RECLAMATION

Managing Water in the West

Upper Deschutes River Basin Study

Technical Memorandum

Compilation and Analysis of Climate Change Information in the Deschutes Basin

THE UPPER DESCHUTES BASIN STUDY

Water for agriculture, rivers & cities

U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Region

December 2018

Mission Statements

U.S. Department of the Interior

PROTECTING AMERICA'S GREAT OUTDOORS AND POWERING OUR FUTURE

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

Bureau of Reclamation

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Acronyms and Abbreviations

Acronym or Abbreviation	Definition
Basin Study	Upper Deschutes River Basin Study
BCSD	Bias Corrected and Spatially Downscaled
BSWG	Basin Study Work Group
CMIP5	Coupled Model Inter-comparison Project
CRBIA	Columbia River Basin Impacts Assessment
ET	Evapotranspiration
GCM	Global climate model
HDe	Hybrid Delta ensemble
HRU	Hydrologic Response Units
LWD	Less-warming/dry
LWW	Less-warming/wet
MWD	More-warming/dry
MWW	More-warming/wet
NIWR	Net irrigation water requirement
NRCS	Natural Resources Conservation Service
NSE	Nash-Sutcliff Efficiency
OWRD	Oregon Water Resources Department
PRMS	Precipitation-Runoff Modeling System
RCP	Representative Concentration Pathway
Reclamation	Bureau of Reclamation
RMJOC	River Management Joint Operating Committee
SMRF	Spatial Modeling for Resources Framework
SWE	Snow water equivalent
USGS	U.S. Geological Survey
VIC	Variable Infiltration Capacity
WRCC	Western Regional Climate Center

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1. Introduction

The Upper Deschutes River Basin Study (Basin Study) has been completed by the Bureau of Reclamation (Reclamation) and the Basin Study Work Group (BSWG). The $1.5 million, 3-year study was funded on a 50/50 cost-share basis by Reclamation's WaterSMART Program and the Oregon Water Resources Department (OWRD).

1.1. Goals of Study

Technical memoranda were developed to document various aspects of the Basin Study. This technical memorandum describes the compilation and analysis of climate change information for the Basin Study. This process consisted of three major steps:

- Selection of previously developed climate-adjusted meteorological data and bias corrected spatially-downscaled future climate model projections (Reclamation 2014).
- Hydrologic modeling to generate simulated streamflows using the meteorological data selected in Step 1. Though this step was unsuccessful, the models and issues were documented.
- Development of future climate-adjusted demands using meteorological data selected in Step 1 and calculated net irrigation water requirement.

1.2. Background

The Basin Study leveraged resources from many previous studies. The climate analysis used data and processes that were developed for the Columbia River Basin Impacts Assessment (CRBIA) (Reclamation 2016). The CRBIA was a Columbia River Basin-wide assessment of potential future climate impact and included the development of meteorological and hydrologic datasets for use in subsequent studies like the Basin Study.

Although the CRBIA resulted in a set of climate-adjusted streamflows within The Upper Deschutes River Basin, the streamflows were revisited for the Basin Study. There were two reasons for this:

1. The CRBIA used the Variable Infiltration Capacity (VIC) model to develop streamflows throughout the Columbia River Basin. VIC is a grid-based model that calculates the amount of water stored within in each grid cell using meteorological input data (Liang et al. 1994). It uses a surface routing tool to calculate streamflow at individual points. However, it does not calculate subsurface flow from grid cell to grid cell. Since the Upper Deschutes River Basin has large amounts of subsurface flow that contributes to streamflow, this model underrepresents a major physical process that dominates streamflow in the basin.
2. The CRBIA VIC model was developed for the entire Columbia River Basin and as a result was only calibrated to one location in the Upper Deschutes River Basin.

Given the limitations of the streamflows generated with the CRBIA VIC model, the Basin Study explored other hydrology models that could possibly better represent groundwater-surface water interactions. The Basin Study attempted to leverage a GSFLOW model of the Upper Deschutes River subbasin (the portion of the Upper Deschutes River Basin above the confluence with the Crooked River) that was being developed by the U.S. Geological Survey (USGS) concurrently with the Basin Study (Gannet et al. 2017). GSFLOW (Markstrom et al. 2008) couples MODFLOW (McDonald and Harbaugh 1988), the USGS groundwater flow model, and Precipitation-Runoff Modeling System (PRMS) (Markstrom et al. 2015), the USGS precipitation-based hydrology model. The GSFLOW model was expected to provide more accurate streamflows than the VIC model given that it had the potential to better represent the groundwater-surface water processes that occur in the Upper Deschutes River subbasin. The GSFLOW model did not extend to the Crooked River subbasin, so Reclamation developed a PRMS model of the Crooked River subbasin. In addition, the Crooked River subbasin does not experience the same level of groundwater-surface water interaction that occurs in the Upper Deschutes, so the PRMS model was determined to be sufficient.

Because the GSFLOW model was calibrated for purposes not related to the Basin Study (primarily flows at gages and groundwater levels near the confluence of the Upper Deschutes River and Crooked River subbasins), its calibration quality was low with respect to streamflow especially in the upper basin. Therefore, the bias correction process was not as effective in the upper basin, particularly on streamflow in Crescent, Tumalo, and Whychus Creeks. Similarly, the effectiveness on inflows (streamflow) into Crane Prairie and Wickiup reservoirs was also limited. Given the uncertainty associated with the hydrology models throughout the basin, no results are presented in this report.

1.3. Historical Climate in the Upper Deschutes River Basin

The climate in The Upper Deschutes River Basin is characterized as “Mediterranean,” with cool, wet winters and warm, dry summers, and exhibits seasonal variability. Figure 1 shows the monthly temperature range and average monthly precipitation that occurred at the Redmond Airport from 1996 to 2008 (WRCC 2018). Redmond is located near the center of the basin near much of the irrigated agriculture where precipitation averages about 7 inches annually. The watershed also includes portions of the Cascades mountain range where precipitation can exceed 125 inches per year (Taylor 1993) and typically accumulates as snow that melts in the spring, contributing to streamflow.

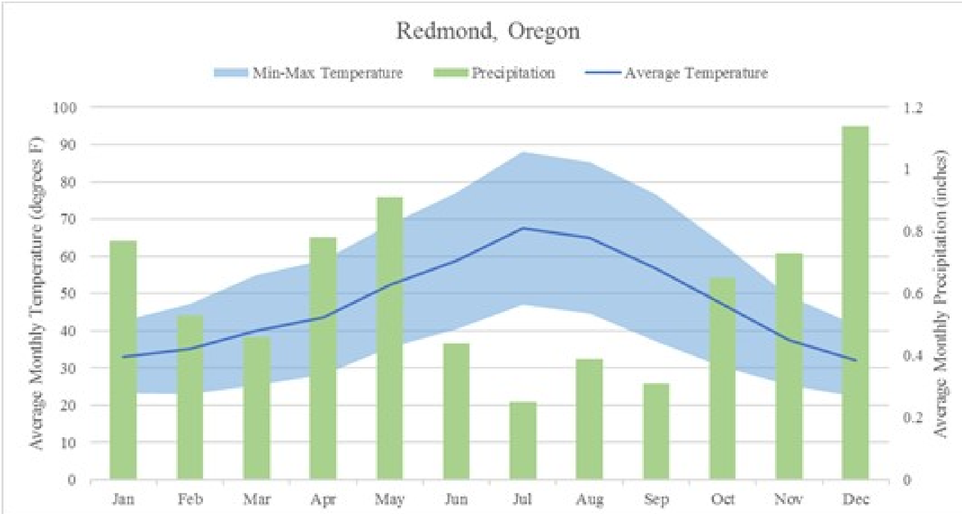

Figure 1. Monthly average temperature and precipitation at Redmond, Oregon, from measured data 1996 to 2008 (WRCC 2018).

2. Selection of Future Climate Scenarios

A complete detailed explanation of the climate scenario selection process can be found in the CRBIA technical appendix on climate change and hydrology (Reclamation 2016). A summary of that technical appendix is presented in this section.

Climate change scenarios were developed using data from the Bias Corrected and Spatially Downscaled (BCSD) CMIP5 Climate and Hydrology Projections archive hosted by the Lawrence Livermore National Laboratory (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/). These climate projections were generated through the fifth iteration of the Coupled Model Inter-comparison Project (referred to as CMIP5) and were statistically downscaled to the 1/8-degree using the BCSD method (Reclamation 2014). These data were combined into scenarios using the Hybrid Delta Ensemble Method (HDe) approach (Reclamation 2010a), which has been used in other basin study applications.

The HDe approach uses monthly change factors, calculated from select groups (or ensembles) of downscaled global climate model (GCM) projections, to adjust historical daily gridded meteorological datasets for input to a hydrologic model. In this case, the gridded meteorological datasets that are being adjusted are the Livneh (Livneh et al. 2013) and Daymet[1] (Thornton et al. 1997) datasets[2], with the Livneh dataset being used for VIC modeling over the Crooked River

[1] Daymet data accessed on February 26, 2017. Daily precipitation and minimum and maximum air temperature were downloaded for the period January 1, 1980 to December 31, 2013 for 587 arc-minute locations throughout the Deschutes basin (Gannett et al. 2017).

[2] A comparison of the Daymet and Livneh datasets was not conducted for this study, so there could be some bias introduced by the usage of the two different datasets.

area and the Daymet dataset being used for GSFLOW modeling over the mainstem Deschutes River Basin.

Ten HDe climate change scenarios (five scenarios for two future periods) were evaluated for use in the Basin Study. The Planning Team and Steering Committee determined that that the 30-year periods surrounding the 2040s (2030-2059) and 2060s (2050-2079) would be most relevant for the alternatives that would be evaluated for the Basin Study. For this analysis, Representative Concentration Pathway (RCP) emission scenarios 4.5 and 8.5 were considered.

Figure 2 and Figure 3 show scatter plots of the projections and projection ensembles (scenarios) for the 2040 and 2060 periods. Each point in these plots represents an individual downscaled CMIP5 projection. Horizontal lines across the plot represent the 20 percent, 50 percent, and 80 percent changes in temperature and vertical lines represent the 20 percent, 50 percent, and 80 percent changes in precipitation. The ten nearest-neighbors to the intersection of these lines make up the projection ensembles for each of the five scenarios, including: less-warming/dry (LWD), less-warming/wet (LWW), more-warming/dry (MWD), more-warming/wet (MWW), and median. Note that all the models agree that temperatures will warm over the next century in the Deschutes Basin, hence the use of the terms “less-warming” and “more-warming” as opposed to “cooler” and “warmer.”

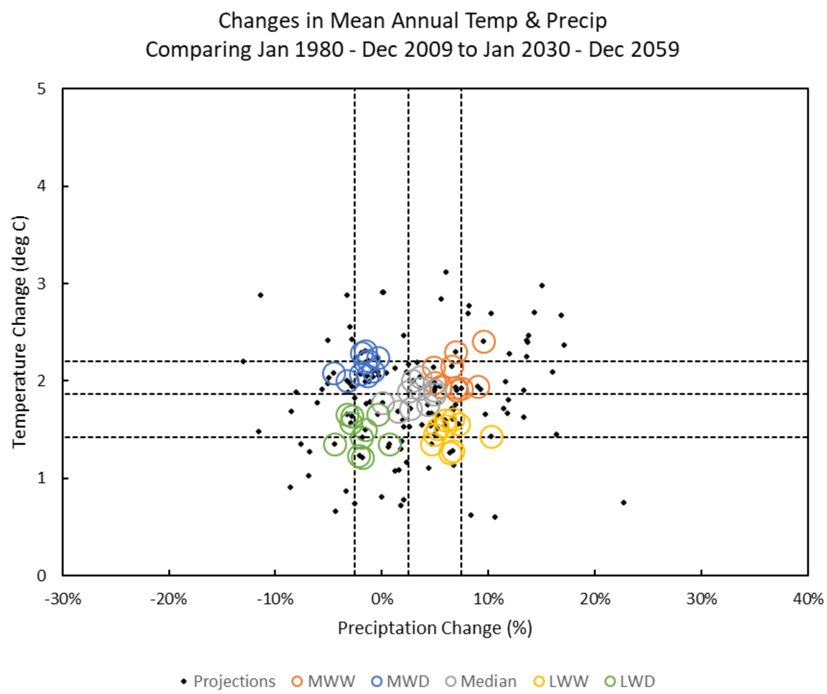

Figure 2. Scatter graphs of projected changes in temperature and precipitation for the Deschutes River basin for the 2040s (2030 to 2059) relative to the historical (1980 to 2009).

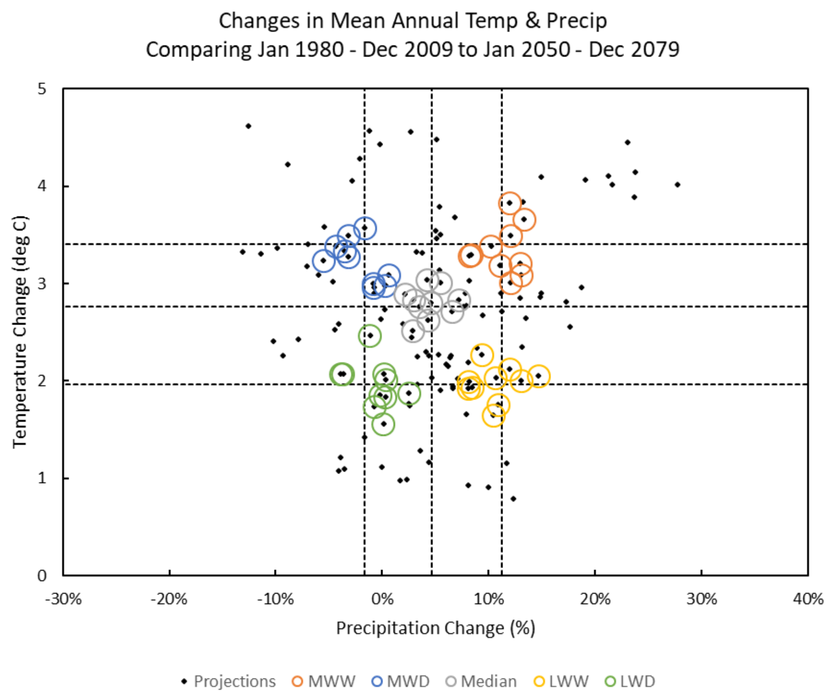

Figure 3. Scatter graphs of projected changes in temperature and precipitation for the Deschutes River basin for the 2060s (2050 to 2079) relative to the historical (1980 to 2009).

Figure 4 and Figure 5 show the monthly median temperature change projected by the five HDe scenarios for the 2040s and 2060s relative to the historical period (1980 to 2009). Note that all the scenarios indicate an increase in temperature ranging from about 2 to 8 degrees Fahrenheit per month depending on the scenario. The scenarios with the largest temperature increase are the MWW, MWD, and Median for the 2060s.

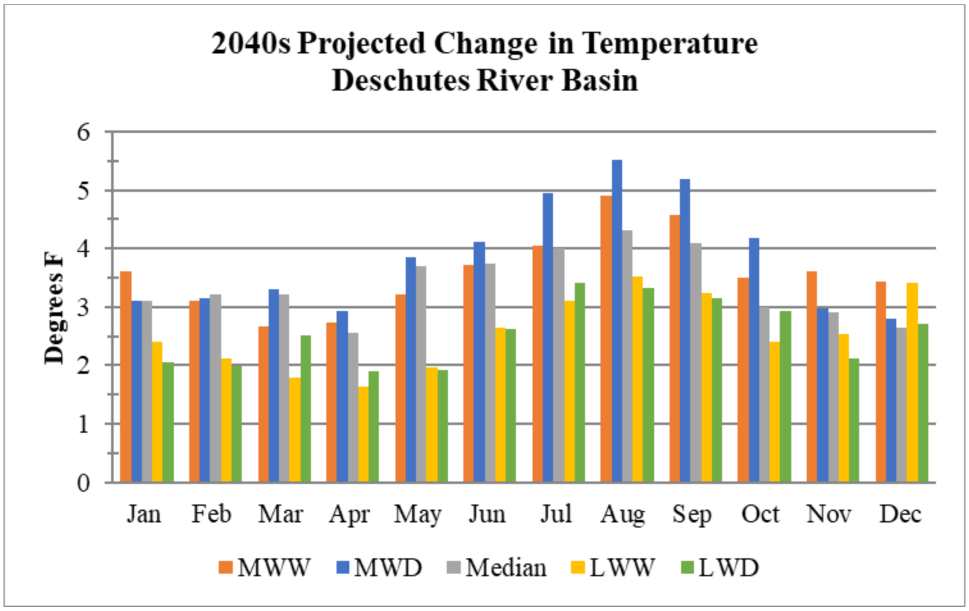

Figure 4. Projected 2040s monthly 50th percentile change in temperature.

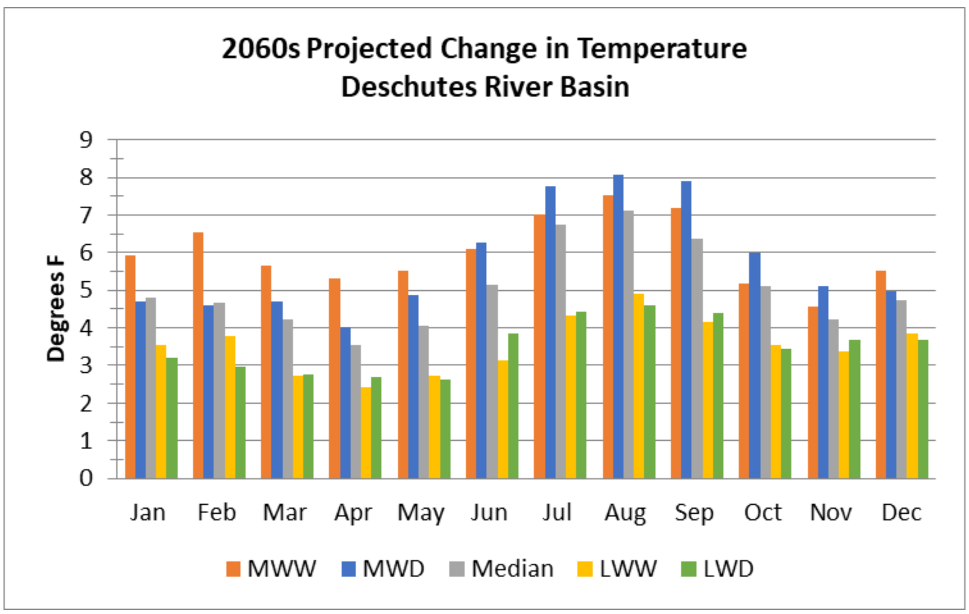

Figure 5. Projected 2060s monthly 50th percentile change in temperature.

Figure 6 and Figure 7 show the monthly median change in precipitation represented by each of the five HDe scenarios for the 2040s and 2060s. Compared to the projected changes in temperature, precipitation projections are more varied with some scenarios showing an increase in precipitation and others showing a decrease. The 2060s show a wider range of change than the 2040s with more reduction in precipitation in the summer months.

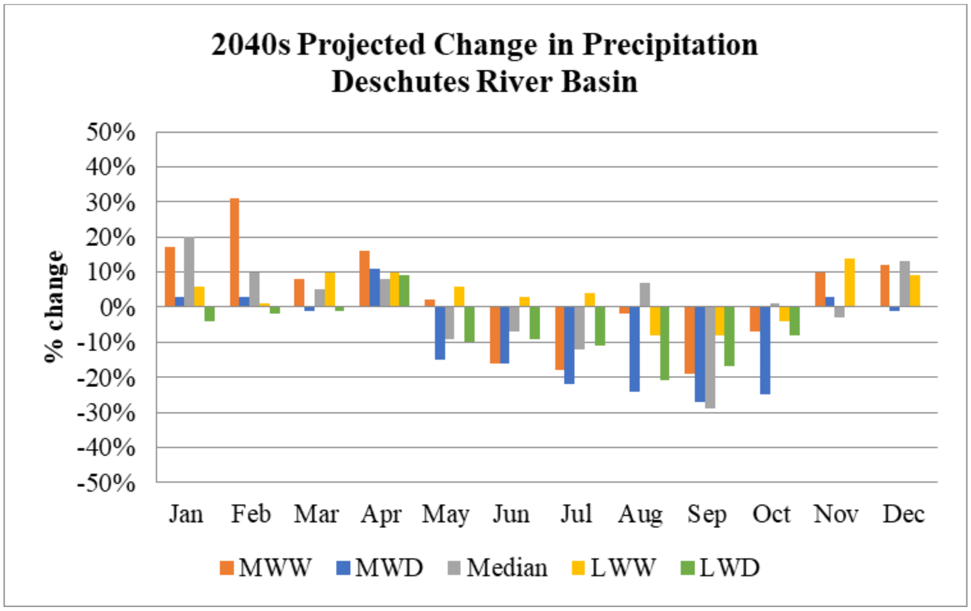

Figure 6. Projected 2040s monthly 50th percentile change in precipitation.

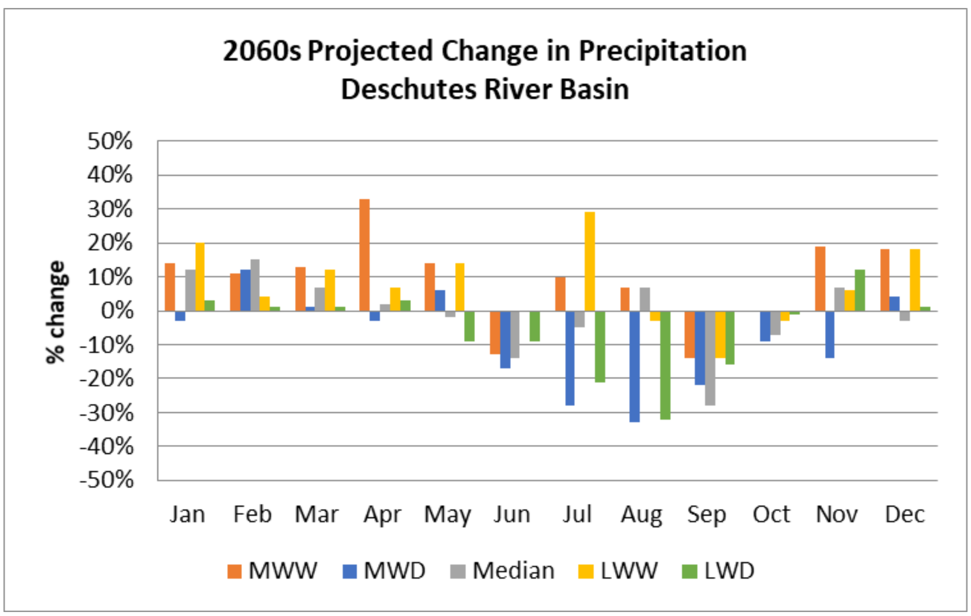

Figure 7. Projected 2060s monthly 50th percentile change in precipitation.

3. Hydrologic Models

The Basin Study used three different hydrologic models (VIC, GSFLOW, and PRMS) to simulate climate-adjusted streamflows for the Upper Deschutes and Crooked River subbasins (Figure 8). The VIC model covers the entire domain including the Upper Deschutes and

Crooked River subbasins. The GSFLOW model covers the portion of the Upper Deschutes River Basin that is in contact with the highly permeable volcanic aquifer including the Upper Deschutes, Little Deschutes, Middle Deschutes, Tumalo Creek, and Whychus Creek (Table 1). Flows in the Upper Deschutes portion of the basin are considered groundwater-dominant and therefore have a dampened shape and a streamflow peak that occurs later than that for snowmelt-dominated systems. The PRMS model covers the Crooked River subbasin. Flows in the Crooked River portion of the basin follow a typical snowmelt dominated pattern with the largest runoff occurring in the spring and early summer and much lower flows occurring in the late summer and fall.

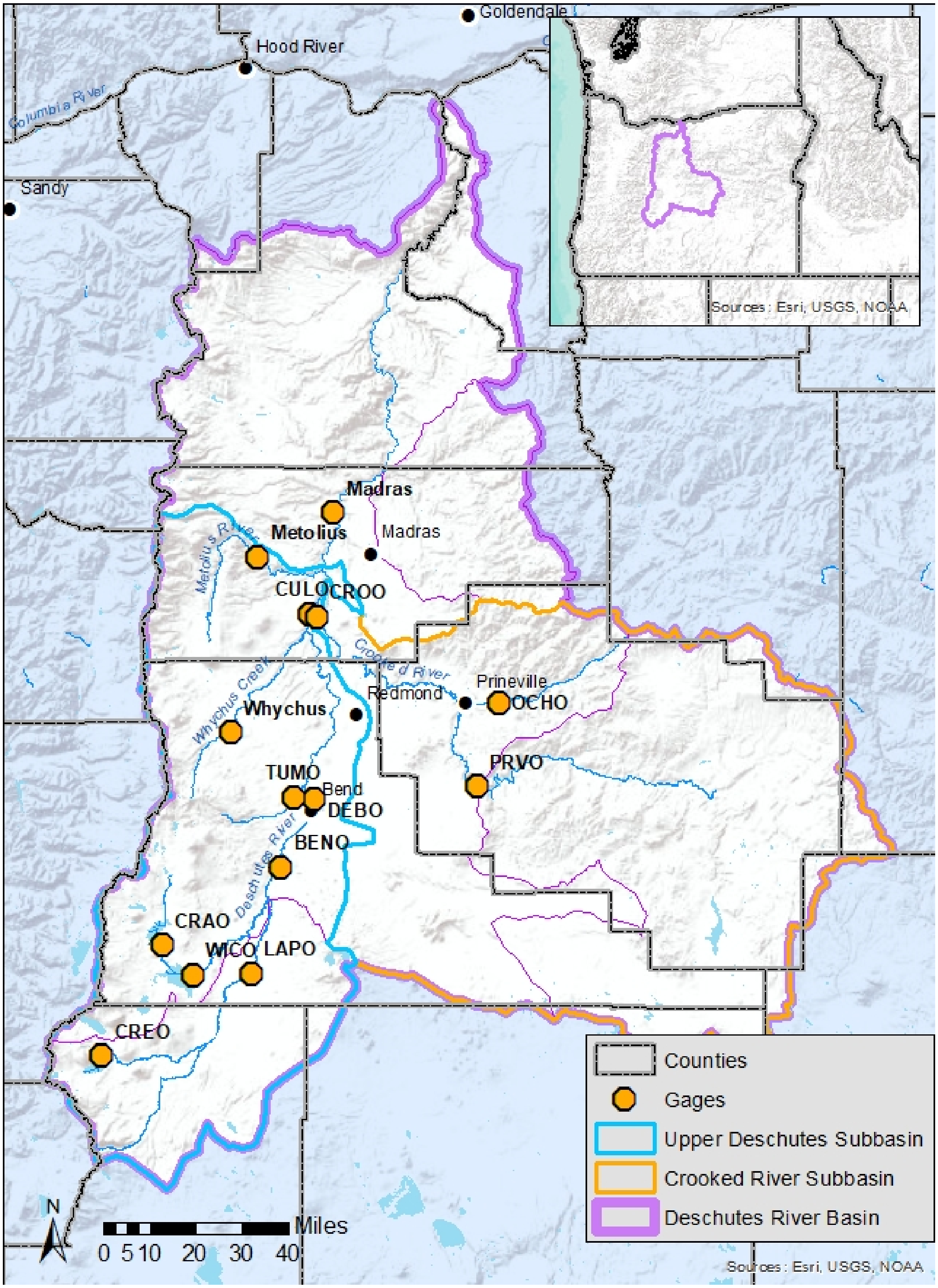

Figure 8. Upper Deschutes and Crooked River subbasins. The Upper Deschutes is modeled using GSFLOW and VIC, and the Crooked River is modeled using PRMS.

Table 1. Locations where climate-adjusted flows are calculated along with models used for calculation.

Site Name	OWRD Gage Number	Reclamation Gage Name	Model for Climate-Adjusted Hydrology[3,4,5]
Deschutes River below Crane Prairie Reservoir	14054000	CRAO	VIC, GSFLOW
Deschutes River below Wickiup Reservoir	14056500	WICO	VIC, GSFLOW
Crescent Creek below Crescent Lake	14060000	CREO	VIC, GSFLOW
Little Deschutes River near La Pine	14063000	LAPO	VIC, GSFLOW
Deschutes River at Benham Falls	14064500	BENO	VIC, GSFLOW
Deschutes River at Bend	14070500	DEBO	VIC, GSFLOW
Tumalo Creek below Tumalo Feed Canal	14073520	TUMO	VIC, GSFLOW
Whychus Creek Near Sisters	14075000	Whychus	VIC, GSFLOW
Deschutes River near Culver	14076500	CULO	VIC, GSFLOW
Crooked River Near Prineville	14080500	PRVO	PRMS
Ochoco Creek below Ochoco Reservoir	14085300	OCHO	PRMS
Crooked River below Opal Springs	14087400	CROO	PRMS
Metolius River near Grandview	14091500	Metolius	VIC, GSFLOW
Deschutes River near Madras	14092500	Madras	VIC, GSFLOW

3.1. Variable Infiltration Capacity (VIC)

The VIC model (Liang et al.1994) was developed at the University of Washington and is a large-scale, semi-distributed hydrologic model. The VIC model of the Columbia River Basin was developed and calibrated for the RMJOC-I (River Management Joint Operating Committee) Climate Change Study (Reclamation 2010b). Since this was a region-wide look at potential future hydrologic conditions, the VIC model was only calibrated to basin outlets. In the case of the Deschutes, the model was calibrated to unregulated flow at the Madras gage, which is downstream of the confluence of the Upper Deschutes and the Crooked rivers.

VIC does not simulate lateral groundwater flow and therefore had difficulty simulating the streamflow and hydrology of The Upper Deschutes River basin. An example is the Deschutes River below Wickiup Reservoir where the raw VIC output largely showed a hydrograph

[3] The VIC model was developed for the RMJOC-I study and was used to develop flows in the basin using CMIP5 temperature and precipitation inputs.
[4] The GSFLOW model of the Upper Deschutes Basin was developed by the USGS and was completed in 2017 (Gannett et al. 2017). GSFLOW (Markstrom et al. 2008) is a coupled groundwater and surface water flow model that integrates Precipitation-Runoff Modeling System (PRMS; Markstrom et al. 2015) and Modular Groundwater Flow Model (MODFLOW; McDonald and Harbaugh 1988). Details of model development and calibration can be found in Gannett et al. (2017).
[5] The PRMS model was developed by Reclamation and is documented in this technical memorandum.

indicative of a snowmelt dominated system (Figure 9) with a large peak flow in June and a much smaller baseflow through the rest of the year.

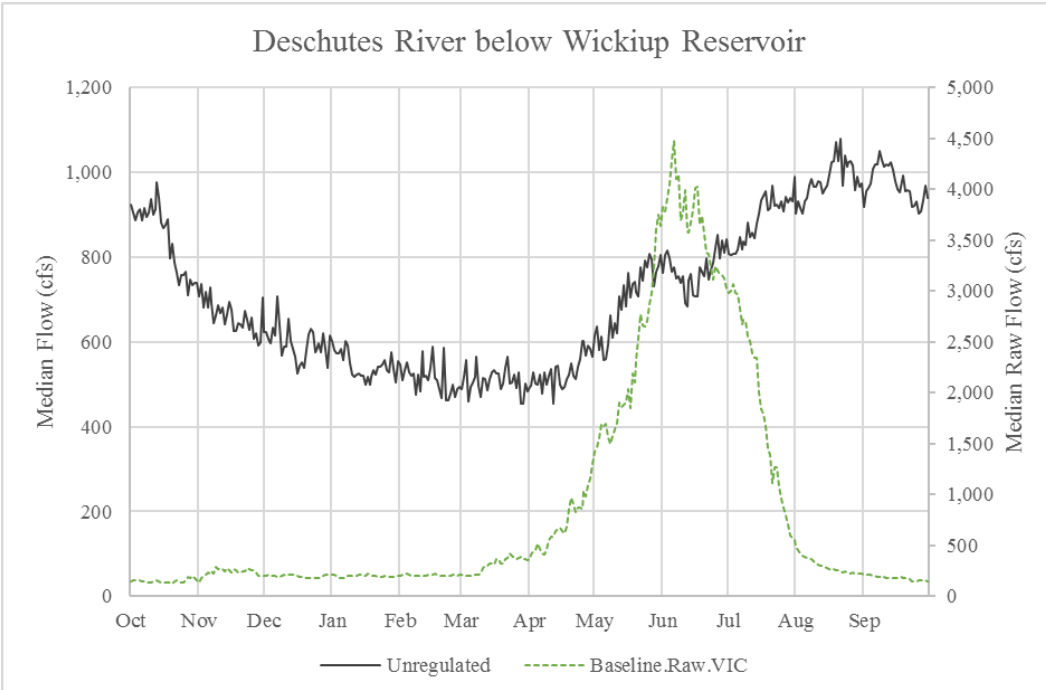

Figure 9. Historical unregulated median flow and raw modeled flow from the VIC model at the Deschutes River below Wickiup gage.

In addition, since the flows at Madras are largely influenced by the Upper Deschutes flows, the calibrated VIC flow in the Crooked River subbasin exhibited some of the groundwater dominated characteristics that do not exist in that subbasin.

Additional information about the development of this model and the resulting hydrologic data can be found in Reclamation 2010b and Reclamation 2016.

3.2. Precipitation-Runoff Modeling System (PRMS)

The PRMS is a USGS watershed scale model that uses a distributed parameter approach to simulate the physical processes of a basin (Markstrom et al. 2015). PRMS can simulate evaporation, transpiration, runoff, infiltration, canopy interception, subsurface flow, and groundwater flow.

The basin is broken down into Hydrologic Response Units (HRU) to represent areas of similar hydrologic processes. Each PRMS module performs a water budget to route the precipitation to streamflow. The inputs can be simple or more complex depending on available data. In this case, the model was set up to only require daily precipitation and daily minimum and maximum air temperature.

3.2.1. Model Setup

For the Basin Study PRMS model development, the Crooked River subbasin was defined to be the drainage area above the Crooked River gage at Opal Springs (CROO, Figure 10). The subbasin was broken into three smaller subbasins representing the area above the Ochoco Creek below Ochoco Reservoir (OCHO) gage, the area above the Crooked River near Prineville (PRVO) gage, and the remaining area above CROO.

The model stream network has a total of 166 stream segments to route water from 484 HRUs downstream towards the basin outlet. Using the stream segments, the HRUs were delineated and further separated into elevation bands to capture the low, mid, and upper elevation snow melt. Elevation plays an important role in the Crooked River subbasin where low elevation snow accumulates in the early winter, then can experience a rain-on-snow event (usually January or February) leading to a significant streamflow peak. The higher elevation snow melts more gradually later in the year. Breaking the HRUs into finer elevation bands allows the model to better capture these varying elevation melt events.

The meteorological inputs to the Crooked River PRMS model were daily precipitation along with daily maximum and daily minimum air temperature. The model uses the climate by HRU module where the inputs are pre-distributed to each HRU. The Livneh daily CONUS near-surface gridded meteorological dataset (Livneh et al. 2013) provided 1/16th degree daily precipitation and maximum and minimum air temperature, and was downscaled using the Spatial Modeling for Resources Framework (SMRF; Havens et al. 2017). SMRF downscaled the 1/16th degree dataset to a 100-meter DEM to account for elevational gradients in the precipitation and air temperature at a fine spatial scale. With the dataset downscaled to 100 meters, the average value over the HRU was calculated which takes into account the elevation and size of the HRU.

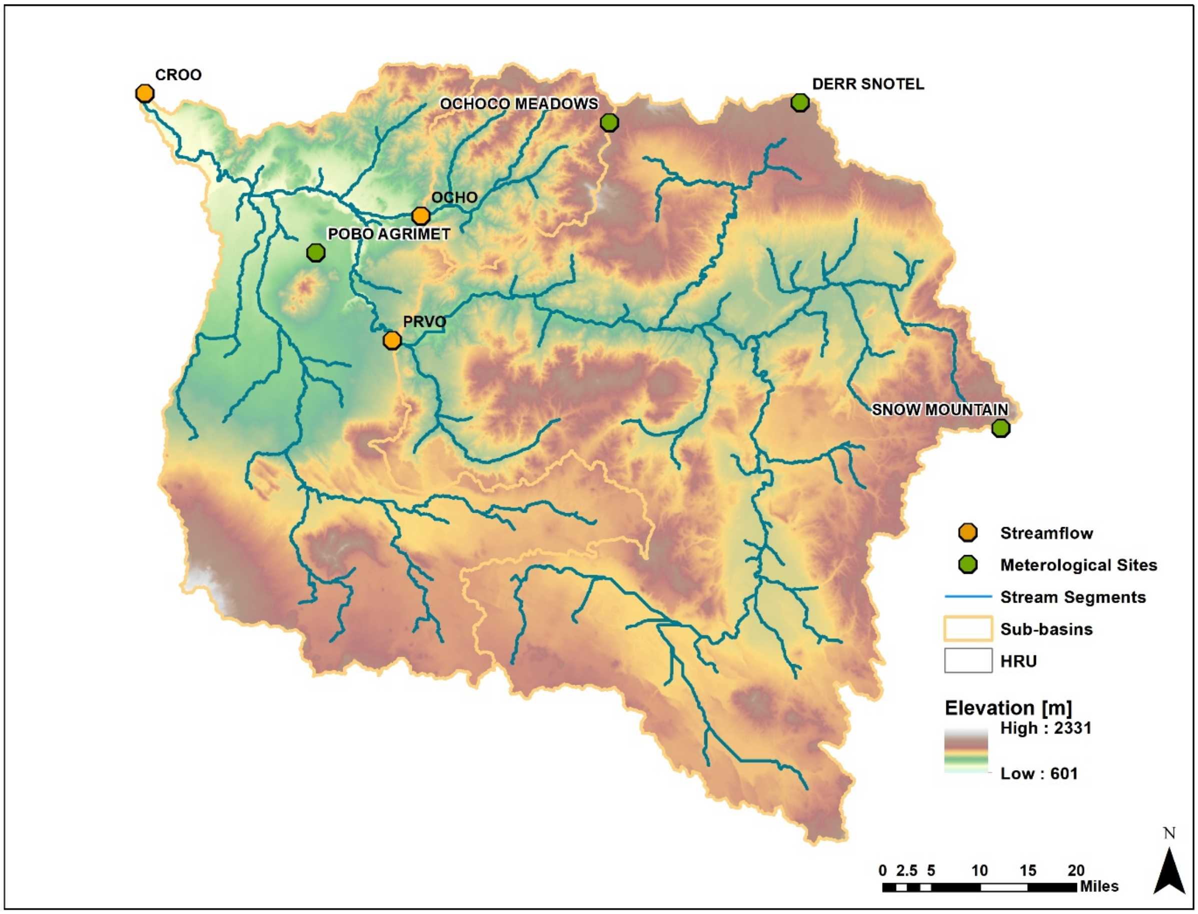

Figure 10. PRMS model setup for the Crooked River with a total of 484 HRU's and 166 stream segments. Three subbasins were delineated based on the 3 gage locations.

3.2.2. Calibration

Multiple measurement sites within the basin were used to calibrate the Crooked River PRMS model. Streamflow calibration was performed at five locations; three of these were unregulated streamflow at the Crooked River at Opal Springs (CROO), Crooked River near Prineville (PRVO), and Ochoco Creek below Ochoco Reservoir (OCHO) for the period of 1980 to 2009. Two additional sites in the Ochoco basin were used to calibrate the snowmelt timing but did not have a full period of measurements; these sites were assumed to have minimal regulation since they were upstream of the reservoirs.

Data from four meteorological stations in the subbasin were used to calibrate aspects of the PRMS model. The Powell Butte AgriMet site (POBO) provided data on precipitation, temperature, wind, solar radiation, and soil parameters. The other three stations, Ochoco Meadows, Derr, and Snow Mountain, from the Natural Resources Conservation Service (NRCS) Snotel network provide data on precipitation, temperature, and snow water equivalent (SWE).

The calibration approach was an iterative process that adjusted model parameters so that the output would match streamflow volumes and SWE. The steps below outline calibrating to varying data resolutions including yearly volumes, monthly volumes, monthly SWE, and finally down to the daily streamflow timing. Multiple iterations were performed to ensure that the newly calibrated parameters were not detrimentally affecting volume, SWE, and timing.

The first step in the calibration procedure was to calibrate the PRMS module that estimates the incoming solar radiation. The measured solar radiation at Powell Butte was aggregated into monthly averages to calibrate the solar radiation parameters.

The yearly water volume from streamflow provided an estimate as to whether enough precipitation is entering and leaving the basin since point measurements of precipitation or even gridded data may not be fully representative of total precipitation volume. Comparing the yearly volumes to historical measurements, the parameters controlling evaporation and transpiration (ET) were calibrated. Calibrating the parameters that control ET ensure that the modeled ET was within reasonable values and was used to change the amount of simulated runoff to be commiserate with the observed values. The precipitation and temperature inputs have monthly HRU adjustment factors that were adjusted to refine the amount of precipitation as rain or snow that comes into the subbasin.

Once the model was calculating yearly volumes that were reasonably close to the measured data, monthly average SWE was adjusted to ensure that the snowmelt timing is captured correctly. The parameters that affect monthly average SWE values were adjusted to account for rain on snow and early melt events.

In a snow-dominated catchment like the Crooked River, ensuring the model properly calculated average SWE can ensure that it accurately captures monthly streamflow volume. The monthly streamflow was also used to calibrate the majority of the soil, groundwater, and climate parameters. Adjusting soil parameters further calibrated the volume and shape of the monthly hydrograph.

After the model was properly calculating monthly streamflow volumes and timing, the daily timing was addressed. The timing and volume of individual events like a rain-on-snow or spring melt event were captured by matching daily streamflow. Adjustments to the soil and surface runoff parameters were used to reduce the peak flow volumes and correct the recession of the hydrograph where necessary.

Once the first round of calibration was complete, the procedure was repeated to re-adjust the parameters that affect the yearly volumes, monthly average SWE, monthly volumes, and daily timing.

3.2.3. Results

The yearly volume at PRVO (Figure 11) calibrated well with a coefficient of determination (R^2), value of 0.71 and a Nash-Sutcliff Efficiency (NSE; Nash and Sutcliffe 1970) of 0.79. The acceptable range for R^2 and NSE are typically between 0.6 and 1.0. The year-to-year variability in calibration could be due to the underlying Livneh dataset producing either too much or too little precipitation for a given year. This variation in volume could affect the calibration of the monthly and daily streamflow by changing the volume of runoff at the monthly and daily scale. The monthly volume captured the monthly timing of the snowmelt and spring runoff with an R^2 of 0.79 and as NSE of 0.81. The daily streamflow calibration captured the early spring snowmelt runoff from the lower elevation snowpack with a R^2 of 0.59 and an NSE of 0.635.

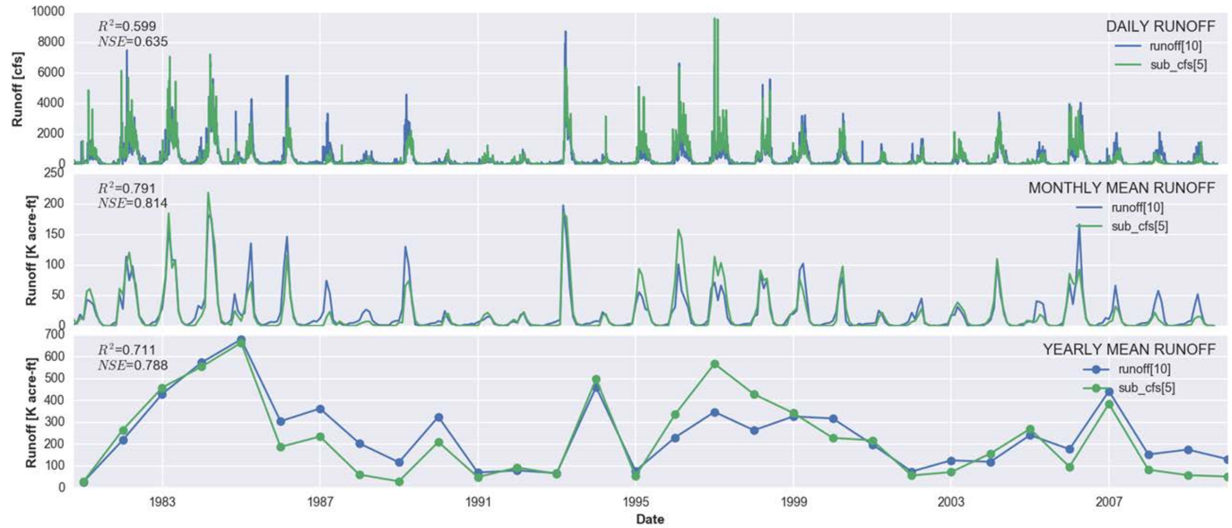

Figure 11. Crooked River at Prineville calibration for daily streamflow, monthly volume, and yearly volume (blue is observed or unregulated, and green is simulated).

The Ochoco calibration was more difficult than Prineville due to it being a smaller basin which can impact the quality of the gridded input data, and due to the unregulated dataset used for comparison having a higher degree of uncertainty (Reclamation 2017). To aid the calibration of Ochoco, two gages above the reservoir were used to calibrate the multiple snowmelt runoff peaks from early season rain on snow events. The gages did not span the entire period of record and were only available after 2000. The yearly volume calibration (Figure 12) was quite variable from year-to-year and had an R^2 of 0.14 and an NSE of 0.54. The monthly streamflow volume timing performed well when the yearly volume matched closely; however, the overall calibration quality was low (R^2 0.01 and NSE 0.53). The daily timing captured the early snowmelt events but had difficulty matching the unregulated data with an R^2 of -0.31 and an NSE of 0.26.

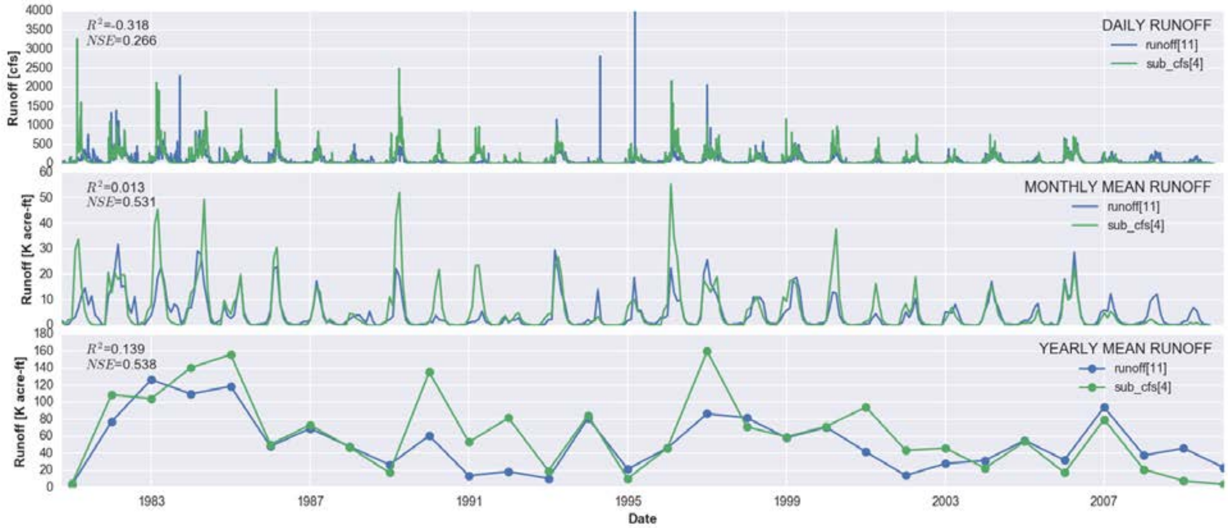

Figure 12. Ochoco calibration for daily streamflow, monthly volume, and yearly volume (blue is observed or unregulated, and green is simulated).

The Prineville and Ochoco subbasins drain into the Crooked River subbasin above CROO. The streamflow at Crooked River at Opal Springs (CROO) is influenced by cross-watershed groundwater flow from the Deschutes River. Based on observations and results from the Deschutes GSFLOW model, the groundwater contribution was fairly constant. Since the PRMS model focused on the surface processes, the constant groundwater contribution was removed from the measured streamflow used in the calibration process. The estimated groundwater contribution was added back in once calibration was complete. The calibration results (Figure 13) for the Crooked River are dominated by the larger Prineville subbasin. The yearly volumes matched well with observed data, having an R^2 value of 0.72 and an NSE of 0.79. The snowmelt peaks from the subbasin were not as noticeable, but instead controlled by Prineville snowmelt. The monthly timing of runoff events was captured with an R^2 value of 0.79 and an NSE of 0.82. The daily streamflow was again dominated by the Prineville runoff with an R^2 value of 0.58 and an NSE of 0.64.

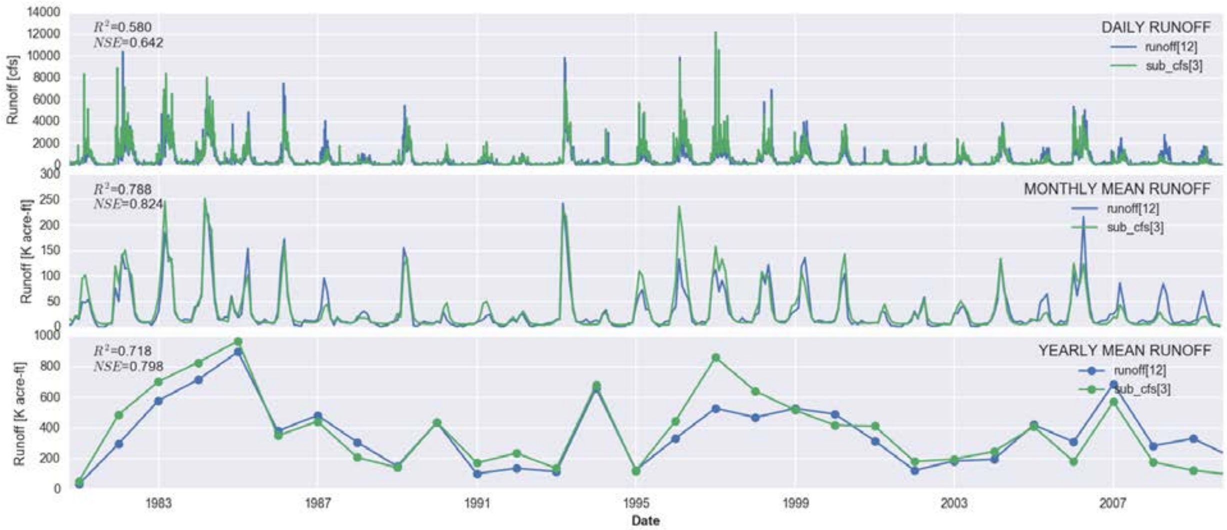

Figure 13. Crooked River calibration for daily streamflow, monthly volume, and yearly volume. The streamflow volume and timing are dominated by the Prineville subbasin runoff. The effects from groundwater flow into the basin were removed prior to calibration as they were fairly constant over the period of record.

Overall, given the timeframe for the model development, the model simulated streamflow at PRVO and CROO well, with OCHO having larger uncertainty. Further calibration improvement could be gained through more complex calibration to fine tune the model parameters, but the current model appears to capture the physical processes of the basin, and by refining the calibration at the gages above the reservoir for a longer time period to ensure that all the snowmelt peaks are captured.

3.3. GSFLOW

GSFLOW (Markstrom et al. 2008) is a USGS integrated model of PRMS and the USGS three-dimensional modular groundwater flow MODFLOW (McDonald and Harbaugh 1988). For the Deschutes basin, the USGS developed the first large scale application of GSFLOW (Gannett et al. 2017). The calibration of this model focused on the groundwater and surface water hydrology of the central and lower portions of the basin, which resulted in poor model performance (i.e. lower quality calibration or poor prediction capability) in the upper basin. An example of the raw GSFLOW output is shown for the Deschutes River below Wickiup gage using a subset of the temperature and precipitation climate scenario data (Figure 14). In this case, GSFLOW better captures the higher baseflows that are indicative of a groundwater-dominated system, however the timing of the peak is not captured. In addition, the overall volume of the hydrograph is larger than the historical median. (Additional information about the model development and calibration can be found in Gannett et al. 2017.)

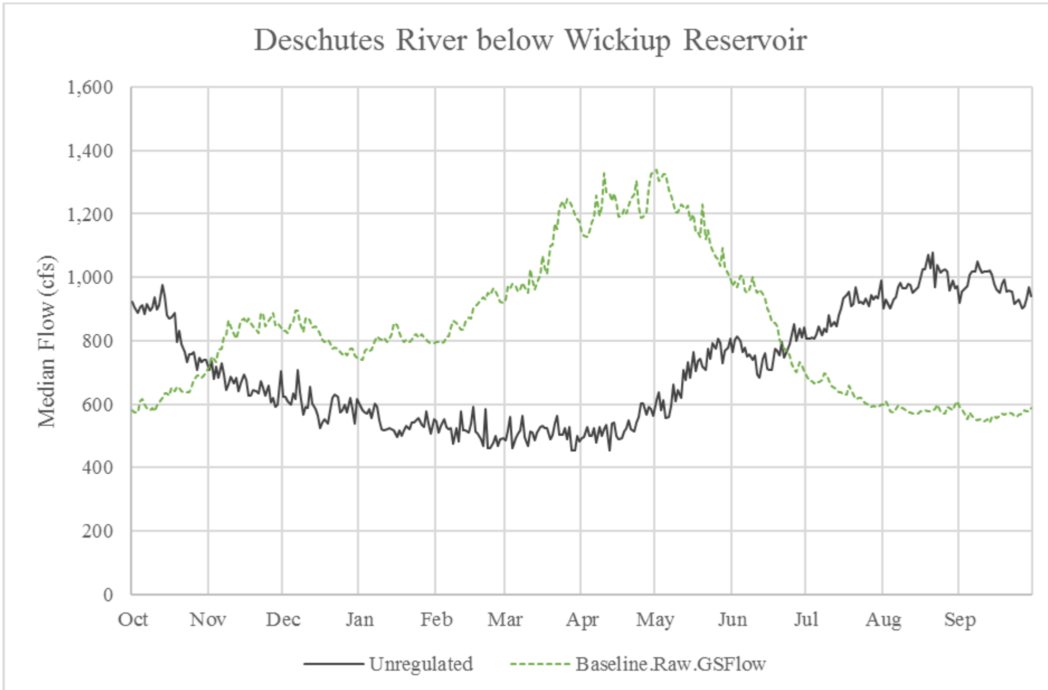

Figure 14. Historical unregulated median flow and raw modeled flow from the GSFLOW model at the Deschutes River below Wickiup gage.

4. Bias Correction

It is common to bias correct hydrologic model output to correct for systematic model error. This study used a quantile mapping bias correction method (Snover et al. 2003; Reclamation 2010b; Reclamation 2016) that adjusts the hydrologic model output using historical unregulated data.

Ideally, the raw baseline model output would closely match the unregulated flows at each location. Recent work during the second phase of the RMJOC climate study (RMJOC-II) has indicated that bias correction procedures are less effective when the output from the hydrologic model differs substantially from historical hydrology. In other words, the calibration of the hydrologic model is important to ensuring that the bias correction process works as intended. In this case, both the VIC and the GSFLOW model raw model output were quite different from the unregulated flows.

Figure 15 shows an example of this difference and the uncertainty that can be introduced using the bias correction process. The dotted lines show the median raw GSFLOW model output for all of the scenarios at Crescent Creek below Crescent Lake. Note that the raw GSFLOW hydrographs are generally flat and do not have a runoff peak, even for the baseline simulation which should closely resemble the unregulated flow.

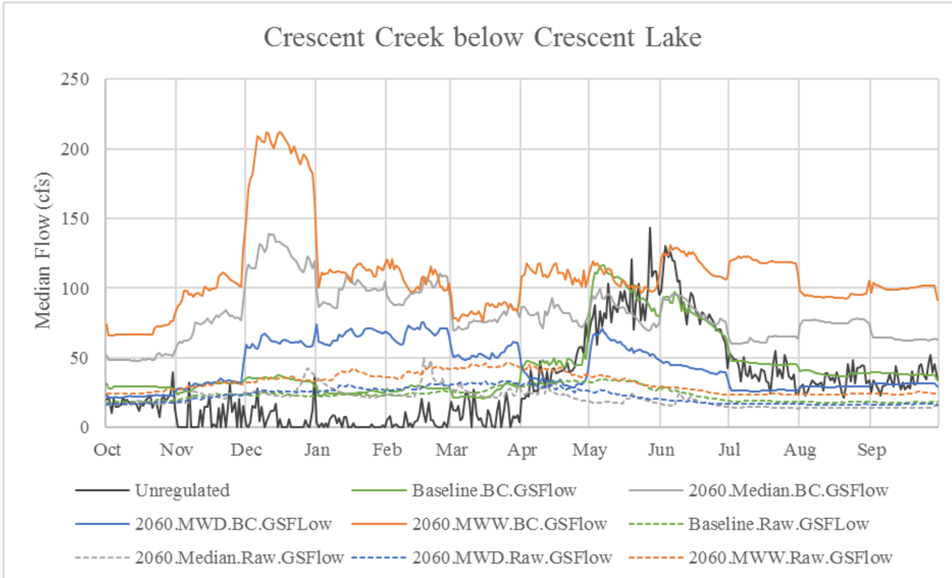

Figure 15. Median raw and bias-corrected GSFLOW output for Crescent Creek below Crescent Lake. (Black is unregulated flow, dotted lines indicate raw model output, solid lines indicate bias corrected output.)

The bias-corrected results indicate a few areas that should be examined further. First, the MWW scenario has a large increase in flow in December, which was not seen in the raw model output or the unregulated hydrograph. Second, the bias-corrected hydrograph also lacks a runoff peak, like the baseline model output, and therefore shows higher flows than would be expected in the summer. When comparing this output to the changes in precipitation and temperature that were used in the modeling, this seems like an unlikely result given that summer precipitation over the basin decreases or stays the same in all of the scenarios (Figure 16).

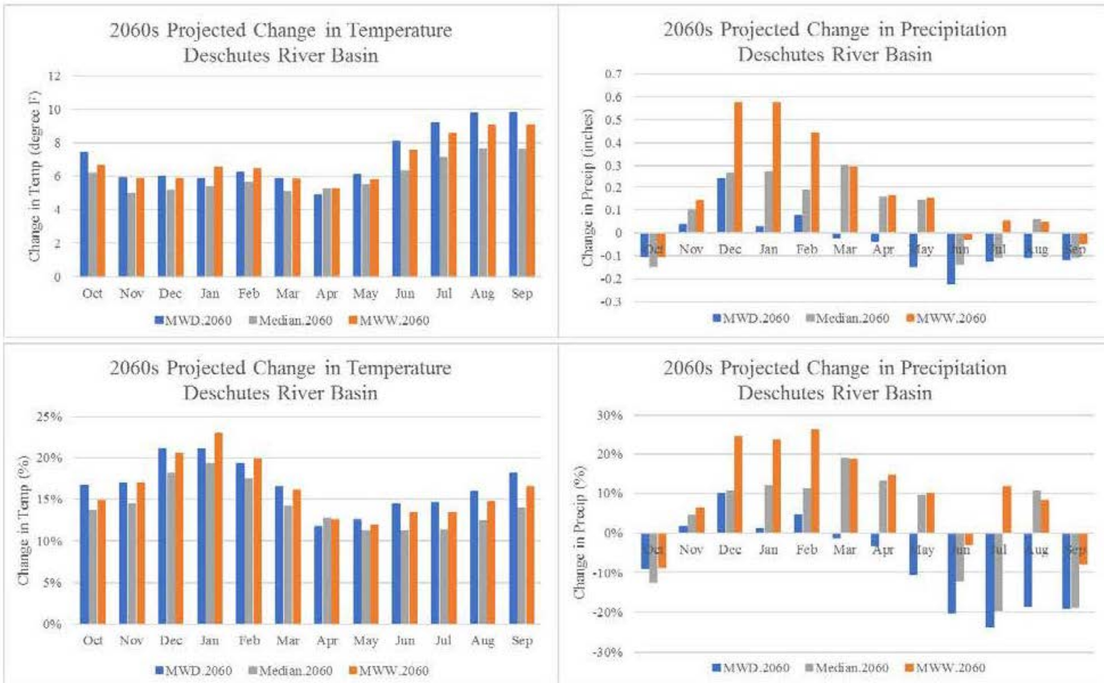

Figure 16. Projected change in temperature (left) and precipitation (right) for the selected climate scenarios.

Figure 17 shows the same model results using the VIC model. The raw model output more closely matches the unregulated hydrograph than the GSFLOW raw output. However, the bias-correction process is likely introducing error, particularly in the winter months when the unregulated flow is very small or zero. Nonetheless, the bias-corrected VIC output more closely represents a hydrologic signal that could be expected from the projected changes in temperature and precipitation. However, VIC does not simulate the physical processes that occur in the basin with respect to groundwater, so it is likely producing reasonable results by using unreasonable calibration parameters.

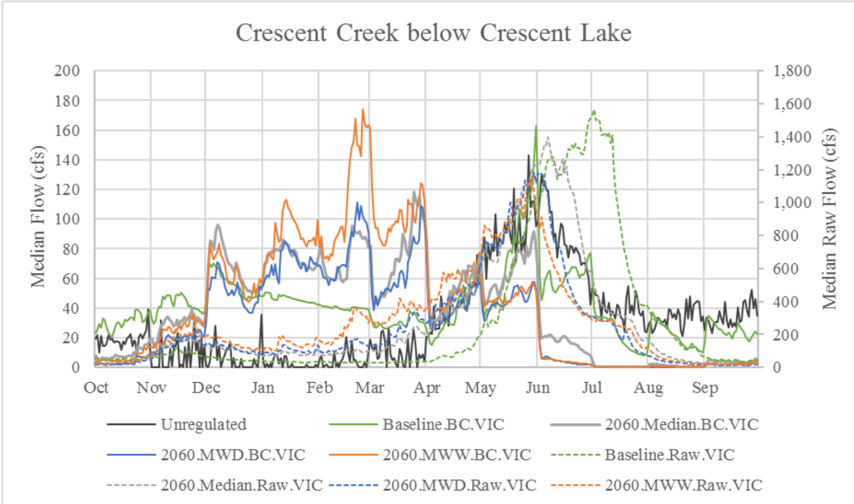

Figure 17. Median raw and bias-corrected GSFLOW and VIC output for Crescent Creek below Crescent Lake.

These uncertainties are introduced by both the GSFLOW and VIC models throughout the Upper Deschutes River basin. Though the VIC model and bias-corrected results appear to better represent the hydrology at Crescent Creek, there are other locations in the basin where this is not the case.[6] This is specifically true where streamflow is generated predominately by groundwater discharge to the stream network, which is not adequately simulated with VIC. Therefore, the Basin Study working group determined that it was appropriate to evaluate both set of data and use both sets for the RiverWare simulations.

5. Impacts of Temperature and Precipitation on Hydrology

Given that the hydrology models were considered insufficient for use in further analysis for the entire basin, some qualitative assessments of potential impacts of changes in temperature and precipitation on future hydrology are offered. The climate scenarios indicate an increase in temperature throughout the year. Warmer temperatures will likely result in precipitation falling more often as rain than snow. This may cause the runoff peak to shift earlier in the year.

There is a wide variation in potential changes in precipitation, but generally the scenarios indicate an increase in winter precipitation. This could result in higher winter and spring runoff volumes. In addition, the scenarios generally indicate a reduction in summer precipitation, which could result in lower natural flows in the summer.

The effects of these changes on regulated hydrology could have the following impacts:

[6] Appendix A shows raw and model output for all of the modeled locations for GSFLOW and VIC.

1. Increased winter and spring runoff volumes could increase the possibility of higher peak flows.
2. Increased winter and spring runoff volumes could increase the likelihood that reservoirs would fill in the spring; however, demands on stored water could increase as noted below.
3. Lower summer natural flows could increase the reliance on stored water for those irrigation districts that have it.

Additional modeling could help to refine these potential impacts.

6. Irrigation ET Demand Adjustment

Just as with the hydrologic data development, this study utilized information developed in previous studies and processes to develop future climate-adjusted demands for use in the RiverWare model. Demands represent the total amount of water that is removed from the river at various points and are a combination of consumptive use, conveyance loss, and on-farm loss.

To define demands for the current conditions model, measured canal diversion data were used. The data were adjusted for potential future climate using estimated changes in net irrigation water requirement (NIWR), which is the amount of water required by a plant to grow, evapotranspiration (ET), less precipitation.

The ET-Demands tool developed by the Desert Research Institute and Reclamation (2015b) was used to calculate ET and NIWR for four weather stations throughout the basin (Figure 18). Using the linear regression method defined in the CRBIA (Reclamation 2016), the measured diversion data were adjusted for future projected weather conditions. Table 2 shows the weather stations that were used for each irrigation district in the Upper Deschutes River basin.

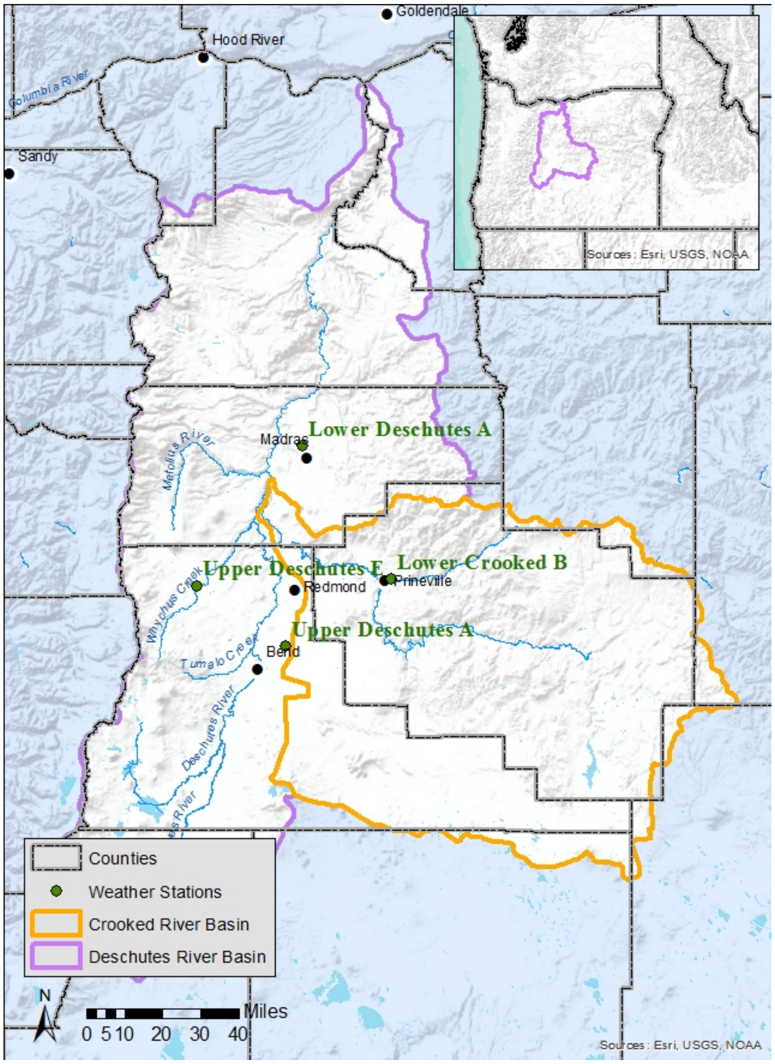

Figure 18. Upper Deschutes basin with defined weather stations.

Table 2. Irrigation districts and the weather stations used to adjust the demands for future climate conditions.

Irrigation District	Weather Station
Arnold Irrigation District (AID)	Upper Deschutes A
Central Oregon Irrigation District (COID)	
Lone Pine Irrigation District (LPID)	
Tumalo Irrigation District (TID)	
Swalley Irrigation District (SID)	
Three Sisters Irrigation District (TSID)	Upper Deschutes E
Ochoco Irrigation District (OID)	Lower Crooked B
All other Crooked River diversions	
North Unit Irrigation District (NUID)	Lower Deschutes A

6.1. Adjustment Equations

To adjust the daily measured diversion data for each irrigation district, NIWR values were calculated using historical meteorological and future projected meteorological data for the three climate scenarios defined in Section 2.0 (2060 MWD, 2060 MWW, and Median) for each weather station.

The NIWR values were aggregated to monthly totals and then were used to develop linear regression relationships. Although the ET-Demands tool calculates ET and NIWR for each day of the year, only the values during the irrigation season (April 1 through October 15) were used. Table 3 shows the linear regression relationships that were developed for each site and climate scenario along with the associated R^2 values.

Table 3. Linear regression equations for each weather station and climate scenario along with R-squared values.

Weather Station	Climate Scenario	Equation	R-squared
Upper Deschutes A	2060.MWD	y = 1.1046x	0.873
	2060.MWW	y = 1.0875x	0.866
	Median	y = 1.0802x	0.857
Upper Deschutes E	2060.MWD	y = 1.1046x	0.839
	2060.MWW	y = 1.0888x	0.835
	Median	y = 1.0706x	0.809
Lower Crooked B	2060.MWD	y = 1.1078x	0.849
	2060.MWW	y = 1.0919x	0.842
	Median	y = 1.0831x	0.837
Lower Deschutes A	2060.MWD	y = 1.0652x	0.861
	2060.MWW	y = 1.0411x	0.850
	Median	y = 1.0411x	0.851

For all scenarios, the total demand value was adjusted using the derived equations which included the embedded conveyance and on-farm loss. It was assumed that the conveyance and on-farm losses would increase proportionally with the amount of water that is being demanded by the crop.

6.2. Adjusted Irrigation Demands

Figure 19 shows the adjusted demands for each district. Note that all demands increase for the all scenarios and all districts. This is because ET is largely dependent on temperature and all scenarios show an increase in temperature. The largest increase is for the MWD scenario because there is a larger increase in temperature combined with less precipitation than the other scenarios, so more irrigation water is required. The smallest increase is for the median scenario because the median scenario has a smaller temperature increase than the other two scenarios.

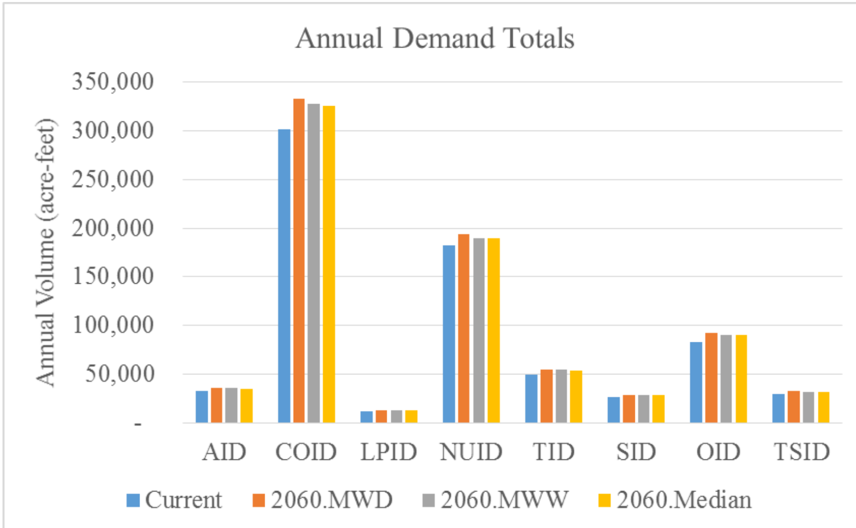

Figure 19. Annual demand volumes for current and future projected climate scenarios.

7. Conclusions

This technical memorandum summarizes the methods and models that were used to select future climate scenarios and adjust hydrologic parameters for use in the water resources (RiverWare) modeling. Developing data for future climate-adjusted hydrology and crop requirements is a new and evolving science and therefore has a large amount of associated uncertainty. This study used the best-available methods and tools; however, there is room for improvement in future studies.

There were challenges with developing future adjusted climate hydrology in the Upper Deschutes River basin due to the groundwater-dominated nature of the system. The characteristic hydrograph that has higher baseflows and attenuated peak flows is not well simulated by the VIC and PRMS hydrology models. The GSFLOW model, which is designed to better capture these behaviors, was calibrated for the lower basin and therefore did not satisfactorily capture the hydrology in the upper basin. Since the flows in the upper basin are critical to water management, this limited the models' use in the Basin Study. In addition, the bias correction procedure introduced an additional layer of uncertainty since the modeled flows were largely different from observed flows.

The issues identified with the hydrology models, GSFLOW, are continuing to be addressed, and the USGS is actively working on calibrating a new version of the GSFLOW model for use in future studies of the upper basin. In the interim, the results of this study should be used with extreme caution since there is considerable uncertainty with both the raw and bias-corrected results.

(*Note: The content of this document was finalized December 2018; formatting for accessibility compliance with Section 508 of the Rehabilitation Act was applied in 2019.*)

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