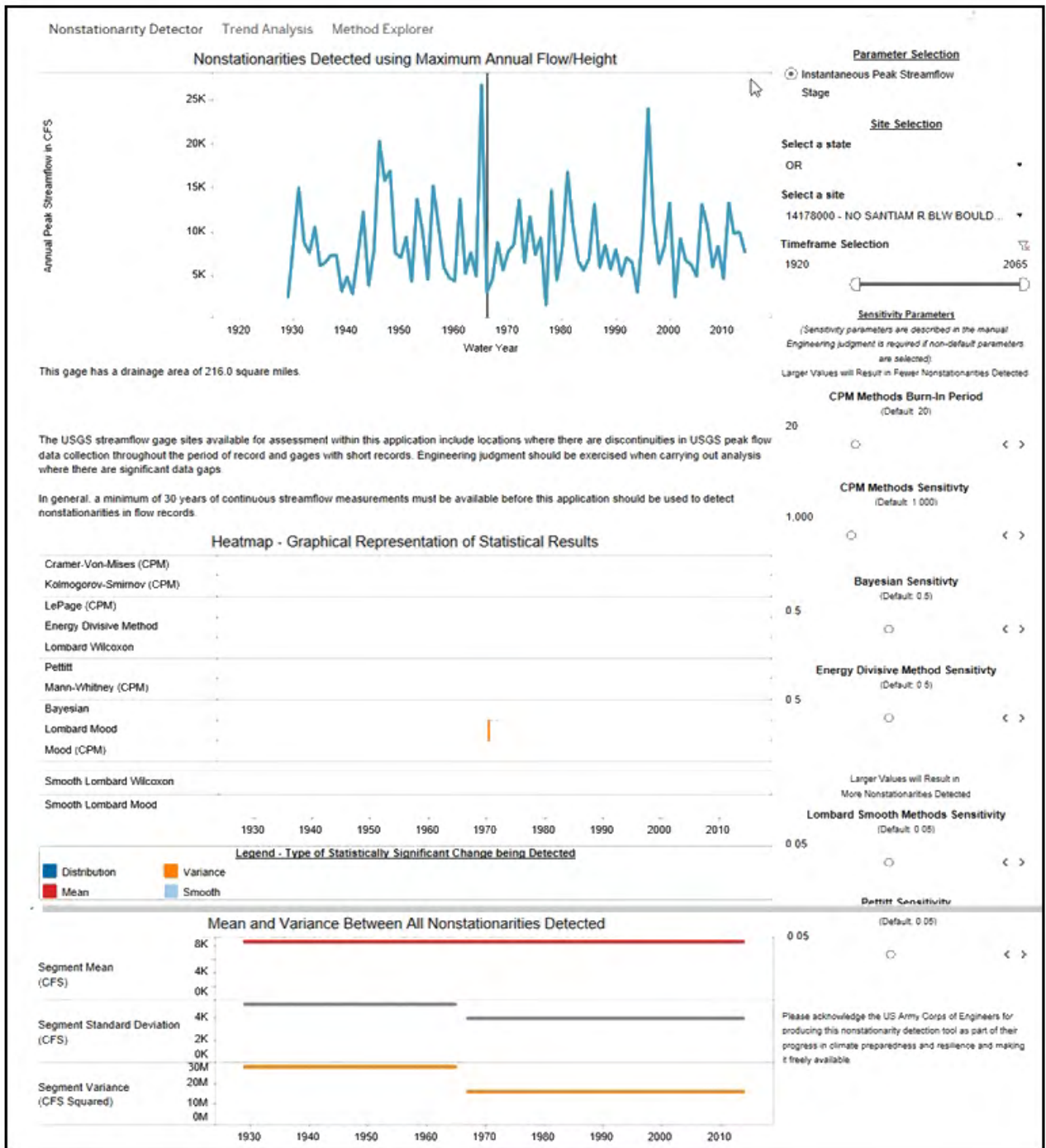
*Figure 4.9 Results from the Nonstationarity Detection Tool for gage 14178000, located on the North Santiam River below Boulder Creek near Detroit, Oregon. This gage is above the Detroit reservoir, so is unregulated.*
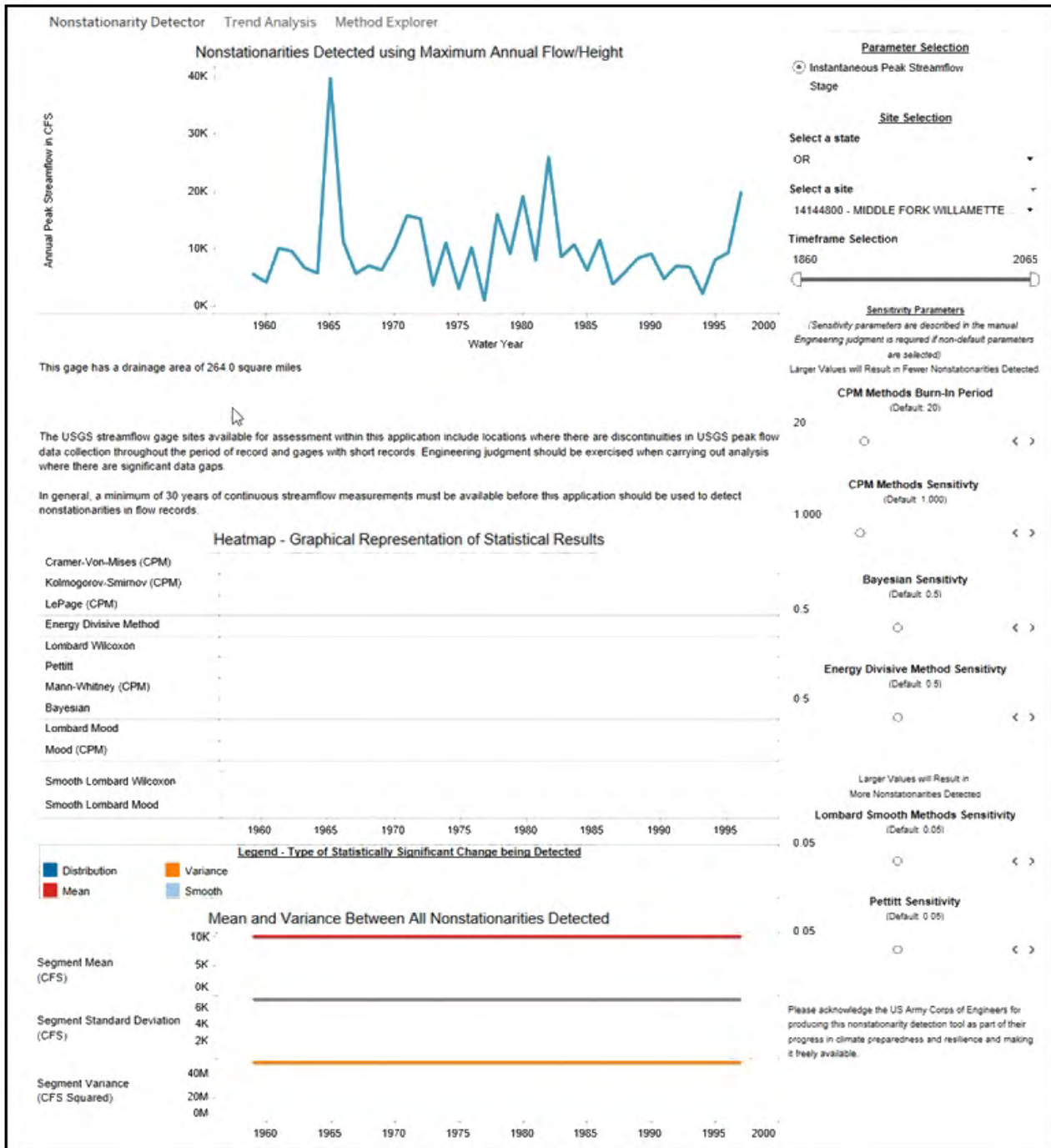
*Figure 4.10 Results from the Nonstationarity Detection Tool for gage 14144800, located on the Middle Fork Willamette River near Oakridge, Oregon. This gage is above the Hills Creek reservoir, so is unregulated, and is one of the most southern gages in the basin.*

## Phase II: Projected Changes to Watershed Hydrology and Assessment of Vulnerability to Climate Change

The USACE Climate Hydrology Assessment Tool was used to examine projected trends in watershed hydrology. The data available from the tool is 1950 to 2099. The data presented for 1950 to 1999 represent the hindcast period where the same carbon emissions are assumed for all global circulation models (GCMs) being applied to generate hydrologic response. The greenhouse gas emissions assumed for the hindcast period have been developed to mimic historically, observed emissions.

The realizations of temperature and precipitation generated for 2000 to 2099 are projected using various, different, anticipated concentration pathways of greenhouse gas emission (RCPs). The results presented in the Projected, Annual Maximum Monthly tab of the Climate Hydrology Assessment tool are representative of flows at the outlet of HUC04 1709 representing the Willamette Basin. Note that the time series generated using the GCMs and representative of the hindcast period do not replicate observed precipitation, temperature or streamflow datasets because of the downscaling technique applied and because they are not based on observed initial conditions and do not use the same boundary conditions for each simulation. The projected range of outputs from the various GCM/RCP combinations used to generate different potential future traces of climate changed hydrology are shown in Figure 4.10 for the annual maximum monthly values. The mean projected annual monthly maximum of all the GCM model outputs is fit with trend line in Figure 4.11 (with a P-value < 0.0001). The detected, increasing trend is statistically significant (0.0001<<0.05).
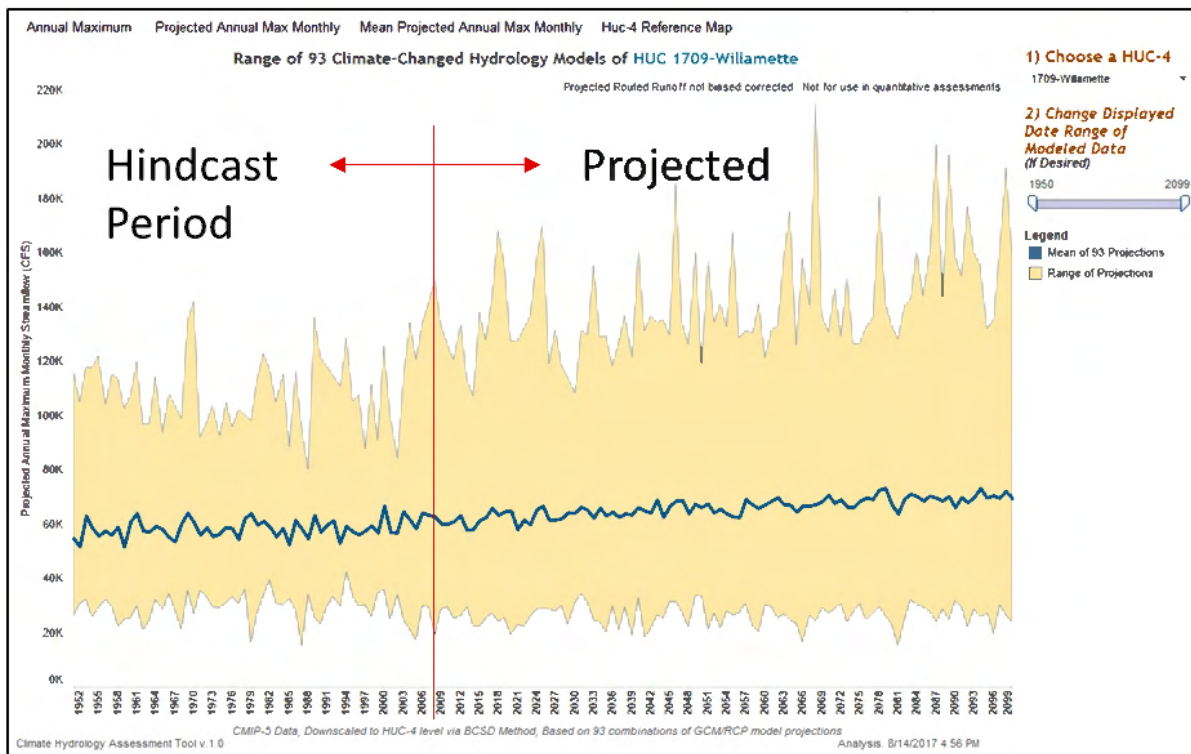


*Figure 4.10 Range in the Projected Annual Maximum, Monthly, flows-Willamette Basin (HUC04 1709).*
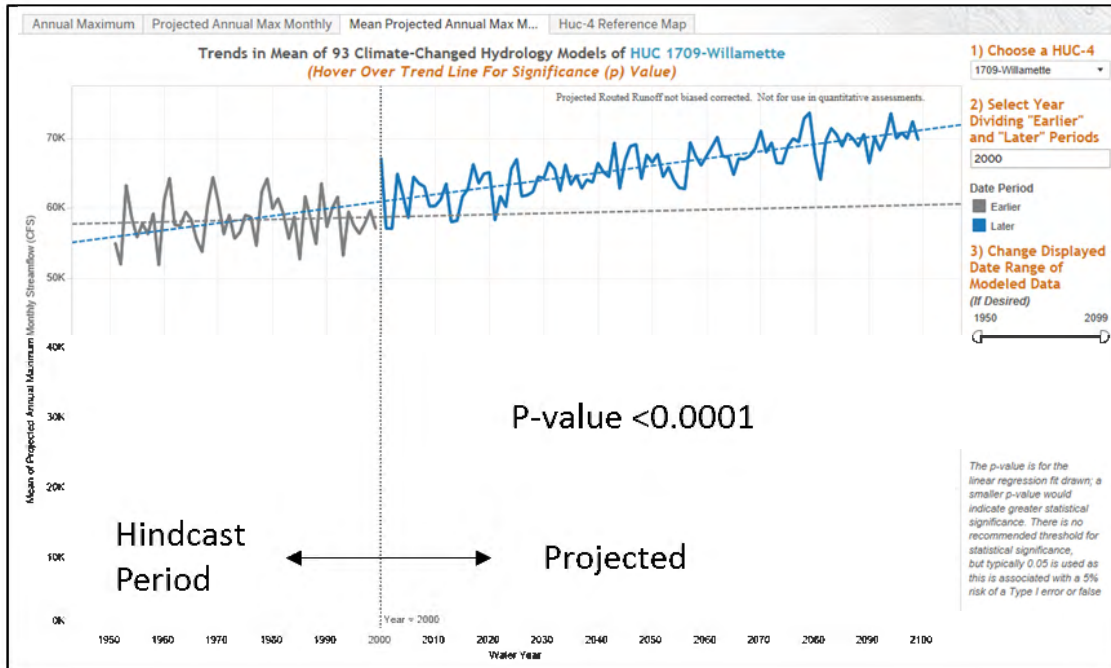
*Figure 4.11 Mean Projected Annual Max, Monthly, flows for Willamette Basin (HUC04 1709).Note P-value < 0.0001.*

These figures are qualitative only and suggest that flood risks will increase in the future relative to the current time. Note that the climate changed hydrology is representative of the unregulated basin condition and that it is produced using statistically downscaled (BCSD), CMIP-5 GCM model output data translated into a runoff response using a coarsely calibrated, VIC hydrology model. There are 93 combinations of GCM/RCPs used to produce the results presented by the tool, at a HUC4 scale, not at a specific gage location. Also note that the projected range of the Salem maxima (the tan area in Figure 4.10) grows much larger in the later years of the x-axis, reflecting an increase in the uncertainty associated with climate change model outputs.

The USACE Screening-Level Climate Change Vulnerability Assessment tool (found at: https://maps.crrel.usace.army.mil/apex/f?p=201:2:3754613296055) was used to explore possible responses in the Willamette Basin to climate change. This tool is available to provide a high level assessment of the relative vulnerability of USACE missions and operations in a given HUC04 watershed to climate change based on analyzing variables tied to specific USACE business lines. This assessment occurs at the HUC4 watershed scale and is presented in a visual format to make the information concise.

The relative vulnerability of a watershed is determined relative to the computed vulnerability for the other 201 HUC04 watersheds in the continental United States (CONUS). CMIP-5 climate data produced using different emission scenarios is applied to obtain a vulnerability score (using National Standard Settings) for two 50 year epochs in the future centered about water years 2050 and 2085. The top 50% of traces by volume are grouped as a "wet" subset of flow traces and the bottom 50% of traces are grouped as a "dry" subset. Displaying the results generated by the vulnerability tool for two epochs of time and two subsets of traces reveals some of the uncertainty associated with the CMIP-5 global circulation model (GCM) data being used to compute some of the indicator variables applied to

generate vulnerability scores. As described in the discussion of the projected, climate changed hydrology used for the Climate Assessment Hydrology Tool, there is a great deal of uncertainty in the data being generated by GCMs and translated into a hydrologic response using the coarsely calibrated, U.S Bureau of Reclamation VIC model developed for the entire country.

A weighted order weighted average (WOWA) vulnerability score is calculated for each epoch, for wet and dry subsets of traces, for each business line at the HUC04 level. A set of predefined indicator variables for each business line are used to compute the WOWA vulnerability score. The watersheds with the top 20% of vulnerability scores in the continental U.S (CONUS) are then defined as relatively vulnerable. Figures 4.13 through 4.15 summarize the results for the Willamette Basin (HUC04 1709).

Figure 4.12 contains two screen shot images of the summary results for HUC04 1709 from the tool for the flood risk reduction and water supply business lines for the Willamette basin. These two business lines are used to illustrate the vulnerability assessment since flood risk reduction is the primary function of the project and the study is focused on investigating future Willamette River basin water demand and more specifically on reallocating WVP conservation storage for the benefit of Endangered Species Act (ESA) listed fish, agricultural irrigation (AI) and municipal and industrial (M&I) water supply.

The WOWA scores for these two business lines, along with hydropower and recreation, which are also relevant for the WBR study, are shown in the table at the bottom of the figure. Note that none of the vulnerability scores for the Willamette Basin business lines are considered relatively vulnerable for either subset of traces or either epoch of time relative to the other 201 HUC4 watersheds in the CONUS. HUC 1709 is not in the top 20% of scores for the U.S. for any of the USACE business lines.

More details about the flood risk reduction and water supply business lines vulnerability scores are shown in Figures 4.13 and 4.14. These two figures break down the total WOWA score from Figure 4.12 into their dominant indicator contributions. Each value shown in the table at the bottom of Figure 4.12 is the sum of the scores from the dominant indicator variables for each business line by epoch and dry/wet subsets. Figure 4.13 shows this in more detail for the flood risk reduction business line and in Figure 4.14 for the water supply business line, with both figures breaking out the dry subset into pie charts for each epoch segmented by the predefined indicator variables for those business line. Note that the indicator variable percent contribution is also shown in the tables in Figures 4.13 and 4.14.

There are slight differences between the sum of the dominant indicator variables and the reported vulnerability score. For example, for the dry subset traces for the 2050 epoch for flood risk reduction the indicator variable values 22.14, 13.06, 6.60, 3.60, and 1.43 sum up to is 46.83, while the 2050 Dry WOWA score for flood risk management in the table at the bottom of Figure 4.12 is 46.84. Differences in the dominant indicator score sums and the WOWA score are from round-off errors in the display of the indicator values.

**Summary of HUC 1709 (Willamette Basin) Results: WOWA Score**

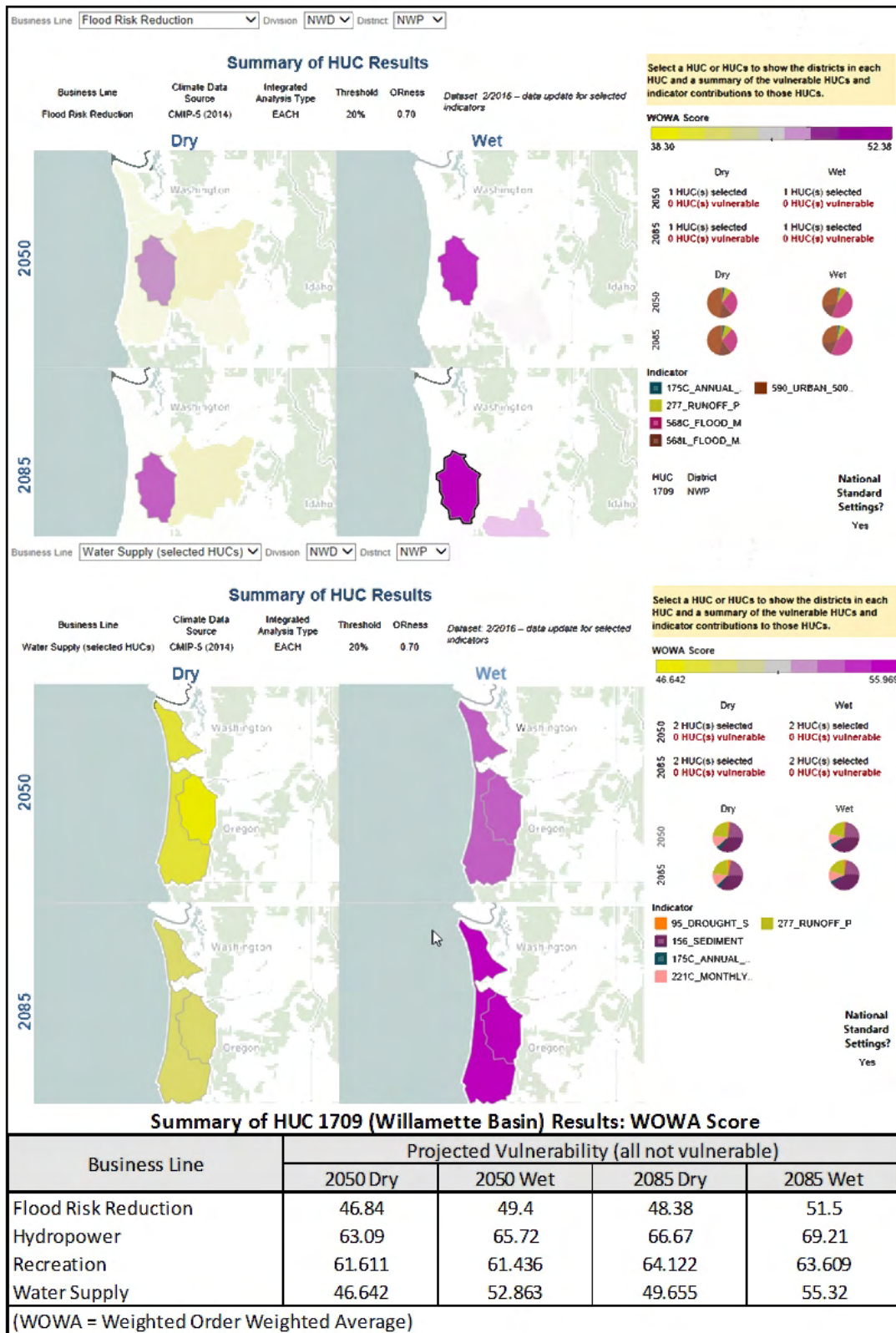| Business Line | Projected Vulnerability (all not vulnerable) | | | |
|---|---|---|---|---|
| | 2050 Dry | 2050 Wet | 2085 Dry | 2085 Wet |
| Flood Risk Reduction | 46.84 | 49.4 | 48.38 | 51.5 |
| Hydropower | 63.09 | 65.72 | 66.67 | 69.21 |
| Recreation | 61.611 | 61.436 | 64.122 | 63.609 |
| Water Supply | 46.642 | 52.863 | 49.655 | 55.32 |
| (WOWA = Weighted Order Weighted Average) | | | | |

*Figure 4.12 Projected Vulnerability for the Willamette Basin (HUC 1709) for Flood Risk Reduction at top and Water Supply at bottom, with the table showing WOWA scores for the relevant business lines for the Willamette Basin.*
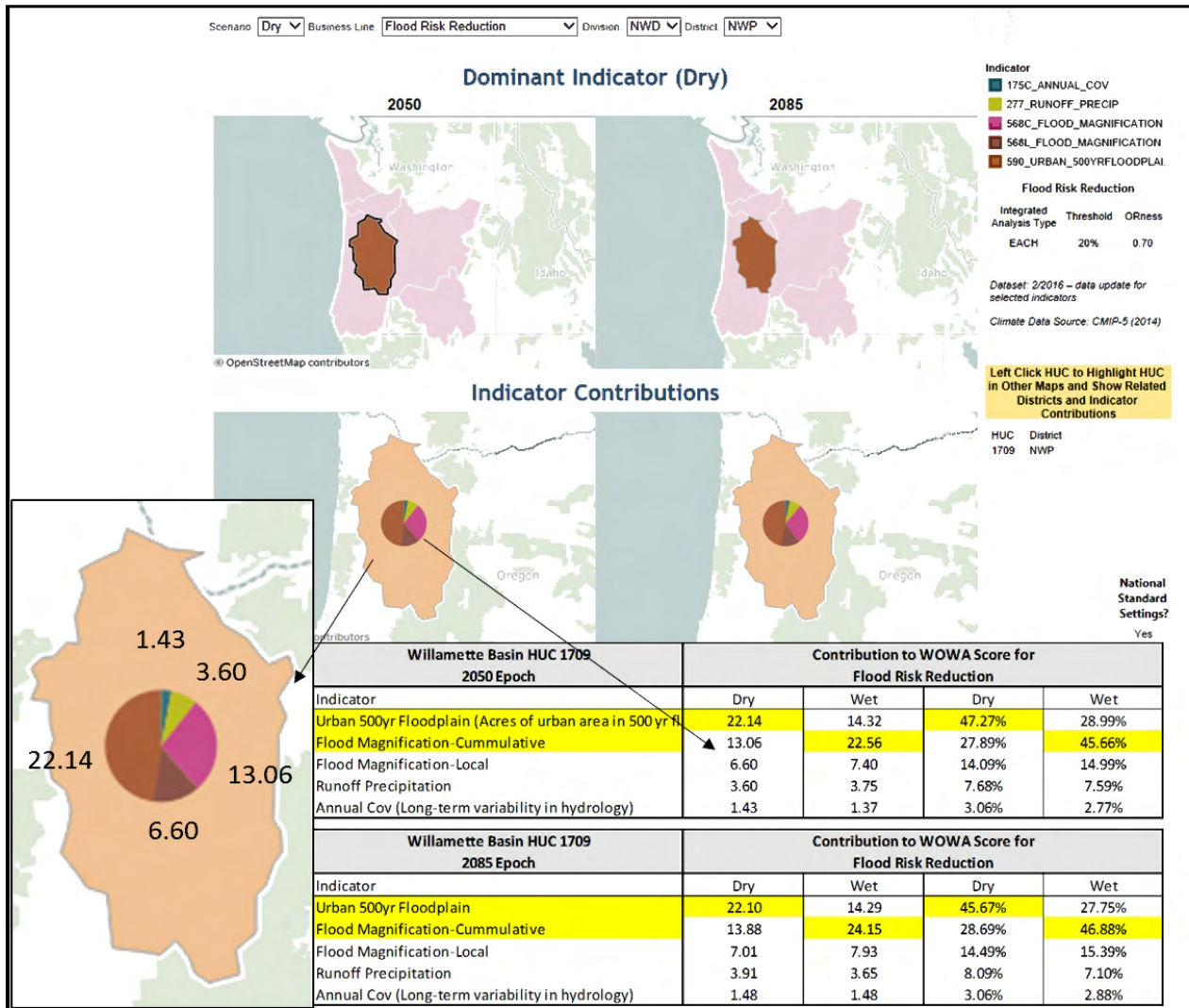
*Figure 4.13 Dominant Indicator contributions for the Willamette Basin (HUC 1709) from the Vulnerability Assessment Tool for the flood risk reduction business line. Screen shot is from the flood risk reduction business line for Dry Subset of Traces. Table includes the indicator contributions for the pie charts for both epochs and dry and wet Subsets of Traces. The dominant indicator variable is highlighted for each epoch and both dry and wet subsets.*
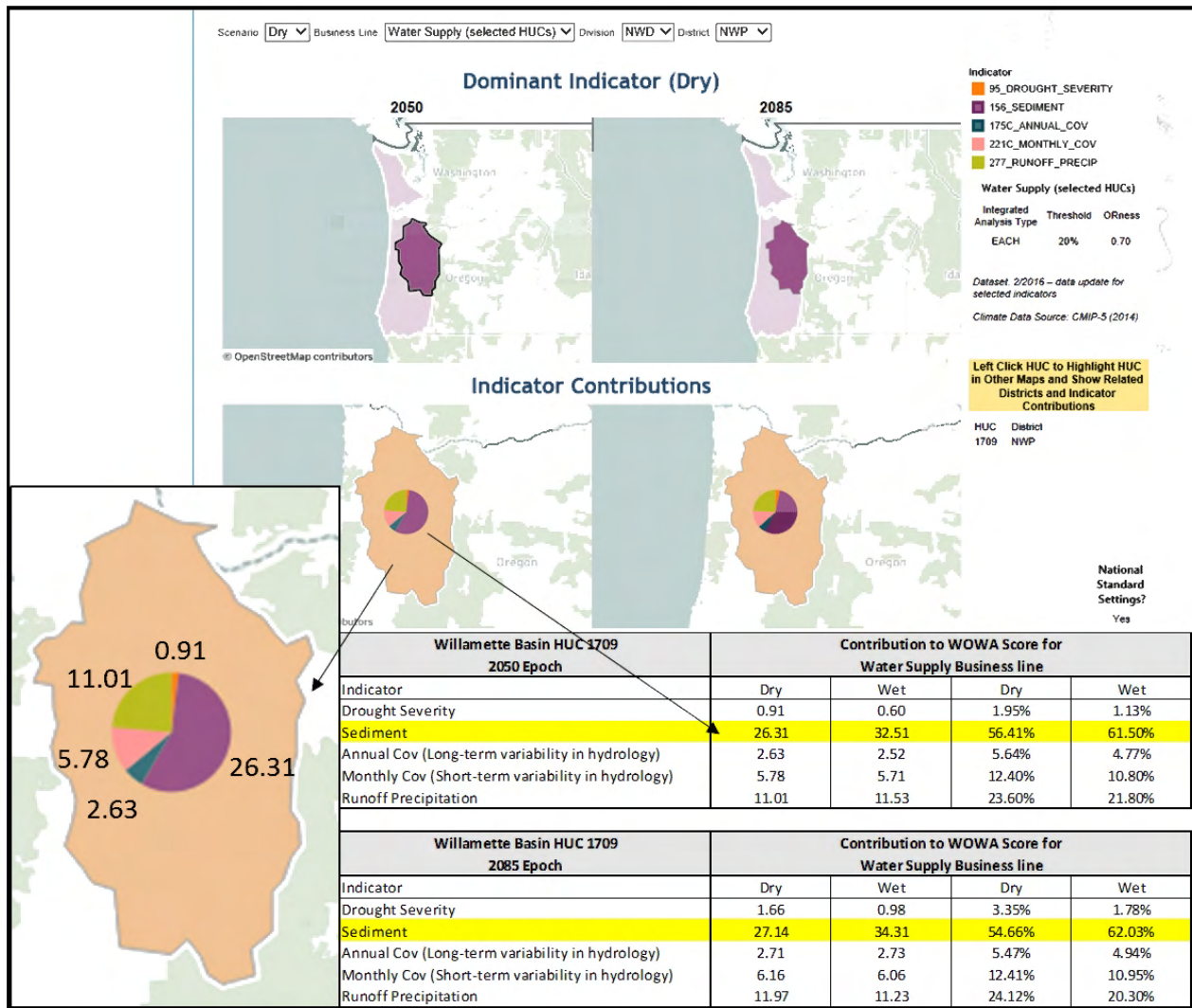
*Figure 4.14 Dominant Indicator contributions for the Willamette Basin (HUC 1709) from the Vulnerability Assessment Tool for the water supply business line. Screen shot is from the water supply business line for Dry Subset of Traces. Table includes the indicator contributions for the pie charts for both epochs and dry and wet subsets of traces. The dominant indicator variable is highlighted for each epoch and both dry and wet subsets.*

The dominant indicators for flood risk reduction are the urban 500-year floodplain (acres of urban area in the 500-year floodplain) variable in dry subsets and the cumulative flood magnification variable in the wet subsets for both epochs. The first variable refers to urbanization increasing the impermeable area, leading to increased stormwater runoff volumes and higher peak flows in the 500-year floodplain (0.2% annual chance exceedance event). The second variable represents how flood flow is predicted to change in the future, with the cumulative magnification referring to all flow generated within the HUC04 watershed and any upstream watersheds. The weight importance of the urban 500-year floodplain is 1.75 and the weight importance of the flood magnification-cumulative is 1.8 in the flood risk reduction business line. Neither of these dominant indicators change in value by much between the two epochs.

A single dominant indicator for water supply for both epochs and both dry and wet subsets is the sediment variable, which does not change much in magnitude between the two epochs. Sedimentation is a leading cause of impairment to rivers and streams, and this indicator uses average annual suspended sediment load predicted by multivariate regression models and projected precipitation to assess future changes in sediment loading. The weight importance of this variable in the water supply business line is 2.

The computed WOWA score breakdowns for two other business lines relevant to the WBR, hydropower and recreation, are shown in Figure 4.15. The dominant indicators for hydropower are the monthly coefficient of variation (CV; short-term variability in hydrology) in dry subsets and the cumulative flood magnification variable in the wet subsets for both epochs. The first indicator measures short-term variability, representing how monthly runoff varies relative to mean runoff on a yearly basis. The second variable represents how flood flow is predicted to change in the future, with the cumulative magnification referring to all flow generated within the HUC04 watershed and any upstream watersheds. The weight importance of the monthly CV is 1.6 and the weight importance of the flood magnification-cumulative is 1.4 in the hydropower business line. Neither of these dominant indicators change in value by much between the two epochs.

A single dominant indicator for recreation for both epochs and both the dry and wet subsets of traces is the low flow reduction variable, which does not change much in magnitude between the two epochs. The low flow reduction variable measures the change in low runoff, which is defined as the ratio of monthly runoff exceeded 90% of the time to that of the base period. The weighted importance of this variable in the recreation business line is 1.3.

| Willamette Basin HUC 1709 2050 Epoch | Contribution to WOWA Score for Hydropower | | | |
|---|---|---|---|---|
| Indicator | Dry | Wet | Dry | Wet |
| Low Flow Reduction | 10.09 | 7.15 | 15.98% | 10.88% |
| Flood Magnification-Cummulative | 14.31 | 21.46 | 22.68% | 32.66% |
| Flood Magnification-Local | 3.18 | 3.56 | 5.03% | 5.42% |
| Runoff Precipitation | 7.44 | 10.37 | 11.79% | 15.77% |
| Annual Cov (Long-term variability in hydrology) | 2.11 | 2.01 | 3.35% | 3.06% |
| Monthly Cov (Short-term variability in hydrology) | 21.18 | 15.57 | 33.57% | 23.69% |
| Sediment | 4.25 | 5.23 | 6.74% | 7.96% |
| Drought Severity | 0.54 | 0.35 | 0.85% | 0.54% |

| Willamette Basin HUC 1709 2085 Epoch | Contribution to WOWA Score for Hydropower | | | |
|---|---|---|---|---|
| Indicator | Dry | Wet | Dry | Wet |
| Low Flow Reduction | 7.79 | 7.50 | 11.69% | 10.84% |
| Flood Magnification-Cummulative | 15.04 | 22.97 | 22.55% | 33.19% |
| Flood Magnification-Local | 4.46 | 3.81 | 6.69% | 5.51% |
| Runoff Precipitation | 10.70 | 10.10 | 16.04% | 14.59% |
| Annual Cov (Long-term variability in hydrology) | 2.15 | 2.18 | 3.23% | 3.15% |
| Monthly Cov (Short-term variability in hydrology) | 22.31 | 16.53 | 33.45% | 23.89% |
| Sediment | 3.25 | 5.52 | 4.87% | 7.98% |
| Drought Severity | 0.98 | 0.58 | 1.46% | 0.84% |

| Willamette Basin HUC 1709 2050 Epoch | Contribution to WOWA Score for Recreation | | | |
|---|---|---|---|---|
| Indicator | Dry | Wet | Dry | Wet |
| Drought Severity | 0.51 | 0.33 | 0.82% | 0.54% |
| Sediment (Change in Sediment Load / Current Load) | 1.28 | 1.52 | 2.07% | 2.47% |
| Monthly Cov | 6.02 | 4.55 | 9.77% | 7.41% |
| Runoff Precipitation | 2.86 | 2.98 | 4.64% | 4.85% |
| Flood Magnification-Cummulative | 4.43 | 6.45 | 7.19% | 10.50% |
| Flood Magnification-Local | 1.87 | 2.10 | 3.04% | 3.42% |
| 90% Exceedance | 13.06 | 12.83 | 21.20% | 20.88% |
| 10% Exceedance | 9.10 | 9.16 | 14.78% | 14.92% |
| Low Flow Reduction | 22.48 | 21.51 | 36.50% | 35.01% |

| Willamette Basin HUC 1709 2085 Epoch | Contribution to WOWA Score for Recreation | | | |
|---|---|---|---|---|
| Indicator | Dry | Wet | Dry | Wet |
| Drought Severity | 0.93 | 0.55 | 1.45% | 0.86% |
| Sediment (Change in Sediment Load / Current Load) | 1.31 | 1.59 | 2.04% | 2.50% |
| Monthly Cov | 6.41 | 4.83 | 10.00% | 7.60% |
| Runoff Precipitation | 3.11 | 2.24 | 4.85% | 3.52% |
| Flood Magnification-Cummulative | 4.70 | 6.91 | 7.33% | 10.86% |
| Flood Magnification-Local | 1.99 | 2.92 | 3.10% | 4.60% |
| 90% Exceedance | 13.23 | 13.00 | 20.63% | 20.43% |
| 10% Exceedance | 9.15 | 9.22 | 14.28% | 14.49% |
| Low Flow Reduction | 23.29 | 22.36 | 36.32% | 35.15% |

*Figure 4.15 Dominant Indicator contributions for the Willamette Basin (HUC 1709) from the Vulnerability Assessment Tool for the hydropower and recreation business lines with the primary indicator highlighted for each epoch and both dry and wet subsets.*

# 5 Summary of Climate Change Impacts on the Willamette Basin

In the Willamette basin, the reservoir storage projects operate to a rule curve, where water from the reservoirs is drafted in the fall to have space available to temporarily store water during flood events, which is then released in preparation for additional storm events during the winter months. As spring approaches and flood events are of reduced magnitude, the reservoirs begin to refill over a couple months, according to their rule curves, to provide conservation storage during the late spring, summer, and early fall. The rule curves were developed circa 1960-1970 so that the reservoirs would likely refill around the end of May, when stored water releases begin in order to meet multi-purpose water supply demands. Future studies for refill timing under climate change will need to account for the increase in vulnerability in the basin to winter flooding and both increased water demand and decreased water availability during the conservation season. Climate change will have effects on the demand for agricultural irrigation and on municipal and industrial demand. Those estimates of demand due strictly to climate change (as opposed to growth) are documented in Appendices A and B. An estimate of the increased need for stored water releases for supplemental BiOp flows, taking into account the potential future effects of climate change, is summarized in Section 3 of this appendix.

Based on an assessment of projected, climate changed hydrology produced by the Climate Impact Group for the Willamette River at Salem, the estimated future increase needed for cumulative, stored water volume for supplemental BiOp flows occurring between April and October is between 60 KAF to 230 KAF over any twenty year period. The average volume increase is 160 KAF in supplemental flows per 20 year increment. There is a great deal of uncertainty in these numbers, including the selected emission scenario, range of initial conditions used to prime the GCMs, the ability of a given GCM to replicate the physical drivers of future changes in climate, the techniques used to disaggregate GCM inputs into a temporal and spatial scale relevant to water resources planning, and uncertainty associated with the hydrologic model applied. This estimated April-October volume increase in supplemental flow needed to fulfil future BiOp targets is provided only for discussion purposes, and is not adopted for any proposed re-allocation of storage to accommodate climate change impacts.

In additional to the calculation of estimated available flow volume decrease at Salem using projected climate changed hydrology for the future, this appendix provides general information about climate change in the Willamette Basin through a literature review and results of the online USACE climate impact assessment tools: the Climate Hydrology Assessment Tool with regression analysis, the Nonstationarity Detection Tool, and the relative Vulnerability Assessment Tool.

The literature review highlights that the warming climate is expected to bring warmer, drier summers to the basin, while the winters may have more rain and less snow. There is some indication that the maximum flows will increase in the wintertime and that less water will be available to meet water supply objectives in the summer months.

The Climate Hydrology Assessment Tool is used to find observed trends in the observed, annual maximum flows at Salem. Additionally, a regression analysis is performed on the unregulated, annual maximum flows at Salem, annual minimum flows at Salem and the April through October total volume

of water passing Salem. These assessments use the SLM5M data record (unregulated flow) computed at Salem, from the 2010 Level Modified Flow dataset.

- There is no significant trend in the observed, regulated annual maximum flow record at Salem
- The unregulated data record, SLM5M (1928-2008), presented no trends in annual maximum or the total volume in the record for April through October for each year in the record. There was a statistically significant trend in the annual minimum values of the record.
- There is a statistically significant, projected increasing trend in the mean of the unregulated annual maximum monthly values of projected climate changed flows for the Willamette Watershed.

Observed climate trends were also assessed using the USACE Nonstationarity Detection Tool (NSD Tool). This tool was used on observed peak flows at Salem for the full gage record, 1893 to 2014. As anticipated, when the full period of record was assessed multiple tests flagged nonstationarities implying robustness and consensus, with a measurable decrease in the magnitude of the dataset's mean at the time of the completion of all dams (circa 1970) in the basin. There was a statistically significant monotonic trend with a negative slope.

The NSD Tool was also applied to the observed Salem peak flow record for the period post the completion of all USACE dams in the basin: 1970-2014. When the NSD tool was applied to this portion of the dataset no nonstationarities or monotonic trends were detected. Two additional locations, both unregulated, one above Detroit Dam and Reservoir and one above Hills Creek Dam and Reservoir, were also assessed with the NSD tool. No nonstationarities and no monotonic trends were detected at either site.

A screening level, relative, vulnerability assessment was performed using the USACE Vulnerability Assessment tool. Four business lines – flood risk reduction, water supply, hydropower, and recreation were the focus of this assessment. Note that both water supply and recreation are secondary project purposes in the WVP, while flood risk management is a primary purpose for all reservoirs. Hydropower, at the projects with turbines, is also a high priority purpose at the reservoirs. Note that the Willamette Basin Review (WBR) study is focused on investigating future Willamette River basin conservation season water demand and the reallocation of the WVP conservation storage for the benefit of Endangered Species Act (ESA) listed fish, agricultural irrigation (AI), and municipal and industrial (M&I) water supply. The WBR study is not focused on flood risk management, as that function occurs outside of the conservation season in the basin, and changes to flood risk management outside of the conservation season are not relevant to the reallocation of storage. The finding was that the Willamette Basin is not considered vulnerable relative to the other 201 HUC04 watersheds in the continental United States to the potential future impacts of climate change.

None of the research studies described in this appendix address the timing of the transition point between the higher winter flows and the lower summer flows for the future climate scenarios. This is due in part to the bias correction method, which used historical data to bias correct and downscale the outputs from the climate models, thus making the timing in the historical record implicitly embedded in

the results. The likelihood of a Willamette reservoir refilling depends partly on the timing of spring flows, not just the inflow value, so it is difficult to determine how exactly reservoir refill will be affected by the higher winter flows/lower summer flows.

One of the tools in water management of the Willamette Basin is a water year type classification that is defined by the total amount of storage in the reservoir during a ten day window each May. This classification scheme is defined in the BiOp and also used in reservoir modeling of the basin in HEC-ResSim. Within the historical record of the flow dataset used for ResSim analysis for the WBR (which was the 2010 Level Modified Streamflows, 1928-2008), the four classifications and their frequency of occurrence are Abundant (occurs during 44 years between 1928-2008), Adequate (occurs during 14 years between 1928-2008), Insufficient (occurs during 11 years between 1928-2008), and Deficit (occurs during 11 years between 1928-2008). The climate impact analysis does not address the frequency of occurrence of any of these water year classifications because the designations are at least in part dependent on the refill of the reservoirs.

This climate impact assessment is not meant to support any particular alternative presented in the main Feasibility Study. As noted in the main report and Appendix C, the current agriculture irrigation (AI), municipal and industrial (M&I), and fish and wildlife (F&W) streamflow demands are already greater than the amount of water available in the basin in the drier years, including both regulated and unregulated streams. The Alternatives A, B, C, and D in the main report subdivide (reallocate) the conservation storage space differently for the three user groups identified, but the water management implementation plan to reduce each group's use of water proportionally in drier years is the same in each of those four alternatives. (Refer to the main report for more details about the water management implementation plan or the ResSim analysis appendix for a description of how reductions were modeled.) The purpose of the WBR is not to guarantee water availability in the basin, but to define the storage space allotted to each group.

The potentially higher annual maximum flows in the Willamette Basin, which were described in this climate impact assessment, are not relevant to the WBR study because the timing of these highest flows is in the winter season when reservoirs are evacuated to have space available for the primary purpose, flood risk management. The reallocation of storage space in the Willamette reservoirs to AI, M&I, and F&W does not mean that the storage space is guaranteed to fill, and since flood risk management is the primary function of the dams, operations for flood events will always take precedence over water supply operations. The main report makes clear that the reallocation is to storage space, not the water itself.

# 6    References.

Bonneville Power Administration, 2010 Level Modified Streamflow, August 2011.

Chang, Heejun and Jones, Julie, Climate Change and Freshwater Resources in Oregon, Portland State University, 2010.

Climate Impacts Group, Final Report for the Columbia Basin Climate Change Scenarios Project, University of Washington, 2010, full report website link:
http://warm.atmos.washington.edu/2860/report/

Climate Impacts Group, website of Site Specific Data, for the Willamette River at Salem, link:

http://warm.atmos.washington.edu/2860/products/sites/?site=4060

NOAA Fisheries. 2008. Endangered Species Act Section 7(a)(2) Consultation, Biological Opinion and Magnuson-Stevens Fishery Conservation and Management Act Essential Fish Habitat Consultation, Consultation on the Willamette River Basin Flood Control Project. Log Number F/NWR/2000/02117. Northwest Region, Seattle, WA.

The Oregon Climate Change Research Institute, Historical Trends and Future Projections of Climate and Streamflow in the Willamette Valley and Rogue River Basins, June 2015.

U.S. Army Corps of Engineers, Engineering and Construction Bulletin 2016-25 (Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects), issued 16 Sept 2016.

U.S. Army Corps of Engineers, Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions, Pacific Northwest Region 17, September 2015.

U.S. Army Corps of Engineers, Appendix D, Willamette Basin Review – Flow Dataset Used for ResSim Analyses, 2017.

U.S. Army Corps of Engineers, Willamette Basin Year in Review, Water Year 2015 (commonly referred to as the After Action Report, AAR), October 2016.

U.S. Army Corps of Engineers, Master Water Control Manual for the Willamette Valley Project, Oregon, 2017, Draft version.

U.S. Army Corps of Engineers, Appendix C, WBR – Calculation of Water Volumes Required to Meet Willamette BiOp Minimum Flows, 2017.

U.S. Army Corps of Engineers website with climate impact analysis tools:
https://maps.crrel.usace.army.mil/projects/rcc/portal.html

U.S. Fish and Wildlife Service (USFWS). 2008. Endangered Species Act Section 7 Consultation, Biological Opinion on the Continued Operation and Maintenance of the Willamette River Basin Project and Effects to Oregon Chub, Bull Trout, and Bull Trout Critical Habitat Designated Under the Endangered Species

Act. File Number 8330.F0224(07). Tails Number 13420-2007-F-0024. Oregon Fish and Wildlife Office, Portland, OR.

Willamette Water 2100, Oregon State University, http://inr.oregonstate.edu/ww2100.