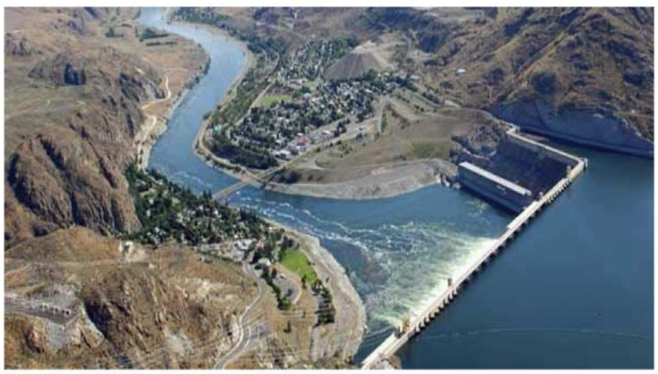
RECLAMATION
Managing Water in the West

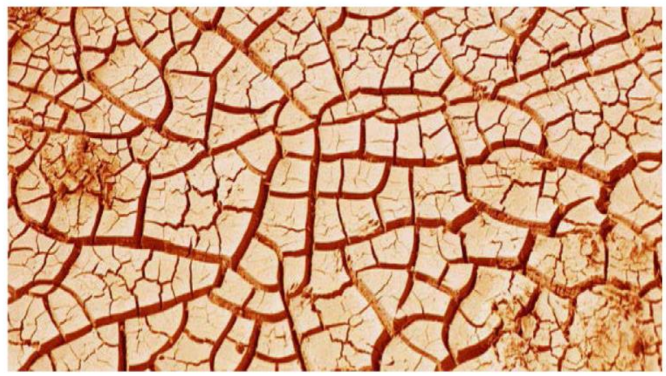
West-Wide Climate Risk Assessment

Columbia River Basin

Climate Impact Assessment

Final Report





U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Regional Office

March 2016

Mission Statements

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.

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.

Photographs on front cover: The shrub-steppe around Grand Coulee Dam, parched desert soil, a crop field with rain clouds, and snow covered mountain peaks. These images represent the varied ecosystems in the Columbia River Basin.

West-Wide Climate Risk Assessment

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Final Report

Prepared for

United States Congress

Prepared by

U.S. Department of the Interior
Bureau of Reclamation

U.S. Department of the Interior
Bureau of Reclamation
Policy and Administration
Denver, Colorado

March 2016

Notes Regarding this West-Wide Climate Risk Assessment – Impact Assessment

The Columbia River Basin Impact Assessment is a reconnaissance-level assessment of the potential hydrologic impacts of climate change in the Columbia River Basin. For this study, it was necessary to isolate the impacts of climate change from other changes that may occur within the basin. Therefore, Reclamation has assumed that current water operations by all water management entities in the Columbia River Basin would continue unchanged in the future. This assessment does not consider any operational changes that may or may not be made by basin stakeholders in the future and does not reflect the position of any entity regarding future operational changes. The results should not be interpreted as an indication of actions that Reclamation or other entities may or may not take to maintain compliance with environmental laws such as the Endangered Species Act or National Environmental Policy Act. Possible adaptation and mitigation strategies to address imbalances in future water supply and demand in the basin may be considered in a subsequent Basin Study, which would include interested stakeholders.

Abbreviations and Acronyms

Abbreviation or Acronym	Definition
°C	degrees Centigrade
°F	degrees Fahrenheit
Assessment	Columbia River Basin Impact Assessment
BCSD	Bias Corrected Spatially Downscaled
BPA	Bonneville Power Administration
cfs	Cubic feet per second
CH	Critical Habitat
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
ESA	Endangered Species Act
ET	Evapotranspiration
FCRPS	Federal Columbia River Power System
GCM	Global Climate Models or General Circulation Models
GIS	Geographic Information System
HD	Hybrid-Delta
LCCs	Landscape Conservation Cooperatives
LW/D	Less Warming/Drier
LW/W	Less Warming/Wetter
M	Median
MW/D	More Warming/Drier
MW/W	More Warming/Wetter
NIWR	Net Irrigation Water Requirements
PN Region	Reclamation's Pacific Northwest Region
PNRO	Pacific Northwest Regional Office
R&D	Research and Development
Reclamation	Bureau of Reclamation
RMJOC	River Management Joint Operating Committee

Abbreviation or Acronym	Definition
RMJOC-1 Study	2011 RMJOC Climate Change Study, Parts I–IV
RMJOC-2 Study	RMJOC Climate Change Study 2 (anticipated 2016/2017)
SECURE	2011 SECURE Water Act Section 9503(c) – Reclamation Climate Change and Water Report
SWA	2009 SECURE Water Act Subtitle F of P. L. 111-11
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
UW CIG	University of Washington Climate Impacts Group
VIC	Variable Infiltration Capacity (Hydrologic Model)
WACCIA	Washington Climate Change Impacts Assessment
WaterSMART	Water (Sustain and Manage America's Resources for Tomorrow)
WRM	Water Resources Model
WWCRA	West-Wide Climate Risk Assessment

EXECUTIVE SUMMARY

Background and Purpose

The Bureau of Reclamation (Reclamation) is working with partners and stakeholders to assess the risks and impacts of climate change to Western U.S. water resources, and to identify climate adaptation strategies. Adequate and safe water supplies are fundamental to the health of citizens, strength of the economy, and protection of the environment and ecology in the Western U.S. Global climate change poses a significant challenge to the protection of these resources. Section 9503 of the SECURE Water Act, Subtitle F of Title IX of P. L. 111-11 (2009) (SWA), authorizes Reclamation to evaluate the risks and impacts of climate change in western river basins and to work with stakeholders to identify climate adaptation strategies.

The Columbia River Basin was one of the major Reclamation river basins identified for evaluation in the SWA. The basin is in the Pacific Northwest region of the United States and extends over seven U.S. states (Washington, Oregon, Idaho, Montana, Wyoming, Nevada, and Utah), 13 Federally recognized Indian reservations, and southern British Columbia, Canada. The Columbia River is the largest river in the Pacific Northwest at over 1,240 miles long and with a drainage area of roughly 260,000 square miles, 15 percent of which is within Canada. The Columbia River Basin has numerous Federal and non-Federal hydropower production facilities that account for nearly 80 percent of the energy production in the Pacific Northwest. Additionally, the basin supplies irrigation water and provides habitat for various fish and wildlife species including Endangered Species Act (ESA) species such as bull trout, steelhead, white sturgeon, and other salmonids.

Earlier climate investigations have estimated that the basin's average mean-annual temperature has increased by approximately 2 °F since the late 1800s. Also, while trends in precipitation have not been detected, the Columbia River Basin has experienced a general decline in spring snowpack since the mid-20th century due to more precipitation occurring as rain (rather than snow) and earlier snowmelt runoff (Knowles et al. 2007 and Regonda et al. 2005; as cited in Reclamation 2011, p. 45).

Reclamation requires programs throughout the agency to incorporate climate change considerations. Specifically, climate change is identified in the Reclamation Manual Climate Change Adaptation Policy (CMP-P16), Reclamation Climate Change Adaptation Strategy, Reclamation Infrastructure Investment Strategy, and Reclamation Principles, Requirements, and Guidelines. In addition, Reclamation has conducted various climate change analyses which are presented in the 2011 SECURE Water Act Section 9503(c) – Reclamation Climate Change and Water Report (2011 SECURE Report) and the upcoming 2016 SECURE Water Act Section 9503(c) – Reclamation Climate Change and Water Report (2016 SECURE Report). To understand further climate change impacts in the Columbia River Basin, the

Columbia River Basin Impact Assessment (Assessment) was conducted under the WaterSMART Basin Study Program as a West-Wide Climate Risk Assessment (WWCRA) activity. Climate impact assessments like this one are intended to provide an initial look and generate reconnaissance-level data and analysis on the potential impacts of climate change over a major river basin. The information from this assessment will be used in further investigations throughout the basin.

Objectives and Scope

In the Columbia River Basin, water management challenges exist in the form of competing water demands for agriculture; power production; environmental requirements; and municipal, industrial, and recreational uses—all of which are compounded by increasing populations. Results from this Assessment will provide important information to the water management community in the Columbia River Basin on the type and scale of the challenges that climate change is likely to pose in the basin. The Assessment is intended to be an initial analysis to characterize the future climate and hydrology in the Columbia River Basin. It is anticipated that as further analyses are conducted over the coming years, this Assessment will be referenced as a starting point, and models and tools will be refined to identify areas needing further study.

The Assessment establishes a foundation of information and data for stakeholders to use in developing more in-depth climate change analyses, climate change tools, and adaptation strategies through more detailed Basin Studies; operations and maintenance planning; feasibility level analyses; and other activities. For instance, the model data and outcomes from this Assessment are currently being applied to the Upper Deschutes Basin Study, Boise General Investigation Study, Crooked River Reservoir Pilot Study, and the River Management Joint Operating Committee (RMJOC) 2 Climate Change Study. In addition, a specific outcome of the Assessment is being used in the Upper Deschutes Basin Study. Assessment analyses showed that the Deschutes River is groundwater dominated; therefore, an alternate tool, GSFlow, has been chosen to develop future climate flows for this river.

This report documents the evaluation of past, current, and potential future climate and hydrology of the Columbia River Basin. It also considers the impacts to Reclamation mission areas through analysis of potential changes in water supply and investigation of methodologies for incorporating groundwater processes and changing water demands (due to climate change) into more detailed future analyses. This Assessment lays the necessary groundwork for further quantifying impacts to the following eight components outlined in the SWA:

- Water and power infrastructure/operations
- Water delivery
- Flood control operations

- Water quality
- Fish and wildlife habitat
- ESA listed species and critical habitat
- Flow and water-dependent ecological resiliency
- Recreation

The Assessment builds upon the modeling and evaluation conducted along the mainstem of the Columbia River and select tributaries summarized in both the 2011 SECURE Report and the RMJOC Climate Change Study Reports, Parts I–IV (2010–2011) (RMJOC-1 Study). The methodologies used, lessons learned, and results generated by these earlier studies informed the objectives and scope of this Assessment.

As part of the Assessment, the Pacific Northwest (PN) Region Project Team conducted hydrologic modeling and a climate evaluation for the Columbia River Basin as whole. At the time of the RMJOC-1 Study, it was known that the smaller tributaries to the Upper Snake River (e.g. Henrys Fork), Deschutes River, and Yakima River would need additional analysis and inflow projection locations to better capture future changes. In response to this need, the PN Region Project Team generated future climate change inflow data at a total of 157 locations across the Columbia River Basin, including all of the locations necessary for input into the PN Region's Upper Snake River Basin water resources planning model (Figure ES-1). As a major regulated headwater system in the Columbia River Basin, the evaluation of impacts and generation of regulated flows from the Upper Snake River Basin above Brownlee is crucial for informing further analysis of downstream impacts. For this reason, more in-depth analysis of climate change impacts to water resources (e.g., water supply and delivery) was focused in this area.

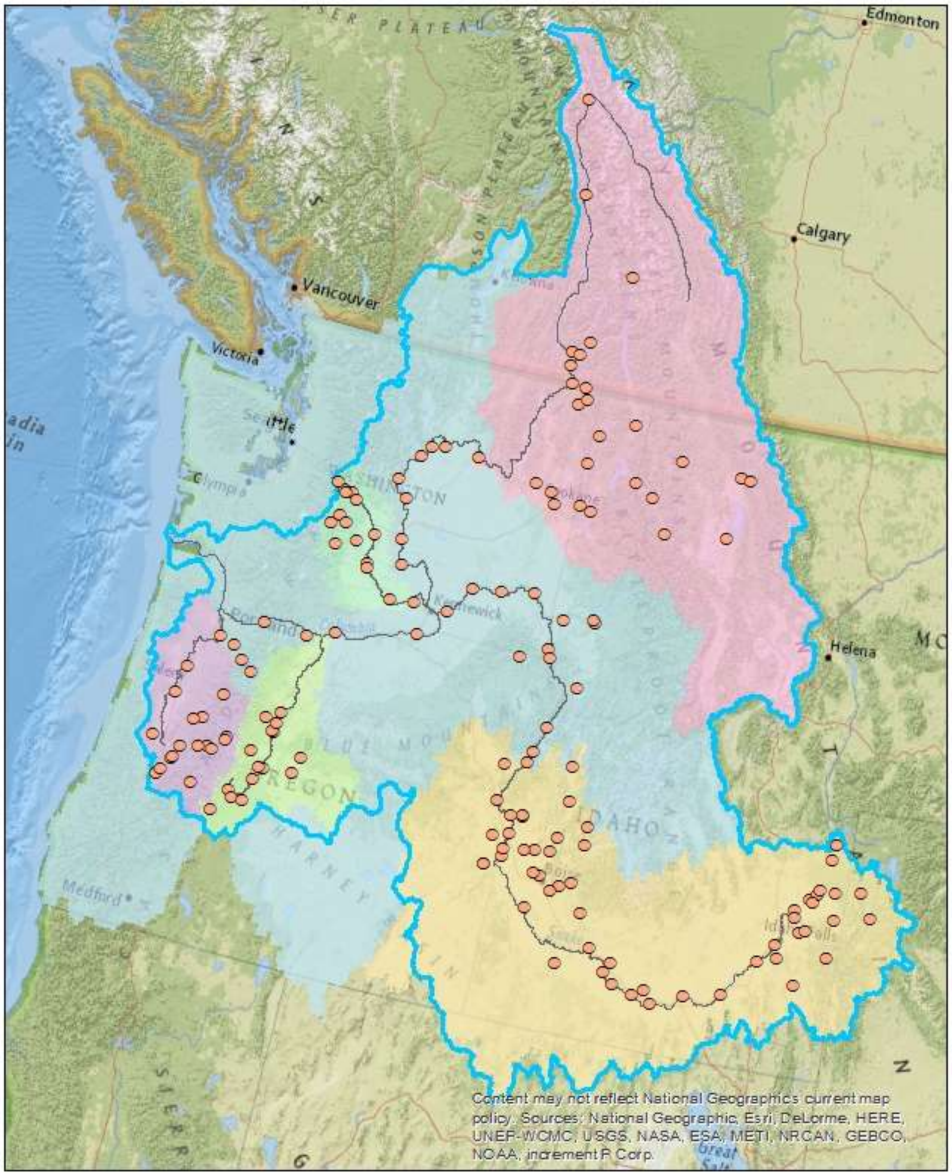

Figure ES-1. Map of 157 locations for which projected future streamflow were generated.

This Final Report summarizes research and analyses completed for the Assessment. Analyses cited in this report are drawn from the four Technical Memorandums developed for each primary study area of the Assessment. These Technical Memorandums are titled as follows:

- Climate Change Analysis and Hydrologic Modeling
- Water Resources Model
- Determining Agricultural Diversions for Use in Water Resources Models
- GIS Coordination and Data Management

An internal review was conducted for each Technical Memorandum followed by a technical sufficiency review. All Technical Memorandums are included as appendices to this report.

Assessment Results

Future Changes in Climate Conditions

In the Assessment, five climate change scenarios of simulated temperature, precipitation, and runoff were generated separately for four future periods and six sub-areas across the Columbia River Basin. The future periods included 2010 through 2039, 2030 through 2059, 2050 through 2079, and 2070 through 2099. These 30-year periods are referred to as being "centered around" the 2020s, 2040s, 2060s, and 2080s respectively. The five climate change scenarios included the following[1]:

- Less Warming Wetter (LW/W) – a cluster of 10 future projections around the 20th percentile change in temperature and 80th percentile change in precipitation;
- Less Warming Drier (LW/D) – a cluster of 10 future projections around the 20th percentile change in temperature and 20th percentile change in precipitation;
- Median (M) – a cluster of 10 future projections around the 50th percentile change in temperature and 50th percentile change in precipitation;
- More Warming Wetter (MW/W) – a cluster of 10 future projections around the 80th percentile change in temperature and 80th percentile change in precipitation; and,
- More Warming Drier (MW/D) – a cluster of 10 future projections around the 80th percentile change in temperature and 20th percentile change in precipitation.

These areas include the Yakima, Deschutes, Upper Snake, Grand Coulee, and Willamette subbasins, along with the larger Columbia River Basin. In the Pacific Northwest, generally speaking, the downscaled climate model projections used in the Assessment project warming temperatures going into the future, with the amount of warming varying by season and location. Changes in precipitation varied more widely than those for temperature, but mostly agreed in their simulation of increased precipitation during the cool season and decreased precipitation during the warm season.

As compared to temperature changes projected for the other subbasins considered in this Assessment, the Upper Snake River Basin exhibited the largest increases in temperature and followed the pattern seen in the other subbasins with the largest increases occurring during the summer months. Almost all scenarios project increased precipitation during the winter

[1] It should be noted that, in some subbasins, the "drier" scenarios did not always represent conditions that were drier than historical observation. Rather, these scenarios represented the "drier" of the scenarios considered by RMJOC-1 Study.

and early spring. Projected conditions for the remainder of the year (May through October) were more varied, but generally indicate drier conditions (decreased precipitation) during those months. Only the Less Warming/Wet scenario corresponded to year-round increases in precipitation.

Changes in temperature and precipitation will have important and varied consequences for water resources across the region, with hydrologic response (for example, timing and magnitude of runoff) depending upon the dominant form of precipitation in the basin and other local characteristics such as elevation, aspect, geology, vegetation, and changing land use (Melillo et al. 2014).

Simulated Changes in Runoff

Daily and mean monthly streamflows were generated for 157 locations throughout the Columbia River Basin. In general, the projected warming and changes in precipitation across the Columbia River Basin are expected to result in increased runoff during the cool season and decreased runoff during the warm season; however, the magnitude and timing of such changes varied across the region.

The following table summarizes results of hydrologic modeling conducted as part of the Assessment for select locations, including the Columbia River above the Dalles, Snake River at Brownlee Dam, and Yakima River at Parker. The data shows the percent change of runoff and snow water equivalent from the 1990s (1980 to 2009) to the 2040s (2030 to 2059) and 2080s (2070 to 2099). Note that these periods represent the 30-year intervals centered on the referenced decade.

Table ES-1. Results of hydrologic modeling conducted for the Columbia River above the Dalles, Snake River at Brownlee Dam, and Yakima River at Parker. Data shows the simulated percent change from the 1990s (1980 to 2009) to the 2040s (2030 to 2059) and 2080s (2070 to 2099) of mean April 1st snow water equivalent; mean annual runoff; mean December through March runoff; and mean April through July runoff.

Hydroclimate Metric (Change from 1990s period)	2040s	2080s
Columbia River above the Dalles		
Mean April 1st Snow Water Equivalent[2] (%)	-58% to -33%	-76% to -43%
Mean Annual Runoff (%)	-5% to +10%	-4% to +15%
Mean December-March Runoff (%)	+13% to +44%	+26% to +91%
Mean April-July Runoff (%)	-8% to +8%	-17% to +10%
Snake River at Brownlee Dam		
Mean April 1st Snow Water Equivalent (%)	-66% to -42%	-80% to -43%
Mean Annual Runoff (%)	-5% to +11%	+4% to +18%
Mean December-March Runoff (%)	+5% to +29%	+14% to +71%
Mean April-July Runoff (%)	-7% to +15%	-4% to +21%
Yakima River at Parker		
Mean April 1st Snow Water Equivalent (%)	-56% to -33%	-81% to -45%
Mean Annual Runoff (%)	-10% to +8%	-12% to +13%
Mean December-March Runoff (%)	+23% to +65%	+44% to +128%
Mean April-July Runoff (%)	-28% to -6%	-56% to -14%

Impacts of Climate Change on Regulated Water Storage and Delivery

The evaluation of impacts and generation of regulated flows from the Upper Snake River Basin above Brownlee is essential for informing further analysis of the Columbia River Basin as a whole. A monthly Water Resource Model (WRM) of the Snake River Basin

[2] Calculated change in total snow water equivalent volume in the subbasin.

above Brownlee Reservoir was used for this analysis. The WRM includes the Boise River Basin and Payette River Basin as well as the Snake River Basin from its headwaters at Jackson Lake downstream to Brownlee Reservoir. The modeling in the Upper Snake River Basin was used to answer questions and fill in information gaps identified in the RMJOC-1 Study.

The WRM results were used to determine the potential impacts of climate change on four metrics—system inflow, system reservoir contents, regulated flow, and requested water (shortage and natural versus stored flow delivery). Figure ES-2 identifies the streamflow and reservoir locations in the Snake River Basin above Brownlee Reservoir (BRN) that were studied in the Assessment. Descriptions of each reservoir and streamflow abbreviation are available in Appendix B.

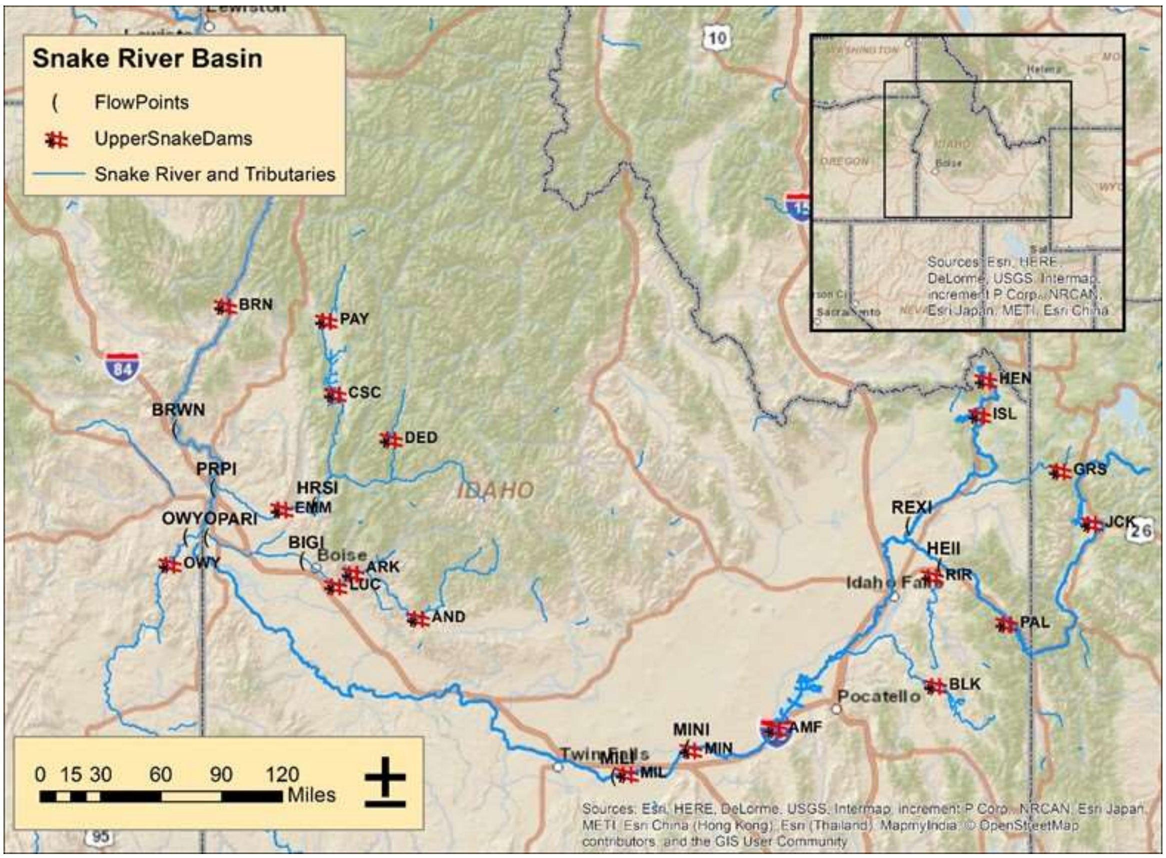

Figure ES-2. Streamflow and reservoir locations in the Snake River Basin above Brownlee Reservoir (BRN) presented in the Assessment. Reservoir labels have three letter designations and were placed to the right of the point. Streamflow labels have four letter designations and were placed above the point.

Across the entire Upper Snake system, inflows and regulated flows were projected to increase through the spring with decreases seen in the summer months. In general, the increase in spring inflow allowed reservoirs to refill in a higher number of years than in the Baseline, but with peak storage occurring earlier through each period due to the earlier and increased spring runoff. The decline in system inflows in the late summer months caused increased dependency on stored water. In turn, shortages increased when water users used all of their stored water, which led to lower storage carryover levels (calculated at the end of October).

Overall, large increases in regulated basin outflow were seen throughout the Upper Snake WRM with regulated flows exceeding flood stage in two of the three basins evaluated—Snake River Basin above Milner and Boise River Basin—for at least one climate change scenario. Specifically, increased system inflow in the MW/W scenario, especially pronounced in the 2080 period, exceeded the amount that could be stored in the Snake River Basin above Milner. Under such conditions, where reservoirs reach maximum storage capacity, there is no further capacity (without altering reservoirs' flood control targets) to store high inflows and therefore downstream flooding occurs.

The modeling run in this Assessment showed that water delivery remained relatively unchanged across the entire Upper Snake system (although larger request differences from the baseline were seen in the Boise River Basin) due to the fact that most water users have both natural flow and stored water rights. This means that, when natural flow supplies are diminished, water users are able to continue to receive water from their stored supplies in reservoirs. Water users were able to rely more heavily on their stored water accounts due to increased spring runoff refilling reservoirs in a higher number of years.

Determining Agricultural Diversions for Use in Water Resources Models

In the Assessment, two methods were studied for developing future irrigation diversion inputs for more detailed water resources modeling using the projected future crop needs identified in Reclamation's West-Wide Climate Risk Assessments: Irrigation Demand and Reservoir Evaporation Projections Report. The two methods evaluated are the Total Irrigated Acres Method and the Linear Regression Method. Both methods produced similar projected future irrigation diversions. Since the Linear Regression Method requires less input data (i.e. the irrigated acreages are not needed for the calculation), it was considered the preferred method.

Stakeholder Outreach

Coordinated outreach efforts to internal and external stakeholders were conducted throughout the 2-year Assessment period to raise awareness of the study. Activities included attending public meetings, writing and distributing quarterly updates, developing a website for the Assessment (http://www.usbr.gov/pn/climate/crbia/), and hosting a webinar series (available on the Assessment website).

GIS Coordination and Data Management

As part of this Assessment, web mapping technology was determined advantageous to sharing climate change information and data for further climate change analyses. Reclamation's existing public web mapping application, *Streamflow Projections for the Western United States* (http://gis.usbr.gov/Streamflow_Projections), was updated to efficiently share data generated from the Assessment and previous studies with internal and external partners. In addition, Reclamation's existing internal web mapping application, *Tessel*, was extended to provide context for visualizing previous and ongoing climate and hydrology modeling work in the Pacific Northwest Region.

For the Assessment, climate data management centered largely on the acquisition, organization, and logical storage of thousands of digital files. The approach to data management used for the Assessment was coordinated with Reclamation's Policy and Administration Office. The file-based data management strategy, the Dublin Core metadata procedure, and delivery of data with web mapping technology can all be replicated by Reclamation offices west-wide to conduct similar climate Impact Assessments or Basin Studies. In addition to supporting climate change efforts, the data management strategy would support the Department of the Interior's Open Data initiative and Reclamation's Open Water Data initiative.

Summary of Possible Impacts and Next Steps

This Assessment provides the initial analysis of climate change impacts to the Columbia River Basin, and it lays a foundation of climate and hydrology data to facilitate more in-depth basin investigations in the future. Further, this Assessment supports findings of previous climate change analyses projecting warmer temperatures in the Columbia River Basin moving through the 21st century. Additionally, it supports findings that, while the mean amount of annual precipitation is not anticipated to change significantly, its timing is projected to change, with increased precipitation during the cool season and decreased precipitation during the warm season.

In the Assessment it was determined that in "transitional" subbasins where the dominant form of precipitation is neither rain nor snow, but currently a mix of both, impacts of climate change will be more pronounced with the dominant form of precipitation shifting from snow to rain. Such changes are projected to result in increased flows during the winter and decreased flows during the summer. Impacts in rain- and snow-dominant subbasins are projected to be less pronounced. While some snow-dominant subbasins are likely to shift towards transitional conditions (mixed rain and snow dominance), many snow-dominant subbasins currently have winter temperatures well enough below freezing that warming may not cause winter temperatures to cross the freeze/thaw threshold (Appendix A).

Many reservoir systems in the Columbia River Basin were designed under the assumption that snowpack would serve as a large upstream reservoir, accumulating and storing water through the winter and gradually releasing it during the spring and summer melt. In transitional (mixed rain/snow) locations, changes to seasonal runoff may pose challenges to water management as flows increase during the flood control period (when excess water is considered a hazard) and flows decrease during the irrigation season (when water is an important economic and ecological asset). In the Columbia River Basin, the timing and volume of flows will vary among the subbasins.

This Assessment generated high-level analysis over the Columbia River Basin on the projected impacts of climate change in the basin, and how those impacts relate to water supply, storage, and delivery. The Assessment serves to guide Reclamation and its stakeholders in identifying areas where climate change is projected to have near- and long-term impacts. Table ES-2 below summarizes the projected impacts of climate change on the eight SWA resource categories. In particular, these impacts are outlined in terms of their overall 21st century possible impacts and their contributing factors. Lastly, as seen in the far right column of Table ES-2, this Assessment offers some potential next steps for Reclamation and water resource managers to consider.

Table ES-2. Summary of Possible Impacts by SWA Resource Category.

SWA Resource Category	Overall 21st Century Possible Impacts	Contributing Factors	Potential Next Steps
Hydropower Generation	Possible increased power generation in late winter and spring	The possible increase in late winter and spring flows could result in higher power generation during that time period	Use Assessment as part of the Infrastructure Investment Strategy for hydropower modernization
	Possible decreased generation in the summer	Lower flows in the summer could result in decreased power generation during a period of increased demand due to higher temperatures	

SWA Resource Category	Overall 21st Century Possible Impacts	Contributing Factors	Potential Next Steps
Reservoir Conditions and Water Delivery	Potential to increase fill of reservoirs during spring runoff	The possible increase of precipitation falling as rain rather than snow would result in reservoirs filling more quickly and at a greater frequency with less water (runoff) available in the late summer; the increased ability to fill storage may help reduce overall water delivery shortages	Update and refine climate change analysis for specific locations or future actions Conduct Basin Study in subbasins with near-term impacts indicated Use Assessment data to refine analysis for feasibility studies
	Higher reliance on stored water than natural flow	Possible decreased natural flow will place heavier reliance on stored and groundwater supplies earlier in the irrigation season which may result in lower reservoir storage levels at the end of the irrigation season	Conduct Basin Study in subbasins with near-term impacts indicated Use Assessment data to refine analysis for feasibility studies Evaluate future agriculture water needs by using this Assessment to identify locations

SWA Resource Category	Overall 21st Century Possible Impacts	Contributing Factors	Potential Next Steps
Flood Control Operations	Possible increased reservoir discharges during the late winter/spring to follow flood control rule curves	Possible increases in early season runoff in high volume water years could contribute to releases earlier in the flood control period that could decrease the ability to fill the system if inflows decrease too early following the releases	Use Assessment model data to conduct Reservoir Operations Pilot Initiative If the Infrastructure Investment Strategy applies, use Assessment information
	Possible increase in downstream flood risk	The possible increase in precipitation falling as rain rather than snow may result in increased downstream flooding due to decreased ability to forecast runoff and larger winter/early spring runoff events. The runoff period may be shorter in duration and higher in magnitude in transitional basins making reservoir regulation and flood control operations challenging	

SWA Resource Category	Overall 21st Century Possible Impacts	Contributing Factors	Potential Next Steps
Water Quality	Possible increased water temperature	Possible climate warming and reduced reservoir storage during the hottest months could contribute to increased water temperatures	Conduct Basin Study in subbasins with near-term impacts indicated If the Infrastructure Investment Strategy applies, use Assessment information Do basin-specific water quality modeling for Columbia River Basin subbasin locations that indicate near-term climate impacts
	Possible increased total dissolved gas (TDG)	The potential increase in flood control season flows could result in increased spill, which could contribute to increased TDG content below dams	If the Infrastructure Investment Strategy applies, use Assessment information Do basin-specific water quality modeling for Columbia River Basin subbasin locations that indicate near-term climate impacts

SWA Resource Category	Overall 21st Century Possible Impacts	Contributing Factors	Potential Next Steps
Fish and Wildlife Habitat	Possible decreased summer flow	Climate change results indicate a similar average volume of annual precipitation, yet water supplies are anticipated to be lower at various times of the year with similar or increased demands. It could likely be difficult to maintain environmental flows in the summer months which would negatively impact fish and wildlife habitat	Conduct Basin Study in subbasins with near-term impacts indicated Refine Assessment models for environmental compliance analysis
ESA Listed Species	Adult Salmonid Migration – Potential negative impacts in summer months	The possible reduced flows during late summer may undercut Federal agencies' efforts to augment summer flows	Conduct Basin Study in subbasins with near-term impacts indicated Refine Assessment models for Biological Assessments
	Incubating eggs and juvenile Coho, chum, Chinook, and steelhead survival – Potential negative impacts in winter months	The possible increase in winter flooding due to more rain than snow could disrupt critical habitat	Conduct Basin Study in subbasins with near-term impacts indicated

SWA Resource Category	Overall 21st Century Possible Impacts	Contributing Factors	Potential Next Steps
Flow and Water Dependent Ecological Resilience	Non-adaptable species may possibly be negatively impacted	Possible reduced reservoir storage in the late summer and reduced spring runoff due to decreasing snowpack could contribute to reduced river flows, which could reduce the ability to buffer the system in extreme years	Use Landscape Conservation Cooperatives (LCC) Partnerships for additional research Conduct Basin Study in subbasins with near-term impacts indicated
Recreation	Possible decrease in reservoir recreation season	Possible lower reservoir levels in the late summer could impact the surface area available for recreation	Conduct Basin Study in subbasins with near-term impacts indicated
	Possible decrease in stream recreation season	Higher spring runoff flows and decreased late summer flows could create unfavorable stream recreation conditions leading to a shorter season	

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1 STUDY INTRODUCTION

1.1 Study Background and Purpose

The Bureau of Reclamation (Reclamation) is working with partners and stakeholders to assess the risks and impacts of climate change to Western U.S. water resources, and to identify climate adaptation strategies. Adequate and safe water supplies are fundamental to the health of citizens, strength of the economy, and protection of the environment and ecology in the Western U.S. Global climate change poses a significant challenge to the protection of these resources. Section 9503 of the SECURE Water Act, Subtitle F of Title IX of P.L. 111-11 (2009) (SWA), authorizes Reclamation to evaluate the risks and impacts of climate change in western river basins and to work with stakeholders to identify climate adaptation strategies. The Columbia River Basin was one of the major Reclamation river basins identified for evaluation in the SWA.

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In the Columbia River Basin, water management challenges exist in the form of competing water demands for agriculture; power production; environmental requirements; and municipal, industrial, and recreational uses—all of which are compounded by increasing populations. Results from this Assessment will provide important information to the water management community in the Columbia River Basin on the type and scale of the challenges that climate change is likely to pose in the basin. The Assessment is intended to be an initial analysis to characterize the future climate and hydrology in the Columbia River Basin. It is anticipated that as further analyses are conducted over the coming years, this Assessment will be referenced as a starting point, and models and tools will be refined to identify areas needing further study.

The Assessment establishes a foundation for stakeholders to develop more in-depth analyses, climate change tools, and adaptation strategies through more detailed Basin Studies; operations and maintenance planning; feasibility level analyses; and other activities. For example, the model data and outcomes from this Assessment are currently being applied to the Upper Deschutes Basin Study, Boise General Investigation Study, Crooked River Reservoir Pilot Study, and RMJOC-2 Study. Also, a specific outcome of the Assessment is being used in the Upper Deschutes Basin Study. Assessment analyses showed that the Deschutes River is groundwater dominated; therefore, an alternate tool, GSFlow, has been chosen to develop future climate flows for the river.

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- Flow and water-dependent ecological resiliency
- Recreation

The Assessment builds upon the modeling and evaluation conducted along the mainstem of the Columbia River and select tributaries summarized in the River Management Joint Operating Committee (RMJOC) Climate Change Study Reports Parts I–IV (2011) (RMJOC-1 Study). Multiple Basin Studies have also been completed in the Columbia River Basin, including the Henrys Fork Basin Study, the Yakima River Basin Study (leading to the Yakima Integrated Plan), and the Hood River Basin Study. The methodologies used, lessons learned, and results generated by these earlier studies informed the objectives and scope of this Assessment. The Sacramento and San Joaquin Basins Impact Assessment (2014) and the Upper Rio Grande Impact Assessment (2013) were also used as guides for this Assessment, helping to maintain consistency across Reclamation's regions.

As part of the Assessment, the Pacific Northwest (PN) Region Project Team conducted hydrologic modeling and a climate evaluation for the Columbia River Basin as whole. At the time of the RMJOC-1 Study, it was known that the smaller tributaries to the Upper Snake River (e.g. Henrys Fork), Deschutes River, and Yakima River would need additional analysis and inflow projection locations to better capture future changes. In response to this need, the PN Region Project Team generated future climate change inflow data at 157 locations across the

Columbia River Basin, including all of the locations necessary for input into the PN Region's Upper Snake River Basin water resources planning model. As a major regulated headwater system in the Columbia River Basin, the evaluation of impacts and generation of regulated flows from the Upper Snake River Basin above Brownlee is crucial for informing further analysis of downstream impacts. For this reason, more in-depth analysis of climate change impacts to water resources (e.g., water supply and delivery) was focused in this area.

Specific activities in this Assessment (many of which were selected to fill in knowledge gaps following the RMJOC-1 Study) include the following:

- Overview of the current climate and hydrology of the Columbia River
- Comparison of observed temperature and precipitation to Global Climate Models (GCMs) projections
- Use of the Hybrid Delta Ensemble approach to generate climate change scenarios from 10-member ensembles of the most recent Coupled Model Intercomparison Project Phase 5 (CMIP5) projections
- Hydrologic modeling using a $1/16^{th}$ degree Variable Infiltration Capacity (VIC) model of the Columbia River Basin
- Bias-correction of VIC model simulated future streamflow using the methodology applied in the RMJOC-1 Study
- Simulation of regulated streamflow and operations using a Water Resources Model (WRM)
- Update of internal and external web mapping applications to make Assessment data readily available to stakeholders

This Final Report summarizes research and analyses completed for the Assessment. Analyses cited in this report are drawn from the four Technical Memorandums developed for each primary study area of the Assessment. These Technical Memorandums are titled as follows:

- Climate Change Analysis and Hydrologic Modeling
- Water Resources Model
- Determining Agricultural Diversions for Use in Water Resources Models
- GIS Coordination and Data Management

An internal review was conducted for each Technical Memorandum followed by a technical sufficiency review. All Technical Memorandums are included as appendices to this report.

The Assessment evaluated the potential impacts of climate change on water supply over the entire Columbia River Basin and water demand in the Snake River Basin above Brownlee Reservoir. The Assessment does not attempt to project what future development or management actions may be (e.g., how population may change, how power generation may evolve, or how land use may change). While factors such as these will undoubtedly be affected by climate change, they are also changing due to societal factors and management actions that are independent of climate change. For the purposes of this Assessment, Reclamation does not presume to know what management actions will be taken by other entities operating in the Columbia River Basin. For these reasons, the results presented here should be considered *estimates* of the hydrologic impacts of climate change only and not *predictions* of the future operation of facilities in the Columbia River Basin.

1.3 Study Document Organization

This Final Report draws from the four technical memorandums and summarizes the research and analyses completed for the Assessment. This document begins with a discussion of the purpose, basis, and authorizations for this Assessment. Next, it provides a description of the basin, analysis methods, and a discussion of the study results. The following list describes the information presented in each chapter of this report.

- **Chapter 1** introduces the Assessment and describes the motivations for this work, the objectives and scope, and the programs supporting the study.
- **Chapter 2** provides background for the study and presents the historical climate and hydrology of the basin.
- **Chapter 3** presents the methods used for the analysis of trends in climate and hydrology in the basin.
- **Chapter 4** describes impacts to climate, hydrology, and water supply within the basin.
- **Chapter 5** discusses potential impacts to water management focus areas, including water and power infrastructure/operations, water delivery, flood control operations, water quality, fish and wildlife habitat (including the habitat of species listed under the ESA), water-dependent ecological resiliency, and water-related recreation.
- **Chapter 6** provides a summary of basin-wide climate change impacts and presents recommendations for Reclamation's next steps in a more detailed characterization of climate change impacts and ways for local water-management entities to engage in such efforts. Additionally, this section identifies uses of this Assessment in current Reclamation efforts.

1.4 Reclamation's Programs Supporting the Study

A key component of Reclamation's implementation of the SWA is the Basin Study Program. Reclamation's Basin Study Program is managed under the Department of the Interior's Sustain and Manage America's Resources for Tomorrow (WaterSMART) Program, which is working to achieve a sustainable water management strategy to meet the Nation's water needs now and in the future. To learn more about WaterSMART, please visit: http://www.usbr.gov/WaterSMART/

The Assessment is an activity of the West-Wide Climate Risk Assessments (WWCRA), which is a component of Reclamation's WaterSMART Basin Study Program. WWCRA activities include identifying climate change information needs of water resource managers, compiling and analyzing water resources data, and developing tools and guidance for water resource managers. The WWCRAs include the following activities:

1. Water supply assessments
2. Water demand assessments
3. Operational assessments

Individual basin Impact Assessments, such as this one, provide information on the potential risks of climate change to Reclamation facilities and operations (including water and power delivery, recreation, flood control, and ecological resources), as well as a foundation of climate change data, information, and tools for use in future Basin Studies.

Since the WWCRA Impact Assessments emphasize impacts to Reclamation facilities and operations and are not focused on the development of adaptation strategies, they are conducted by Reclamation alone and are not cost-shared with non-Federal partners. This allows Reclamation to develop consistent baseline information in a time frame consistent with the reporting requirements of SWA 9503(c). Results from these WWCRA activities contribute to Reclamation's SECURE Reports to Congress every 5 years, Basin Studies, and other regional programs and projects.

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2 LOCATION AND BACKGROUND

2.1 Basin Description

The Columbia River Basin is located in the Pacific Northwest region of the United States and extends over seven U.S. states (Washington, Oregon, Idaho, Montana, Wyoming, Nevada, and Utah), 13 Federally recognized Indian reservations, and southern British Columbia, Canada. The Columbia River is the largest river in the Pacific Northwest at over 1,240 miles long and with a drainage area of roughly 260,000 square miles, 15 percent of which is within Canada. The Columbia River headwaters are within the Rocky Mountains of British Columbia, and its mouth is at the Oregon coast in Astoria. The river flows northwest into Canada before heading south into the State of Washington and continues westerly forming the boundary between Oregon and Washington before it drains into the Pacific Ocean.

The Columbia River has an annual average runoff of approximately 200,000,000 acre-feet (275,000 cubic feet per second) with roughly 25 percent of that volume originating in the Canadian portion of the basin (BPA 2001). Major tributaries to the Columbia River include the Snake River in Idaho (largest tributary to the Columbia River with a drainage area of 108,000 square miles); the Owyhee River in Nevada and Oregon; the Yakima, Spokane, and Methow rivers in Washington; the Kootenai and Pend Oreille rivers originating in Montana; and the Willamette, Deschutes, John Day, and Cowlitz rivers in Oregon. The Columbia River flows through diverse landforms including mountains, arid plateaus, rolling uplands, deserts, rainforests, and deep gorges. The river provides habitat for various fish and wildlife species including ESA species such as bull trout, steelhead, white sturgeon, and other salmonids.

The Columbia River Basin is home to six species of anadromous Pacific salmonids: Chinook, Coho, sockeye, chum, pink salmon[3], and steelhead. The basin's salmon and steelhead runs were once among the largest in the world, with an estimated average of between 10–16 million fish returning to the basin annually. In addition to anadromous salmonids, the Columbia River and its tributaries are home to sturgeon, lamprey, whitefish, rainbow and cutthroat trout, and bull trout (char), among other species. Many animals, including bald eagles, osprey, and bears, also rely on fish from the Columbia River and its tributaries to survive and feed their young.

Figure 1 shows the location of major dams in the Columbia River Basin that are owned and operated by Reclamation, U.S. Army Corps of Engineers (USACE), Canada, and others. The Federal Columbia River Power System (FCRPS) consists of 31 hydropower facilities, 14 of which are owned and operated by Reclamation, including Grand Coulee, the largest hydropower generating facility in the United States. The Columbia River also has numerous non-Federal hydropower production facilities. The combination of these facilities and the FCRPS facilities

[3] Pink salmon are not listed under the Endangered Species Act.

accounts for nearly 80 percent of the energy production in the Pacific Northwest. Many other facilities located on Columbia River tributaries are also authorized for uses such as water delivery, flood control, ecological resource support, and recreation. These facilities are primarily owned and/or operated by Reclamation, the USACE, other agencies, public utility districts, and private entities.

Reclamation's Pacific Northwest Region has a significant presence throughout the Columbia River Basin, with several offices working in response to actions affecting hydrology, power generation, and ecological resources in the basin. These include Grand Coulee Dam and Power Office, the Columbia-Cascades Area Office with field offices in Washington (Yakima and Ephrata) and Oregon (Bend and Umatilla/Hermiston); the Columbia Snake Salmon Recovery Office Tributary Habitat Program; various programs at the Snake River Area Office with field offices in Boise and Heyburn, Idaho; and multiple Regional Resource and Technical Services programs.

Figure 1. Map of major Dams in the Columbia River Basin (Courtesy of USACE Northwestern Division).

2.2 Surface Water Flows

There is a high degree of variability in surface water flows in the Columbia River Basin as water flows through dry and wet areas of the diverse landscape. The basin is generally cooler and wetter on the western side of the Cascades and warmer and drier to the east toward the Rocky Mountains. The basin has dramatic elevation changes ranging from sea level to high mountains. The headwaters of the Columbia River and its major tributaries are in high elevation and snow dominant watersheds. Snow dominant watersheds are sufficiently cold in the winter to allow for precipitation to fall in the form of snow, and for that snow to accumulate and remain until temperatures rise in the spring and summer. High elevation summers tend to be short and cool while the lower elevation interior regions are subject to greater temperature variability. As the effects of climate change increase average temperatures in the Columbia River Basin, several watersheds are vulnerable to changing from snow dominant to rain dominant, especially tributaries in lower elevations.

This shift in precipitation type and its effect on runoff timing will affect Columbia River storage ability. Barton et al. (2012) found that reservoirs in the Columbia River Basin can only store approximately 20 percent of the average annual runoff. Meanwhile, demand for water is increasing in response to population growth in the Pacific Northwest. Table 1 shows the varied uses of the basin's surface water, such as public supply, irrigation, livestock, aquaculture, mining and thermoelectric power. Table 2 shows that the estimated surface water use in 2010 was over 23 million acre-feet, which is just over 10 percent of the average annual runoff of 200 million acre-feet in Idaho, Oregon, and Washington.

Table 1. Surface-water withdrawals by water-use category for Idaho, Oregon, and Washington, 2010, in thousand acre-feet per year (Maupin et al. 2014). [Values may not sum to totals because of independent rounding]

State	Public supply	Self-supplied domestic	Irrigation	Live-stock	Aqua-culture	Self-supplied industrial		Mining		Thermoelectric power		Total		
N/A	N/A	N/A	N/A	N/A	N/A	Fresh	Saline	Fresh	Saline	Fresh	Saline	Fresh	Saline	Total
Idaho	30.4	0	11,500	10.1	3,010	19.2	0	21.2	0	0	0	14,600	0	14,600
Oregon	471	7.93	3,750	15.7	761	138	0	1.31	0	12.6	0	5,160	0	5,160
Washington	492	0.02	2,630	9.58	142	402	37.1	3.77	0	40.8	0	3,720	37.1	3,760

Table 2. Total surface water and groundwater use in Idaho, Oregon and Washington in 2010 (Maupin et al. 2014).

	Groundwater (in million gallons/day)	Surface water (in million gallons/day)	Ground water (acre-feet/day)	Surface water (acre-feet/day)	Ground water (acre-feet/year)	Surface water (acre-feet/year)	Total (acre-feet/year)
Idaho	4,250	13,000	13,043	39,896	4,760,631	14,561,931	19,322,562
Oregon	2,130	4,300	6,537	13,196	2,385,916	4,816,639	7,202,555
Washington	1,600	3,350	4,910	10,281	1,792,238	3,752,497	5,544,735
TOTAL	7,980	20,650	24,490	63,373	8,938,785	23,131,067	32,069,852

2.3 Groundwater Supply

Groundwater is an important source of water to the overall water supply in the Columbia River Basin. It is used to support agriculture in addition to providing a large portion of drinking water supply for some urban populations and most rural populations (see Table 3). In 2010, groundwater withdrawals made up about 30 percent of total water withdrawals in Idaho, Oregon, and Washington (Maupin et al. 2014). In addition to providing water supply, groundwater supports base flows in rivers throughout the Columbia River Basin.

Table 3. Groundwater withdrawals by water-use category for Idaho, Oregon, and Washington, 2010, in thousand acre-feet per year (Maupin et al. 2014). [Values may not sum to totals because of independent rounding]

State	Public supply	Self-supplied domestic	Irrigation	Live-stock	Aqua-culture	Self-supplied industrial		Mining		Thermoelectric power		Total		
N/A	N/A	N/A	N/A	N/A	N/A	Fresh	Saline	Fresh	Saline	Fresh	Saline	Fresh	Saline	Total
Idaho	237	88.6	4,280	43.2	73.6	36.5	0	1.43	0	0.99	0	4,760	0	4,760
Oregon	128	67.3	2,140	3.36	37.4	2.94	0	8.37	0	1.66	0	2,390	0	2,390
Washington	528	126	894	21.5	96.9	111	0	15.0	0	1.76	0	1,800	0	1,800

Eight of the 62 primary aquifer systems in the U.S. identified by the U.S. Geological Survey are located within the Columbia River Basin. Reclamation projects are associated with the Columbia Plateau, Pacific Northwest, and Snake River Plain primary aquifer types, along with other local systems. The three primary aquifer types are comprised of fractured basalt at depth with interbedded and overlying sediments.

Many aquifer systems in the Columbia River Basin receive a large amount of seasonal recharge from the irrigated agriculture system, including canal seepage and excess water applied to cropland. In the Snake River Plain and Columbia Plateau systems, groundwater storage volumes increased from the early 1900s through the 1960s after which point groundwater storage volumes decreased primarily due to increased pumping (U.S. Geological Survey (USGS) 2013). Since that time, both groundwater systems have experienced depletions in groundwater storage.

2.4 Basin Development History

Humans have inhabited the Columbia River Basin for more than 15,000 years, with a transition to a sedentary lifestyle about 3,500 years ago (U.S. National Research Council 2004). Starting in the 19th and 20th centuries, Columbia Basin rivers were engineered for navigation, flood control, irrigation, hydropower generation, and other uses. Dam construction, construction of irrigation and drainage systems, changing land use patterns, and river channelization, as well as groundwater pumping, has significantly altered flows and sediment distribution in the basin. These activities have also affected the relationship between surface water and groundwater throughout the basin. Operation of flood control and water storage dams alters the amount of water that is conveyed through the river.

The Columbia River Basin and its tributaries have 61 major dams (see Figure 1 for locations) along with numerous minor dams and diversion structures that have been constructed by Reclamation, USACE, Canada, and others. These facilities alter flows by storing and releasing water in a manner that generally decreases flood peaks and alters the distribution of the timing of the flows. The major dams also trap significant amounts of sediment, causing buildup and increases in channel elevation upstream, and riverbed degradation (lowering of the riverbed) and coarsening of riverbed sediment in the reaches below the dams.

Another noteworthy basin development is the significant population growth that has been changing the Pacific Northwest. Between 2000 and 2010, the U.S. Census the population of Idaho, Oregon, and Washington increased 21.1 percent, 12.0 percent, and 14.1 percent respectively (U.S. Census Bureau 2011). The increasing populations place increased pressure on infrastructure, residential and business development, agricultural demands, energy production, and recreation. These pressures underscore the demand for water delivery and hydropower from Reclamation facilities.

3 ASSESSMENT APPROACH

Since the RMJOC-1 Study was the primary basis for the Assessment's analysis approach, a background of the RMJOC-1 Study process is provided in this section to clarify which refinements were made in the Assessment. The RMJOC-1 Study was a collaborative effort among the Bonneville Power Administration (BPA), USACE, and Reclamation. The study documented the impact of climate change on the Federal hydropower system, and flooding on the mainstem Columbia River. The RMJOC-1 Study, Parts I–IV was a 2-year effort completed in 2011 in which the mainstem Columbia River and the Upper Snake River subbasin above Brownlee Reservoir (including the Boise and Payette rivers), Deschutes River Basin, Yakima River Basin, and other tributaries to the Columbia River were analyzed. The three agencies completed a four-part series of reports:

1. *Climate and Hydrology Datasets for Use in the River Management Joint Operating Committee Climate Agencies' Longer-Term Planning Studies: Part I - Future Climate and Hydrology Datasets (December 2010)*
2. *Climate and Hydrology Datasets for Use in the RMJOC Climate Agencies' Longer-Term Planning Studies: Part II - Reservoir Operations Assessments for Reclamation Tributary Basins (January 2011)*
3. *Climate and Hydrology Datasets for Use in the RMJOC Climate Agencies' Longer-Term Planning Studies: Part III - Reservoir Operations Assessment: Columbia Basin Flood Control and Hydropower (May 2011)*
4. *Climate and Hydrology Datasets for Use in the RMJOC Climate Agencies' Longer-Term Planning Studies: Part IV - Summary (May 2011)*

The RMJOC-1 Study used climate and hydrologic data developed by the University of Washington Climate Impacts Group (UW CIG). In turn, the RMJOC-1 Study developed climate change scenarios using bias corrected and spatially downscaled (BCSD) Coupled Model Intercomparison Project Phase 3 (CMIP3) climate change projections (e.g., temperatures, precipitation). The RMJOC-1 Study then used two techniques to evaluate climate change scenarios—Hybrid-Delta and Transient. Two future time periods of the Hybrid-Delta scenarios were defined as the 30-year period surrounding the 2020s (2010 to 2039) and the 30-year period surrounding the 2040s (2030 to 2059), while Transient projections were evaluated from 1950 through 2099.

At the time of the RMJOC-1 Study, it was known that the smaller tributaries to the Upper Snake River (e.g. Henrys Fork), Deschutes River, and Yakima River would need additional analysis and inflow projection locations to better capture future changes. In response to this need, the PN Region Project Team generated future climate change inflow data across the Columbia River Basin, including all of the locations necessary for input into the PN Region's Upper Snake River Basin water resources planning model.

3.1 Climate Change Analysis and Hydrologic Modeling

As part of the Assessment, almost 300 locations were originally selected for VIC model generation of future flow time series and bias correction post-processing; however, this inventory was scaled back due to a lack of available historical flow data for use in the bias correction process. Therefore, simulated historic and future climate change flows were generated for 157 locations throughout the Columbia River Basin (see map of locations Figure 2).

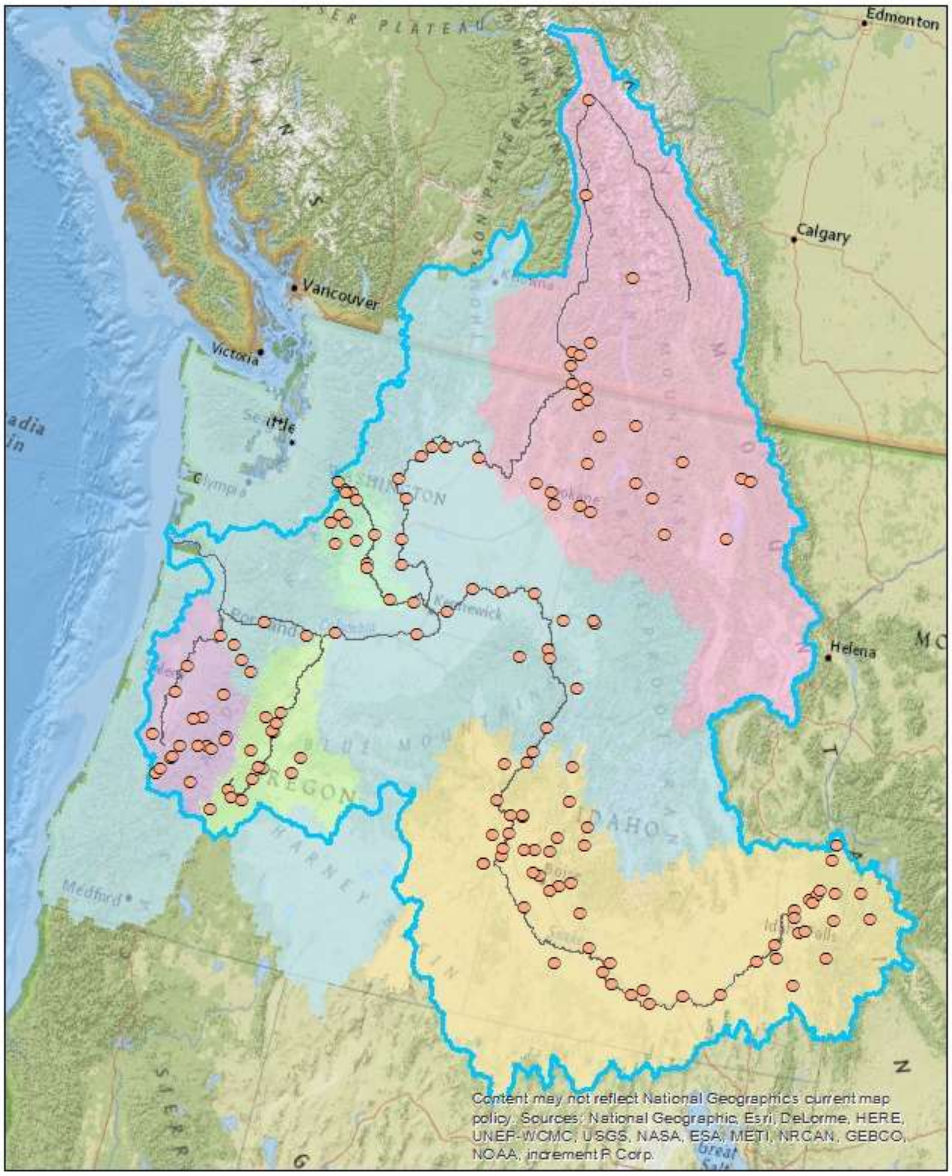

Figure 2. Map of 157 locations for which projected future streamflow were generated.

The Hybrid-Delta Ensemble method was used to develop gridded datasets representing a range of climate change scenarios. Each climate change scenario gridded dataset was then run through the VIC model to produce simulated future streamflow and subsequently bias-corrected using the same methods discussed in the RMJOC-1 Study, Part I. This final step is used to help remove simulation bias on both a monthly and annual basis in order to arrive at the final flow inputs for the water resources model.

This process was used to generate flows for four future periods, including 2010 through 2039, 2030 through 2059, 2050 through 2079, and 2070 through 2099. These 30-year periods are referred to as being "centered around" the 2020s, 2040s, 2060s, and 2080s respectively. Five scenarios of future temperature and precipitation conditions were selected to characterize the future climate to be evaluated in each 30-year period. These five scenarios include[4]:

- Less Warming Wetter (LW/W) – a cluster of 10 future projections around the 20th percentile change in temperature and 80th percentile change in precipitation;
- Less Warming Drier (LW/D) – a cluster of 10 future projections around the 20th percentile change in temperature and 20th percentile change in precipitation;
- Median (M) – a cluster of 10 future projections around the 50th percentile change in temperature and 50th percentile change in precipitation;
- More Warming Wetter (MW/W) – a cluster of 10 future projections around the 80th percentile change in temperature and 80th percentile change in precipitation; and,
- More Warming Drier (MW/D) – a cluster of 10 future projections around the 80th percentile change in temperature and 20th percentile change in precipitation.

Since the RMJOC-1 Study, an additional suite of GCM simulations known as CMIP5 has become available. The Assessment developed hydrologic scenarios based on a cluster of 10 projections from these updated CMIP5 model runs. A total of 231 bias corrected and spatially downscaled CMIP5 monthly climate projections selected at the subbasin scale were considered in this Assessment. In its climate change analyses, the PN Region Project Team used the Climate Analysis Toolkit (a free plugin for HydroDesktop) to analyze the downscaled climate projection data and develop future climate datasets for subsequent hydrological modeling. Details on this work are described in Section 4 and provided in-depth in the Climate Change Analysis and Hydrologic Modeling Technical Memorandum in Appendix A.

The following table outlines the PN Region Project Team's methodology selections for the Assessment by describing the Assessment's steps, the choices available for each step, the PN Region Project Team's selections, and guidance for the decisions.

[4] It should be noted that, in some subbasins, the "drier" scenarios did not always represent conditions that were drier than historical observation. Rather, these scenarios represented the "drier" of the scenarios considered by the RMJOC-1 Study.

Table 4. Columbia River Basin Impact Assessment methodology selections.

Step	Description of Step	Choices	Selection for use in Assessment
1	Select Global Climate Projection Context	CMIP3 or CMIP5	Selected CMIP5
2	Select how future climate will be characterized	Period-change (Delta or Hybrid-Delta) or transient	Selected Hybrid-Delta ensemble method
3	Select number of change scenarios	Selections by 20/80 percent, 10/90 percent, 25/75 percent leading to MW/W, MW/D, LW/W, LW/D, C	20/80 percent was selected. Selected five change scenarios bracketed by Less Warming/Drier (LW/D), Less Warming/Wetter (LW/W), More Warming/Wetter (MW/W), and More Warming/Drier (MW/D). A fifth scenario indicating the central change (50 percent) or Median (M) was selected as well.
4	Select whether change scenarios informed by a single projection or an ensemble of several	Single projection or ensemble	Ensemble (10 nearest-neighbors to the intersection of the 20^{th}, 50^{th}, and 80^{th} percentile changes in temperature and precipitation)

Step	Description of Step	Choices	Selection for use in Assessment
5	Based on the decisions above, determine options for generating hydrology	Use existing available future hydrology or generate new future hydrology consistent with climate assumptions made above with original modeling	Generated new future hydrology
5a	If generating new hydrology, select model	VIC 1/16th or 1/8th degree grid and routing tool (other hydrologic models are available)	Selected VIC 1/16th degree grid model and routing tool for routing flow to selecting locations (VIC model has been applied to Columbia River Basin already through the RMJOC-1 Study) For generating future climate-adjusted weather under each climate change scenario, 1/8th degree precipitation and temperature changes computed from the 1/8th degree BCSD CMIP5 climate projections were interpolated to 1/16th degree before being used to adjust the 1/16th degree "base historical" weather data developed by UW CIG.

Step	Description of Step	Choices	Selection for use in Assessment
5b	If generating new hydrology, determine flow routing locations of interest	Identify locations in the subbasin of interest that have gages with long-term Periods of Record to "train" simulated historical and future climate change flows to.	Several key locations have been identified in previous efforts (RMJOC-1 Study) and will continue to be used. The PN Region Project Team also identified additional sites. Initially 300 VIC model flow routing points were identified for study. However, several points were excluded because it was determined that there was not sufficient historical gage data to bias correct them. Therefore, only 157 points with sufficient historical flow data were retained for analysis.

3.2 Water Resource Modeling

A monthly Water Resource Model (WRM) of the Snake River Basin above Brownlee Reservoir was used for this analysis. The WRM includes the Boise River Basin and Payette River Basin as well as the Snake River Basin from its headwaters at Jackson Lake downstream to Brownlee Reservoir. As a major regulated headwater system in the Columbia River Basin, the evaluation of impacts and generation of regulated flows from the Upper Snake River Basin above Brownlee is crucial for informing further analysis of downstream impacts. For this reason, more in-depth analysis of climate change impacts to water resources (e.g., water supply and delivery) was focused in this area.

The modeling in the Upper Snake River Basin was used to answer questions and fill in information gaps identified in the RMJOC-1 Study. Principally, the PN Region Team focused their efforts on the Upper Snake River Basin to verify RMJOC-1 Study results that showed that all the scenarios chosen for the basin in the RMJOC-1 Study trended towards the wet (as compared to the simulated historical baseline). Also, as part of the Assessment, the PN Region Team refined the Upper Snake River Basin WRM based on lessons learned in the RMJOC-1 Study. For instance, while the RMJOC-1 Study operated under the assumption that all regulated water delivery differences were due to shortage, the Assessment split the study of delivery into requested water and shortage under each climate change scenario. This split provided a fuller picture of delivery changes. In addition, since the RMJOC-1 Study, CMIP5 became available to provide new projections.

The WRM simulates reservoir operating procedures and distributes natural flow and stored water ownership while following minimum flow requirements, and adhering to water right legal constraints and other system requirements such as flood control. Other model parameters include a simplified rental pool operation, and reservoir targets adjusted to calibrate to historical system reservoir storage contents during the period October 1, 1980, through September 30, 2008 (Appendix B).

In the RMJOC-1 Study, the Upper Snake River MODSIM model (version 8.1) was used to determine the potential effects of climate change scenarios on four major metrics in the Upper Snake River subbasin (i.e., inflow to reservoirs, reservoir volume, flow at specific locations, and flow augmentation impacts). In this Assessment, the model was updated to MODSIM version 8.4.4 and re-calibrated and validated before it was used to evaluate four similar metrics—system inflow, system reservoir contents, regulated flow, and requested water (shortage and natural versus stored flow delivery).

All climate change scenario simulations are compared to a Baseline simulation which represents a regulated MODSIM simulation using a simulated historical water supply from the VIC model. Simulated flows generated by the VIC model, which use simulated historical inputs of precipitation and temperature, were bias-corrected using the same process described in the RMJOC-1 Study, Part I to remove bias on both a monthly and annual basis. The VIC simulated historical (Baseline) and simulated future climate change flows generated in the climate change analysis and hydrologic modeling task were used as input to the Upper Snake River MODSIM model. Next, analyses were conducted of associated output.

Output parameters analyzed in this Assessment include:

- Monthly median unregulated system inflow
- Monthly median system reservoir contents
    - Number of years system reservoir contents filled
- Monthly median regulated flow
    - Number of years regulated flow exceeded flood stage
- Monthly median requested water
    - Monthly median requested water shortage
    - Monthly median requested natural versus stored flow delivery

Details on this work are provided in the “Columbia River Basin Regulated Water Storage and Delivery” section and the Water Resources Modeling Technical Memorandum in Appendix B.

3.3 Agricultural Diversions

Agricultural consumptive use is a large subset of water use in the Columbia River Basin and is a necessary set of information when modeling water resources. For historical analysis, diversions can be quantified by looking at actual diversion rates that are typically measured by various entities.

In 2015, Reclamation completed the WWCRA: Irrigation Demand and Reservoir Evaporation Projections study (2015 WWCRA Demand Study) (Reclamation 2015a) which analyzed projected future water demands for eight major river basins in the Western U.S.—California Central Valley, Colorado River Basin, Columbia River Basin, Klamath River Basin, Missouri River Basin, Rio Grande River Basin, and Truckee and Carson River Basins. The analysis focused on required crop evapotranspiration (ET), the amount of water required by the crop to grow, and net irrigation water requirement (NIWR)—the amount of irrigation water required for evapotranspiration less the amount of precipitation. The demand quantity required for the WRM is the total amount of water that is diverted from the river, of which ET and NIWR are only a portion. The remaining part of the demand can be made up of canal seepage and on-farm losses, and together are referred to as system loss. Therefore, the data in the 2015 WWCRA Demand Study must be adjusted to reflect the total demand prior to using it in the WRM.

This portion of the Assessment focused on evaluating methods to adjust the simulated future NIWR data from the 2015 WWCRA Demand Study so that it could be used in water resources modeling analyses of future climate in more detailed studies, such as Basin Studies. Two methods were evaluated and tested using MODSIM nodes from the Upper Snake River WRM—the Total Irrigated Acres method and the Linear Regression method.

Both methods used a relationship between historical diversion and historical NIWR to obtain an estimate of system loss that could be applied to the future projected NIWR data. The first method, called the Total Irrigated Acreage method, calculated future diversion estimates by quantifying the amount of irrigated acres for each model diversion location and multiplying the acres by the projected NIWR estimates with consideration of system losses (i.e. canal seepage and on-farm inefficiencies). The second method, called the Linear Regression method, calculated future diversion estimates based on the empirical relationship between historical diversion data and historical NIWR. Details on this work are provided in the "Determining Agricultural Diversions for Use in Water Resources Models" section below and the Technical Memorandum of the same name in Appendix C.

3.4 Public and Stakeholder Outreach

Reclamation Public Affairs staff coordinated outreach efforts to internal and external stakeholders throughout the 2-year Assessment period. Specific outreach efforts included the following:

Informational Meetings

Individual meetings were conducted with the Federal Caucus (members include Reclamation, BPA, USACE, Bureau of Indian Affairs, Environmental Protection Agency, National Oceanographic and Atmospheric Administration Fisheries, National Resources Conservation Service, U.S. Fish and Wildlife Service, U.S. Forest Service, Bureau of Land Management, and U.S. Geological Survey), the Columbia River Treaty group, and the Northwest Power and Conservation Council to ensure Assessment efforts were not in conflict or duplicative of efforts related to any of those group's respective activities.

Quarterly Updates

An e-newsletter was released quarterly to provide stakeholders updates on Reclamation's efforts and status on the Assessment. The e-newsletter was sent to an expanding list of interested internal and external individuals. The first issue came out on August 30, 2014, and gave a summary of the Assessment and what could be expected in terms of results and timing. Subsequent issues, distributed quarterly, updated readers on the Assessment's progress and released preliminary results.

Webinar Series

To raise awareness about the Assessment, Reclamation hosted a five-part webinar series with presentations on September 4 and 25, October 8 and 22, and November 5, 2014. The series introduced the Assessment to Reclamation staff and external individuals involved in the Columbia River Basin. The series was created to highlight the processes used in the Assessment and to demonstrate the Assessment's high-level of scientific integrity. A total of 240 participants attended at least one webinar in the series including members of the groups identified above. These webinars provided an opportunity for questions, feedback, and active participation from participants. Videos of the webinar presentations are posted on the Assessment website for access by all stakeholders.

Website

Additionally, a website was established to provide a location to house information and inform stakeholders about the Assessment. The website (http://www.usbr.gov/pn/climate/crbia/) includes an overview of the Assessment, related web links, a map of the study area, timelines, a library of the Assessment webinars and quarterly updates, and the Assessment Interim Report. This Final Report will be added to the website upon completion.

3.5 GIS Coordination and Data Management

As part of the Assessment, Reclamation's existing public web mapping application, *Streamflow Projections for the Western United States* (http://gis.usbr.gov/Streamflow_Projections), was updated to efficiently share data generated from the Assessment and previous studies with internal and external partners. In addition, Reclamation's existing internal web mapping application, *Tessel*, was extended to provide context for visualizing previous and ongoing climate and hydrology modeling work in the Pacific Northwest Region. A number of interactive data-driven layers are available in the internal web mapping including, but not limited to, Reclamation features (dams, diversions, hydropower plants, reservoirs, canals, etc.), major hydrography, terrain, imagery, jurisdictional boundaries, and watershed boundaries. Custom functionality was also created to support download of observed historical, simulated historical, and simulated future climate change flow data for locations where modeling was conducted for the Assessment.

For the Assessment, climate data management centered largely on the acquisition, organization, and logical storage of thousands of digital files. A well-understood data organization and file structure were important for data access and discovery, as well as to ensure data integrity. An often overlooked aspect of a standardized file structure is the inherent information provided by the structure itself. The approach to data management used for the Assessment was coordinated with Reclamation's Policy and Administration Office. The file-based data management strategy, the Dublin Core metadata procedure, and delivery of data with web mapping technology can all be replicated by Reclamation offices west-wide to conduct similar climate Impact Assessments or Basin Studies.

The GIS Coordination and Data Management Technical Memorandum in Appendix D provides further details on GIS data structure, organization, naming conventions, and metadata created as part of the Assessment. The memorandum also includes methods, functions, and processes developed for processing and managing data, as well as the web-based discovery and delivery of data products. Not only does this data management strategy support climate change efforts, but it also supports the Department of the Interior's Open Data initiative and Reclamation's Open Water Data initiative.

3.6 Important Assumptions and Sources of Uncertainty

The results presented in the Assessment are based on reasonable assumptions about our future. There are many uncertainties associated with any projection of future climatic changes. Among other impacts, we do not actually know how technology, policy, or social forces will influence what greenhouse gasses are emitted into the atmosphere. In addition, output from each model used in the Assessment carries with it uncertainties associated with the necessary simplifications and ability of any software program to exactly replicate the modeled system, and each statistical transformation of model output increases these uncertainties. By definition, these uncertainties are difficult to quantify, but can have significant effects on the simulations generated. The modeling tools are continually being refined, and, as planning moves forward, the simulations developed by these tools will have to be re-examined as well.

4 IMPACT ASSESSMENT: PROJECTED CLIMATE AND WATER SUPPLY, STORAGE AND DELIVERY

This section provides an overview of the climate characteristics of the Columbia River Basin, along with observed trends and estimated future changes. It also summarizes how the projected impacts of climate change might affect basin water resources, from changes in basin runoff to changes in reservoir storage and water delivery.

4.1 Climate in the Columbia River Basin: Past, Present, and Future

4.1.1 Discussion and Overview of the General Climate Characteristics of the Columbia River Basin

Climate is distinguished from weather by a longer timescale, years as opposed to days or weeks, over which meteorological conditions are viewed. Meteorological conditions include temperature, precipitation, solar radiation, wind, atmospheric pressure, and humidity, among others. Evaluations of changes in climate include both natural variability and human-induced long-term changes in climate.

Seasonal to decadal climate variability in the Columbia River Basin is influenced by the El Niño Southern Oscillation (ENSO), which operates on an annual timescale, and the Pacific Decadal Oscillation (PDO), which operates on a decadal timescale. Generally speaking, ENSO warm phase (El Niño) conditions tend to correspond to winters that are warmer and dryer than average in the Pacific Northwest, while ENSO cool phase (La Niña) conditions generally correspond to cooler and wetter winters. Similarly, warm phase PDO winters tend to be warmer and drier, while cool phase PDO winters tend to be cooler and wetter. When ENSO and PDO are in-phase (both warm phase or both cool phase), their influence and the potential for temperature and precipitation extremes increases. Such natural variations in climate will continue into the future along with changes due to increased greenhouse gas concentrations from human activities.

Geographically, the basin has a wide variety of climates that are strongly influenced by the highly varied topography over the area. A maritime climate occurs in most coastal areas, typically between the Pacific Ocean and high Cascade Mountain Range; an alpine climate in the highest mountains; and semi-arid and arid climates east of the higher mountains. The climate within the basin generally varies from cooler and wetter on the western “windward” side of the Cascades to warmer and drier on the eastern “leeward” side to the Rocky Mountains (Oregon Climate Change Research Institute 2010; as cited in Reclamation 2011, p. 62). Approximately two-thirds of the region's precipitation occurs in just half the year between October and March. From late spring to early fall, high pressures to the west generally keep the region fairly dry; however, extended severe droughts in the basin are relatively rare.

4.1.2 Observed Trends in Climate Conditions over the Columbia River Basin

The 2014 Climate Change Impacts in the United States: The Third National Climate Assessment (Mote et al. 2014) and the 2011 SECURE Report (Reclamation 2011), found that, over the course of the 20th century, warming has been prevalent in the Northwest and Columbia River Basin (Figure 3). The mean annual temperature in the basin has increased by approximately 2 °F since the late 1800s. Basin moving-mean annual precipitation, depicted within Figure 3 (bottom panel), ranges from 20 to 25 inches. While a trend in precipitation over the period of record is not detected, the Columbia River Basin has experienced general decline in spring snowpack since the mid-20th century due to more precipitation occurring as rain (instead of snow) and earlier snowmelt runoff (Knowles et al. 2007 and Regonda et al. 2005; as cited in Reclamation 2011, p. 45). Luce and Holden (2009) evaluated the distribution of streamflow reductions from 1948 to 2006 and revealed significant trends in annual streamflow reductions during dry years; suggesting that dry years have been getting increasingly "dry" (as cited in RMJOC-1 Part I, 2010).

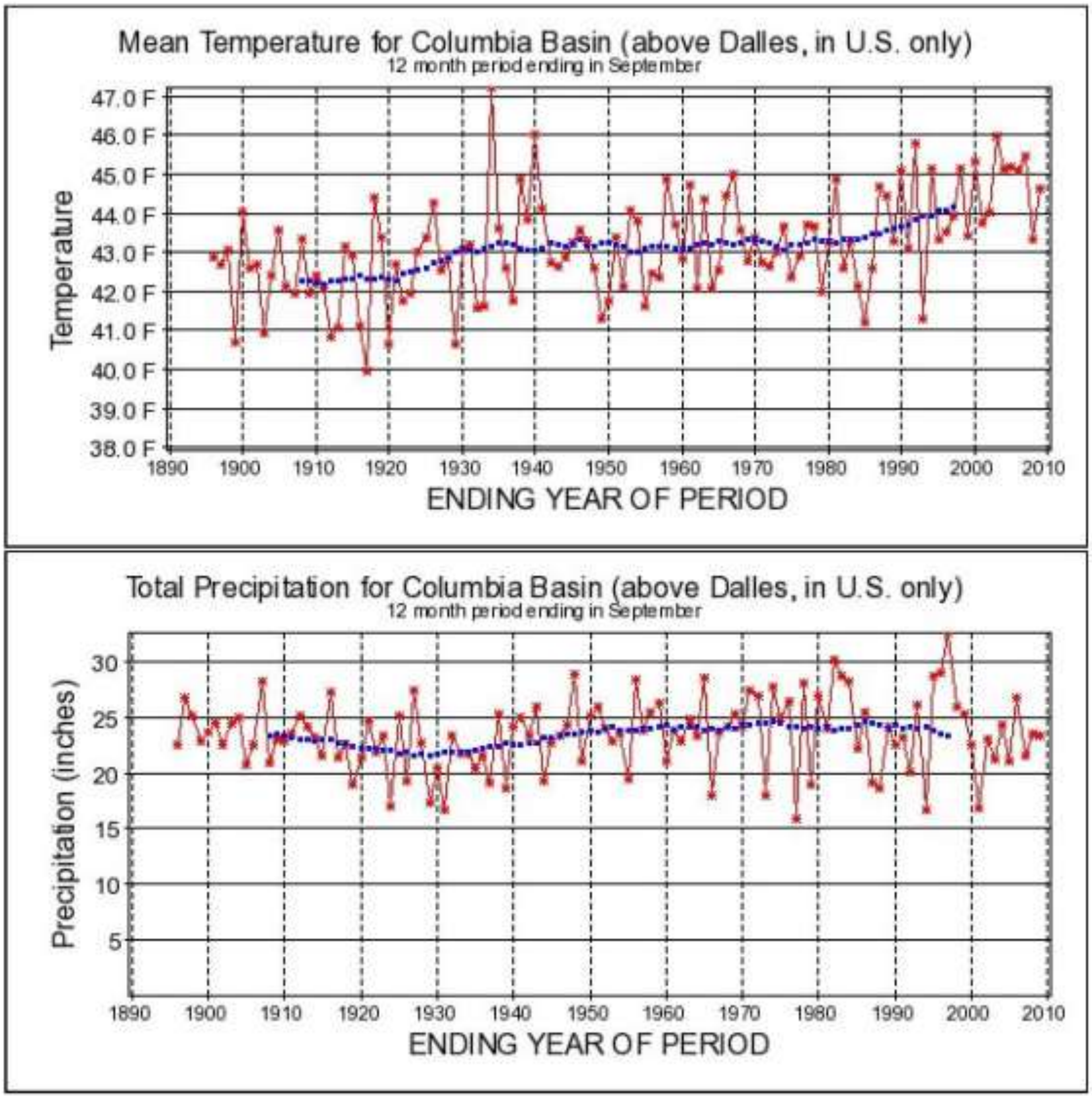

Figure 3. Observed annual (red) and moving-mean annual (blue) temperature and precipitation, averaged over the Columbia River Basin above The Dalles.

Source: Western Climate Mapping Initiative (WestMap) available at: http://www.cefa.dri.edu/Westmap/. Red line indicates annual time series for the given geographic region. Blue line indicates 25-year moving annual mean values, where each value is plotted on the center year of its respective 25-year period. WestMap data are derived from the PRISM climate mapping system (Daly et al. 2004 and Gibson et al. 2002; as cited in Reclamation 2011, p. 44).

4.1.3 Future Changes in Climate Conditions over the Columbia River Basin

In future years, important changes are anticipated in the climate of the Columbia River Basin. Analysis of the selected CMIP5 GCM ensembles suggest the basin will experience increases in both temperature and precipitation over the remainder of this century. Figure 4 through Figure 6 below show historical data for Pacific Northwest (1) mean annual precipitation, (2) maximum temperature, and (3) minimum temperature (from Livneh et al. 2013), along with the 2080 projected mean annual change relative to each modeled climate scenario. These figures illustrate the general trend characterized by the Assessment towards warmer and wetter across the region, as well as the spatial variation of the change magnitude.

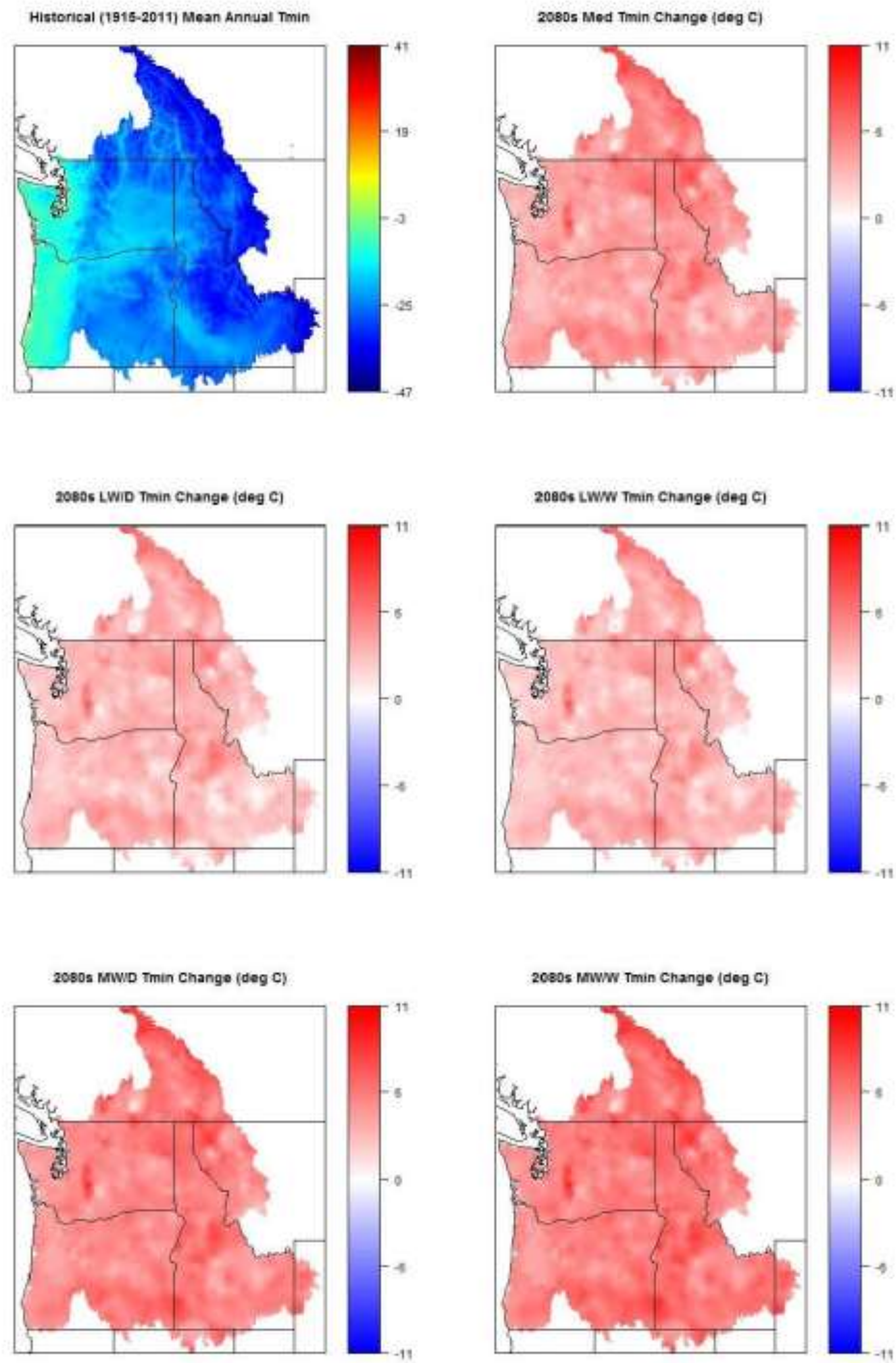

Figure 4. Mean annual minimum temperature for the period of January 1915 through December 2011 (from Livneh et al. 2013), and maps of the change in degrees Celsius between historical and 2080 period averages for each Hybrid-Delta climate scenario. Note: LW/W = Less Warming Wetter; LW/D = Less Warming Drier; M = Median; MW/W = More Warming Wetter; MW/D = More Warming Drier

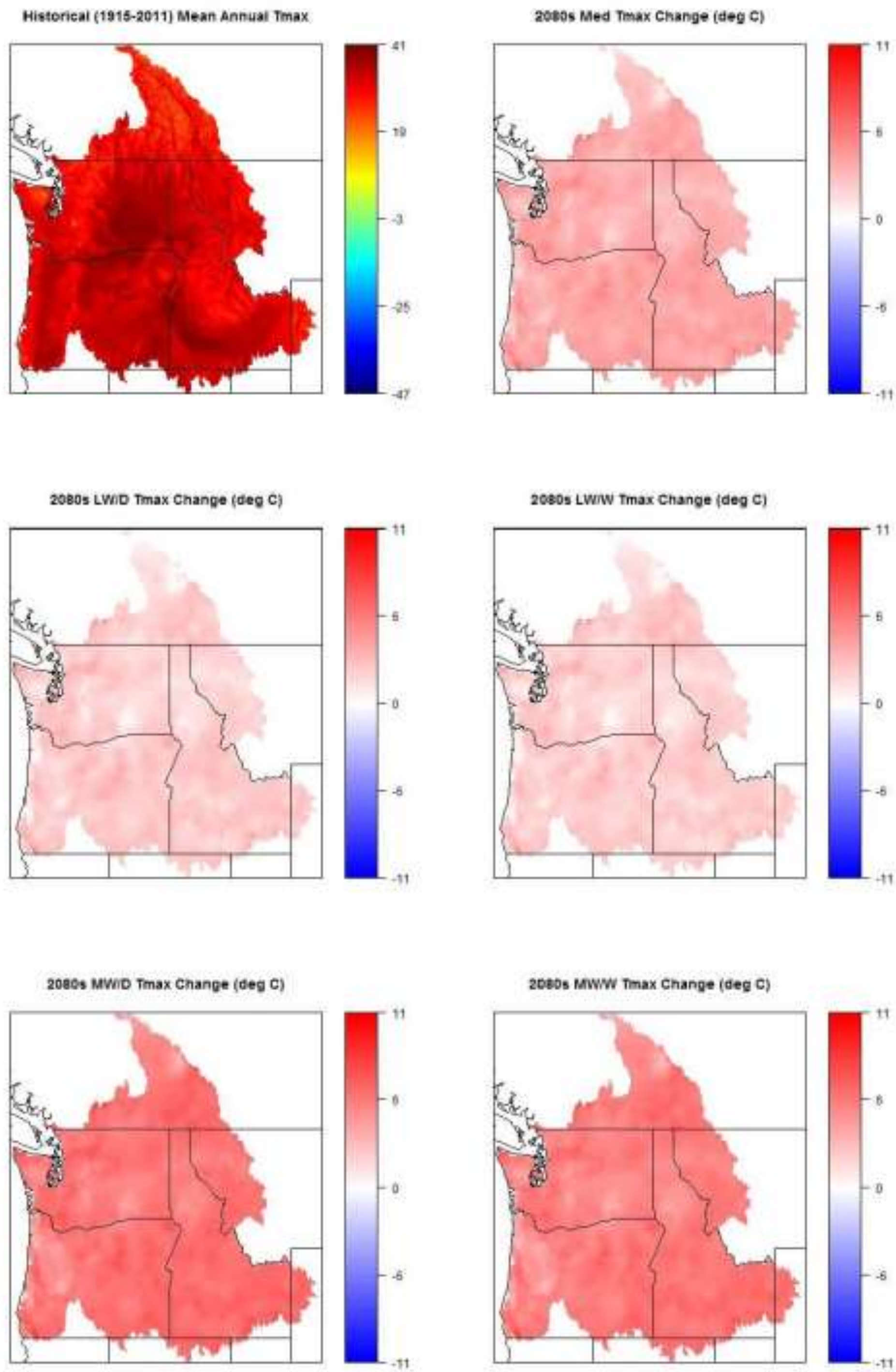

Figure 5. Mean annual maximum temperature for the period of January 1915 through December 2011 (from Livneh et al. 2013), and maps of the change in degrees Celsius between historical and 2080 period averages for each Hybrid-Delta climate scenario. Note: LW/W = Less Warming Wetter; LW/D = Less Warming Drier; M = Median; MW/W = More Warming Wetter; MW/D = More Warming Drier

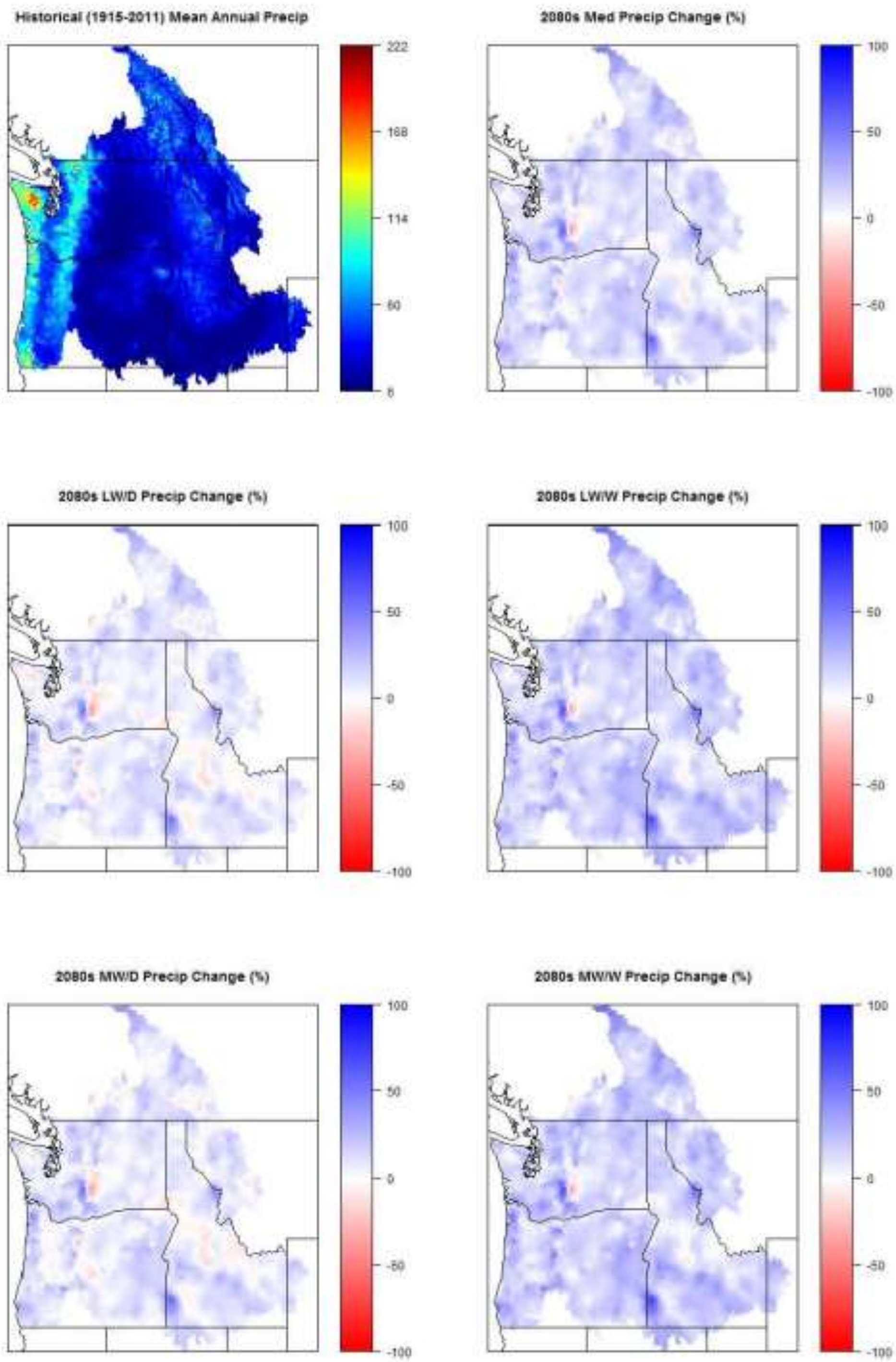

Figure 6. Mean annual precipitation for the period of January 1915 through December 2011 (from Livneh et al. 2013), and maps of percent change between historical and 2080 period averages for each Hybrid-Delta climate scenario. Note: LW/W = Less Warming Wetter; LW/D = Less Warming Drier; M = Median; MW/W = More Warming Wetter; MW/D = More Warming Drier

In the Pacific Northwest, generally speaking, the downscaled climate model projections used in this study project warming temperatures going into the future, with the amount of warming varying by season and location. Changes in precipitation varied more widely than those for temperature, but mostly agreed in their simulation of increased precipitation during the cool season and decreased precipitation during the warm season. Figure 7 and Figure 8 illustrate these trends over the Columbia River Basin and the range of predictions (the projection envelope) provided by the 231 BCSD CMIP5 projections.

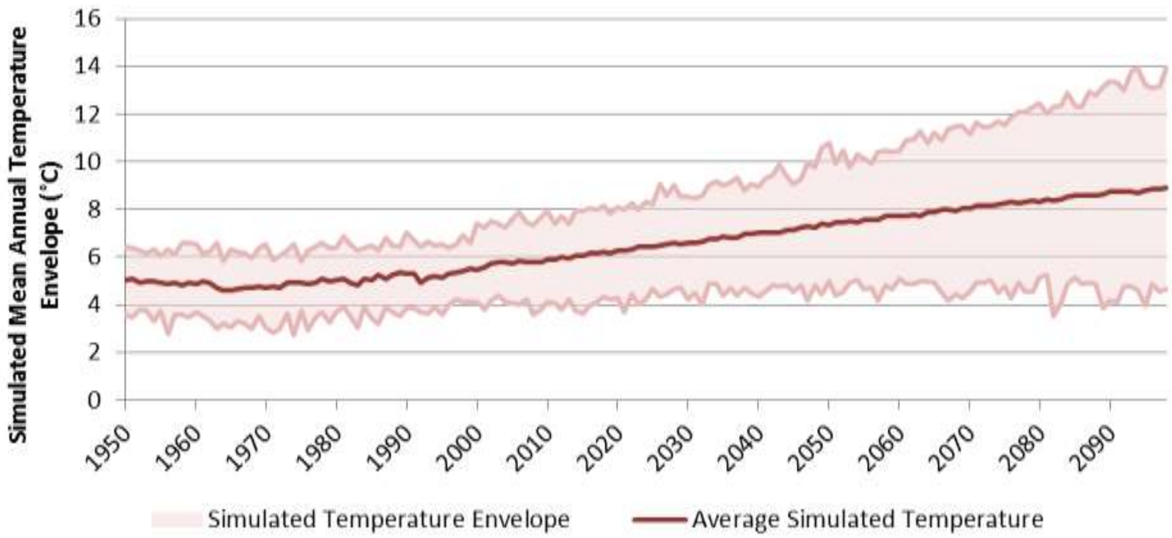

Figure 7. CMIP5 231-member ensemble envelopes of average annual temperature for the Columbia River Basin from 1950-2099.

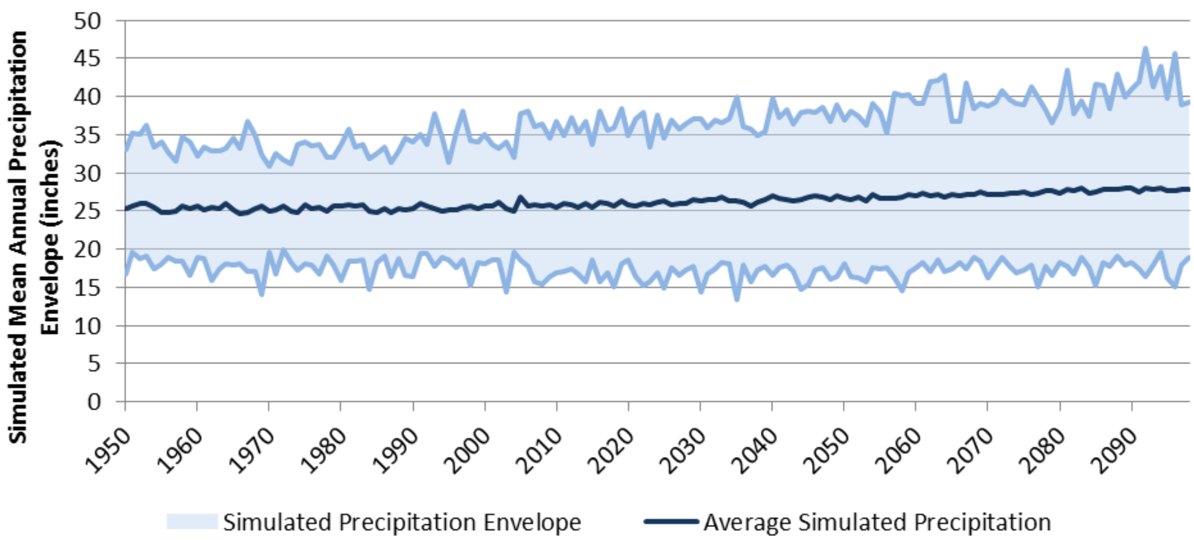

Figure 8. CMIP5 231-member ensemble envelopes of average annual precipitation for the Columbia River Basin from 1950-2099.

Sections 4.1.3.1 through 4.1.3.4 below highlight the projected changes in temperature and precipitation for select locations within the Columbia River Basin that were studied in the Assessment. These locations are illustrated in Figure 9.

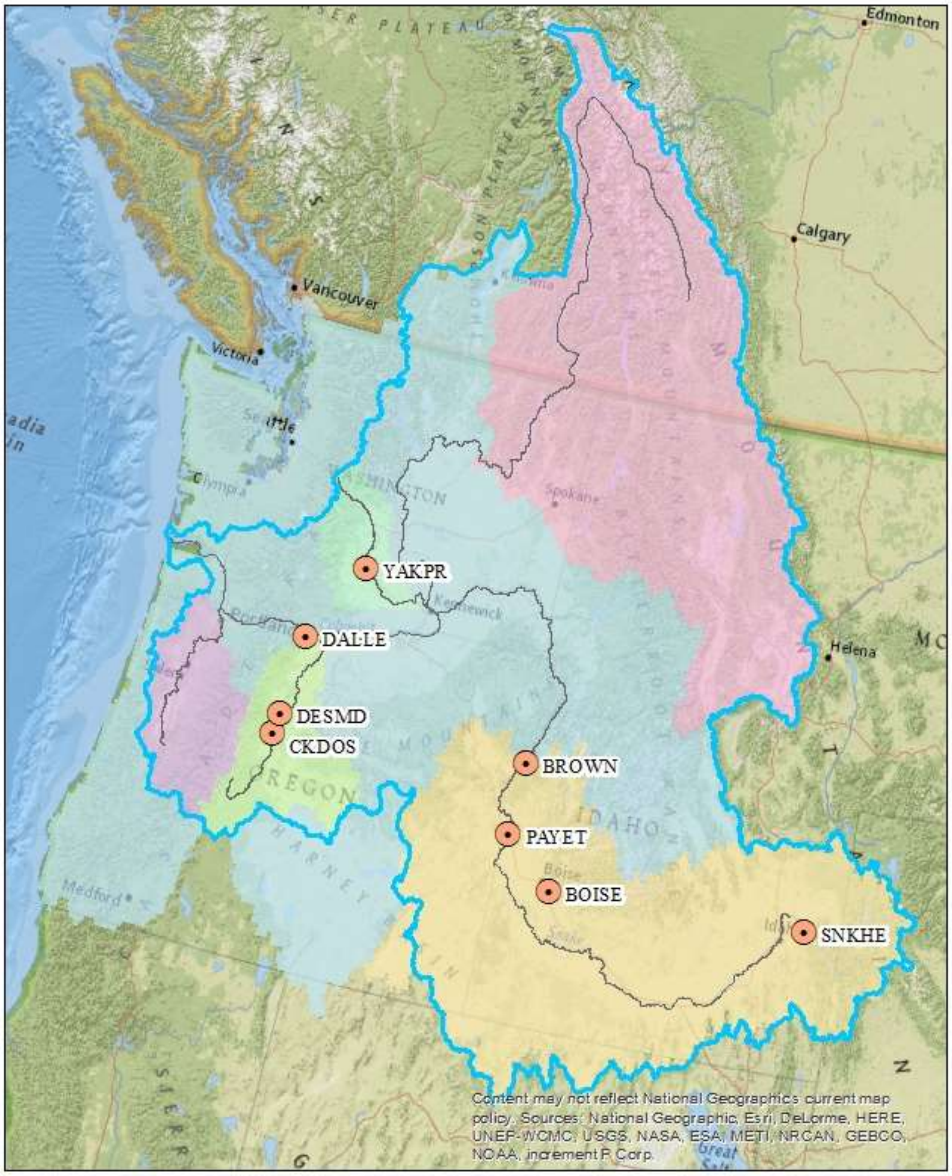

Figure 9. Map of select locations for the climate hydrology assessment.

4.1.3.1 Mainstem Columbia River

In the Columbia River Basin, the Assessment results suggest that by the end of the century there will be increases in temperature in mid-summer and mid-winter (smaller increases in the spring and fall), and a general trend towards increased cool season precipitation and decreased warm season precipitation. Only the Less Warming/Wet scenario suggested year-round increases in precipitation.

4.1.3.2 Yakima River Basin

Similar to the patterns exhibited in the other parts of the Columbia River Basin, all five scenarios (More Warming/Dry, More Warming/Wet, Median, Less Warming/Dry, and Less Warming/Wet) suggest increasing temperatures in the Yakima subbasin over the next century, with the largest increases in temperature projected to occur during the summer months. Precipitation projections are more varied between scenarios, but generally suggest a pattern of wetter conditions through the spring, winter, and fall and drier conditions during the summer months.

Below are graphs of the 2080s projected change in temperature and precipitation relative to the historical 1980-2009 period for the Yakima River Basin (Figure 10). These are representative of the graphs generated for the subbasins studied in the Assessment and presented in the Appendix A. The results identified in this Assessment are similar to the results of the Yakima Basin Study completed in 2011 as it also used model data from the RMJOC-1 Study.

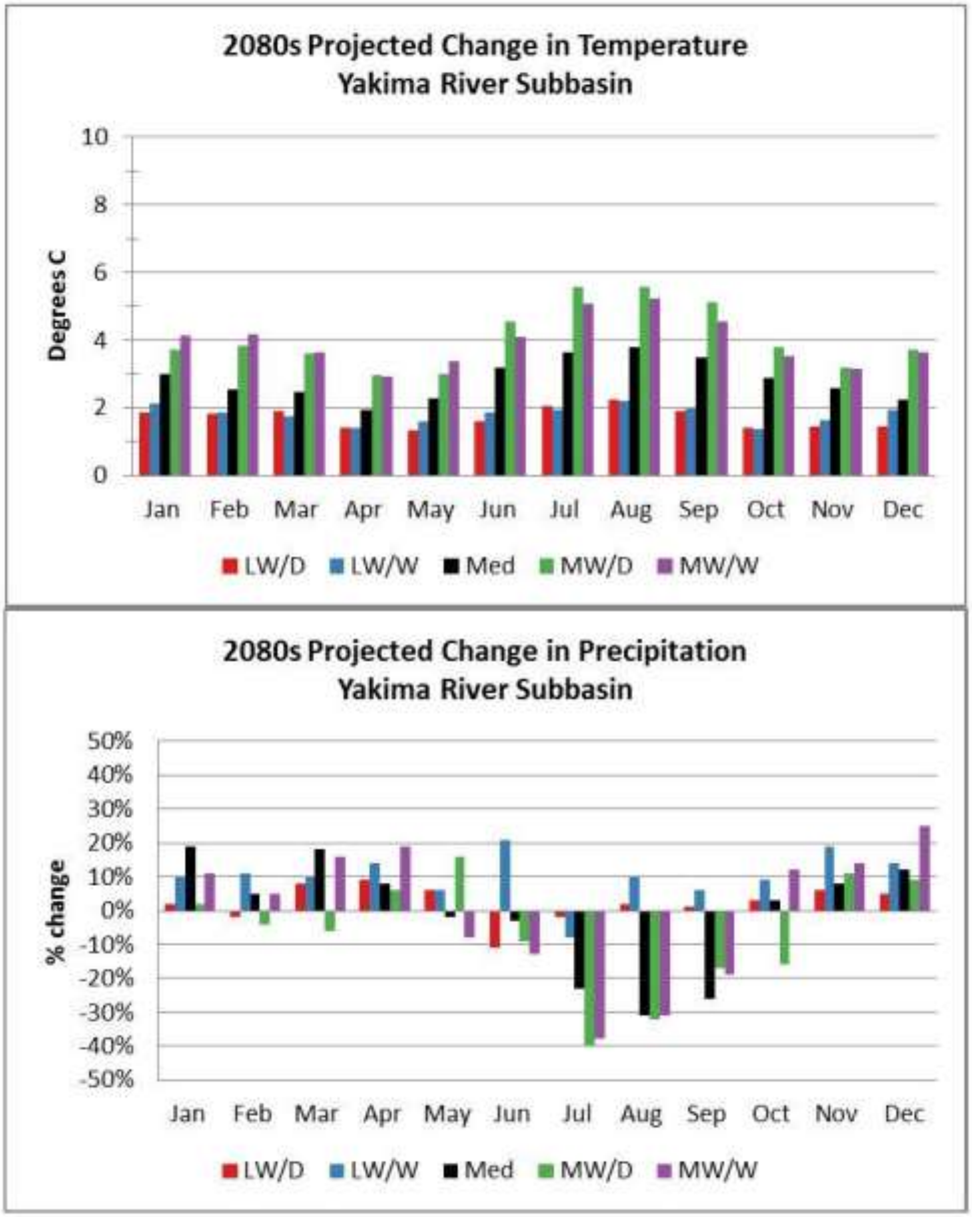

Figure 10. Yakima River subbasin projected 2080s monthly 50th-percentile change in temperature (top) and precipitation (bottom) for five scenarios (Less Warming/Dry, Less Warming/Wet, Median, Warming/Dry, and More Warming/Wet) relative to the historical 1980-2009 period.

4.1.3.3 Upper Snake River Basin

As compared to temperature changes projected for the other subbasins considered in this Assessment, the Snake River Basin exhibited the largest increases in temperature and followed the pattern seen in the other subbasins with the largest increases occurring during the summer months. Almost all scenarios project increased precipitation during the winter and early spring. Projected conditions for the remainder of the year (May through October) were more varied, but generally indicate drier conditions (decreased precipitation) during those months. Only the Less Warming/Wet scenario corresponded to year-round increases in precipitation.

4.1.3.4 Deschutes River Basin

As with all of the other subbasins considered in this Assessment, all scenarios projected increases in temperature for the Deschutes River Basin, with the largest increases occurring during the summer months. Projected changes in precipitation were more varied than those for temperature; however, the results suggest a trend towards increased precipitation during the cool season and decreased precipitation during the warmer season.

4.1.3.5 Impacts of Future Changes in Climate Conditions over the Columbia River Basin

In the Assessment, climate change impacts were most pronounced in “transitional” subbasins, or basins where the dominant form of precipitation is neither rain nor snow, but is currently a mix of both. These subbasins generally experience winter temperatures that are at- or near-freezing and are therefore particularly sensitive to warming that shifts the subbasin to rain-dominance. Runoff in rain-dominant subbasins, on the other hand, is not as sensitive to warming as these basins already experience winter temperatures above the freezing mark and are projected to remain rain-dominant going into the future. Many snow-dominant subbasins, while projected to experience warming, currently have winter temperatures well enough below freezing that such warming may not cause winter temperatures to cross the freeze/thaw threshold. Other snow-dominant subbasins are likely to shift towards transitional conditions.

Changes in temperature and precipitation will have important and varied consequences for water resources across the region, with hydrologic response (for example, timing and magnitude of runoff) depending upon the dominant form of precipitation in the basin and other local characteristics such as elevation, aspect, geology, vegetation, and changing land use (Melillo et al. 2014).

4.2 Impacts of Climate Change on Water Supply

This section summarizes model simulation results that describe the various hydrologic impacts associated with the climate change scenarios considered by this Assessment. The Assessment focused on changes in mean runoff (monthly and annual) in its interpretation and evaluation of impacts to water supply under various climate change scenarios. It should be noted, however, that the magnitude of change may vary with exceedance percentile; meaning that the projected changes to higher than average (or lower than average) runoff values may differ in magnitude than the changes indicated by a comparison of the average values.

4.2.1 Simulated Changes in Runoff

In future years, more pronounced changes are anticipated in the hydrology of the Columbia River Basin, including earlier snowmelt runoff and increased variability in streamflow. Daily and mean monthly streamflows were generated for 157 locations throughout the Columbia River Basin. These locations are shown in Figure 2 and a complete list of sites, including their coordinates and corresponding subbasins, is included in Appendix A. In general, the projected warming and changes in precipitation across the Columbia River Basin are expected to result in increased runoff during the cool season and decreased runoff during the warm season; however, the magnitude and timing of such changes varied across the region.

The following table summarizes results of hydrologic modeling conducted as part of the Assessment for select locations, including the Columbia River above the Dalles, Snake River at Brownlee Dam, and Yakima River at Parker. The data shows the percent change of runoff and snow water equivalent from the 1990s (1980 to 2009) to the 2040s (2030 to 2059) and 2080s (2070 to 2099). Note that these periods represent the 30-year intervals centered on the referenced decade.

Table 5. Results of hydrologic modeling conducted for the Columbia River above the Dalles, Snake River at Brownlee Dam, and Yakima River at Parker. Data shows the simulated percent change from the 1990s (1980 to 2009) to the 2040s (2030 to 2059) and 2080s (2070 to 2099) of mean April 1st snow water equivalent; mean annual runoff; mean December through March runoff; and mean April through July runoff.

Hydroclimate Metric (Change from 1990s period)	2040s	2080s
Columbia River above the Dalles		
Mean April 1st Snow Water Equivalent[5] (%)	-58% to -33%	-76% to -43%
Mean Annual Runoff (%)	-5% to +10%	-4% to +15%
Mean December-March Runoff (%)	+13% to +44%	+26% to +91%
Mean April-July Runoff (%)	-8% to +8%	-17% to +10%
Snake River at Brownlee Dam		
Mean April 1st Snow Water Equivalent (%)	-66% to -42%	-80% to -43%
Mean Annual Runoff (%)	-5% to +11%	+4% to +18%
Mean December-March Runoff (%)	+5% to +29%	+14% to +71%
Mean April-July Runoff (%)	-7% to +15%	-4% to +21%

[5] Calculated change in total snow water equivalent volume in the subbasin.

Hydroclimate Metric (Change from 1990s period)	2040s	2080s
Yakima River at Parker		
Mean April 1st Snow Water Equivalent (%)	-56% to -33%	-81% to -45%
Mean Annual Runoff (%)	-10% to +8%	-12% to +13%
Mean December-March Runoff (%)	+23% to +65%	+44% to +128%
Mean April-July Runoff (%)	-28% to -6%	-56% to -14%

Sections 4.2.1.1 through 4.2.1.4 highlight these changes for select locations within the Columbia River Basin. These select locations are illustrated in Figure 9.

4.2.1.1 Mainstem Columbia River

For the Columbia River Basin, simulated changes varied in both positive and negative direction and magnitude; however, all but one scenario suggests an increase in mean annual volume by the end of the century. The results of this Assessment indicate a shift towards earlier peak runoff (shifting from June to May), as well as the potential for significant increases in late-winter and early-spring flows. During the summer and fall months, all scenarios suggest that flows will decline over the remainder of the century. These trends are not only consistent with the results of the upstream locations discussed previously, but also with the Columbia River Basin's general trends in warming, increased winter/spring precipitation, and decreased summer precipitation.

4.2.1.2 Yakima River Basin

The results of this Assessment suggest relatively small changes in annual runoff volume for the Yakima River near Parker, Washington (YAKPR) location over the course of this century. However, changes to the magnitude and timing of peak runoff in the basin are likely to be significant. Under all scenarios, flows at YAKPR increase substantially during the winter and decrease during the spring and summer. Such a change is characteristic of a shift from a snow-dominant hydrograph (strongly influenced by spring snowmelt and exhibiting peak runoff in the late spring) towards a rain-dominant hydrograph with peak flows occurring during the wet season.

Figure 11 illustrates the simulated annual runoff volume exceedance lines (representing the percent of time that a particular runoff volume is equaled or exceeded) for YAKPR, while Figure 12 through Figure 14 illustrate the simulated future runoff in terms of mean annual volume, percent change in mean annual volume, mean monthly volume, and percent change in mean monthly volume. These figures are representative of the graphs that were generated for the eight select locations studied in the Assessment and presented in the Appendix A.

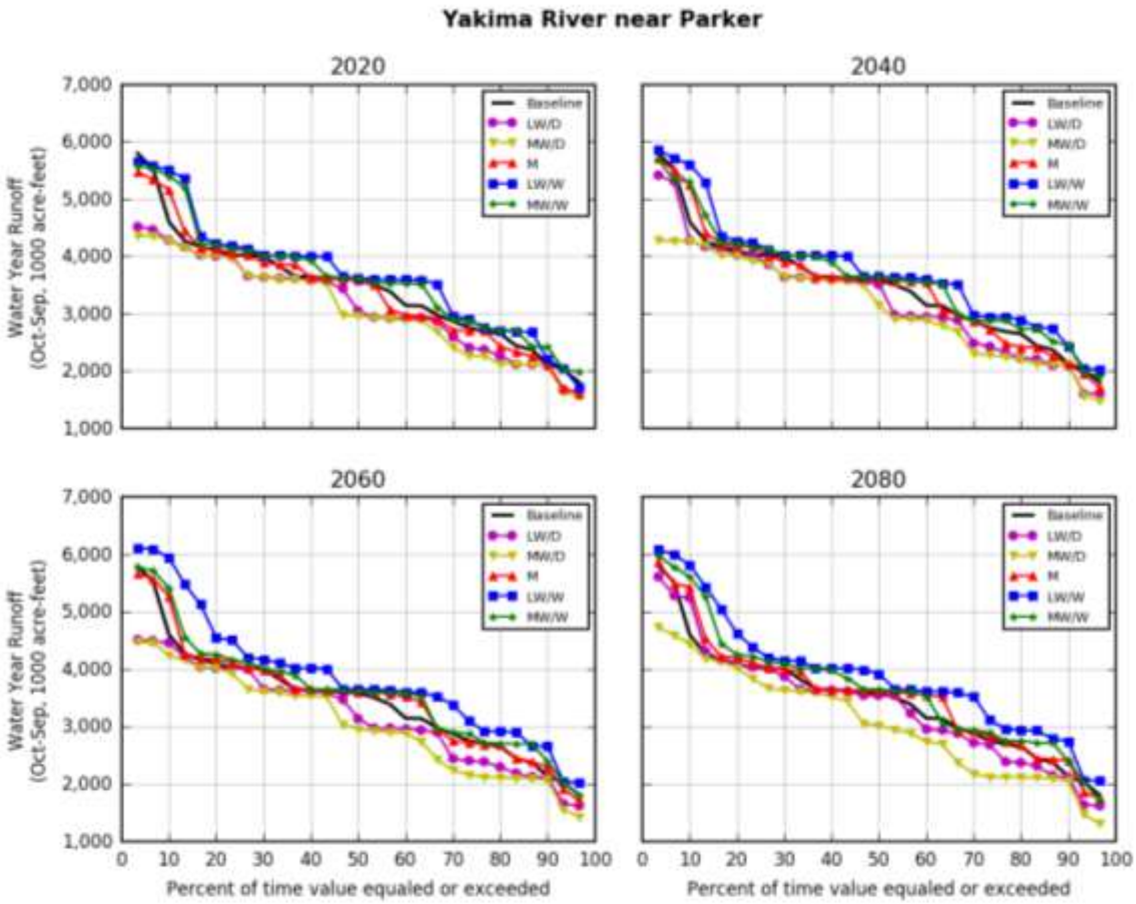

Figure 11. Exceedance plots for annual runoff at Yakima River near Parker, Washington (YAKPR) depicting the percent of time (x-axis) that a particular runoff volume (y-axis) is equaled or exceeded.

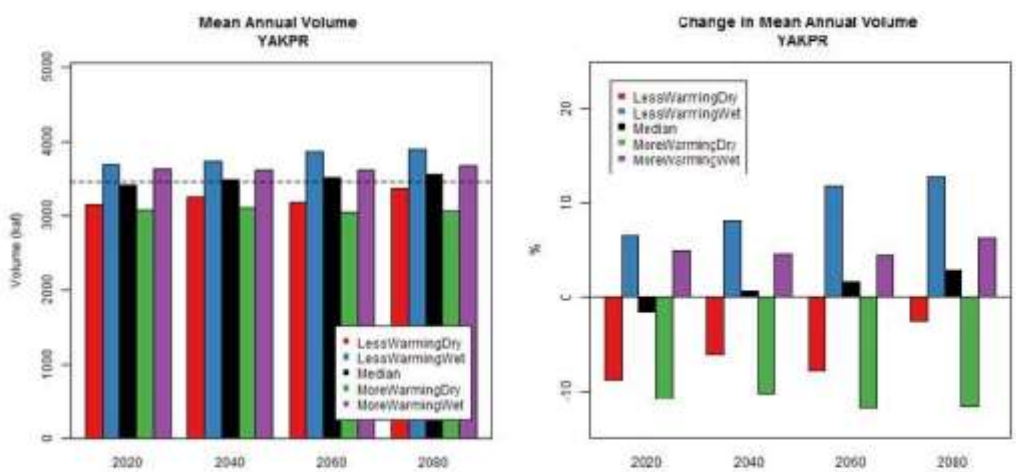

Figure 12. Mean annual volume (left) and change in mean annual volume (right) at YAKPR.

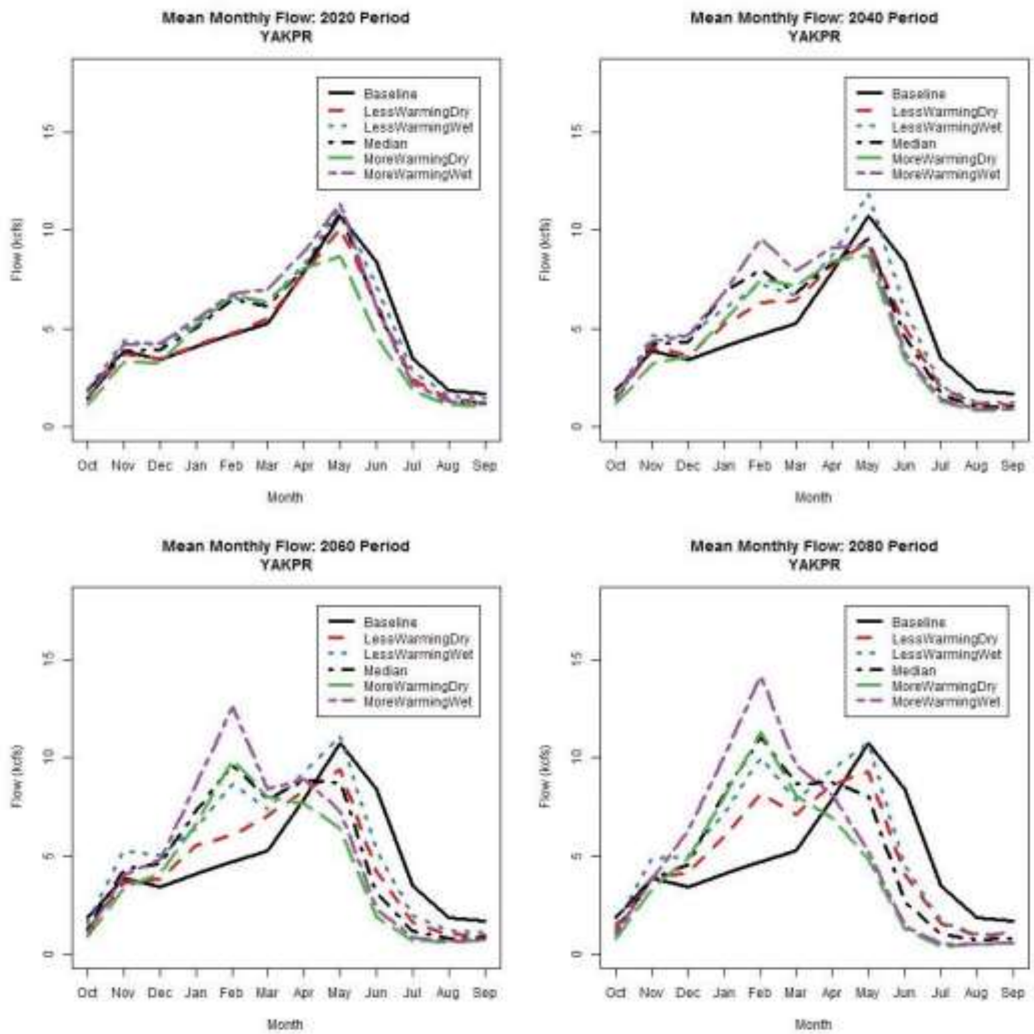

Figure 13. Mean monthly flow at YAKPR.

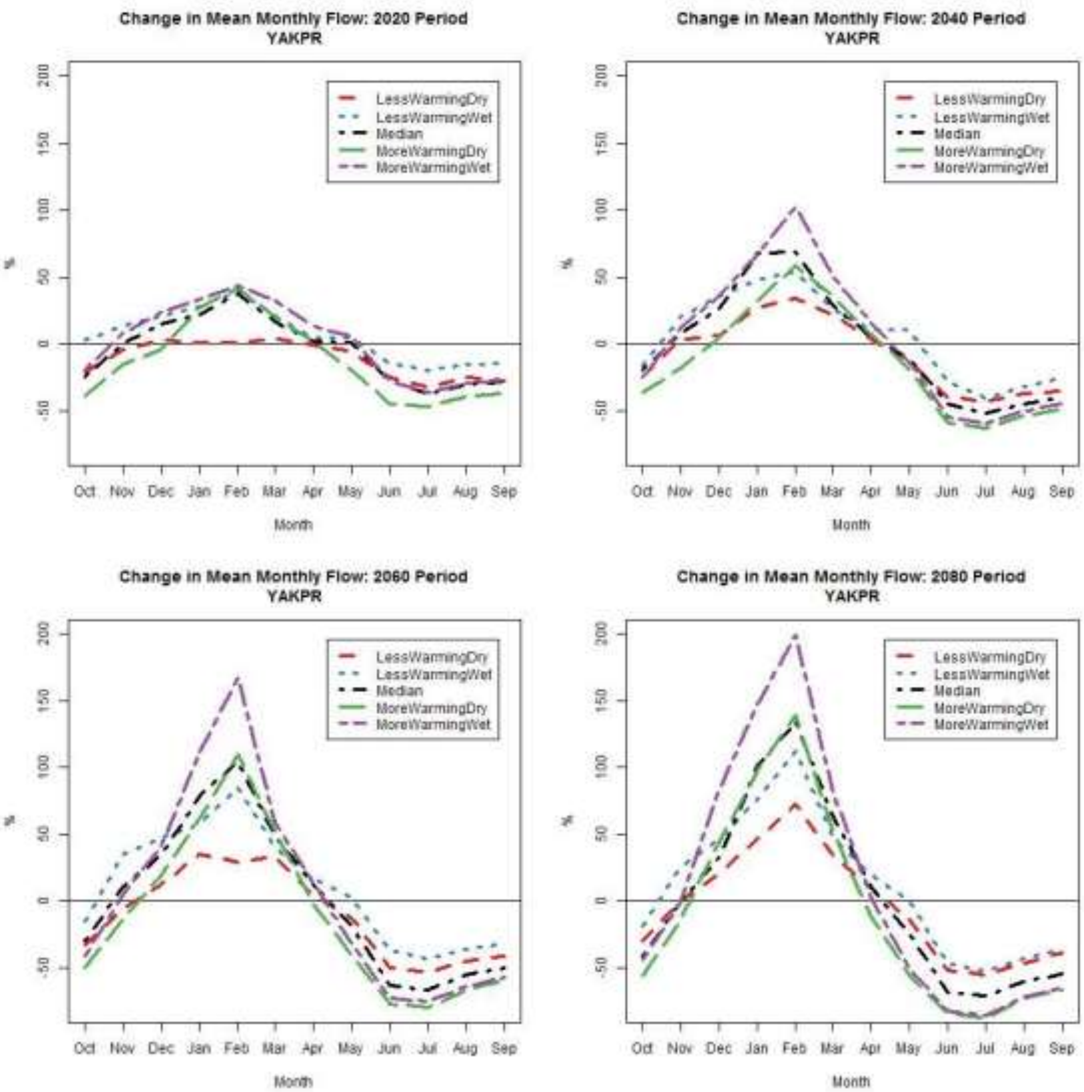

Figure 14. Change in mean monthly flow at YAKPR.

4.2.1.3 Upper Snake River Basin

The results of this Assessment suggest that the total annual runoff for the four select locations in the Upper Snake River Basin (Snake River at Brownlee Dam; Snake River near Heise, Idaho; Boise River at Lucky Peak; and Payette River near Payette, Idaho) will increase by the end of the century for most of the scenarios considered. However, simulations for the earlier periods (2020s, 2040s, and 2060s) showed more varied results. In addition, the Assessment results suggest a shift towards earlier runoff and larger peak flows, with winter and early-spring runoff increasing substantially by the end of the century, and summer and fall runoff decreasing. These changes are consistent with the projected warming and increased early-spring precipitation expected in the Snake River Basin, as well as the effects of increased temperature on evapotranspiration rates.

4.2.1.4 Deschutes River Basin

4.2.1.4.1 Deschutes River near Madras, Oregon

Of all of the locations studied in the Assessment, the simulated runoff volumes for Deschutes River near Madras, Oregon, showed the smallest changes relative to the historical baseline mean annual volume. While this study found little change in the overall annual volume of runoff at this location, results suggest that winter and spring flows will increase over the next century, while summer and fall flows will decrease. However, the performance of the VIC model for the Deschutes River near Madras, Oregon, was poor and the results presented here relied heavily on bias correction due to the effects of groundwater. As discussed further in Section 4.2.2.1, the VIC model is not able to reproduce the significant interactions between surface water and groundwater.

4.2.1.4.2 Crooked River below Opal Springs near Culver, Oregon

The simulated runoff volumes for the Crooked River below Opal Springs near Culver, Oregon, location also showed small changes relative to the historical baseline mean annual volume. The seasonal changes simulated for this location show trends similar to those generated for the sites in the Upper Snake River Basin (Section 4.2.1.3). Specifically, simulations indicate that spring peaks will increase in magnitude over the next century. The results of this study also suggest there will be an increase in winter flows and a decrease in spring and early-summer flows; however, the changes at this location are relatively small compared to the seasonal changes simulated at the other locations studied in the Assessment.

4.2.1.5 Water Resource Impacts Associated with Hydrologic Changes

It is notable that most reservoir systems have been designed based on historical hydrologic patterns and these patterns are changing. Many reservoir systems in the Columbia River Basin were designed under the assumption that snowpack would serve as a large upstream reservoir, accumulating and storing water through the winter and gradually releasing it during the spring and summer melt. In many locations, changes to seasonal runoff may pose challenges to water management as more water comes down the river during the flood control period (when excess water is considered a hazard) and less water comes down the river during the irrigation season (when water is an important economic and ecological asset).

4.2.1.6 Comparison of Projections with Previous RMJOC-1 Study Results

The PN Region Project Team conducted a side-by-side comparison of the results generated by this Assessment and those produced by the 2011 RMJOC-1 Study at five locations within the Columbia River Basin. Generally speaking, this Assessment produced results similar to those generated by the RMJOC-1 Study with some nuances. While the two studies showed similar shifts in peak flow timing and reductions in summer flows, the results of this Assessment demonstrated larger peak runoff values and less pronounced increases in winter flows. Figure 15 provides an example of the side-by-side illustrations provided in Appendix A. The illustration shows Assessment (identified as CRBIA) results (left side of figure) and RMJOC-1 Study results (right side of figure) for simulated monthly runoff for the 2020s and 2040s under each climate scenario. The source of the differences between these two studies was not investigated in detail; however, the differences may be the result of a number of factors, including the following:

- CMIP5 climate change projections were used for this Assessment while CMIP3 projections were used for the RMJOC-1 Study.
- This Assessment selected projections for each scenario at the subbasin-scale while the RMJOC-1 Study selected projections for the Columbia River Basin as a whole.
- This Assessment used the Hybrid-Delta Ensemble methodology to develop climate change scenarios while the RMJOC-1 Study used the Hybrid-Delta method and single GCM projections.

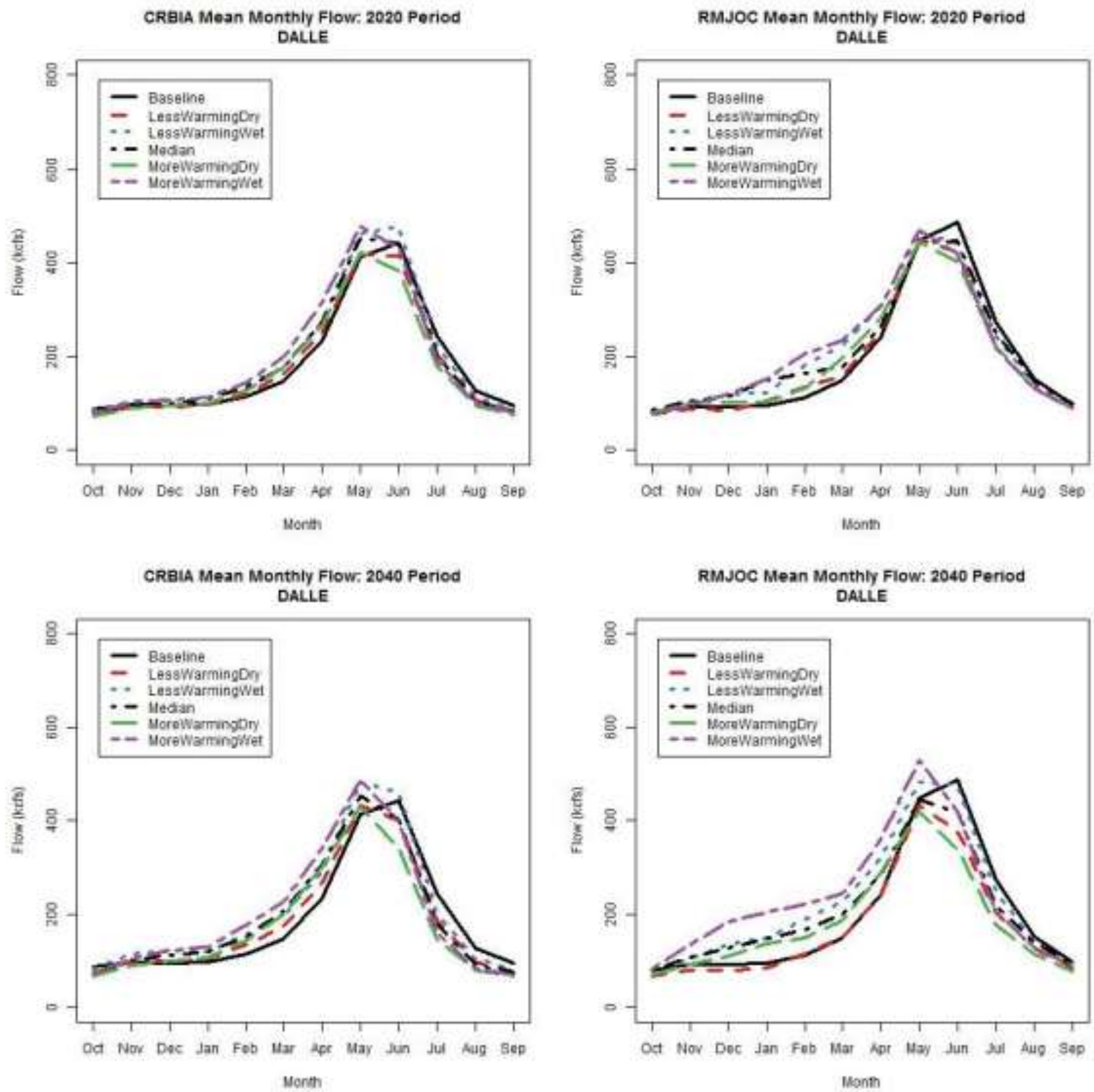

Figure 15. The Assessment (CRBIA) (left) and the RMJOC-1 Study (right) simulated mean monthly runoff volumes for the Columbia River at The Dalles (DALLE) for the 2020s (top) and 2040s (bottom).

4.2.2 Groundwater Discharge to Surface Water

Reduced mountain snowpack, earlier snowmelt, and reductions in spring and summer streamflow volumes originating from snowmelt could affect surface water supplies and could trigger heavier reliance on groundwater resources. However, warmer, wetter winters could increase the amount of water available for groundwater recharge, but this area needs further study. Also, according to Lettenmaier et al. (2008; as cited in Reclamation 2011, p. 59), depletions to natural groundwater recharge are sensitive to climate warming.

Groundwater may also be impacted by human responses to changes in the climate. As streamflow variability increases, groundwater pumping may increase to supplement water supply. In addition, recharge that occurs from water delivery systems and on-farm infiltration may decrease as water users develop more efficient means of moving water to their lands. Both of these activities could result in decreased groundwater supported baseflow in streams.

4.2.2.1 Identification of Groundwater Dominated Systems

In the Columbia River Basin, several streams have a large component of flow supplied by groundwater, also known as baseflow. Since climate change has the potential to impact groundwater supplies, streamflows may also be affected. Hydrologic tools, such as the VIC model, that are used to develop future hydrologic flows tend to be better suited for simulating flows that follow a snowmelt runoff pattern than those basins that have flows that are largely made up of baseflow. In particular, monthly mean summary hydrographs in baseflow driven systems tend to have a flatter signature than hydrographs in snowmelt driven systems. Figure 16 shows an example of this behavior for the gage at Boise River at Glenwood Bridge, a snowmelt driven system, and the gage at Deschutes River at Benham Falls, a baseflow driven system. The figure demonstrates that the median variability is much larger in the Boise River than in the Deschutes. The Deschutes naturalized flow at Benham Falls may only vary a few hundred cubic feet per second (cfs) in a single year due to the large influence of groundwater. Conversely, in the Boise River the spring runoff may produce flows that are thousands of cfs larger than winter flows.

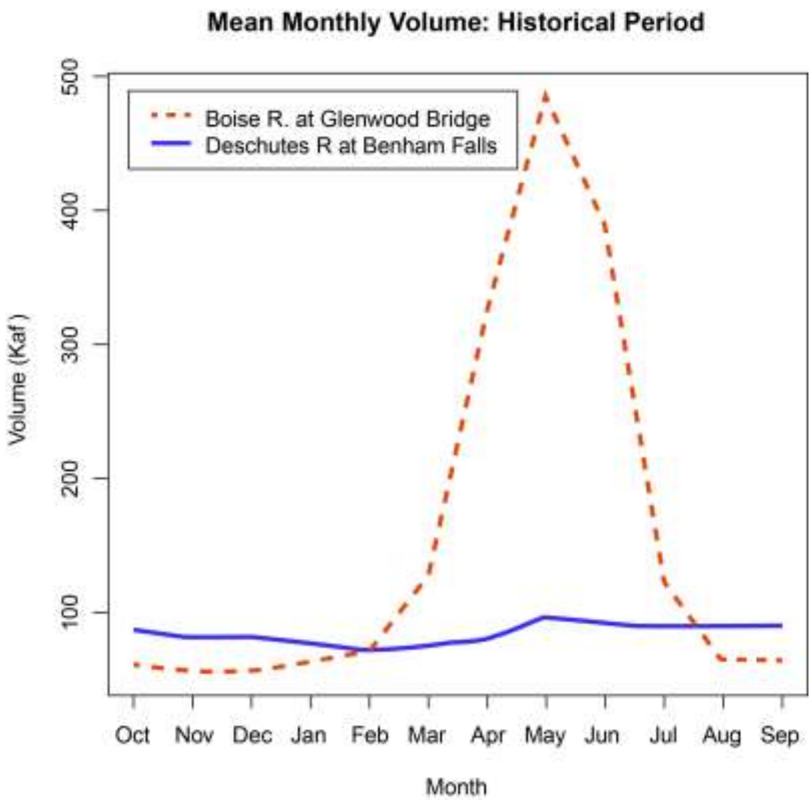

Figure 16. Mean monthly volume for the historical period of naturalized flow at (1) Boise River at Glenwood Bridge (red) and (2) Deschutes River at Benham Falls (blue).

The VIC model is a common tool for developing future hydrologic flows in the Columbia River Basin, but is limited in its ability to simulate runoff in basins that have a large baseflow component. As part of the Assessment, the PN Region Project Team worked to determine if an alternate tool should be used when developing simulated future hydrologic flows for a particular basin. Towards this end, the team examined monthly mean summary hydrographs for the 157 flow points in the Columbia River Basin. A ratio was developed for each of the 157 gages of the minimum flow divided by the maximum flow. Larger ratios reflect a flatter hydrograph which indicates the basin flows may be dominated by baseflow.

In the Columbia River Basin, most locations within the Deschutes basin had larger ratios, and therefore are considered to be groundwater dominated. Because of this, an alternate tool, GSFlow, has been chosen to develop future climate flows for the Upper Deschutes River for the currently on-going Upper Deschutes River Basin Study. Details on this work are provided in the Appendix A.

4.3 Impacts of Climate Change on Agricultural Diversions and Reservoir Storage and Delivery

This section outlines the analysis of agricultural diversions conducted as part of the Assessment. It also summarizes model simulation results that describe climate change impacts on Columbia River Basin regulated water storage and delivery.

4.3.1 Agricultural Diversions

As identified in the 2011 SECURE Report (Reclamation 2011), the seasonal volume of agricultural water demand could increase if growing seasons become longer and if farmers' practices and legal constraints adapt to this opportunity by introducing more crop cycles per growing season. According to Gutowski et al. (2008; as cited in Reclamation 2011, p. 60), this possibility is based on studies suggesting that the average North American growing season increased by about 1 week during the 20th century; and it is projected that, by the end of the 21st century, it may be more than 2 weeks longer than typical of the late 20th century.

According to this Assessment, the climate changes projected result in increased air temperatures, which could likely lead to higher plant water consumption and surface water evaporation. As noted by Stockle et al. (2010), projected changes in runoff timing could decrease water available for irrigation delivery in the summer months, which could cause heat stress to field crops and fruit trees. However, certain crops could benefit, at least in the short-term, from longer growing seasons and/or increased carbon dioxide levels in the atmosphere (as cited in Mote et al. 2014, p. 497). In the long-term, agricultural water demand could decrease on average due to crop failures caused by changes in pests, diseases, and weeds. In general, rising temperatures could lead to broader pest ranges, earlier pest arrival, and more generations of pests in a growing season (Parmesan 2006; as cited in Mote et al. 2014, p. 497).

Specific to the Columbia River Basin, a Pacific Institute 2009 study (as cited in Reclamation 2011, p. 60) suggests that agricultural lands requiring irrigation may increase by up to 40 percent by 2080 due to prolonged dry periods and severe drought. The study also suggests that livestock water demands will increase significantly due to augmented hydration needs caused by higher atmospheric temperatures (Reclamation 2011).

4.3.1.1 Determining Agricultural Diversions for Use in Water Resources Models

As part of this Assessment, the PN Region Project Team evaluated two methods that allow 2015 WWCRA Demand Study (Reclamation 2015a) agricultural diversion data to be applied to water resources models. As described in Appendix C, the process requires that the projected future NIWR values be adjusted for non-consumptive uses (i.e. canal seepage and on-farm infiltration) and to the appropriate spatial scale for the WRM diversion location. This was tested on two water resource model nodes—A_BPump and PeopAber—in the Upper Snake River WRM using the Total Irrigated Acreage Method and the Linear Regression Method, described in section 3.3.

Using the Total Irrigated Acreage Method, the change in demand for both nodes was greatest in the summer months for the MW/D scenario. This is consistent with the idea that crops would require more irrigation water in dryer and warmer conditions. The maximum change for A_BPump, approximately 2,000 acre-feet, is roughly 15 percent of the total maximum diversion. The maximum change for PeopAber, approximately 20,000 acre-feet, is roughly 20 percent of the total maximum diversion. The changes are smallest for the LW/W scenario, which is also consistent with the idea that crops would require less irrigation water in less warm and wetter conditions (see Figure 17 and Figure 18).

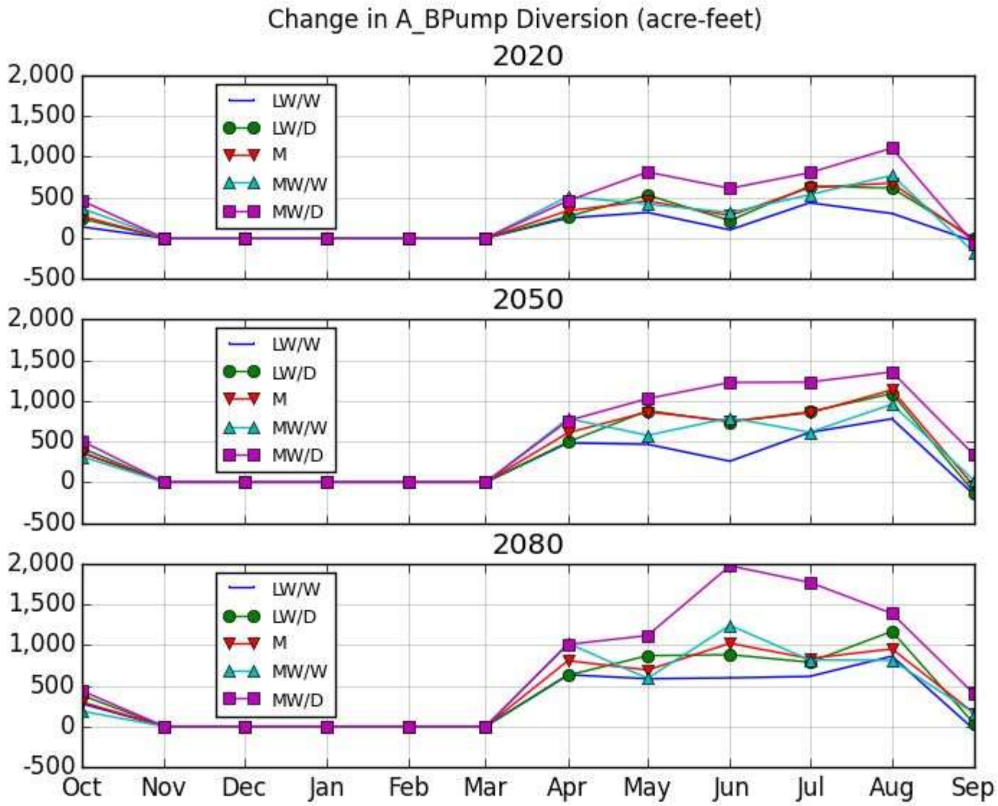

Figure 17. Total Irrigated Acres Method: Average difference between the calculated future diversion and the baseline for the A_BPump water resources node for scenarios of Less Warming/Dry (LW/D), Less Warming/Wet (LW/W), More Warming/Dry (MW/D), More Warming/Wet (MW/W), and Median (M) tendency conditions.

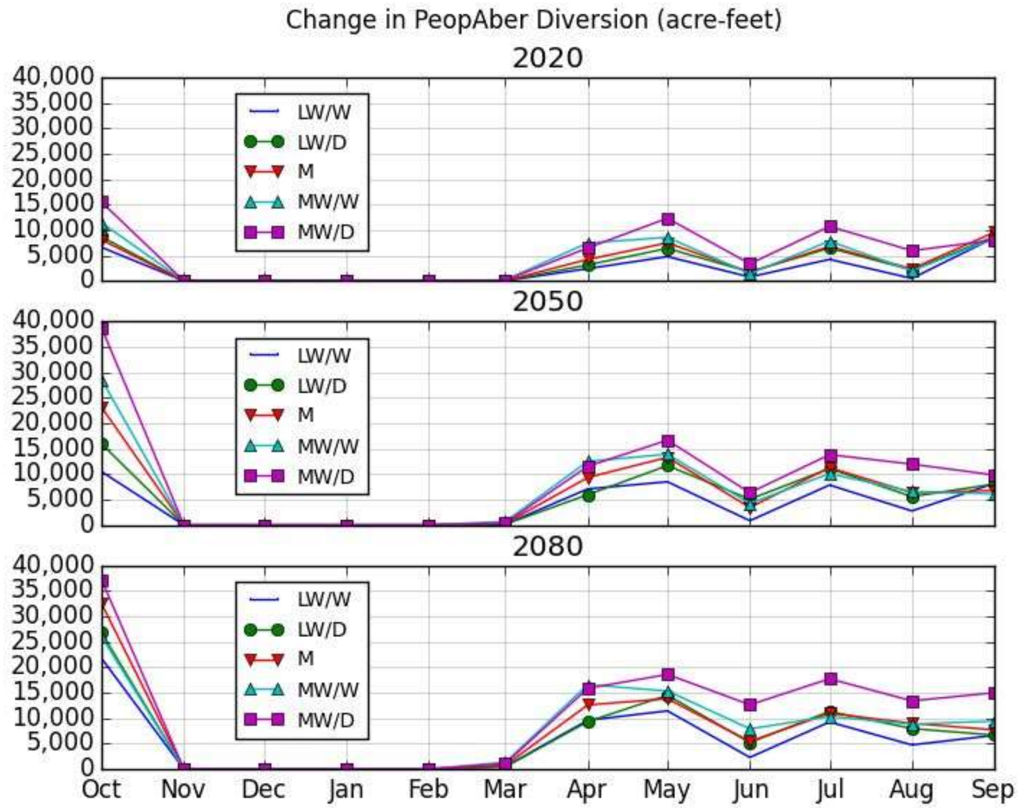

Figure 18. Total Irrigated Acres Method: Average difference between calculated future diversion and baseline for the PeopAber water resources model node for scenarios of Less Warming/Dry (LW/D), Less Warming/Wet (LW/W), More Warming/Dry (MW/D), More Warming/Wet (MW/W), and Median (M) tendency conditions.

As in the Total Irrigated Acreage Method, in the Linear Regression Method the greatest change in future projected diversion is also in the MW/D scenario and the smallest change is in the LW/W scenario (Figure 19 and Figure 20).

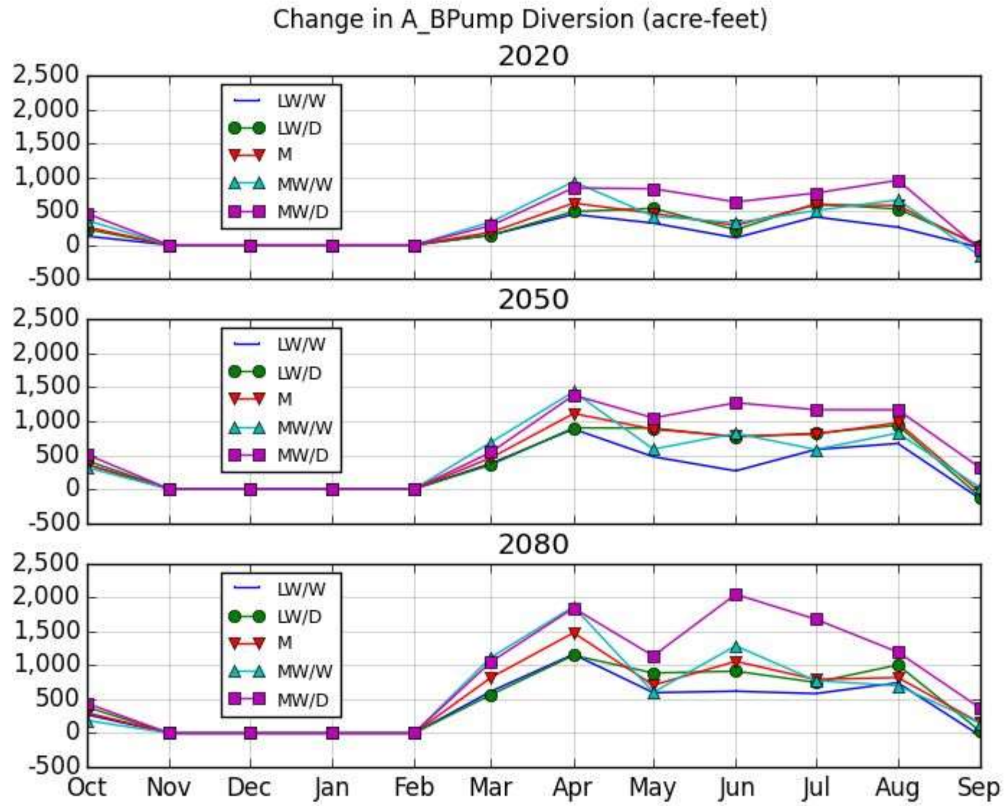

Figure 19. Linear Regression Model: Average difference between the calculated future diversion and the baseline for the A_BPump water resources node for scenarios of Less Warming/Dry (LW/D), Less Warming/Wet (LW/W), More Warming/Dry (MW/D), More Warming/Wet (MW/W), and Median (M) tendency conditions.

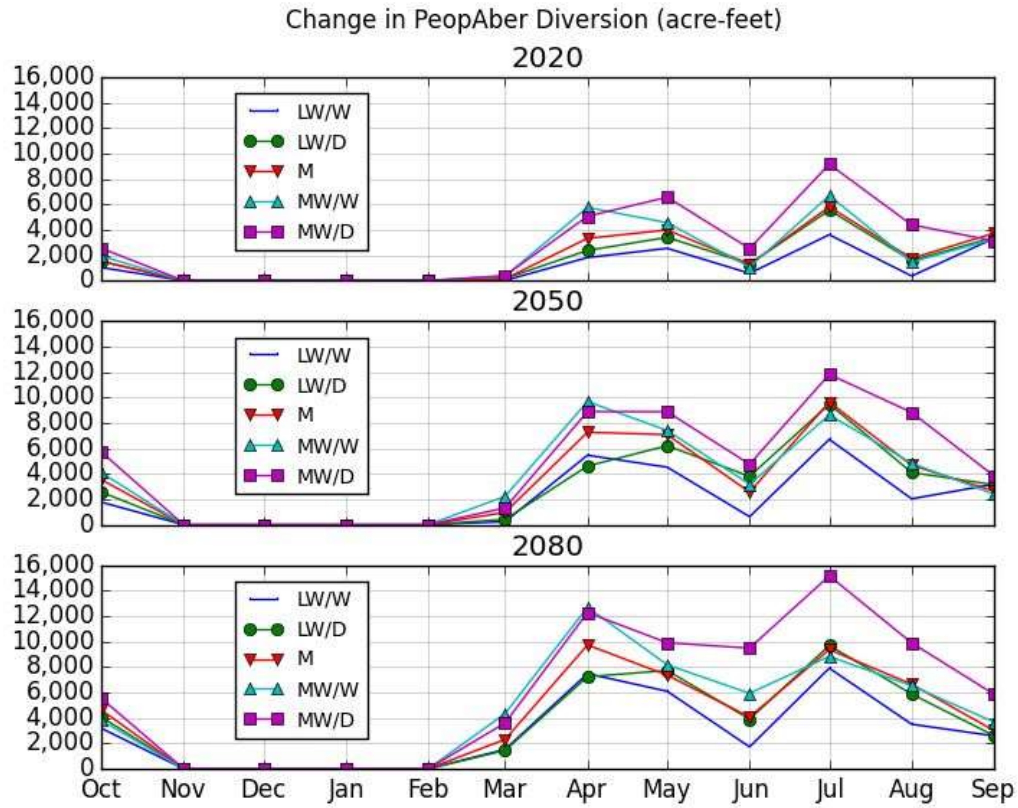

Figure 20. Linear Regression Model: Average difference between the calculated future diversion and the baseline for the PeopAber water resources node for scenarios of Less Warming/Dry (LW/D), Less Warming/Wet (LW/W), More Warming/Dry (MW/D), More Warming/Wet (MW/W), and Median (M) tendency conditions.

Overall, both methods produced similar projected future irrigation diversions for the water resources model nodes. Since the Linear Regression Method requires less input data (i.e. the irrigated acreages are not needed for the calculation), it suggested as the preferred method.

The changes in diversion volumes noted in this Assessment are simply due to changes in NIWR that result from projected future climate conditions. Other systematic changes may occur if crop distribution, land use, or system efficiencies (i.e. lining canals or converting from flood to sprinkler irrigation) change with the changing climate. All diversion increases are currently limited by legal water right diversion rates. To understand the impacts of these changes on the system, the demands could be included in a water resource model application. This more extensive level of analysis was not conducted for this study. For more details on agricultural consumption in the Columbia River Basin, see Appendix C.

4.3.2 Columbia River Basin Regulated Water Storage and Delivery

Climate change impacts on the Upper Snake River Basin regulated water storage and delivery were simulated in the Assessment using a WRM that included the Boise River Basin and Payette River Basin, as well as the Snake River Basin from its headwaters at Jackson Lake downstream to Brownlee Reservoir. The evaluation of impacts and generation of regulated flows from the Upper Snake River Basin above Brownlee is essential for informing further analysis of the Columbia River Basin as a whole. Figure 21 identifies the streamflow and reservoir locations in the Snake River Basin above Brownlee Reservoir (BRN) that were studied in the Assessment. The WRM was used to evaluate four metrics—system inflow, system reservoir contents, regulated flow, and requested water (shortage and natural versus stored flow delivery). The results of the WRM effort are summarized below and included in full in Appendix B.

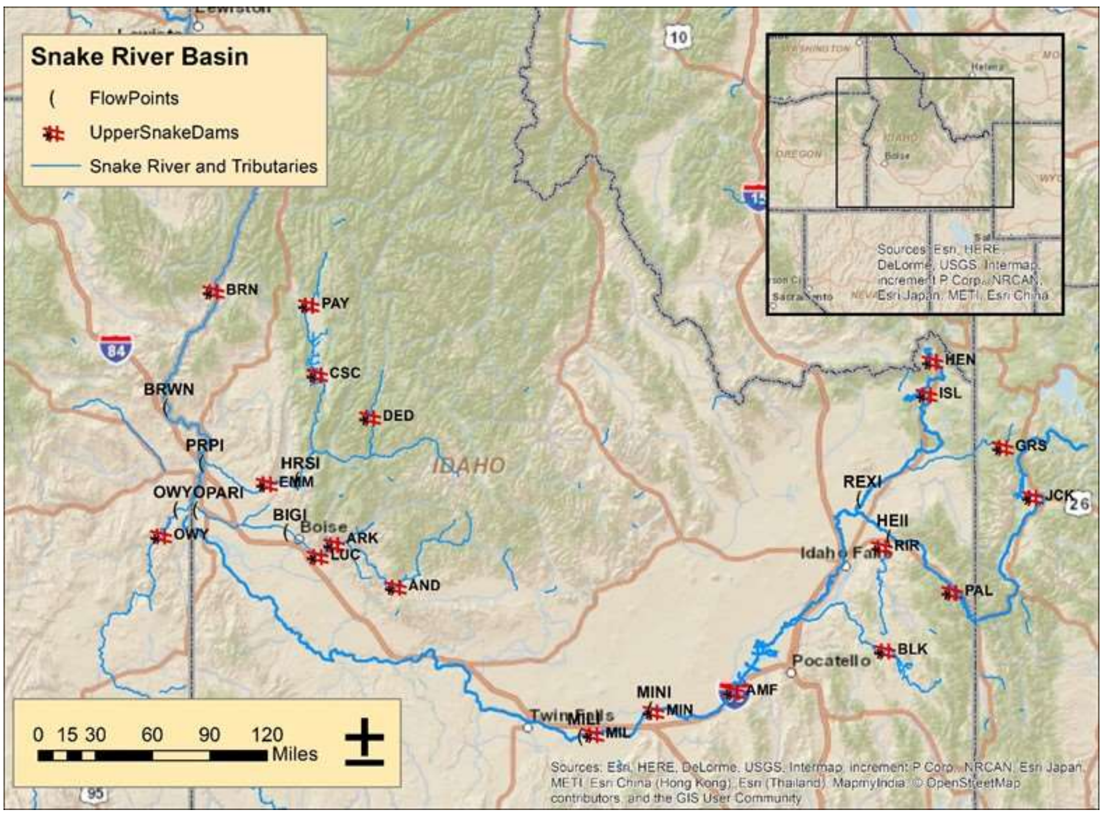

Figure 21. Location of reservoirs in the Snake River Basin above Brownlee Reservoir (BRN) and streamflow presented in the Assessment. Reservoir labels have three letter designations and were placed to the right of the point. Streamflow labels have four letter designations and were placed above the point.

Twenty (plus the baseline) 30-year ensemble informed Hybrid-Delta CMIP5 climate change scenarios identified above in Section 3 were run through the WRM. Across the entire Upper Snake system, inflows and regulated flows were projected to increase through the spring with decreases seen in the summer months. In general, the increase in spring inflow allowed reservoirs to refill in a higher number of years than in the Baseline, but with peak storage occurring earlier through each period due to the earlier and increased spring runoff. The decline in system inflows in the late summer months caused lower storage carryover levels (calculated the end of October) due to increased system demand and delivery of stored water.

Overall, large increases in regulated basin outflow were seen throughout the Upper Snake WRM with regulated flows exceeding flood stage in two of the three basins evaluated—Snake River Basin above Milner and Boise River Basin—for at least one climate change scenario. Specifically, increased system inflow in the MW/W scenario, especially pronounced in the 2080 period, exceeded the amount that could be stored in the Snake River Basin above Milner. Under such conditions, where reservoirs reach maximum storage capacity, there is no further capacity (without altering the reservoirs' flood control targets) to store high inflows and downstream flooding occurs.

Water delivery remained relatively unchanged across the entire Upper Snake system (although larger request differences from the baseline were seen in the Boise River Basin) due to the fact that most water users have both natural flow and stored water rights, meaning when natural flow supplies are diminished, water users are able to continue to receive water from their storage accounts. Water users were able to rely more heavily on their stored water accounts due to increased spring runoff refilling reservoirs in a higher number of years.

4.3.2.1 Snake River Basin above Milner

For this section on the Snake River Basin above Milner location, graphs and tables will be presented that display Assessment results for the four metrics—system inflow, system reservoir contents, regulated flow, and requested water (shortage and natural versus stored flow delivery). These are representative of the graphs and tables generated for the Boise and Payette River basins, also studied in the Assessment and outlined in Appendix B.

4.3.2.1.1 System Inflow

For all future periods in the Snake River Basin above Milner, inflows were projected to increase in the spring and decrease through the summer (Figure 22). Increases in spring inflow occur earlier through each period with peak inflow occurring in May for all periods and for all scenarios, with sharp declines in June for the MW/D and MW/W scenarios beginning in the 2060 period.

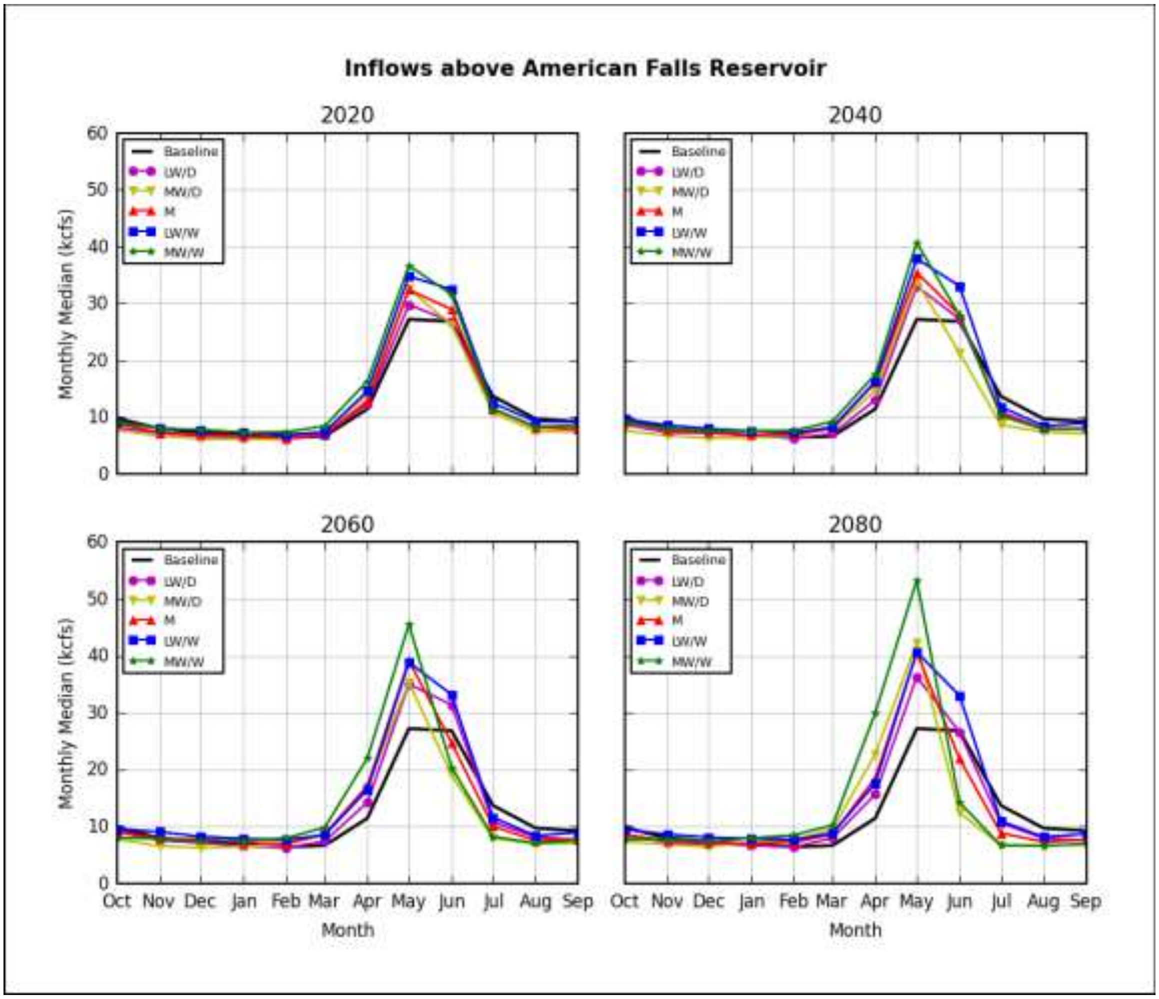

Figure 22. Monthly median unregulated inflow above American Falls Reservoir. Inflows were projected to increase through the spring and decrease through the summer.

4.3.2.1.2 System Reservoir Contents

Eight reservoirs were modeled for the system reservoir contents in the Snake River Basin above Milner (Figure 21). Due to the increased and earlier spring runoff, modeled system reservoir contents refill in a higher number of years (Table 6). These results are in spite of reduced carryover storage levels, which occurred 50 percent of the time as seen in the end of October contents shown in Figure 23. Outside of the spring refill months, system reservoir contents are lower than the Baseline for nearly every scenario and every period. This increases irrigators' dependency on stored water contracts to satisfy irrigation requests, which, in turn, reduces median storage carryover levels.

Through each period, and essentially from the drier to the wetter scenarios, the number of years the reservoir system filled increased. In other words, the system filled to capacity in more years through each period and from the drier to wetter scenarios. Table 6 provides a summary of the number of years the modeled reservoir system contents filled (greater than or equal to 4,000,000 acre-feet).

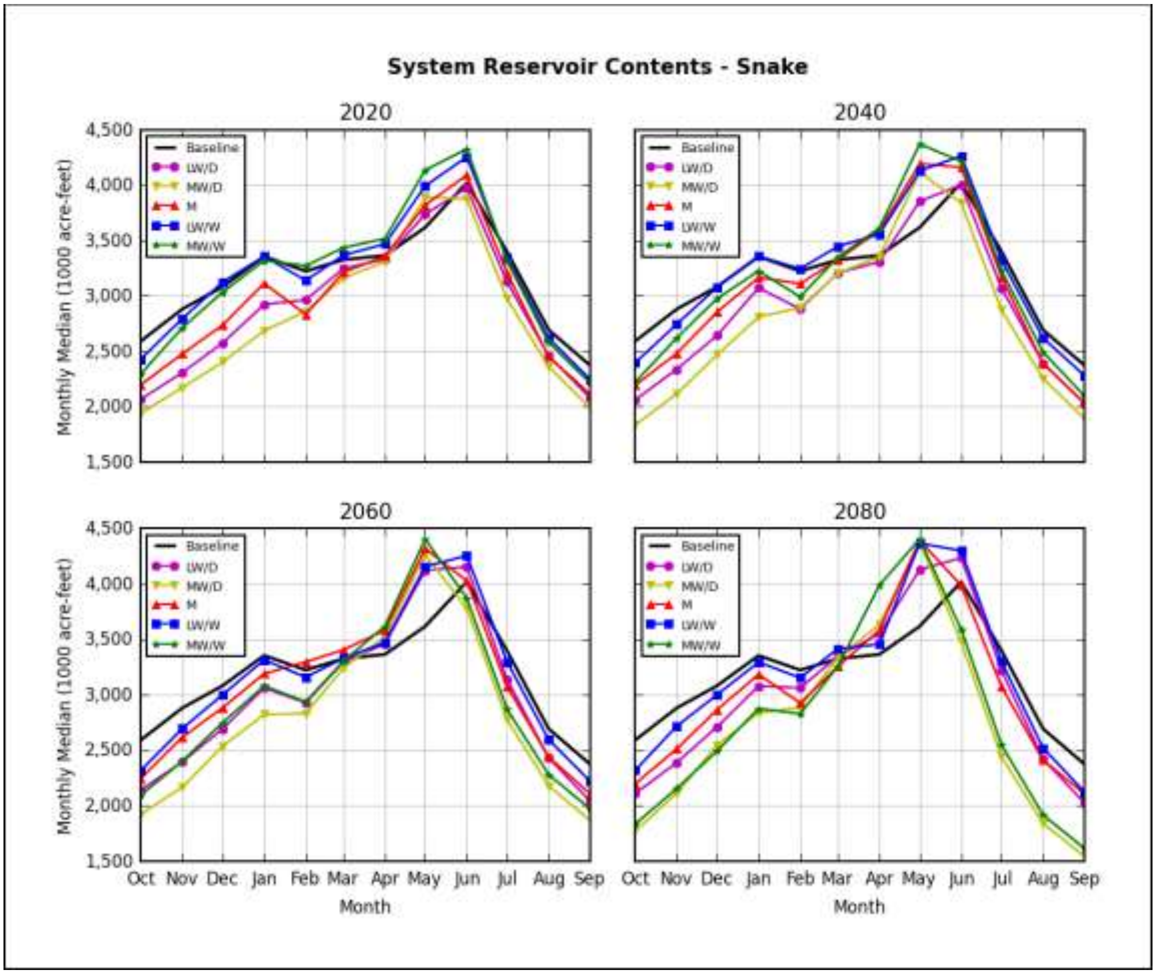

Figure 23. Monthly median system storage contents in the Snake River Basin above Milner for five simulated future climate change scenarios in four future periods 2020s, 2040s, 2060s, and 2080s.

Table 6. Number of years in the 30-year modeled period when the maximum reservoir system contents were greater than or equal to 4,000,000 acre-feet (maximum capacity) in the Snake River Basin above Milner.

	Baseline (years)	LW/D (years)	MW/D (years)	Median (years)	LW/W (years)	MW/W (years)
2020	18	18	18	19	25	26
2040	18	19	19	25	27	27
2060	18	20	21	26	25	28
2080	18	25	24	27	27	27

4.3.2.1.3 Regulated Flow

For the Snake River Basin above Milner, modeled regulated future streamflow increased in the spring months of March through May. This occurred because of the increased and earlier spring runoff (Figure 22) and because reservoirs reached maximum capacity or were constrained by flood control refill targets (Figure 23). As shown in Figure 24, at the Snake River at Heise, Idaho 50 percent of the time regulated flows were above flood stage levels in May for the MW/W scenario in the 2080 period. At the Snake River below Minidoka Dam, Idaho (Figure 25), 50 percent of the time flood stage levels were exceeded starting in the 2060 period in May for the MW/W scenario. Additionally, at this location flood stage levels were exceeded for the MW/W and MW/D scenarios in the 2080 period in May. These changes are likely to lead to more forced spills or uncontrolled releases in the reservoir system.

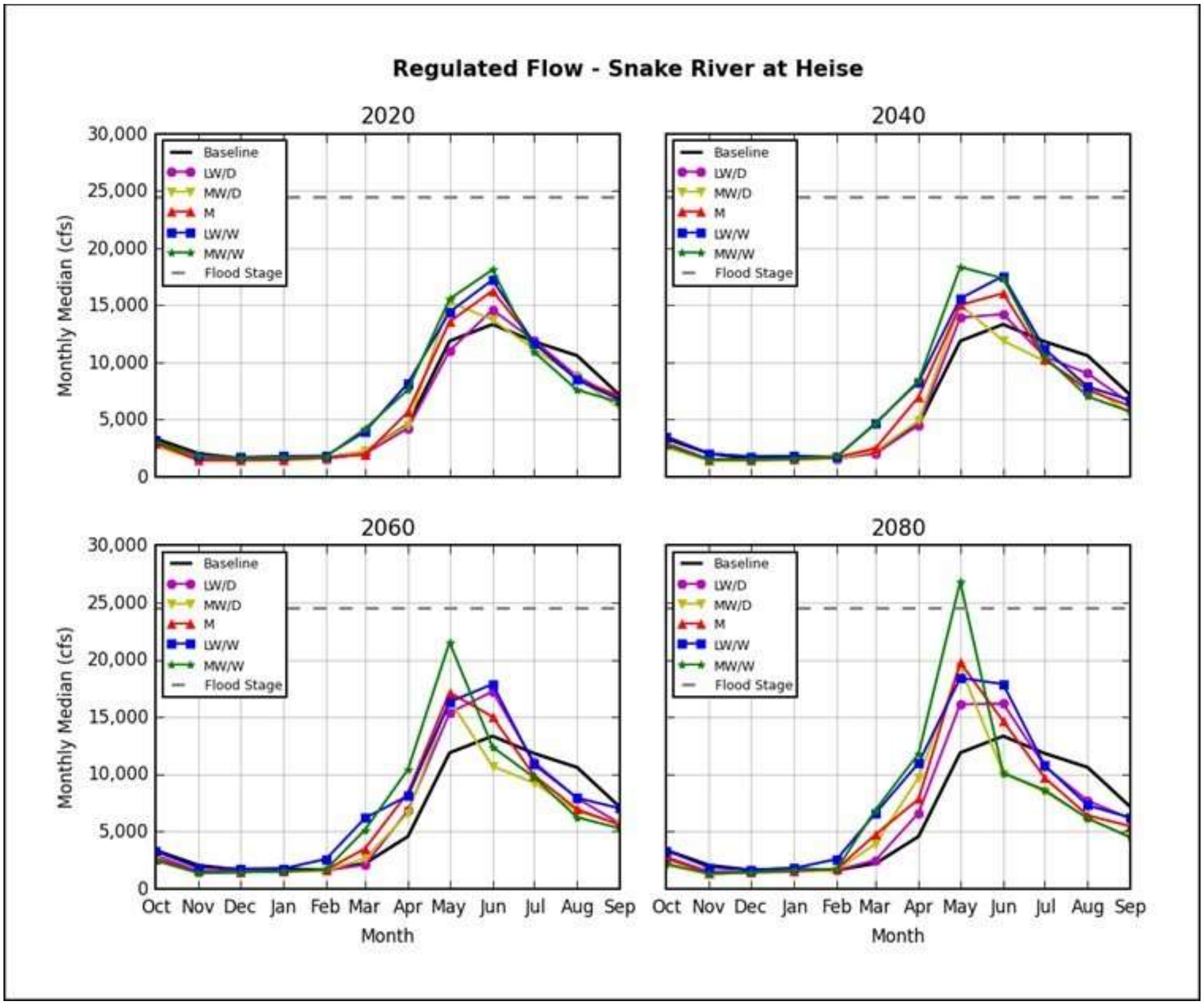

Figure 24. Monthly median regulated flow on the Snake River at Heise.

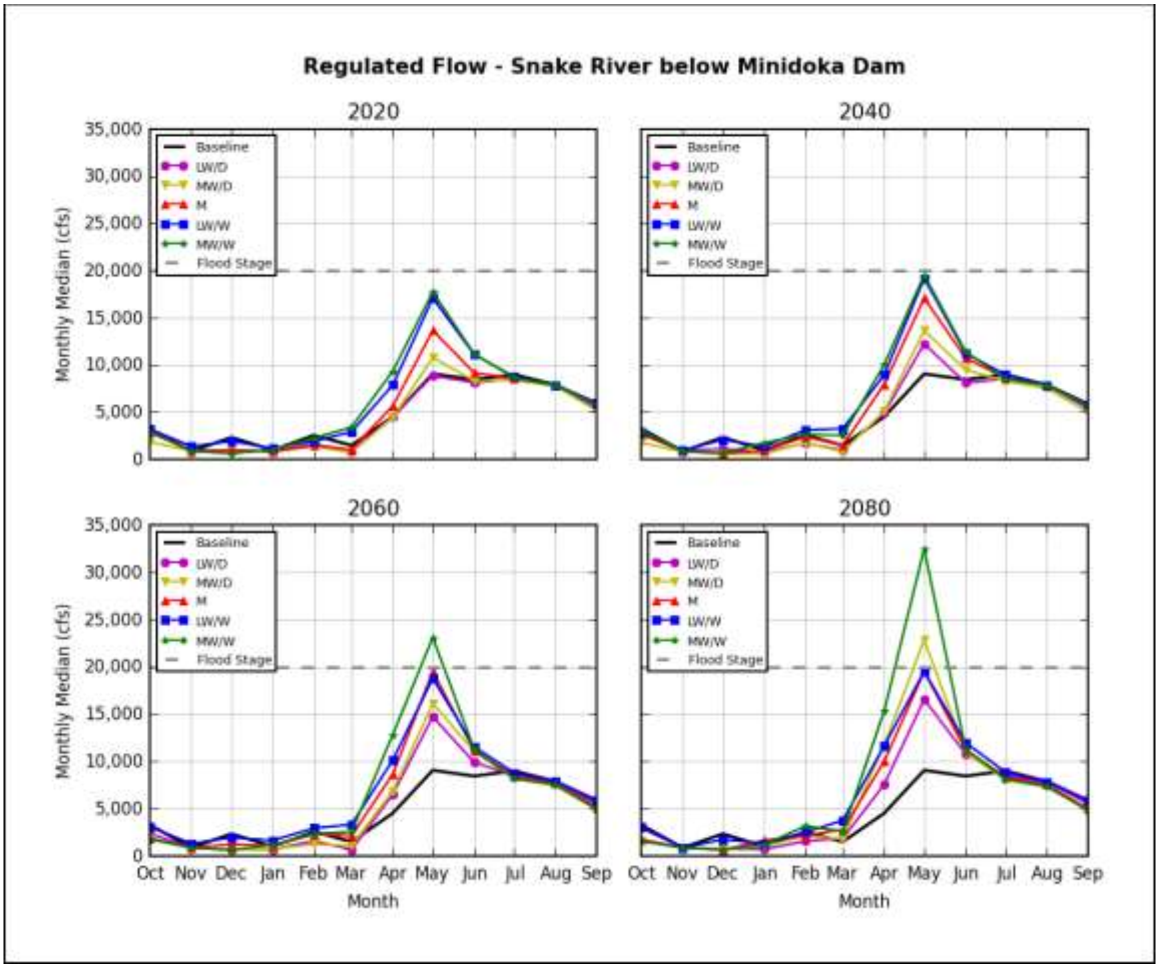

Figure 25. Monthly median regulated flow on the Snake River below Minidoka Dam, Idaho.

The same patterns of increased spring regulated flows are seen at Brownlee Reservoir (Figure 26), although with peak flow shifting towards April rather than May, due to regulated flows from the Boise River Basin and the Payette River Basin, and any unregulated tributary flows between Minidoka Dam and Brownlee Reservoir.

Regulated flow in March, April, and May begins to rather significantly increase as early as the 2020 period for the LW/W and MW/W scenarios with April flows nearly doubling for all scenarios except for the Median and LW/D scenarios in the 2080 period. These are the median or 50 percent exceedance flows, so even higher flows would be seen in wet years.

It should be noted that no flood stage constraints were modeled from Milner Dam to Brownlee Reservoir because there is no formal flood stage requirement through this section of the Snake River. In addition, there is no downstream dam to further regulate flows to Brownlee Reservoir. If regulated flows below Minidoka Dam are greater than flood stage, this means there is no further upstream capacity to control downstream flooding. Flood risk vulnerability was assumed to be minimal below Milner Dam.

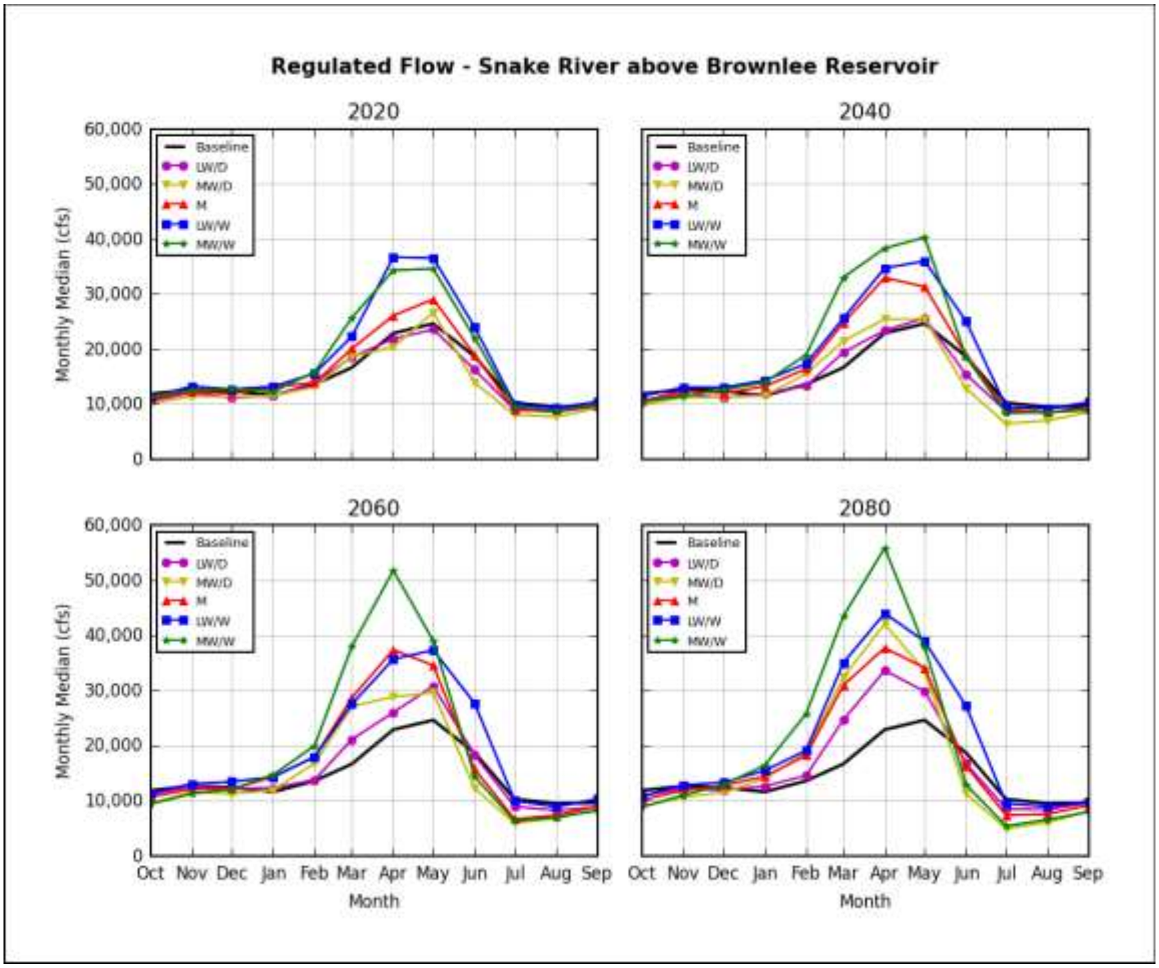

Figure 26. Monthly median regulated flow on the Snake River above Brownlee Reservoir, Idaho.

4.3.2.1.4 Requested Water (shortage and natural versus stored flow delivery)

The modeled water requests in the Snake River Basin above Milner remained similar in nearly every scenario and every period (Appendix B). Through most periods and scenarios, irrigation delivery was satisfied less by natural flow water rights and increasingly through stored water contracts. This occurs simply because all scenarios show natural flow water declines in July, August, and September.

It is projected that there may be system shortages to requests for water, this would mostly be observed in July and August when requests for irrigation water are high and natural flow is declining. Modeled peak system shortage occurs in the 2080 period in July and August at approximately 150,000 acre-feet, yet modeled shortages of 50,000 acre-feet are seen as early as the 2020 period for the MW/D and LW/D scenarios.

One water user object or node in the WRM was chosen as a representative basin water user to present the impact of climate change on water rights. In the Snake River Basin above Milner this node is labeled “Northside” and represents a water user with more significant water requests, as well as a water user with both natural flow water rights and stored water rights that can be used to satisfy requests. Through most periods and scenarios, irrigation delivery to this representative node was satisfied less by natural flow water rights and increasingly through stored water contracts (Figure 27 and Figure 28). As indicated, this occurs because all scenarios show natural flow water declines in July, August, and September. For irrigators with minimal stored water right contracts, it is expected that a moderate to significant water shortage would occur. However, most demands in the Upper Snake River Basin have both natural flow and stored water contracts, so a portion of the natural flow water right shortages could be offset by stored water delivery.

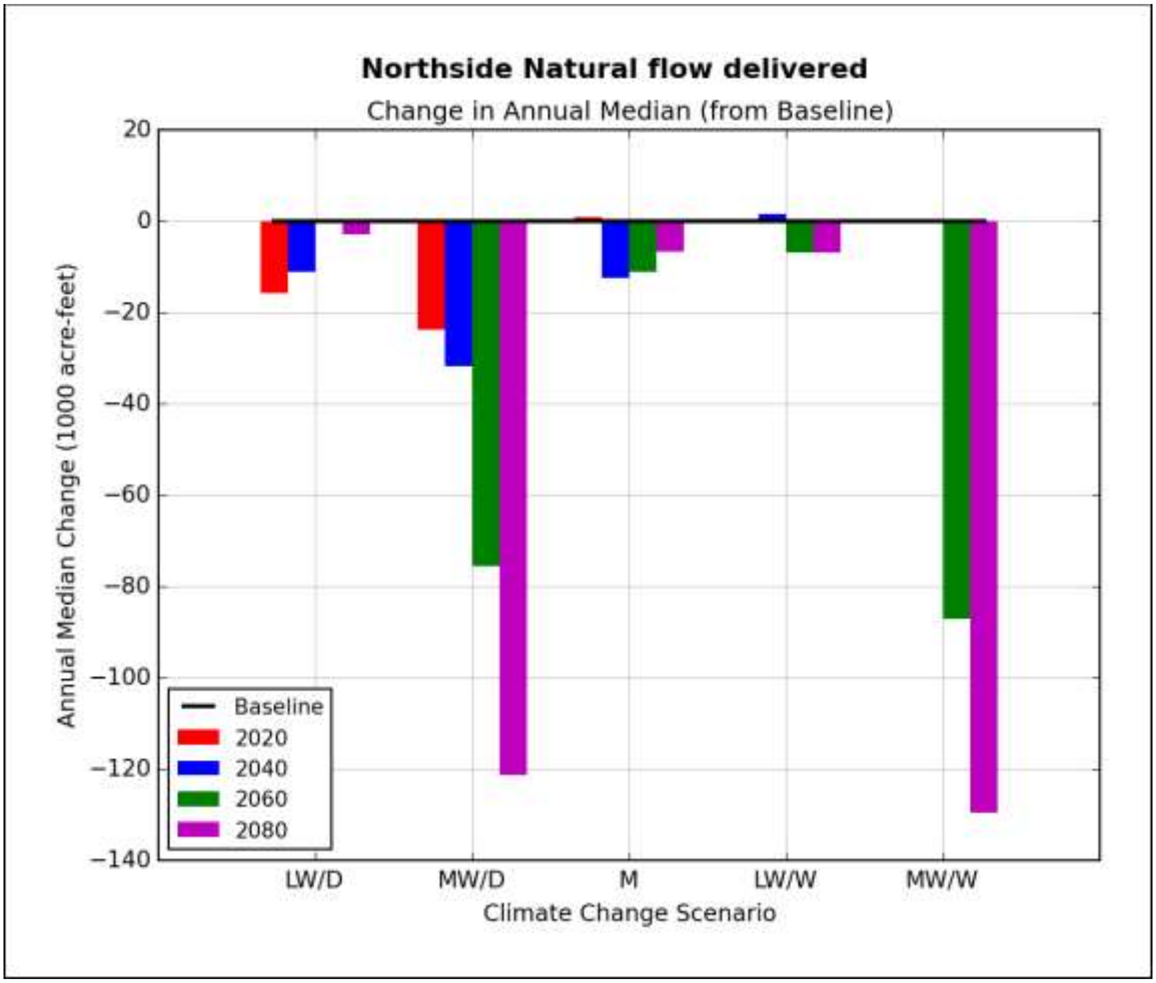

Figure 27. Annual median change in natural flow water delivery to the Northside modeled water user.

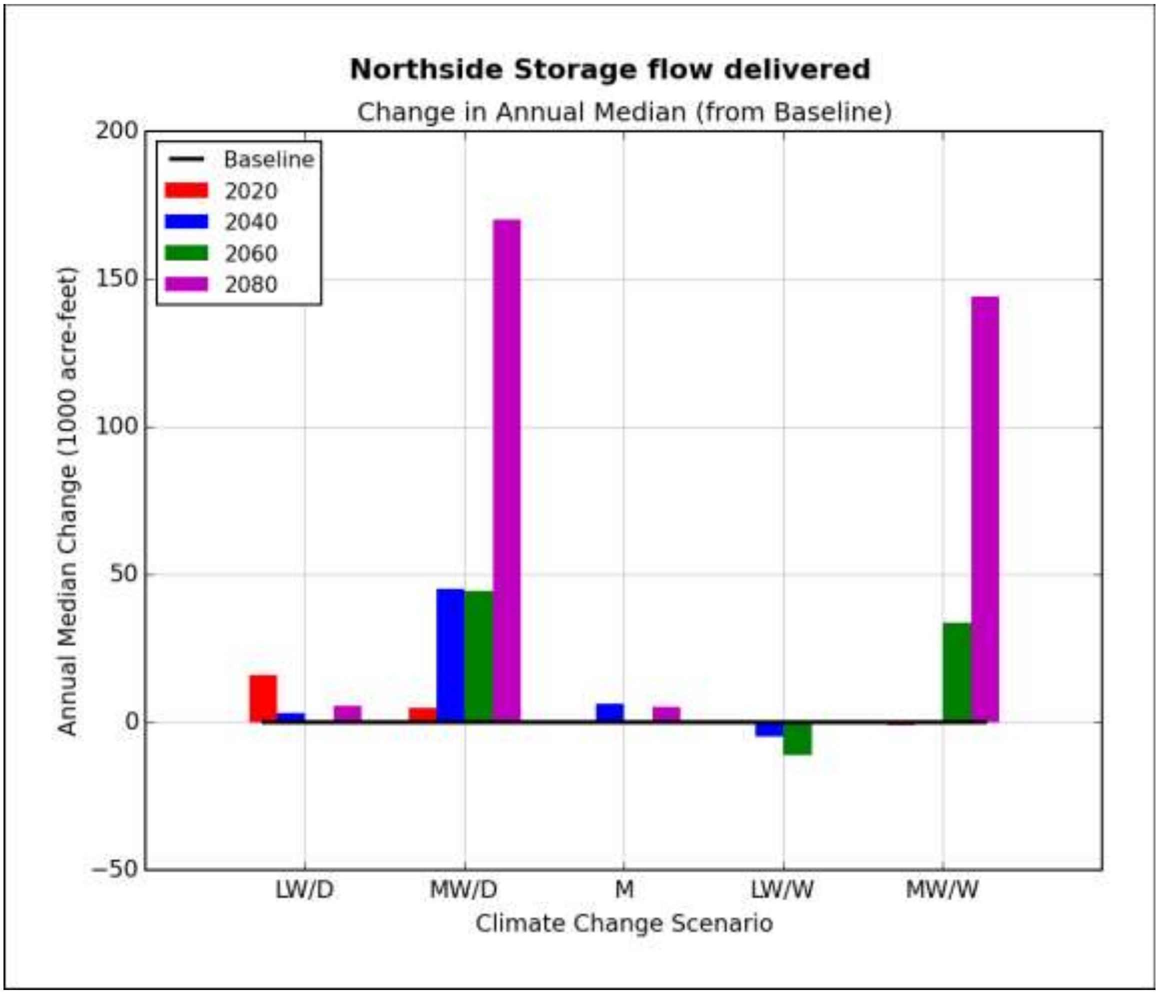

Figure 28. Annual median change in stored water delivery to the Northside modeled water user.

4.3.2.2 Boise River Basin

4.3.2.2.1 System Inflow

For all future periods in the Boise River Basin, inflows are projected to increase in the spring and decrease through the summer. Spring increases occur earlier through each period with peak runoff shifting from May to April by the 2080 period for all scenarios.

4.3.2.2.2 System Reservoir Contents

Three reservoirs—Anderson Ranch, Arrowrock and Lucky Peak—were modeled for the system reservoir contents in the Boise River Basin (Figure 29). Due to increased and earlier spring runoff, system reservoir contents continue to refill in a higher number of years despite reduced carryover storage levels (end of October contents). Outside of the spring refill months, system reservoir contents are generally lower than Baseline conditions due to an increasing dependency on stored water to satisfy requested water that was not satisfied by natural flow deliveries.

Through each period, and essentially from the drier to the wetter scenarios, there was an observed increase in the number of years the reservoir system contents filled (900,000 acre-feet) across the Boise River Basin.

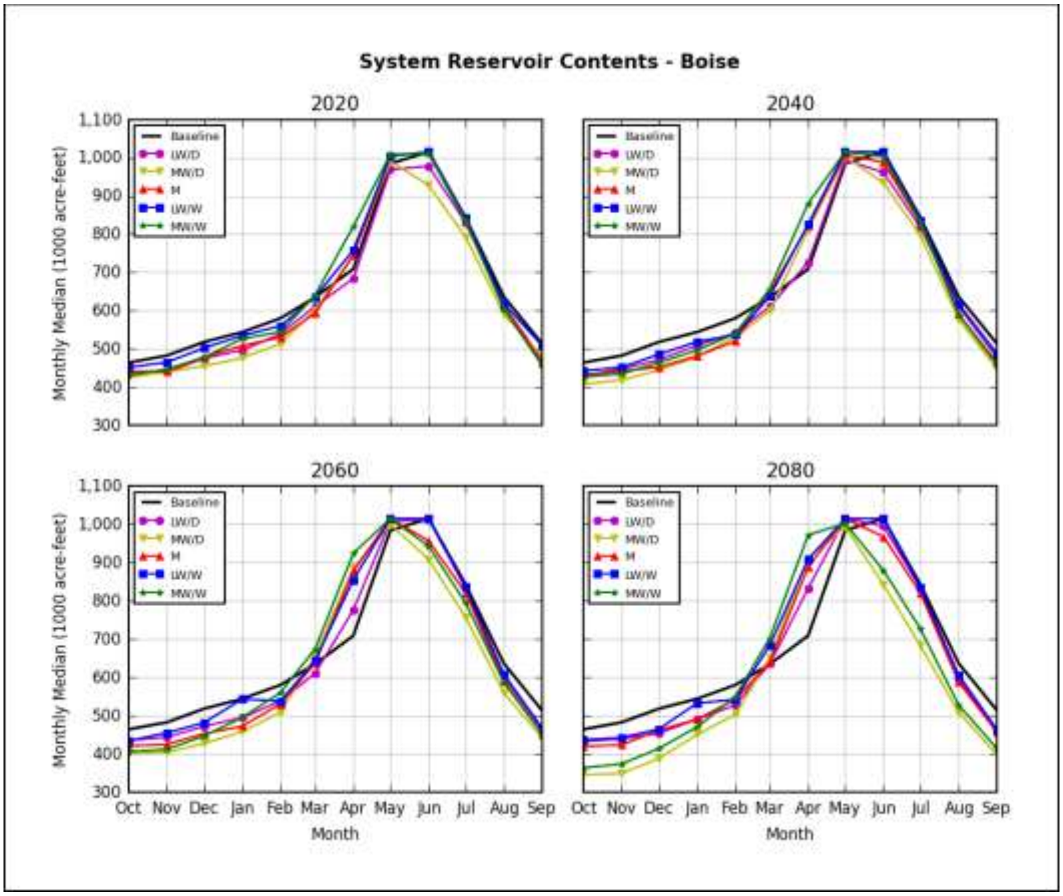

Figure 29. Monthly median of system reservoir contents in the Boise River basin for five simulated future climate change scenarios in four future periods 2020s, 2040s, 2060s, and 2080s.

4.3.2.2.3 Regulated Flow

For the Boise River Basin, modeled regulated future streamflow increased in the spring months under most climate change scenarios from March through May. This is due to the increased and earlier spring runoff, and reservoirs reaching maximum capacity or being constrained by flood control fill targets. As natural system inflows declined through the summer months, so did regulated streamflow, although not by the same amount due to the increased stored water released to satisfy water requests. Through each period, and essentially from drier to wetter scenarios, the number of years that flood stage targets are exceeded is projected to increase across the Boise River Basin (Table 7 and Table 8). This is considered a major impact as development increasingly encroaches upon the Boise River flood plain adding to flood risk and flood management needs.

Table 7. Number of years in the 30-year modeled period when modeled regulated flows on the Boise River at the Glenwood Bridge, Idaho (BIGI) were greater than a flood stage flow of 7,000 cfs.

	Baseline	LW/D	MW/D	Median	LW/W	MW/W
2020	3	2	2	5	9	7
2040	3	5	4	7	10	11
2060	3	7	7	8	8	12
2080	3	9	9	10	11	15

Table 8. Number of years in the 30-year modeled period when modeled regulated flows on the Boise River near Parma, Idaho (PARI) were greater than a flood stage flow of 7,000 cfs.

	Baseline	LW/D	MW/D	Median	LW/W	MW/W
2020	3	4	5	7	10	10
2040	3	7	7	9	11	12
2060	3	10	12	10	12	16
2080	3	12	11	13	15	19

4.3.2.2.4 Requested Water (shortage and natural versus stored flow delivery)

In the Boise River Basin, reductions in requested water were seen for most scenarios as early as the 2020 period in the months of June, July, August, and September. Median level requested water shortages are seen in July in all periods and for nearly all scenarios. Through all periods and scenarios, irrigation delivery is satisfied less by natural flow water rights and increasingly through stored water contracts.

4.3.2.3 Payette River Basin

4.3.2.3.1 System Inflow

For all future periods in the Payette River Basin, inflows were projected to increase in the spring and decrease through the summer. Spring increases occur earlier through each period with peak runoff shifting from May in the 2020 and 2040 period to April or May in the 2060 and 2080 periods depending on the climate change scenario. For all periods and all climate change scenarios, sharp declines in June flows were simulated. Median inflows are less than the Baseline for all periods and all scenarios in the months of June, July, August, and September.

4.3.2.3.2 System Reservoir Contents

Three reservoirs—Payette, Deadwood, and Cascade—were modeled for the system reservoir contents in the Payette River Basin (Figure 30). Due to increased and earlier spring runoff, system reservoir contents continue to refill generally in a higher number of years than the

Baseline, despite reduced carryover storage levels (end of October contents). Outside of the spring refill months, system reservoir contents are lower than the Baseline for every scenario and every period. This is due to the reduced natural streamflow in June, July, August, and September that decreases the amount of irrigation water available to natural flow water rights and increases irrigators' dependency on stored water contracts to satisfy irrigation demand, which in turn reduces median storage levels as identified at other locations. Through each period, and essentially from the drier to the wetter scenarios, the number of years the reservoir system contents filled (850,000 acre-feet) increased across the Payette River Basin.

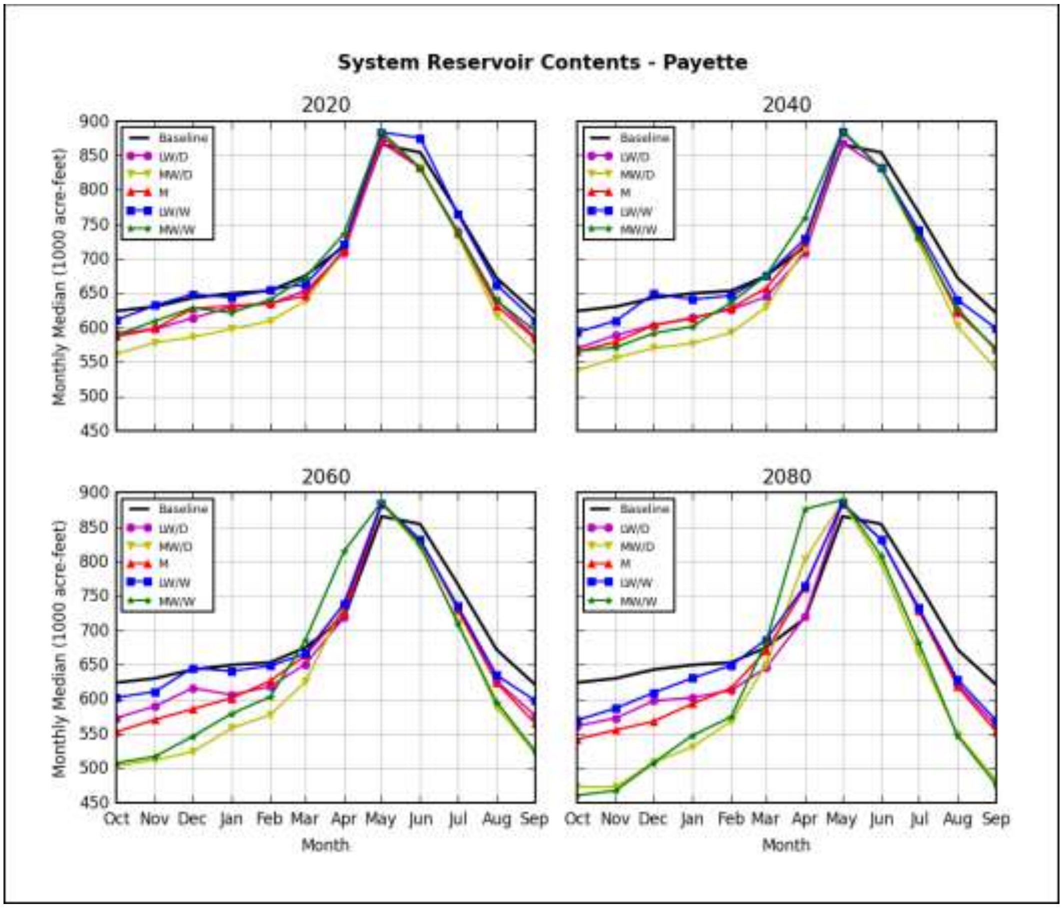

Figure 30. Monthly median of system reservoir contents in the Payette River Basin for five simulated future climate change scenarios in four future periods 2020s, 2040s, 2060s, and 2080s.

4.3.2.3.3 Regulated Flow

For the Payette River Basin, modeled regulated future streamflow increased from roughly February through April. As system inflows declined through the summer months, so did regulated streamflow, although not by the same amount due to the increased stored water released to satisfy water requests. As shown in Figure 31, regulated flows were below flood stage levels for all periods and all scenarios on the Payette River at Horseshoe Bend, Idaho.

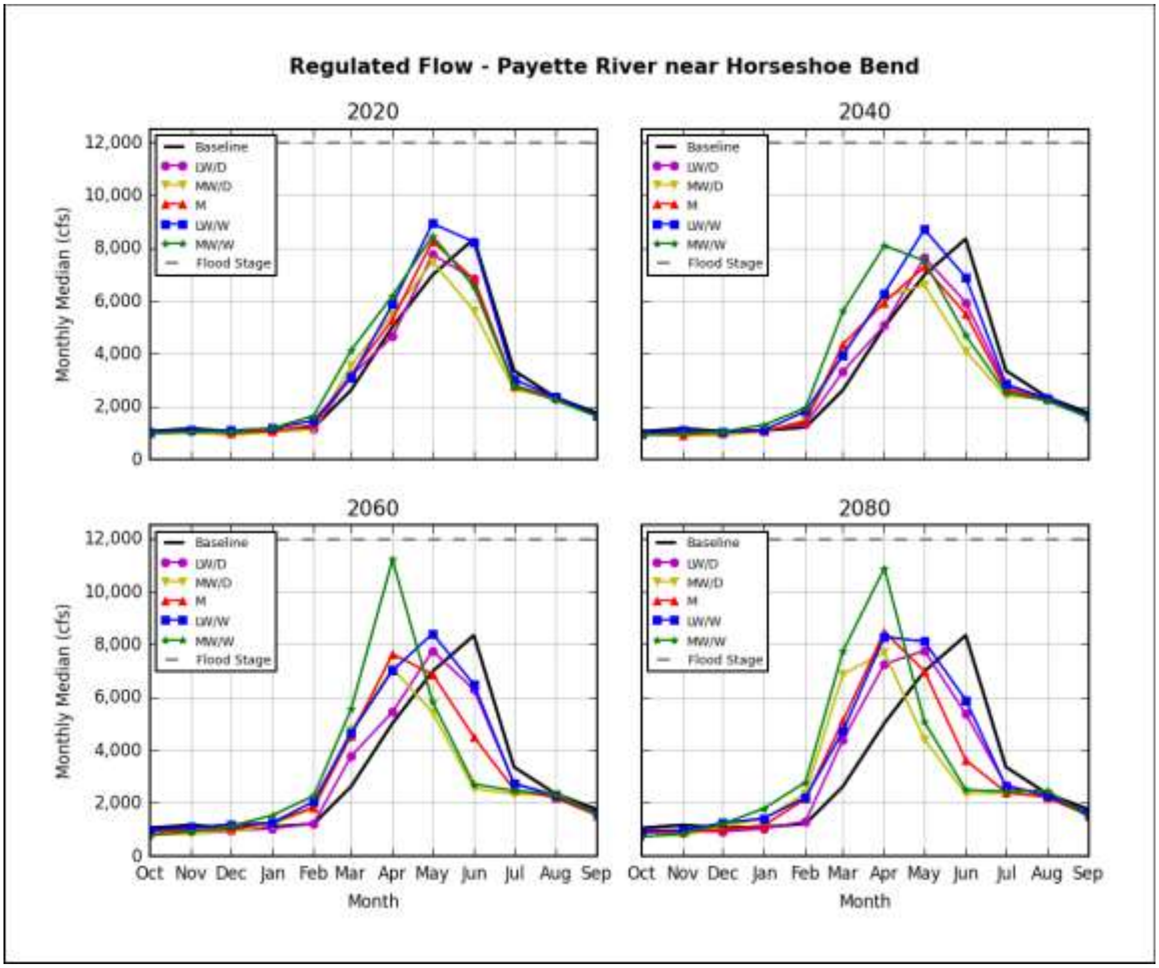

Figure 31. Monthly median regulated flow on the Payette River near Horseshoe Bend, Idaho.

4.3.2.3.4 Requested Water (shortage and natural versus stored flow delivery)

In the Payette River Basin, very little change was seen in requested water for all scenarios across all periods. No water user shortage was seen across all periods and all scenarios. However, as seen in the other basins, demand shortage is minimized or, in this case, eliminated by available storage water contracts. Through all periods and scenarios irrigation delivery is satisfied less by natural flow water rights and increasingly through stored water contracts.

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5 WATER MANAGEMENT IMPLICATIONS OF CLIMATE CHANGE

The following sections summarize the implications of possible climate change impacts based on the hydrologic simulations developed in the Assessment. This information is for use in the management of the Columbia River system via the parameters defined in the SWA.

- Section 5.1 discusses water infrastructure and operations, including reservoir conditions and water delivery and hydropower generation impacts.
- Section 5.2 discusses flood control operations impacts.
- Section 5.3 discusses water quality impacts.
- Section 5.4 discusses fish and wildlife habitat, including environmental flow targets, ESA-listed species, and critical habitat impacts.
- Section 5.5 discusses flow and water-dependent ecological resiliency impacts.
- Section 5.6 discusses impacts to recreation.

5.1 Water and Power Infrastructure and Operations

5.1.1 Hydropower Generation

The FCRPS consists of 31 Federal hydroelectric dams owned by either Reclamation or USACE. Additionally, the Columbia River houses hydroelectric dams owned by Canada, private entities, and others. The anticipated change in runoff patterns (higher flows in the late winter and spring, leading to lower summer flows) identified in this Assessment and also in the RMJOC-1 Study, would result in a change in the regulated outflows from the Projects. The possible increase in late winter and spring flows would lead to higher power generation during that time period. However, the projected reduction in flows in the summer could result in decreased power generation during a period of increased power demand due to higher temperatures caused by climate change (Figure 32 and Figure 33). Wilbanks et al. (2012) found that increases in energy demand are also expected to occur in response to increased groundwater pumping for irrigated agriculture and the pumping and treatment of water for municipal uses. The extent of these increased demands is anticipated to be compounded by the significant population growth in the Pacific Northwest.

In addition, the increase in late winter and spring outflows could result in an increase in the frequency of forced spills[6] at most of the projects, thereby reducing the amount of water available to generate hydropower. It is notable that hydropower operations are affected indirectly when climate change affects air temperatures, humidity, or wind patterns (Bull et al. 2007; as cited in Reclamation 2011, p. 58).

[6] Dam operators are forced to spill water from reservoirs to follow flood control rule curves, or if the reservoir is full.

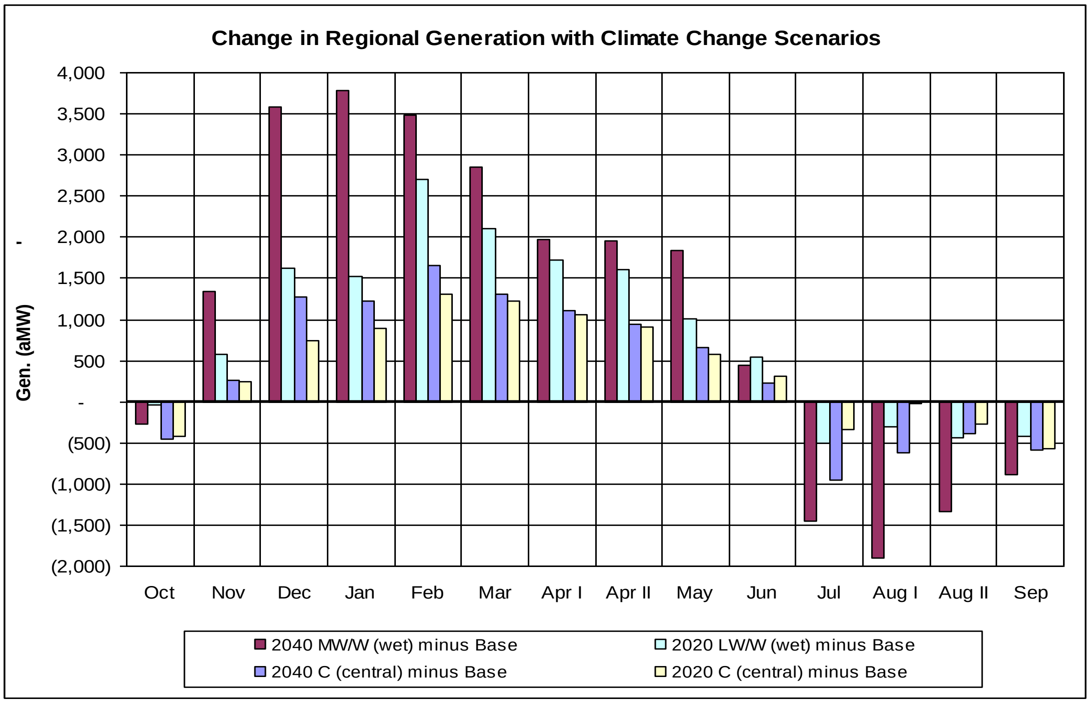

Figure 32. Climate change average changes in regional hydroelectric power generation (RMJOC-1 Part III, 2011). Note that this modeling uses 14 periods instead of 12 in order to produce finer resolution in critical periods.

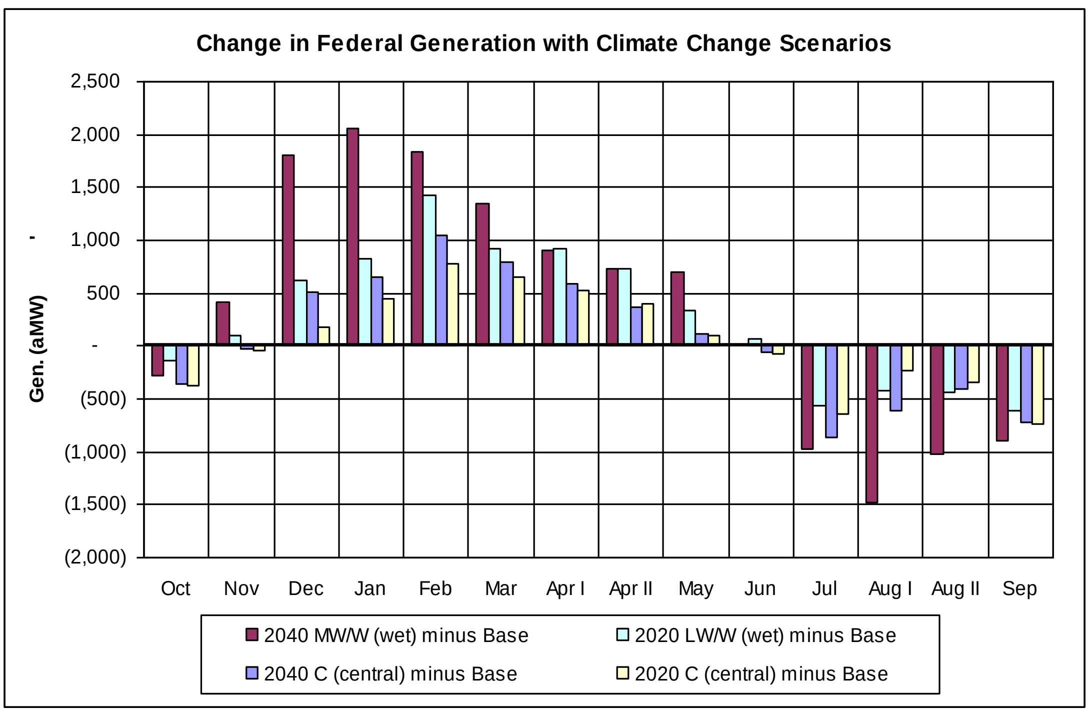

Figure 33. Climate change average changes in Federal hydroelectric power generation (RMJOC-1 Part II, 2011). Note that this modeling uses 14 periods instead of 12 in order to produce finer resolution in critical periods.

Related to the hydropower generation and operations of the FCRPS, work continues for ESA compliance with the ongoing Biological Opinion implementation that includes the completion of the RMJOC-2 Study. Reclamation is working with the USACE to complete the RMJOC-2 Study that is using updated unregulated flows developed during this Assessment for model calibration and streamflow bias correction. The RMJOC-2 Study will be used in the next FCRPS Biological Assessment developed by Reclamation, USACE, and BPA.

5.1.2 Reservoir Conditions and Water Delivery

As identified in section 4.2.1, many reservoir systems in the Columbia River Basin were designed under the assumption that snowpack would serve as a large upstream reservoir, accumulating and storing water through the winter and gradually releasing it during the spring and summer melt. In many locations, changes to seasonal runoff may pose challenges to water management for reservoirs. In particular, challenges may occur as more water comes down rivers during the flood control period (when excess water is considered a hazard). Also, challenges are anticipated in water delivery as less water comes down rivers during the irrigation season (when water is an important economic and ecological asset).

In the climate change models evaluated in this Assessment, the increase in late winter and spring precipitation falling as rain rather than snow would result in reservoirs filling more quickly and at a greater frequency. This characteristic led to a number of periods when project outflows were significantly higher during the late spring period because the reservoirs refilled to full pool too quickly due to early runoff or increased precipitation in the form of rain. Peak flows would occur earlier in the year and possibly necessitate earlier drawdowns[7] of the reservoirs dependent on the increases of winter flows (Appendix A).

The results of this Assessment highlight that future river management procedures would likely need to be revised through a combination of deeper fall and winter reservoir drafting (to better accommodate higher winter flows) and possibly deeper reservoir drafts in the August to September period to compensate for the reduced natural flows in the late summer, which was discussed in Appendix A and Appendix B. Increased drawdowns could also result in lower carryover volumes, thus increasing the potential for water shortages in drought years.

Another consideration is that most water users have both natural flow and stored water rights. Therefore, water users could rely more heavily on groundwater supplies and, most importantly, their stored water rights due to the increased spring runoff that refilled reservoirs such that a portion of the natural flow water right shortages are offset by stored water delivery (Appendix B). However, as natural flows potentially decrease in the summer months, this will put additional demand on the reservoirs, which may result in lower reservoir storage levels at the

[7] Drawdowns are defined as releasing water from reservoirs to lower the water surface levels and decrease the volume of water in the reservoirs, often done in anticipation of high inflows.

end of the irrigation season. A project-specific proactive measure would be to modify reservoir operations before these hydrologic simulations are realized.

Also notable is that, for Reclamation, a significant portion of water delivery is for agricultural purposes. The PN Region Project Team devised two methodologies for evaluating future agriculture diversions—the Total Irrigated Acres method and the Linear Regression method (Appendix C). While the methodologies indicate similar results would be produced, consideration must be given to further understand future crop distribution, irrigated acreages, and system losses. In general, the potential implications of climate change impacts on flows and reservoir operations will directly affect water delivery for agriculture based on the quantity and timing.

Lastly, the Assessment indicates that, among other effects, the effects of climate change on water supplies and reservoir operations could trigger changes in water use (e.g., crop types, cropping dates, environmental flow targets, transfers among different uses, hydropower production, and recreation). Such climate-related changes in water use would interact with market influences on agribusiness and energy management, demographics, land use changes, and other non-climate factors (Reclamation 2011).

5.2 Flood Control Operations

In the mainstem Columbia River, snowpack in the unregulated portions of the basin is referred to as another reservoir for the system and is key to providing adequate irrigation supplies. Climate change could cause fall and winter inflow to reservoirs to increase as a result of more precipitation falling as rain rather than snow. This shift in precipitation type may result in increased downstream flooding due to decreased ability to forecast runoff and larger winter/early spring runoff events. Also, the runoff period may be shorter in duration and higher in magnitude especially in transitional basins making reservoir regulation and flood control operations challenging. In addition, possible increases in early season runoff in high volume water years could contribute to releases earlier in the flood control period (late winter/spring) that could decrease the ability to fill the system if inflows decrease too early following the releases.

Some of the locations analyzed may have operating constraints that limit how quickly Reclamation can draw down the reservoir due to dam safety, downstream safety, or other non-power operational reasons. In addition, it may be desired to limit spill for water quality and power purposes. These constraints will need to be considered if there is a need to draft to the maximum evacuation point earlier in the season (as cited in the RMJOC-1 Part III, 2011, p. 105).

With increased spring system inflow seen in all climate scenarios simulated for the Upper Snake River Basin (Appendix B), there may be increased challenges associated with capturing earlier spring runoff due to spring flood control constraints. In the Snake River Basin above Milner, the simulations show the system contents reach maximum storage capacity in May under the scenarios. However, the duration and magnitude of increased inflows vary based on location and time of year. In general, the results for the month of May indicated system reservoir contents were at their maximum levels and appeared unable to provide any additional flood protection based on the simulations, which use current flood control targets. For example, on the Snake River below Minidoka Dam, Idaho, the WRM was unable to maintain flows below flood stage levels in 21 of 30 years in the MW/W scenario in the 2080 period compared with 4 of 30 years in the Baseline (Appendix B). For project-specific proactive measures, constraints of the WRM could be adjusted to assess potential modifications to reservoir operations before these hydrologic simulations are realized.

5.3 Water Quality

Water quality conditions under climate change depend on several variables including water temperature, flow, runoff rate and timing, and the physical characteristics of the watershed (Lettenmaier et al. 2008; as cited in Reclamation 2011, p. 59). Climate change has the potential to alter all of these variables. Climate change impacts on surface water ecosystems very likely will affect their capacity to remove pollutants and improve water quality; however, the timing, magnitude, and consequences of these impacts are not well understood (Lettenmaier et al. 2008; as cited in Reclamation 2011, p. 59). According to this Assessment, in the summer months there is potential for decreased natural flows and reduced reservoir storage levels due to delivery. These circumstances coupled with higher temperatures could increase water temperatures and negatively affect the aquatic environment.

According to the climate change scenarios for the Columbia River Basin evaluated in this Assessment, the increase in winter and late spring flows could result in higher power generation and increased spill at most dams. This additional spill may increase the total dissolved gas levels below dams that could negatively impact fish. In addition, changes in the amount and timing of flows may increase pollutant delivery, especially sediment, to downstream water bodies.

5.4 Fish and Wildlife Habitat, Including Species Listed under the Endangered Species Act

Assessment results found that water demands for endangered species and other fish and wildlife species could increase with ecosystem impacts due to warmer air and water temperatures and the resulting hydrologic impacts (i.e., runoff timing).

5.4.1 Fish and Wildlife Habitat

Climate change projections in this Assessment are likely to have an array of interrelated and cascading ecosystem impacts with feedbacks to runoff volume, water quality, evapotranspiration, and erosion (e.g., Janetos et al. 2008; Lettenmaier et al. 2008; Ryan et al. 2008). Projections indicate a similar average volume of annual precipitation in the Columbia River Basin system, yet water supplies are anticipated to be lower at various times of the year with similar or increased demands. Climate changes could make environmental river flows more difficult to maintain, which will impact fish and wildlife habitat in the basin.

Other projected impacts are primarily associated with increases in air and water temperatures, especially in the summer months, and include increased stress on fisheries that are sensitive to a warming aquatic habitat; potentially improved habitat for invasive species including quagga mussels (which bear further implications for maintenance of hydraulic structures); and increased risk of watershed vegetation disturbances due to increased fire potential and extent (Melillo et al. 2014). Additional warming-related impacts include poleward shifts in the geographic range of various species, impacts on the arrival and departure of migratory species, amphibian population declines (Reclamation 2011), and an increase in insect outbreaks and tree diseases (Mote et al. 2014).

Specific climate change implications for salmon fisheries in the Pacific Northwest include rising stream temperatures that will likely reduce the quality and extent of freshwater salmon habitat (Mantua et al. 2009). Mantua et al. (2009) also suggest that the duration of periods that cause thermal stress and migration barriers to salmon is projected to at least double by the 2080s which is consistent with other studies in the region (e.g., Battin et al. 2007; as cited in Reclamation 2011, p. 59).

5.4.2 ESA Listed Species

The historic development of the Columbia River Basin has influenced listed species and their habitats, and climate change is likely to exacerbate those impacts. Reclamation currently operates under several biological opinions in the Columbia River Basin, including opinions on the Federal Columbia River Power System, Upper Snake, and Deschutes, Umatilla, Tualatin and Lewiston Orchards Projects and is in consultation about a few other projects. ESA-listed species with habitat in the Columbia River Basin include the following:

Table 9. ESA-listed species with habitat in the Columbia River Basin by species group.

Amphibians • Oregon spotted frog **Birds** • Marbled Murrelet (CH) • Northern spotted owl (CH) • Red knot • Streaked horned lark (CH) • Western snowy plover • Yellow-billed cuckoo **Fish** • Bull Trout (CH) • Chinook Salmon (CH; 5 populations) • Chum salmon (CH) • Coho salmon (CH) • Eulachon • Green sturgeon (CH) • Lahontan Cutthroat Trout • Sockeye salmon (CH) • Steelhead (CH; 5 populations) • White sturgeon (CH) **Mammals** • Canada Lynx • Columbian White Tailed Deer • Gray Wolf • Grizzly Bear • Northern Idaho ground squirrel • Orca • Pygmy Rabbit • Woodland caribou (CH)	**Plants** • Applegate's Milk-vetch • Bradshaw's desert parsley • Golden paintbrush • Howell's Spectacular Thelypody • Kincaid's lupine (CH) • Macfarlane's four-o'clock • Nelson's checkermallow • Showy stickseed • Spalding's catchfly • Umtanum Desert Buckwheat (CH) • Ute Ladies'-tresses • Water Howellia • Wenatchee Mountains Checkermallow (CH) • White bluffs bladderpod (CH) • Willamette Daisy (CH) **Insects** • Fender's blue butterfly (CH) • Taylor's Checkerspot (CH) **Snails** • Banbury springs limpet • Bliss Rapids snail • Bruneau hot springsnail • Snake River physa snail **Reptiles** • Leather back turtle

Notes: CH = Critical Habitat has been designated for the species.

Population = A population of individuals that are more or less alike, and that are able to breed and produce fertile offspring under natural conditions (U.S. Fish and Wildlife Service (USFWS) 2015).

As indicated, total dissolved gas levels due to additional spill could negatively impact listed salmon and steelhead. According to Crozier et al. (2008), several salmon species, especially spring/summer Chinook and sockeye, in the Columbia and Snake River basins could experience increased disease and/or mortality caused by the water quality effects stemming from rising temperatures (as cited in Mote et al. 2014, p. 491). The possible reduced flows during late summer caused by climate change may undercut Federal hydropower system operations' efforts to augment summer flows for migration of listed salmon and steelhead. Another impact to aquatic ecosystems is the potential for increases to winter flood frequency and intensity. According to Hatten et al. 2013, increases in winter flooding would impact incubating eggs and juvenile Coho, Chinook, chum, and steelhead survival. Because of the uncertainties associated with climate change analysis, the full extent of potential impacts on listed species would require further review with this Assessment used as an initial data source.

5.5 Flow- and Water-Dependent Ecological Resilience

Ecological resiliency is generally understood to mean the ability of the ecosystem to recover quickly from anthropogenic (human caused) and natural perturbations (e.g., fire, flood, land, and water uses). As indicated, Reclamation operates under multiple biological opinions along with other documents that require specific actions (e.g., Total Maximum Daily Load, water quality laws) related to ecosystem resiliency. Climate change impacts and trends may require change to current operations to ensure long-term survival of species impacted by changing climate conditions. These operational changes would be conducted through established processes (e.g., ESA consultations).

For Reclamation, the emphasis is on flow and water dependent ecological resiliency, which is primarily fish populations. The impacts to fish populations will largely depend on the resiliency of the aquatic ecosystems and specific species. Though there are multiple species of fish in the Columbia River Basin, Reclamation focuses on salmon and steelhead due to the agency's obligations under the FCRPS Biological Opinion. As indicated, this Assessment will be used through the RMJOC Climate Change Study 2 during the next ESA consultation on FCRPS.

The effects of changing climate on salmon populations depend on the species and life history of interest, local expressions of climate change, characteristics of habitat, and the adaptation of specific populations to geographic variation in habitat characteristics. In addition to the potential for mortality and thermal barriers, another impact from warming in freshwaters is a positive growth response in juveniles, although this will vary substantially with latitude (Schindler and Rogers 2009).

The effects of changes in thermal conditions on salmon populations throughout their range will likely show substantial variation both among and within climatic regions, and among species, populations, and life history strategies. Schindler and Rogers identify protection of biocomplexity of viable habitats and stock diversity as a key to resiliency of aquatic ecosystems in the face of a changing climate. They characterize stock diversity as a system with a high diversity of populations so that their associated dynamics are less sensitive to the variation in an individual population compared to a stock with low diversity (2009).

Several studies have shown the importance of life history variability, or biocomplexity, to the resilience of salmonids in dynamic environments (Rieman and Dunham 2000). Evidence from this work suggests three important elements are necessary for resilience of Pacific salmon in fresh water: (1) the capacity to recover, (2) the diversity of habitats necessary to support the range of salmon life histories, and (3) connectivity. Additionally, Beechie et al. found that restoring floodplain connectivity, restoring streamflow regimes, and re-aggrading incised channels are most likely to improve stream flow and temperature changes and increase habitat diversity and population resilience (2013).

The impacts of climate change and ecological resiliency should also be considered for additional species, such as bull trout, lamprey, other ESA-listed fish species, animals, plants, and other species dependent on the aquatic environment. Reclamation's tributary habitat actions are typically geared to improving salmonid spawning and rearing habitat, providing habitat access, and enhancing instream flows. Reclamation's Columbia Snake Salmon Recovery Office has ongoing work throughout the Columbia River Basin. These efforts should improve spawning and rearing habitat, including providing improved fish passage, refuge from predators, and thermal refugia, all of which could be impacted by, or in some cases help reduce, the potential effects of the projected changes to climate and the hydrologic regime. This Assessment provides a foundational climate change analysis to be used in future efforts related to tributary habitat actions.

Additionally, the Assessment indicates that non-adaptable species may be negatively impacted by climate change. In particular, possible reduced reservoir storage in the late summer and reduced spring runoff due to decreasing snowpack could contribute to reduced river flows. These effects could reduce the ability to buffer the system in extreme years.

5.6 Recreation

The Columbia River Basin offers a number of water-dependent recreational activities, which are likely to be affected by climatic changes that impact the system hydrology. The reservoirs and rivers in the Columbia River Basin provide recreational opportunities such as camping, boating, swimming, fishing, nature study, and hunting. Increased summer and winter temperatures may increase the popularity of these water-based activities. Changes in the hydrologic regime and Project operations may alter the timing of boat ramp availability and flows associated with floating rivers. This is in addition to the impacts to fish and wildlife discussed in previous sections, which will affect the associated recreational hunting, fishing, and wildlife viewing.

As shown in the Assessment, climate change could cause higher spring runoff flows and decreased late summer flows. This change in flows could create unfavorable stream recreation conditions and lead to a shorter season. In addition, climate change impacts identified in the Assessment may cause fluctuations in reservoir water depth and surface acreage, which may affect recreation use and economic value in a variety of ways. For instance, extended periods of low reservoir levels in the late summer may decrease overall visitor numbers.

Water-based recreation is also susceptible to impacts of cascading changes, such as from debris flows caused by rainstorms over fire scars, changing water quality, and changes to species presence/absence and abundance. Such impacts may become more common as the climate becomes hotter. Overall, reduced supplies, altered timing of flows, and increased variability will change the availability and nature of recreational opportunities. While this Assessment provides the high-level impacts to recreation, further analyses will be needed to determine the specific impacts since there are a multitude of recreation sites and areas in the Columbia River Basin.

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6 Summary and Next Steps

6.1 Summary of Possible Impacts

This Assessment provides the initial analysis of climate change impacts to the Columbia River Basin, and it lays a foundation of climate and hydrology data to facilitate more in-depth basin investigations in the future. Further, this Assessment supports 2011 SECURE Report findings projecting warmer temperatures in the Columbia River Basin moving through the 21^{st} century. Additionally, it supports findings that, while the mean amount of annual precipitation is not anticipated to change significantly, its timing is projected to change, with increased precipitation during the cool season and decreased precipitation during the warm season (Reclamation 2011).

In the Assessment it was determined that in “transitional” subbasins where the dominant form of precipitation is neither rain nor snow, but currently a mix of both, impacts of climate change will be more pronounced with the dominant form of precipitation shifting from snow to rain. Such changes are projected to result in increased flows during the winter and decreased flows during the summer. Impacts in rain- and snow-dominant subbasins are projected to be less pronounced. While some snow-dominant subbasins are likely to shift towards transitional conditions (mixed rain and snow dominance), many snow-dominant subbasins currently have winter temperatures well enough below freezing that warming may not cause winter temperatures to cross the freeze/thaw threshold (Appendix A).

Many reservoir systems in the Columbia River Basin were designed under the assumption that snowpack would serve as a large upstream reservoir, accumulating and storing water through the winter and gradually releasing it during the spring and summer melt. In transitional (mixed rain/snow) locations, changes to seasonal runoff may pose challenges to water management as flows increase during the flood control period (when excess water is considered a hazard) and flows decrease during the irrigation season (when water is an important economic and ecological asset).

In the Columbia River Basin, the timing and volume of flows will vary among the subbasins. The potential water management implications for the eight SWA components previously listed will impact each subbasin at different levels. As indicated, this Assessment is intended to provide important information to the water management community in the Columbia River Basin on the scale of the challenges that climate change is likely to pose in the basin, and to identify challenges in the subbasins.

For instance, in the Snake River Basin, the projected increase in spring inflow suggests that reservoirs could refill in a higher number of years than the baseline. However, the anticipated decline of system inflows in the late summer could lower carryover levels due to increased system demand and delivery of stored water during the summer. After reviewing this Assessment data, Snake River Basin water managers could consider modified operations to ensure adequate water storage despite the projected shifts in runoff timing caused by climate change.

This Assessment generated high-level analysis over the Columbia River Basin on the projected impacts of climate change in the basin, and how those impacts relate to water supply, storage, and delivery. The Assessment serves to guide Reclamation and its stakeholders in identifying areas where climate change is projected to have near- and long-term impacts. Table 10 below summarizes the possible impacts of climate change on the eight SWA resource categories. In particular, these impacts are outlined in terms of their overall 21st century possible impacts and their contributing factors. Lastly, as seen in the far right column of Table 10, this Assessment offers some potential next steps for Reclamation and water resource managers to consider.

Table 10. Summary of Possible Impacts by SWA Resource Category.

SWA Resource Category	Overall 21st Century Possible Impacts	Contributing Factors	Potential Next Steps
Hydropower Generation	Possible increased power generation in late winter and spring	The possible increase in late winter and spring flows could result in higher power generation during that time period	Use Assessment as part of the Infrastructure Investment Strategy for hydropower modernization
	Possible decreased generation in the summer	Lower flows in the summer could result in decreased power generation during a period of increased demand due to higher temperatures	
Reservoir Conditions and Water Delivery	Potential to increase fill of reservoirs during spring runoff	The possible increase of precipitation falling as rain rather than snow would result in reservoirs filling more quickly and at a greater frequency with less water (runoff) available in the late summer; the increased ability to fill storage may help reduce overall water delivery shortages	Update and refine climate change analysis for specific locations or future actions Conduct Basin Study in subbasins with near-term impacts indicated Use Assessment data to refine analysis for feasibility studies

SWA Resource Category	Overall 21st Century Possible Impacts	Contributing Factors	Potential Next Steps
	Higher reliance on stored water than natural flow	Possible decreased natural flow will place heavier reliance on stored and groundwater supplies earlier in the irrigation season which may result in lower reservoir storage levels at the end of the irrigation season	Conduct Basin Study in subbasins with near-term impacts indicated Use Assessment data to refine analysis for feasibility studies Evaluate future agriculture water needs by using this Assessment to identify locations
Flood Control Operations	Possible increased reservoir discharges during the late winter/spring to follow flood control rule curves	Possible increases in early season runoff in high volume water years could contribute to releases earlier in the flood control period that could decrease the ability to fill the system if inflows decrease too early following the releases	Use Assessment model data to conduct Reservoir Operations Pilot Initiative

SWA Resource Category	Overall 21st Century Possible Impacts	Contributing Factors	Potential Next Steps
	Possible increase in downstream flood risk	The possible increase in precipitation falling as rain rather than snow may result in increased downstream flooding due to decreased ability to forecast runoff and larger winter/early spring runoff events. The runoff period may be shorter in duration and higher in magnitude in transitional basins making reservoir regulation and flood control operations challenging	If the Infrastructure Investment Strategy applies, use Assessment information
Water Quality	Possible increased water temperature	Possible climate warming and reduced reservoir storage during the hottest months could contribute to increased water temperatures	Conduct Basin Study in subbasins with near-term impacts indicated If the Infrastructure Investment Strategy applies, use Assessment information Do basin-specific water quality modeling for Columbia River Basin subbasin locations that indicate near-term climate impacts

SWA Resource Category	Overall 21st Century Possible Impacts	Contributing Factors	Potential Next Steps
	Possible increased total dissolved gas (TDG)	The potential increase in flood control season flows could result in increased spill, which could contribute to increased TDG content below dams	If the Infrastructure Investment Strategy applies, use Assessment information Do basin-specific water quality modeling for Columbia River Basin subbasin locations that indicate near-term climate impacts
Fish and Wildlife Habitat	Possible decreased summer flow	Climate change results indicate a similar average volume of annual precipitation, yet water supplies are anticipated to be lower at various times of the year with similar or increased demands. It could likely be difficult to maintain environmental flows in the summer months which would negatively impact fish and wildlife habitat	Conduct Basin Study in subbasins with near-term impacts indicated Refine Assessment models for environmental compliance analysis
ESA Listed Species	Adult Salmonid Migration – Potential negative impacts in summer months	The possible reduced flows during late summer may undercut Federal agencies' efforts to augment summer flows	Conduct Basin Study in subbasins with near-term impacts indicated

SWA Resource Category	Overall 21st Century Possible Impacts	Contributing Factors	Potential Next Steps
			Refine Assessment models for Biological Assessments
	Incubating eggs and juvenile Coho, chum, Chinook, and steelhead survival – Potential negative impacts in winter months	The possible increase in winter flooding due to more rain than snow could disrupt critical habitat	Conduct Basin Study in subbasins with near-term impacts indicated
Flow and Water Dependent Ecological Resilience	Non-adaptable species may possibly be negatively impacted	Possible reduced reservoir storage in the late summer and reduced spring runoff due to decreasing snowpack could contribute to reduced river flows, which could reduce the ability to buffer the system in extreme years	Use LCC Partnerships for additional research Conduct Basin Study in subbasins with near-term impacts indicated
Recreation	Possible decrease in reservoir recreation season	Possible lower reservoir levels in the late summer could impact the surface area available for recreation	Conduct Basin Study in subbasins with near-term impacts indicated
	Possible decrease in stream recreation season	Higher spring runoff flows and decreased late summer flows could create unfavorable stream recreation conditions leading to a shorter season	

6.2 Next Steps and Future Uses of Assessment Information

The summary above provided the Columbia River Basin-wide potential impacts of climate change while the overall Assessment establishes a foundation for Reclamation and stakeholders to further develop more in-depth climate change analyses, climate change tools, and adaptation strategies. This final section of the Assessment identifies the potential next steps and future uses of the information provided throughout this document and in the appendices.

6.2.1 GIS Coordination and Data Management

As part of this Assessment, use of technology was determined advantageous to sharing climate change information and data for further climate change analyses. The GIS Coordination and Data Management Technical Memorandum in Appendix D describes using a GIS platform to achieve this objective. In the future, the file-based data management strategy, the Dublin Core metadata procedure, and delivery of data with web mapping technology can all be replicated by Reclamation offices west-wide to conduct Basin Studies or similar climate Impact Assessments.

6.2.2 Additional Climate Change Analysis and Hydrologic Modeling

Surface Water and Reservoir Storage

As demonstrated by the comparison of the RMJOC-1 Study results and the results of this Assessment, there will continue to be opportunities to update and refine climate change analysis efforts in terms of methodology (i.e. climate change scenario development), technology (i.e. model formulation and calibration), and data availability. Improvements in any of these areas will help water managers prepare for future impacts of climate change. For example, the Assessment model data will be used in the upcoming RMJOC-2 Study, which is the update to the RMJOC-1 Study.

Integrating climate change flows into other modeling activities is a significant (requiring ample time and resources), yet important step in gaining understanding of how a project or activity will function over time and into the future. This Assessment provides a foundation of model data and reduces time and resource needed for future Columbia River Basin climate change analysis. A potential next step is to apply climate change scenario streamflows (VIC Routed Flow) to specific Columbia River Basin projects or activities, such as a feasibility study. Such a task will require that flows be generated at spatial and temporal scales relevant to the specific impacts models that will use such flows. Impacts models may also need to be modified to accept these flows as input and to generate modified flows suitable for use by other Reclamation activities (i.e. design projects, geomorphic assessments, and planning activities). This will be of increased importance as climate change analysis becomes more prevalent in all Reclamation activities.

Project-specific proactive measures could be taken such as adjusting the constraints of the WRM to assess potential modifications of reservoir operations before these hydrologic simulations are realized. Section 6.2.5 provides a specific step that is being taken to increase water management flexibility. Additional next steps are provided through the WaterSMART Basin Study Program described in Section 6.2.4.

Groundwater

In this Assessment, it was indicated that more research is needed to identify a cutoff ratio above which a model with lateral groundwater transport should be considered. The VIC model is the current standard tool for developing future hydrologic flows in the Columbia River Basin and it is limited in its ability to simulate runoff in basins that have a large baseflow or groundwater component. Groundwater assessments should be conducted for specific basins as there is a large variability in subbasin groundwater systems within the Columbia River Basin. As such, it is not realistic to consider developing a single tool that addresses the entire Columbia River Basin. Instead, potential next steps should focus on developing more detailed models for groundwater subbasins. An example is the alternate tool, GSFlow, which has been chosen to develop future climate flows for the Upper Deschutes River for the currently on-going Upper Deschutes Basin Study.

6.2.3 Agriculture Diversion

The use of the two methods described in this Assessment for identifying future irrigation diversions both assumed current crop distribution, irrigated acreages, and system losses will remain the same under future conditions. To further understand future irrigation diversions, potential work involves a number of tasks with the initial tasks as follows:

- Perform a west-wide analysis on system losses to determine which systems may be more or less sensitive to changes in NIWR.
- Collect and aggregate current irrigated lands spatial data and associate that data with diversion points in water resources models.
- Develop methods that could be used to predict changes to crop distribution, irrigation practices, and land use that may result from future climate conditions.

6.2.4 WaterSMART Basin Study Program Activities

While this Assessment allows Reclamation to fulfill requirements under the SWA to better understand how its facilities, operations, and water delivery commitments to its customers may be affected by climate change, it also establishes a baseline characterization of how climate change may impact water supply, demand, and key water management activities, as called for in the SWA.

WaterSMART Basin Study Program activities are available for stakeholders to pursue next steps in determining the level of potential climate change impacts and water management implications in a subbasin within the Columbia River Basin. WaterSMART Basin Study Program activities include the following:

- **Landscape Conservation Cooperatives**

  The Basin Study Program includes LCCs. The LCCs are partnerships of governmental (Federal, State, Tribal, and local) and non-governmental entities, and are an important part of the Department of the Interior’s efforts to coordinate climate change science activities and development and resource management strategies.

The Columbia River Basin is part of the Great Northern LCC, Great Basin LCC, and North Pacific LCC. Currently, Reclamation is a steering committee member for the Great Northern LCC.

Reclamation participates in LCCs encompassing the 17 Western states to identify, build capacity for, and implement shared applied science activities to support resource management at the landscape scale. More information on LCCs is available at: http://www.usbr.gov/WaterSMART/lcc/

- **West-Wide Climate Risk Assessments**

  West-Wide Climate Risk Assessments activities include identifying climate change information needs of water resource managers, compiling and analyzing water resources data, and developing tools and guidance for water resource managers. The WWCRAs include the following activities:

  1. Water supply assessments
  2. Water demand assessments
  3. Operational assessments

  Individual basin Impact Assessments, such as this one, provide information on the potential risks of climate change to Reclamation facilities and operations (including water and power delivery, recreation, flood control, and ecological resources), as well as a foundation of climate change data, information, and tools for use in future Basin Studies. WWCRA also performs specific studies on topics, such as irrigation demand and reservoir evaporation that are used in further studies or analysis by Reclamation.

- **Basin Studies**

  Fully understanding risks and impacts of climate change will require a study team to evaluate not just the direct impacts of climate change, as projected in this Assessment, but also the secondary impacts that result from human responses to these changes, and the other developments that will go on with or without climate change. These other changes will need to be evaluated through a collaborative process that includes all of the necessary stakeholders in a basin. Basin Studies provide a framework for this collaborative process, and includes various options for stakeholders to build upon the results from this Assessment.

  Basin Studies are in-depth water supply, demand, and operations analyses that are cost-shared with stakeholders and selected through a competitive process. Through Basin Studies, Reclamation works collaboratively with stakeholders to evaluate the ability to meet future water demands in a particular basin and to identify mitigation and adaptation strategies to address potential climate change impacts. More information about Basin Studies is available at: http://www.usbr.gov/WaterSMART/bsp/

Reclamation will continue to refine the results of this Assessment through detailed Basin Studies. Several WaterSMART Basin Studies have been completed or are currently being conducted in the Columbia River Basin. These include the following:

- **Yakima River Basin**

  The Yakima River Basin Study was completed in 2011 as part of the Yakima Basin Integrated Water Resource Plan (Integrated Plan) in order to understand the water supply and demand issues in the basin. The Integrated Plan addresses water resource and ecosystem issues focusing on seven elements that include fish passage, structural and operational changes to the reservoir system, surface and groundwater storage, habitat protection and enhancement, enhanced water conservation, and market reallocation options. Recent Integrated Plan efforts include fish passage planning and construction at Cle Elum Reservoir, raising the Cle Elum pool, and planning for the Kachess Drought Relief Pumping Plant.

- **Henrys Fork Basin**

  The Basin Study partner, Idaho Water Resource Board, continued efforts from the Basin Study completed in 2014 (released in 2015) with further evaluations of a pool raise at Island Park Reservoir in eastern Idaho. Reclamation continues to be involved with this evaluation.

- **Hood River Basin**

  Recently released in December 2015, partners for this Basin Study continue moving forward with information from this study to address future water supply needs.

- **Willamette River Basin Plan of Study**

  The Plan of Study was completed in September 2014 in partnership with the Oregon Water Resource Department.

- **Upper Deschutes River Basin**

  This Basin Study was initiated in 2014. The Basin Workgroup meets regularly and analyses are currently underway. The workgroup will use information from this Assessment to inform the study. The study is anticipated to be completed in 2017.

All of the existing and proposed activities within the WaterSMART Basin Study Program are complementary and represent a multi-faceted approach to the assessment of climate change risks to water supplies and impacts to activities in Reclamation’s mission. Also, WaterSMART Basin Study Program activities help identify adaptation strategies to meet future water demands.

6.2.5 Reservoir Operations Pilot Initiative

As part of Reclamation’s Climate Change Adaptation Strategy and initiated through WWCRA, the Reservoir Operations Pilot Initiative (Initiative) was identified to increase water management flexibility. As climate change alters the hydrologic regime, reservoir operations may need to be adjusted in order to maintain reliable water deliveries, power generation, support for environmental needs and flood control management. In future years, the Initiative will develop Reclamation guidance for making reservoir operations more flexible to adapt to projected climate impacts.

The Reservoir Operations Team (Team), a Reclamation-wide group of regional reservoir operations experts, planning engineers, climate scientists, and hydrologists was established under this Initiative. The Team has outlined a three step process to identify risks, determine impacts, and formulate alternatives for reservoir operations that will be used in developing the guidance. These three steps will be applied to the selected pilot studies throughout Reclamation that will use information from this Assessment.

For the Pacific Northwest Region, the Crooked River Basin in central Oregon was selected. The Crooked River Basin is in the Deschutes subbasin of the Columbia River Basin. The main features to be analysed are the Crooked River, Ochoco Creek, Prineville Reservoir, and Ochoco Reservoir, along with other ancillary features. This study will be conducted over 2 years and began in January 2016.

6.2.6 Infrastructure Investment Strategy

In May 2015, Reclamation completed its Infrastructure Investment Strategy (Strategy) to provide guidance for addressing infrastructure investments under Reclamation stewardship. Reclamation has maintained long-term partnership with many non-Federal entities and achieved a record of reliability through its preventive maintenance programs and substantial investment in major repair and replacement activities. Additionally, Reclamation has provided reliable service across the West by delivering water and power to meet multiple demands, and adapting to public needs and interests (Reclamation 2015b).

As increasing demands are placed on the existing infrastructure, Reclamation is looking ahead and evolving asset management practices to meet the challenges of maintaining infrastructure that continues to age. The Strategy was developed to improve the data used to support and inform asset management decisions, while addressing a range of emerging issues. The issues identified in the Strategy include the demands of a growing population in the West; new design standards; employee safety improvements; regulatory requirements and operational needs; the effects of a changing climate and associated hydrologic conditions; and new opportunities for improvements in yield, efficiency, and reliability (Reclamation 2015b).

The information generated from this Assessment can be used as a next step for implementation of the Strategy. The Assessment provides initial modeling data and impacts of climate change, and information to assist in many of the other issues listed above. For example, possible hydropower generation timing shifts identified in this Assessment could be used as part of the collaboration and prioritization efforts of the Strategy. The timing of hydropower production could also be a factor in ecosystem demands, navigation, and recreational water uses that should be considered in the potential next step.

6.2.7 Other Climate Change Related Activities

Additionally, other studies, analyses, assessments, and research have been conducted or are currently in progress in the Columbia River Basin and its subbasins. These efforts include the following:

Completed Efforts

Studies

- Boise River Climate Change Study (2009)
- RMJOC Climate Change Study 1 — Parts I–IV (2011)
- Icicle Creek Climate Change Qualitative Analysis (2011)
- Upper Snake River Bull Trout Biological Assessment (2013)

SECURE Water Act

- 2011 Report to Congress (2011)
- Ecosystem Resiliency Guidance (2013)

West-Wide Climate Risk Assessments

- West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections (2011)
- West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Irrigation Demand and Reservoir Evaporation Projections (2015)

Current Efforts

Studies

- SECURE Water Act Report to Congress (anticipated March 2016)
- West-Wide Climate Risk Assessments: Hydroclimate Technical Memorandum (anticipated March 2016)
- RMJOC Climate Change Study 2 (anticipated 2016/2017)

Research

- Climate Analysis Toolkit using HydroDesktop
- Evaluating Future Agricultural Water Needs using Integrated Modeling Methods in the Boise River Basin

7 LITERATURE CITED

Parenthetical Reference	Bibliographic Citation
Barton et al. 2012	Barton, J.D. and K. Ketchum. 2012. *The Columbia River Treaty: Managing for Uncertainty*. The Columbia River Treaty Revisited.
Battin et al. 2007	Battin, J., M.W. Wiley, M.H. Ruckelshaus, R.N. Palmer, E. Korb, K.K. Bartz, and H. Imaki. 2007. *Projected impacts of climate change on salmon habitat restoration.* Proceedings of the National Academy of Sciences 104(16): 6720–6725.
Beechie et al. 2013	Beechie, T., H. Imaki, J. Greene, A. Wade, H. Wu, G. Pess, P. Roni, J. Kimball, J. Stanford, P. Kiffney, and N. Mantua 2013. *Restoring salmon habitat for a changing climate*. River Res. Applic., 29: 939–960. doi: 10.1002/rra.2590
BPA 2001	Bonneville Power Administration. 2001. *The Columbia River System Inside Story*, 2nd addition. Prepared for the Federal Columbia River Power System Operation Review: Bonneville Power Administration, U.S. Bureau of Reclamation, and U.S. Army Corps of Engineers. April 2001.
Bull et al. 2007	Bull, S.R., D.E. Bilello, J. Ekmann, M.J. Sale, and D.K. Schmalzer. 2007. *Effects of climate change on energy production and distribution in the United States. Effects of Climate Change on Energy Production and Use in the United States.* A report by the U.S. Climate Change Science Program and the subcommittee on Global Change Research. Washington, DC.
Bureau of Reclamation.	See Reclamation.

Parenthetical Reference	Bibliographic Citation
Crozier et al. 2008	Crozier, L.G., A.P. Hendry, P.W. Lawson, T.P. Quinn, N.J. Mantua, J. Battin, R.G. Shaw, and R.B. Huey. 2008: *Potential responses to climate change in organisms with complex life histories: Evolution and plasticity in Pacific salmon.* Evolutionary Applications, 1, 252-270, doi:10.1111/j.1752-4571.2008.00033.x. [Available online at http:// onlinelibrary.wiley.com/doi/10.1111/j.1752-4571.2008.00033.x/ pdf]
Daly et al. 2004	Daly, C., W.P. Gibson, M. Doggett, J. Smith, and G. Taylor. 2004. *Up-to-date monthly climate maps for the conterminous United States. Proc.* 14th AMS Conf. on Applied Climatology, 84th AMS Annual Meeting Combined Preprints, Amer. Meteorological Soc., Seattle, Washington, January 13–16, 2004, Paper P5.1, CD-ROM.
Gibson et al. 2002	Gibson, W.P., C. Daly, T. Kittel, D. Nychka, C. Johns, N. Rosenbloom, A. McNab, and G. Taylor. 2002. *Development of a 103-year high-resolution climate data set for the conterminous United States.* Proc., 13th MS Conf. on Applied Climatology, Amer. Meteorological Soc., Portland, Oregon, May 13–16, 181–183.
Gutowski et al. 2008	Gutowski, W.J., G.C. Hegerl, G.J. Holland, T.R. Knutson, L.O. Mearns, R.J. Stouffer, P.J. Webster, M.F. Wehner, and F.W. Zwiers. 2008. *Causes of Observed Changes in Extremes and Projections of Future Changes in Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands.* T.R. Karl, G.A. Meehl, C.D. Miller, S.J. Hassol, A.M. Waple, and W.L. Murray (Eds.). A report by the U.S. Climate Change Science Program and the subcommittee on Global Change Research. Washington, DC.
Hatten et al. 2013	Hatten, J.R., T.R. Batt, P. J. Connolly, and A.G. Maule. 2013. *Modeling effects of climate change on Yakima River salmonid habitats.* Climate Change. 124:427-439.

Parenthetical Reference	Bibliographic Citation
Janetos et al. 2008	Janetos, A., L. Hansen, D. Inouye, B.P. Kelly, L. Meyerson, B. Peterson, and R. Shaw. 2008. Biodiversity. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC.
Knowles et al. 2007	Knowles, N., M. Dettinger, and D. Cayan. 2007. *Trends in Snowfall Versus Rainfall for the Western United States, 1949–2001*. Prepared for California Energy Commission Public Interest Energy Research Program, Project Report CEC-500-2007-032.
Lettenmaier et al. 2008	Lettenmaier, D., D. Major, L. Poff, and S. Running. 2008. Water Resources. *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States*. A report by the U.S. Climate Change Science Program, Washington, DC.
Livneh et al. 2013	Livneh, B., E.A. Rosenberg, C. Lin, B. Nijssen, V. Mishra, K.M. Andreadis, E.P. Maurer, and D.P. Lettenmaier. 2013. *A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States: Update and Extensions.* J. Climate, 26.
Luce and Holden 2009	Luce, C.H. and Z.A. Holden. 2009. *Declining annual streamflow distributions in the Pacific Northwest United States, 1948-2006.* Geophysical Research Letters. 36: L16401. doi:10.1029/2009GL039407. 6 pp.
Mantua et al. 2009	Mantua, N.J., I. Tohver, and A.F. Hamlet. 2009. *Impacts of climate change on key aspects of freshwater salmon habitat in Washington State.* Chapter 6 in The Washington Climate Change Impacts Assessment: Evaluating Washington’s Future in a Changing Climate. Climate Impacts Group, University of Washington, Seattle, Washington.
Mantua et al. 2010	Mantua, N., I. Tohver, and A. Hamlet. 2010. *Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State.* Climatic Change, 102, 187-223, doi:10.1007/ s10584-010-9845-2.

Parenthetical Reference	Bibliographic Citation
Maupin et al. 2014	Maupin, M.A., Kenny, J.F., Hutson, S.S., Lovelace, J.K., Barber, N.L., and Linsey, K.S. 2014. *Estimated use of water in the United States in 2010*. U.S. Geological Survey Circular 1405, 56 p., http://dx.doi.org/10.3133/cir1405
Melillo et al. 2014	Melillo, J.M., T.C. Richmond, and G.W. Yohe (Eds.). 2014. *Climate Change Impacts in the United States: The Third National Climate Assessment, Full Report*. U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2.
Mote et al. 2014	Mote, P., A.K. Snover, S. Capalbo, S.D. Eigenbrode, P. Glick, J. Littell, R. Raymondi, and S. Reeder. 2014. Chapter 21: Northwest. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M. Melillo, T.C. Richmond, and G.W. Yohe (Eds.). U.S. Global Change Research Program, 487-513. doi:10.7930/J04Q7RWX.
Oregon Climate Change Research Institute 2010	Oregon Climate Change Research Institute. 2010. *Oregon Climate Assessment Report*. K.D. Dello and P. W. Mote (Eds). College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon. December 2010.
Pacific Institute 2009	Pacific Institute. 2009. *Water Scarcity & Climate Change: Growing Risks for Business and Investors*. A Ceres Report. Boston, Massachusetts.
Parmesan 2006	Parmesan, C. 2006. *Ecological and Evolutionary Responses to Recent Climate Change*. Annual Review of Ecology, Evolution, and Systematics, 37, 637-669, doi:10.1146/annurev.ecolsys.37.091305.110100. [Available online at http://www.jstor.org/stable/pdfplus/30033846.pdf]
Reclamation 2011	Bureau of Reclamation. 2011. SECURE Water Act Section 9503(c) – *Reclamation Climate Change and Water Report to Congress 2011*. Prepared by U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Office of Policy and Administration, Denver, Colorado. April 2011.

Parenthetical Reference	Bibliographic Citation
Reclamation 2015a	Bureau of Reclamation. 2015. *West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Irrigation Demand and Reservoir Evaporation Projections.* Technical Memorandum No. 86-68210-2014-01. Prepared by U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Water Resources Planning and Operations Support Group, Denver, Colorado and Desert Research Institute, Division of Hydrologic Sciences, Reno, Nevada. February 2015.
Reclamation 2015b	Bureau of Reclamation. 2015. *Infrastructure Investment Strategy*. Prepared by U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado. May 2015.
Regonda et al. 2005	Regonda, S.K., B. Rajagopalan, M. Clark, and J. Pitlick. 2005. *Seasonal Cycle Shifts in Hydroclimatology Over the Western United States.* Journal of Climate 18(2): 372–384.
Rieman and Dunham 2000	Rieman, B.E. and J.B. Dunham. 2000. *Metapopulation and salmonids: a synthesis of life history patterns and empirical observations.* Ecology of Freshwater Fish 9:51-64.
RMJOC-1 2011	River Management Joint Operating Committee Climate Change Study Reports, Parts I–IV. 2011. U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, and Bonneville Power Administration. *Climate and Hydrology Datasets for Use in the RMJOC-1 Climate Agencies' Longer-Term Planning Studies.* 2010–2011.
RMJOC-1 Part I, 2010	River Management Joint Operating Committee Climate Change Study Report. 2010. U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, and Bonneville Power Administration. *Climate and Hydrology Datasets for Use in the River Management Joint Operating Committee Climate Agencies' Longer-Term Planning Studies: Part I - Future Climate and Hydrology Datasets.* December 2010.

Parenthetical Reference	**Bibliographic Citation**
RMJOC-1 Part II, 2011	River Management Joint Operating Committee Climate Change Study Report. 2011. U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, and Bonneville Power Administration. *Climate and Hydrology Datasets for Use in the RMJOC Climate Agencies' Longer-Term Planning Studies: Part II - Reservoir Operations Assessments for Reclamation Tributary Basins.* January 2011.
RMJOC-1 Part III, 2011	River Management Joint Operating Committee Climate Change Study Report. 2011. U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, and Bonneville Power Administration. *Climate and Hydrology Datasets for Use in the RMJOC-1 Climate Agencies' Longer-Term Planning Studies: Part III - Reservoir Operations Assessment: Columbia Basin Flood Control and Hydropower.* May 31, 2011.
Ryan et al. 2008	Ryan, M., S. Archer, R. Birdsey, C. Dahm, L. Heath, J. Hicke, D. Hollinger, T. Huxman, G. Okin, R. Oren, J. Randerson, and W. Schlesinger. 2008. Land Resources. In: *The effects of climate change on agriculture, land resources, water resources, and biodiversity.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC. 362 pp.
Schindler and Rogers 2009	Schindler, D. and L. Rogers. 2009. *Responses of salmon populations to climate variation in freshwater ecosystems.* Pages 1127-1142 in C.G. Krueger and C.E. Zimmerman (Eds.). Arctic-Yukon-Kuskokwim Sustainable Salmon Initiative. American Fisheries Society Symposium.
Stöckle et al. 2010	Stöckle, C.O., R.L. Nelson, S. Higgins, J. Brunner, G. Grove, R. Boydston, M. Whiting, and C. Kruger. 2010. *Assessment of Climate Change Impact on Eastern Washington Agriculture.* Climatic Change, 102, 77-102, doi:10.1007/s10584-010-9851-4.
U.S. Census Bureau 2011	U.S. Census Bureau. 2011. *Population Distribution and Change: 2000 to 2010.* 2010 Census Briefs. March 2011.

Parenthetical Reference	Bibliographic Citation
USFWS 2015	U.S. Fish and Wildlife Service. 2015. U.S. Fish and Wildlife Service, Midwest Region website. Endangered Species Glossary. http://www.fws.gov/Midwest/endangered/glossary/index.html (Accessed January 2016).
USGS 2013	U.S. Geological Survey. 2013. *Groundwater Depletion in the United States (1900-2008).* USGS Scientific Investigations Report 2013-5079.
U.S. National Research Council 2004	U.S. National Research Council. 2004. *Managing the Columbia River: Instream Flows, Water Withdrawals, and Salmon Survival*. The National Academies Press, Washington, DC.
Wilbanks et al. 2012	Wilbanks, T., D. Bilello, D. Schmalzer, and M. Scott. 2012. *Climate Change and Energy Supply and Use*. Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment. 79 pp. Oak Ridge National Laboratory, U.S. Department of Energy, Office of Science, Oak Ridge, Tennessee.

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8 APPENDICES

Appendix A: Climate Change Analysis and Hydrologic Modeling

Appendix B: Water Resources Model

Appendix C: Determining Agricultural Diversions for Use in Water Resources Models

Appendix D: GIS Coordination and Data Management

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RECLAMATION
Managing Water in the West

APPENDIX A

West-Wide Climate Risk Assessment

Columbia River Basin

Climate Impact Assessment

Technical Memorandum: Climate Change Analysis and Hydrologic Modeling

U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Regional Office

March 2016

Mission Statements

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.

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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1 INTRODUCTION

1.1 Project Background

The Bureau of Reclamation (Reclamation) is taking a leading role in assessing the risks and impacts of climate change to Western U.S. water resources, and in working with stakeholders to identify climate change adaptation strategies. Adequate and safe water supplies are fundamental to the health of citizens, strength of the economy, and protection of the environment and ecology in the Western U.S. Global climate change poses a significant challenge to the protection of these resources.

Section 9503 of the SECURE Water Act, Subtitle F of Title IX of P.L. 111-11 (2009) (SWA), authorizes Reclamation to evaluate the risks and impacts of climate change in western river basins and to work with stakeholders to identify climate change adaptation strategies. The Columbia River Basin was one of the major Reclamation river basins identified for evaluation in the SWA. The purpose of this Columbia River Basin Impact Assessment (Assessment) (under the WaterSMART Basin Study Program West-Wide Climate Risk Assessments) is to generate reconnaissance-level hydrologic data and analysis on the potential effects of climate change in the basin, and how those effects relate to water supply and demand.

This technical memorandum describes the process that was used to develop future climate scenarios and generate corresponding future streamflow datasets for use in Reclamation's water resource models.

1.2 Purpose and Scope

The purpose of this Technical Memorandum (TM) is to document the climate change analysis and hydrologic modeling used to generate future flows for this Assessment. This process (illustrated in Figure 1.1) consisted of three major steps:

1. Development of climate adjusted meteorological data (for each climate change scenario and future period) using observed climate data (Livneh et al. 2013) and bias-corrected spatially-downscaled future climate model projections (Reclamation 2014).
2. Hydrologic modeling to generate simulated streamflows given the meteorological data developed for each scenario and period in Step 1.

3. Bias correction of simulated streamflows. This step utilized a quantile mapping approach to statistically remove model bias from the simulated streamflow based on a comparison of simulated streamflows and historical unregulated[1] streamflows.

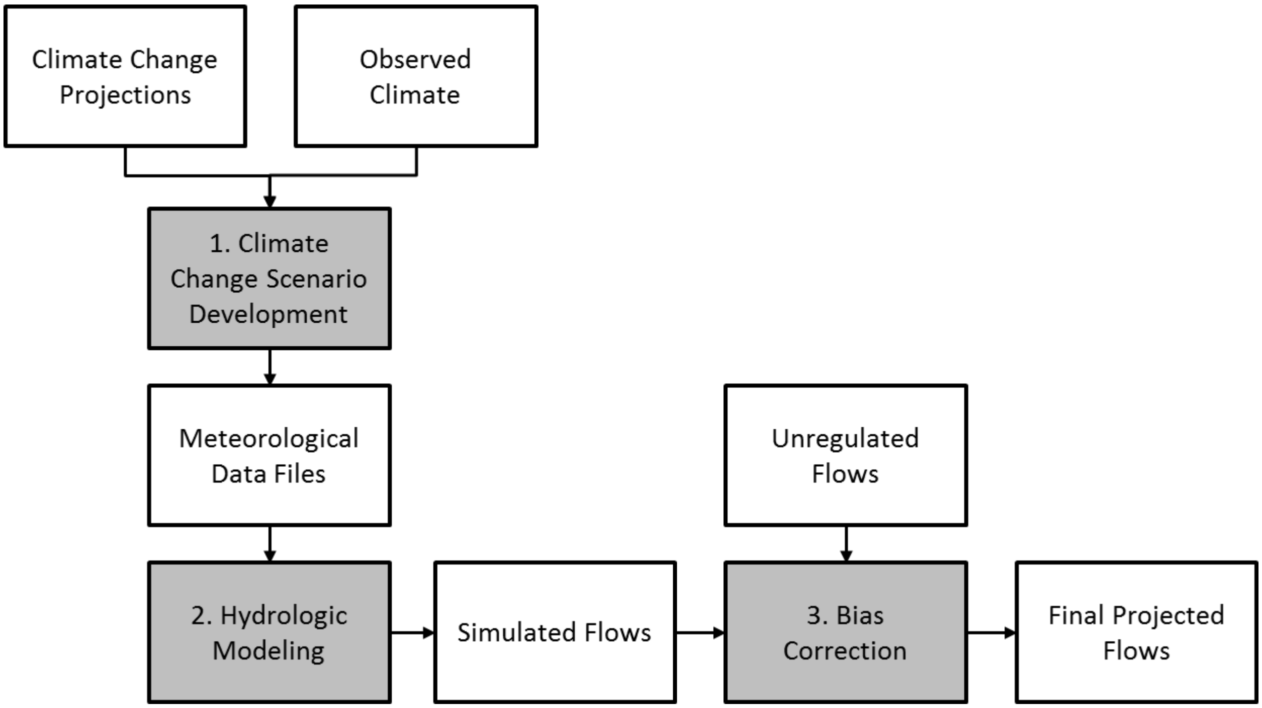


Figure 1.1 Climate change analysis and hydrologic modeling workflow.

[1] Using observed data for streamflow, diversion, and reservoir contents, Reclamation worked collaboratively with the U.S. Army Corps of Engineers to develop unregulated flows at locations throughout the Columbia River Basin.

2 METHODS

2.1 Climate Scenario Development

2.1.1 Climate Projection Datasets

Gridded climate projection datasets (231 projections spanning the years 1950 to 2099) were downloaded directly from the Bias Corrected and Spatially Downscaled (BCSD) CMIP5 Climate and Hydrology Projections (DCHP) archive hosted by the Lawrence Livermore National Laboratory (http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/). These monthly 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). Generally speaking, the downscaled climate model projections used in this study indicate increasing trends in temperature and precipitation in the Pacific Northwest over time. Figure 2.1 and Figure 2.2 illustrate these trends over the Columbia River Basin and the range of predictions (the projection envelope) provided by the 231 BCSD CMIP5 projections. Given the spread of the 231 projections and the assumption that each of these projections are equally likely to occur[2], future climate scenarios (discussed in the next section) were developed using an approach that sampled the range of potential outcomes.

[2] In reality, some of GCM models perform better than others in their ability to reproduce historical climate patterns over a particular area. There is ongoing research under the RMJOC Climate Change Study 2 to identify which models perform the best in the Pacific Northwest and would be best suited

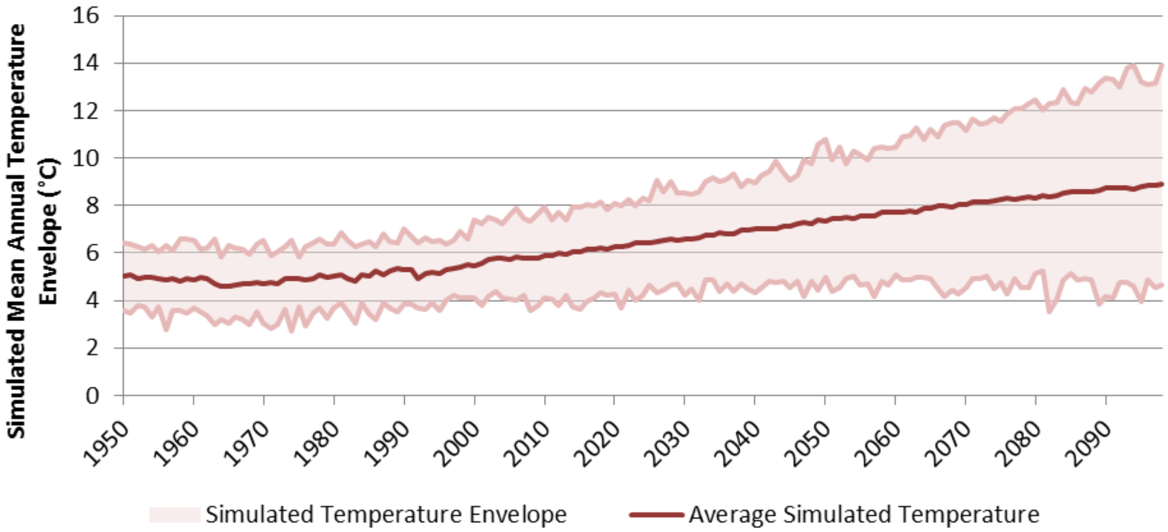


Figure 2.1 CMIP5 231-member ensemble envelopes of mean annual temperature for the Columbia River Basin from 1950-2099.

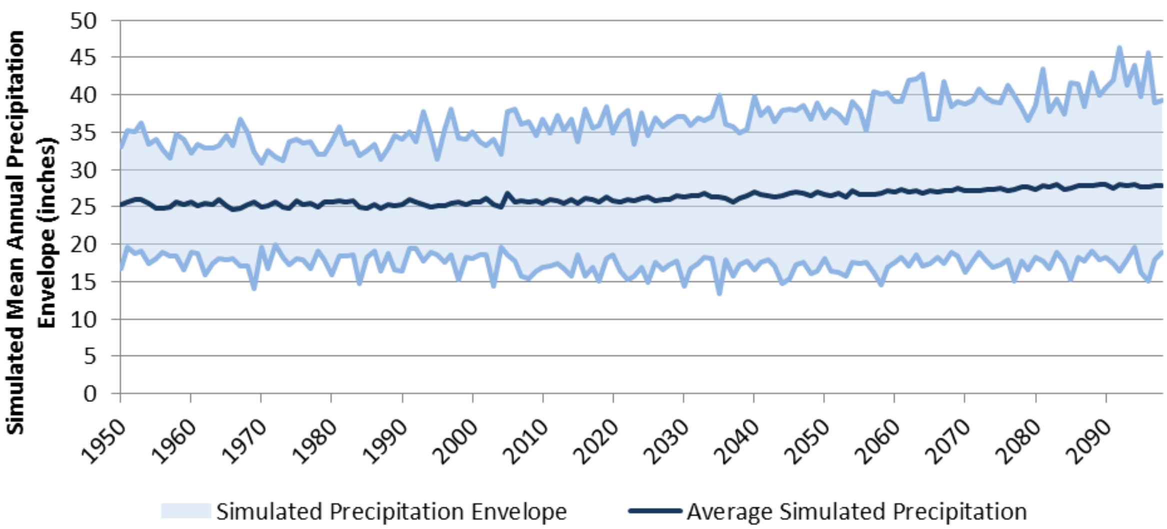


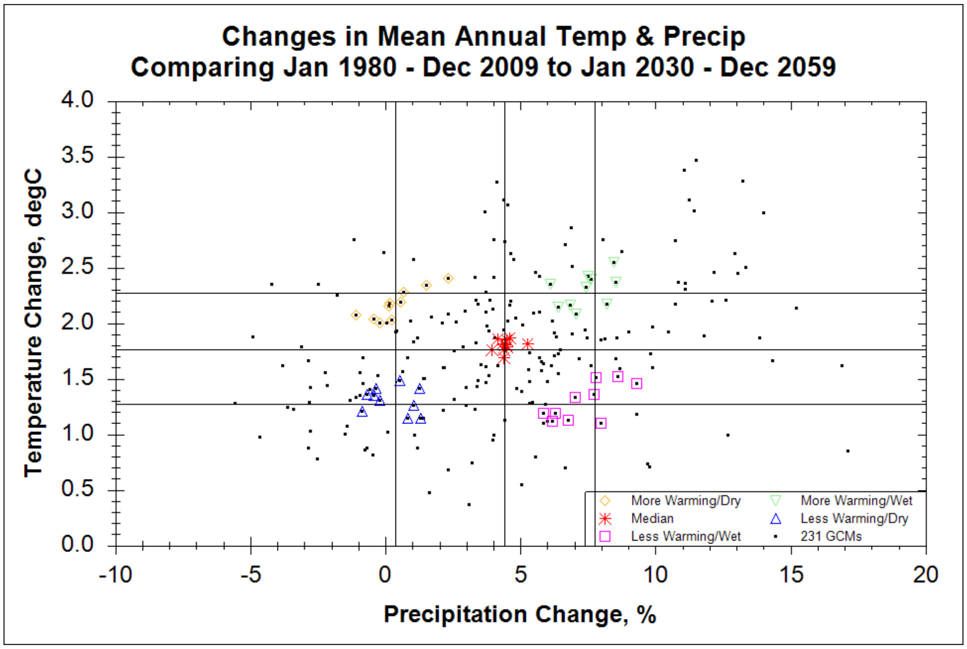
Figure 2.2 CMIP5 231-member ensemble envelopes of mean annual precipitation for the Columbia River Basin from 1950-2099.

2.1.2 Climate Scenario Development

Climate change scenarios (five scenarios for each of the four future periods) were developed using the Hybrid Delta Ensemble (HDe) approach. This method has been used in other recent studies (including the Hood River Basin Study) and is discussed in more detail in the Climate Change and Hydrology Scenarios for Oklahoma Yield Studies technical memorandum (Reclamation 2010). This approach uses select groups (or ensembles) of downscaled global climate model (GCM) projections to calculate monthly change factors arranged by quantile which can then be used to adjust daily gridded meteorological datasets for input to a hydrologic model.

For each future period considered in this Assessment (including the 2020s, 2040s, 2060s, and 2080s[3]), 10-member projection ensembles were selected to characterize the 20^{th}-, 50^{th}-, and 80^{th}-percentile changes in temperature and precipitation. Figure 2.3 shows scatter plots of the projections and projection ensembles for the 2040 and 2080 periods. Each point in these plots represents an individual downscaled CMIP5 projection. Horizontal lines across the plot represent the 20%, 50%, and 80% changes in temperature and vertical lines represent the 20%, 50%, and 80% 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, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median. Note that all models agree that temperatures will warm over the next century, hence the use of the terms “less-warming” and “more-warming” as opposed to “cooler” and “warmer”.

[3] Each period represents a 30-year range centered on the referenced decade (e.g., the 2040s represents the 2030 to 2059 period).



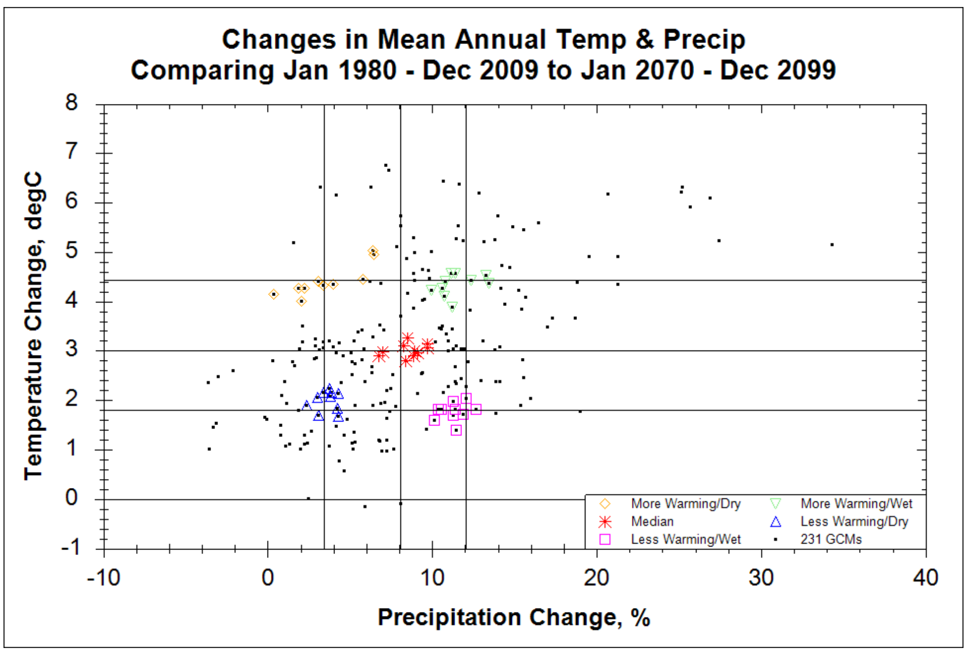


Figure 2.3 Scatter-graphs of projected changes in temperature and precipitation for the entire Columbia River Basin for the 2040s (2030 to 2059) and 2080s (2070 to 2099) periods relative to the historical period (1980 to 2009). Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Taking into account the possibility that the direction and magnitude of projected changes may vary over the diverse geography of the Columbia River Basin, this Assessment selected and evaluated projection ensembles for individual subbasins[4] within the larger Columbia River Basin. In other words, the process described here, from ensemble selection to generation of climate adjusted gridded meteorological data, was repeated and applied separately to each subbasin. Then, once complete, the climate-adjusted gridded datasets for each subbasin were pieced back together for input into the Columbia River Basin Variable Infiltration Capacity (VIC) hydrologic model (Liang et al.1994). This approach is in contrast to the method employed in the RMJOC-1 Climate Change Study which involved the selection of a single set of scenarios for the entire Columbia River Basin.

2.1.3 Climate Analysis Toolkit

This Assessment used the Climate Analysis Toolkit (a free plugin for HydroDesktop) to analyze downscaled climate projection data and develop future climate data for subsequent hydrological modeling (Step 1 in Figure 1.1). This toolkit streamlines the selection of climate projection ensembles and the generation of ensemble informed "period-change" factors—hybrid-delta ensemble, delta ensemble, and hybrid ensemble. Other useful output generated by this tool includes, but is not limited to, GCM scatterplots (as shown in Figure 2.3), ensemble summaries, and VIC meteorological input (forcing) files. For more information on HydroDesktop and the Climate Analysis Toolkit plugin visit http://hydrodesktop.codeplex.com and https://climate.codeplex.com.

2.2 Hydrologic Model

2.2.1 Variable Infiltration Capacity (VIC) Model

Hydrologic conditions were simulated using the Variable Infiltration Capacity (VIC) model (Liang et al.1994), a large-scale, semi-distributed hydrologic model. Figure 2.4 illustrates the surface water hydrologic processes that are represented by VIC. Driven by meteorological inputs ("forcing files"), VIC is used to calculate the amount of water stored within each grid cell as soil moisture or snowpack. Also, VIC is used to calculate the amount of water leaving each grid cell through evapotranspiration and runoff, including both near-surface runoff and

[4] Subbasins included the Yakima, Deschutes, Upper Snake, Grand Coulee, and Willamette. An additional "subbasin," encompassing the larger Columbia River Basin, was used to provide full coverage of the region and to "fill in" between the smaller subbasins.

baseflow. A separate routing model (Lohmann, et al.1996, 1998) translates the VIC grid cell runoff into streamflow at specified locations.

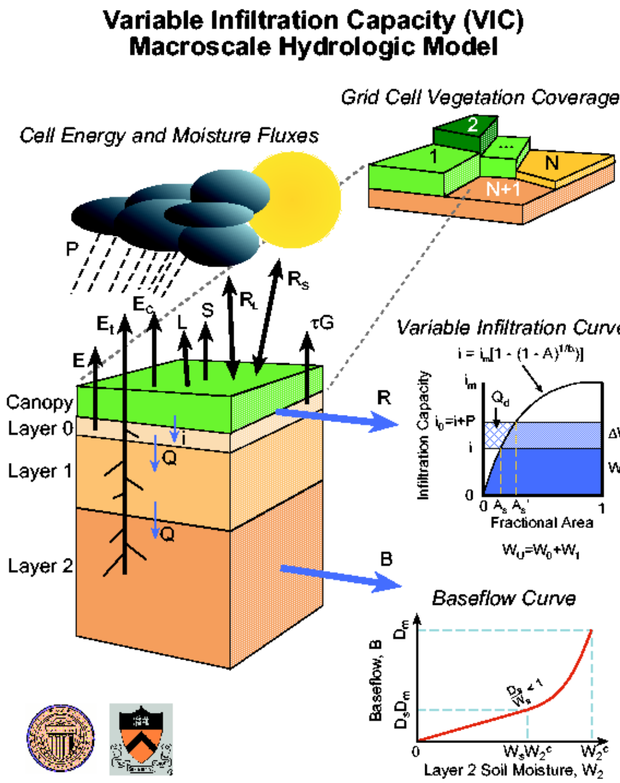


Figure 2.4 Schematic of VIC hydrologic model. (Acknowledgement: Figure from Alan Hamlet, University of Washington Climate Impacts Group)

The particular implementation of the VIC model that was used in this Assessment was originally developed for the RMJOC-1 Climate Change Study (RMJOC-1 2011). An attempt was made to leverage parameter optimization software (PEST) to recalibrate the RMJOC-1 VIC model at the subbasin scale for this Assessment; however, the results produced by this process either showed no significant improvement over the original model version or were suspected to be over-parameterized, exhibiting questionable parameter values and combinations. This is not to say that subbasin-scale VIC parameter estimation using PEST is not a useful approach. Rather, more work is needed outside the scope of this Assessment to understand how to best use this powerful tool.

2.2.2 Meteorological Forcing Files

The gridded 1/16th degree meteorological forcing dataset developed by Livneh et al. (2013) was used for this Assessment and represented baseline historical meteorological conditions across the basin. This dataset was derived from observations collected at approximately 20,000 NOAA Cooperative Observer (COOP) stations across the conterminous United States and includes estimates of daily precipitation, maximum temperature, minimum temperature, and mean wind speed. The dataset also includes other hydrological variables (evaporation, runoff, baseflow, SWE, etc.); however, those variables were not used in this Assessment.

Gridded meteorological forcing files, representing each of the climate change scenarios and periods being evaluated by this Assessment, were generated from the Livneh dataset using the HDe change factors discussed in Section 2.1. This process was automated by the Climate Analysis Toolkit. Given baseline forcing files and GCM projections for a particular area, the tool selects GCM ensembles and generates climate adjusted VIC forcing files.

2.3 Streamflow Bias Correction

As a final step in generating future streamflows, raw VIC output was adjusted to account for simulation biases. This post-simulation bias correction process, introduced in Snover et al. (2003) and applied in the previous RMJOC-1 Climate Change Study (RMJOC-1 2011), employs a quantile mapping approach to "translate" between the simulated and observed datasets. The process[5] begins with the construction of monthly and annual cumulative distribution functions (CDFs) of both simulated and observed data for a particular runoff location. The simulated monthly CDFs are then used to identify the percentile flow associated with each record in the simulated time series, with all the dates in a particular month referencing the simulated CDF for that month. The assigned percentiles are then used to lookup the corresponding percentile flow in the observed CDF. As a final step, monthly flows are adjusted based on mapping between the simulated and observed annual mean flow and daily simulated flows are scaled to match the newly-updated monthly volumes. Figure 2.5 through Figure 2.8 illustrate the results of this process at two different locations: the Snake River at Brownlee Dam and the Deschutes River near Madras, Oregon. VIC performed fairly well at the Snake River at Brownlee Dam and required only slight adjustments in the bias correction process. On the other hand (as discussed in greater detail in Section 3.2), the VIC model did not perform as well in the Deschutes subbasin, requiring much larger adjustments.

[5] The source code used for this process is published on GitHub and can be accessed at: http://github.com/usbr/BiasCorrectQ.

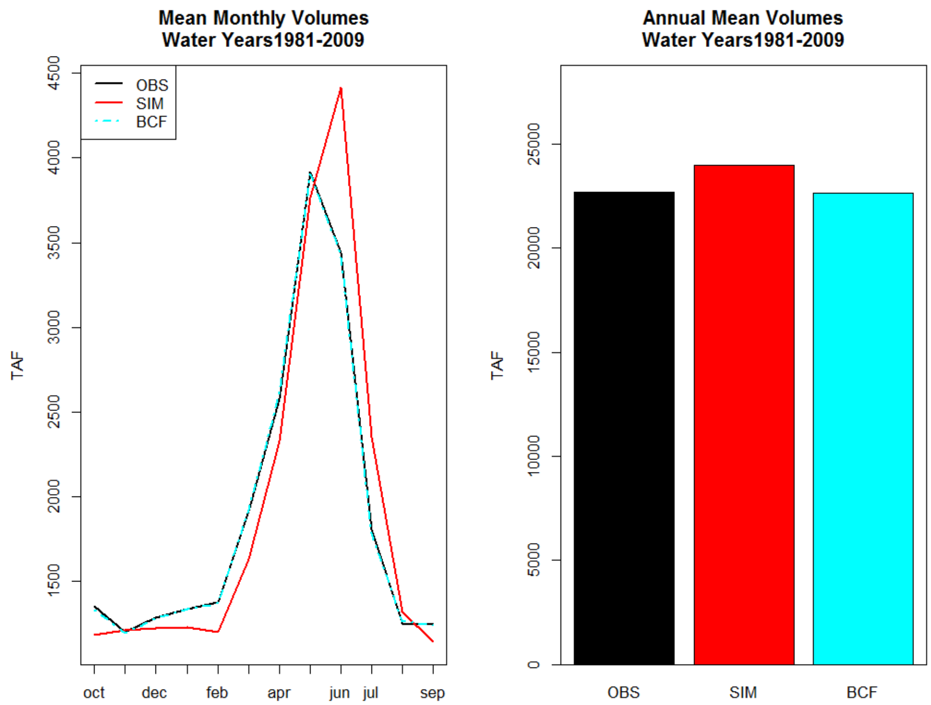


Figure 2.5 Bias correction example for the Snake River at Brownlee Dam. The panel on the left illustrates the VIC simulated mean monthly volumes before bias correction (SIM) and after bias correction (BCF), along with observed (OBS) values. The panel on the right illustrates these same three datasets in terms of mean annual volume.

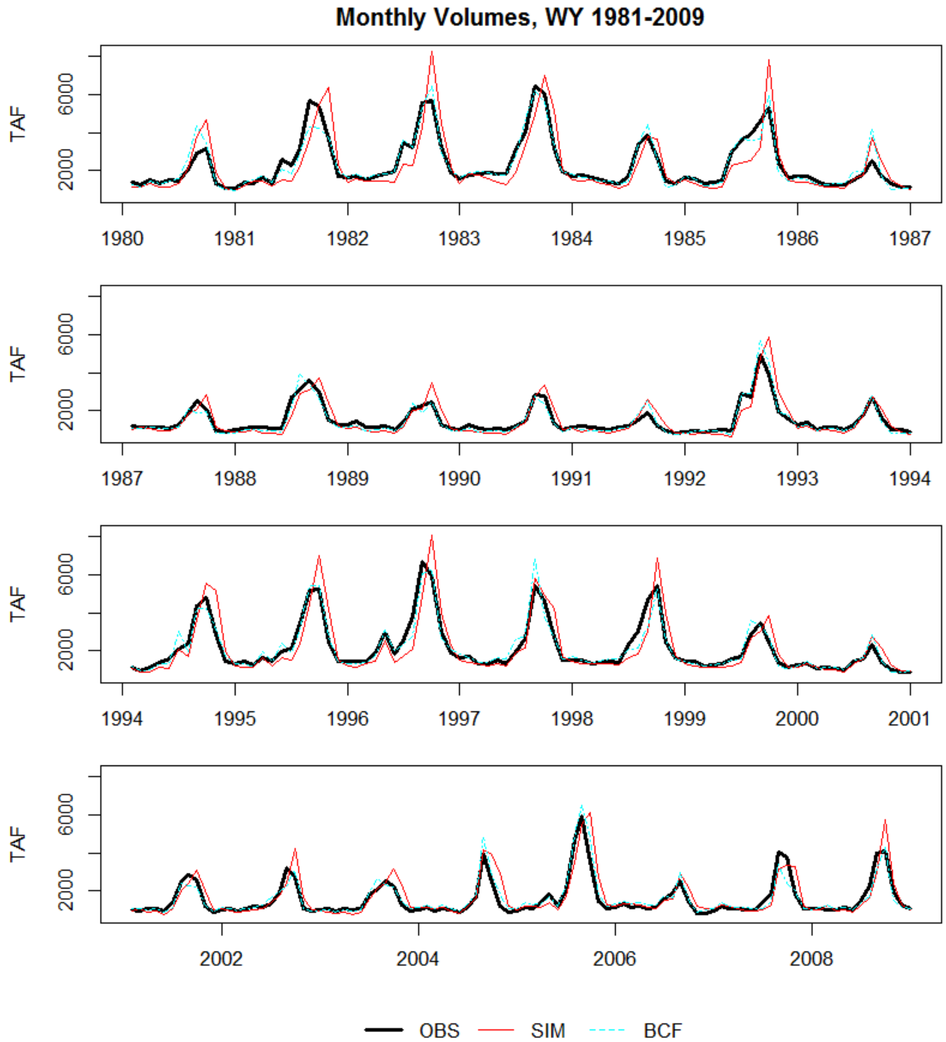


Figure 2.6 Bias correction example for the Snake River at Brownlee Dam. This figure illustrates the observed (OBS), raw VIC output (SIM), and bias corrected VIC output (BCF) in terms of a monthly volume timeseries.

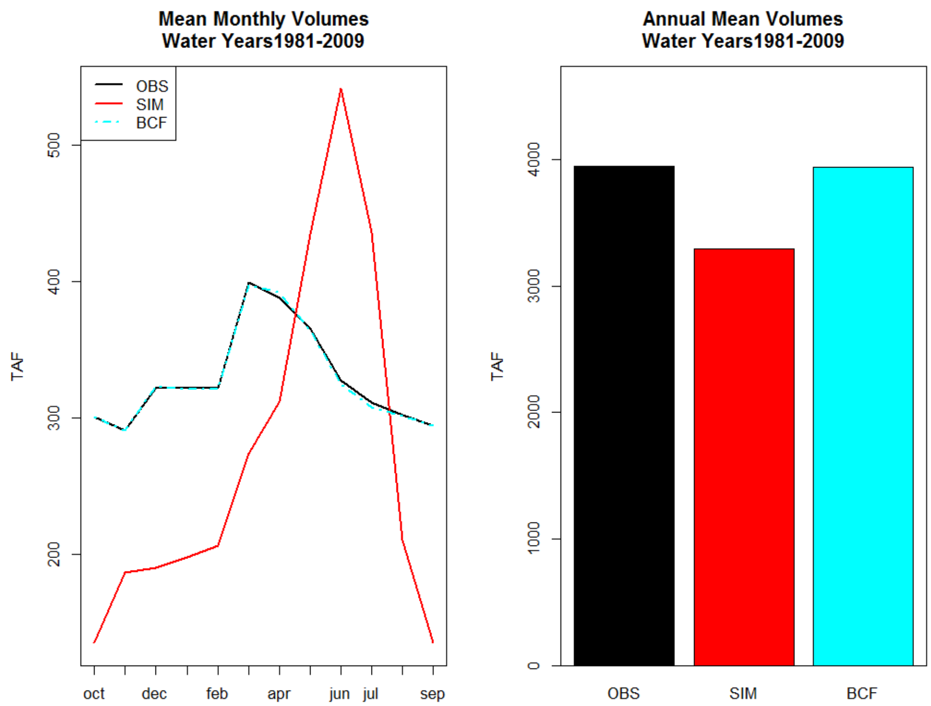


Figure 2.7 Bias correction example for the Deschutes River near Madras, Oregon. The panel on the left illustrates the VIC simulated mean monthly volumes before bias correction (SIM) and after bias correction (BCF), along with observed (OBS) values. The panel on the right illustrates these same three datasets in terms of mean annual volume.

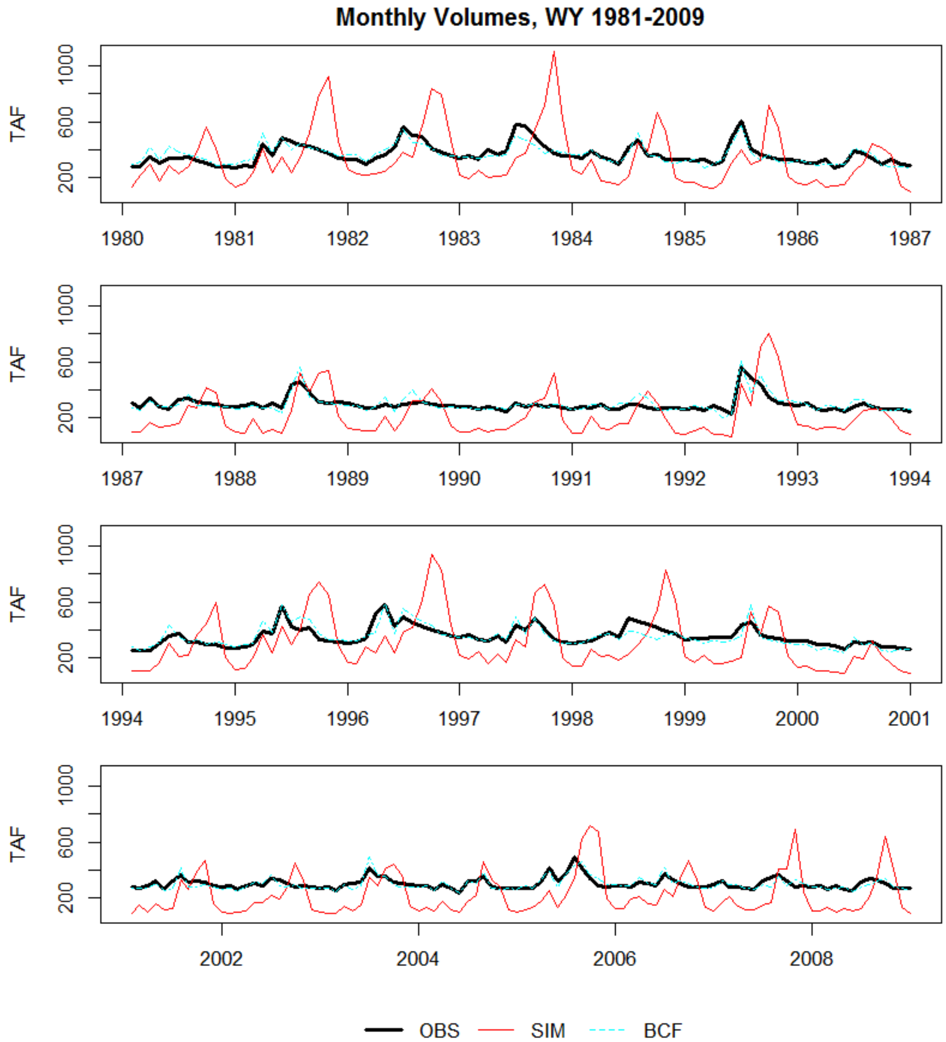


Figure 2.8 Bias correction example for the Deschutes River near Madras, Oregon. This figure illustrates the observed (OBS), raw VIC output (SIM), and bias corrected VIC output (BCF) in terms of a monthly volume timeseries.

3 RESULTS AND DISCUSSION

3.1 Simulated Changes in Climate and Runoff

Five climate change scenarios of simulated temperature, precipitation, and runoff were generated for four future periods in six different areas across the Columbia River Basin. These areas include the Yakima, Deschutes, Upper Snake, Grand Coulee, and Willamette subbasins, along with the larger Columbia River Basin. As discussed previously in Section 2.1, all climate models project warming temperatures going into the future, with the amount of warming varying by season and location. Changes in precipitation varied more widely than those for temperature, but mostly agreed in their simulation of increased precipitation during the cool season and decreased precipitation during the warm season.

Daily and mean monthly streamflows were generated for 157 locations throughout the Columbia River Basin. These locations are shown in Figure 3.1 and a complete list of sites, including their coordinates and corresponding subbasin, is included in the Appendix. In general, the projected warming and changes in precipitation across the Columbia River Basin are expected to result in increased runoff during the cool season and decreased runoff during the warm season; however, the magnitude and timing of such changes varied across the region.

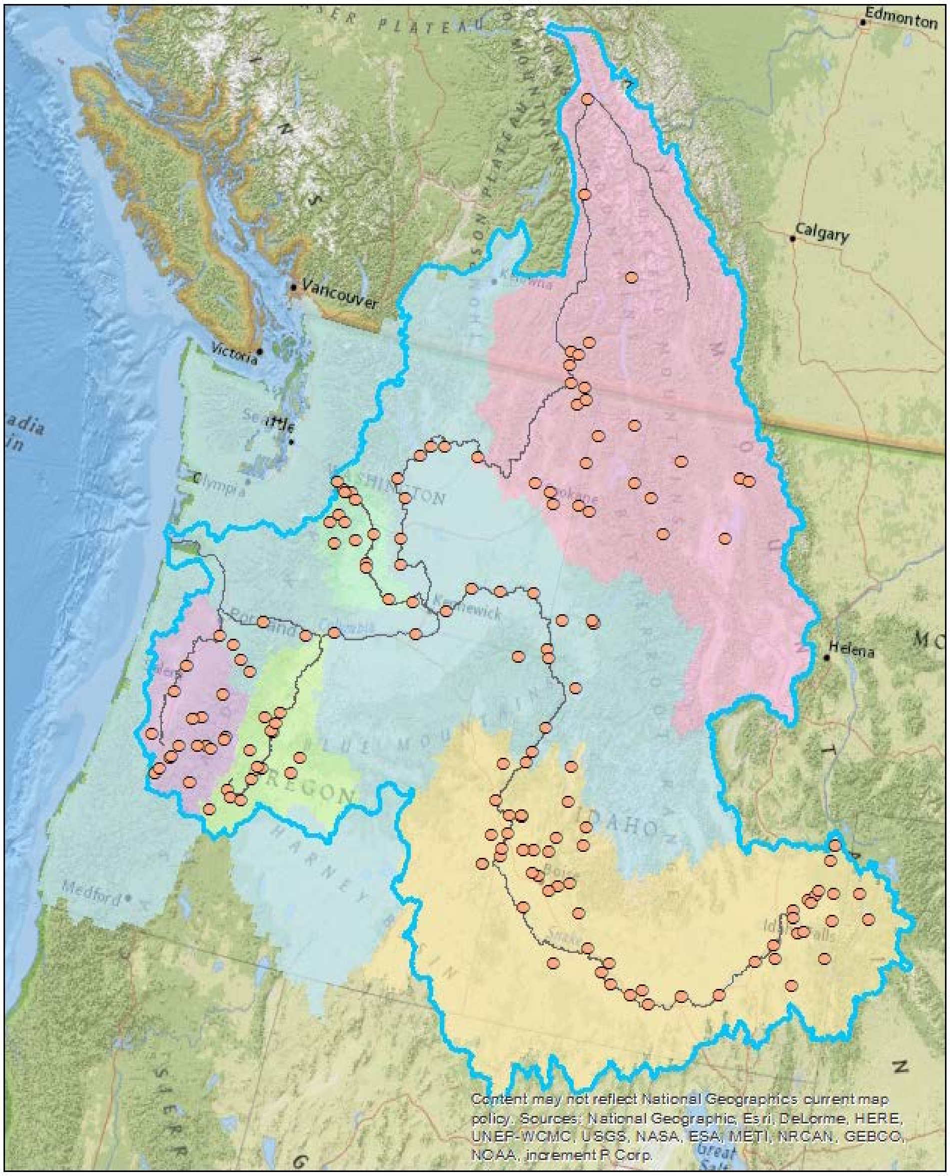


Figure 3.1 Map of 157 locations at which future streamflows were generated.

Climate change impacts were most pronounced in "transitional" subbasins, or basins where the dominant form of precipitation is neither rain nor snow, but is currently a mix of both. These subbasins generally experience winter temperatures that are at- or near-freezing and are therefore particularly sensitive to warming that will shift the subbasin to rain-dominance. Runoff in rain-dominant subbasins, on the other hand, is not as sensitive to warming as these basins already experience winter temperatures above the freezing mark and are projected to remain rain-dominant going into the future. While many snow-dominant subbasins are likely to shift towards transitional conditions, many others currently have winter temperatures well enough below freezing that warming may not cause winter temperatures to cross the freeze/thaw threshold. Figure 3.2 through Figure 3.4 illustrate maps of the historical mean annual minimum (Tmin) and maximum (Tmax) temperatures and mean annual precipitation, as well as the 2080s projected changes under each scenario.

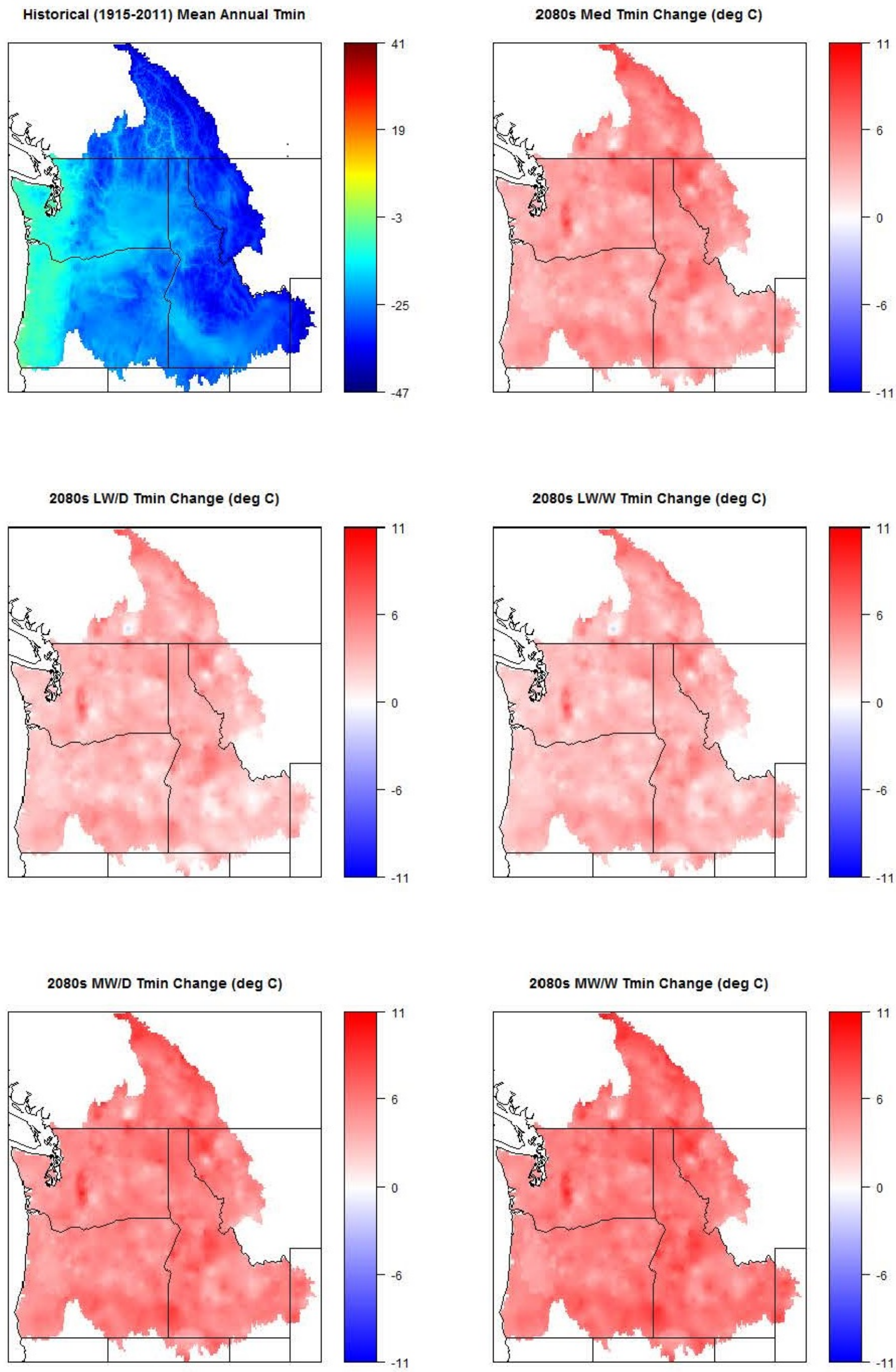


Figure 3.2 Mean annual minimum temperature for the period of January 1915 through December 2011 (from Livneh et al. 2013) and maps of the change in degrees Celsius between historical and 2080 period averages for each Hybrid-Delta climate scenario.

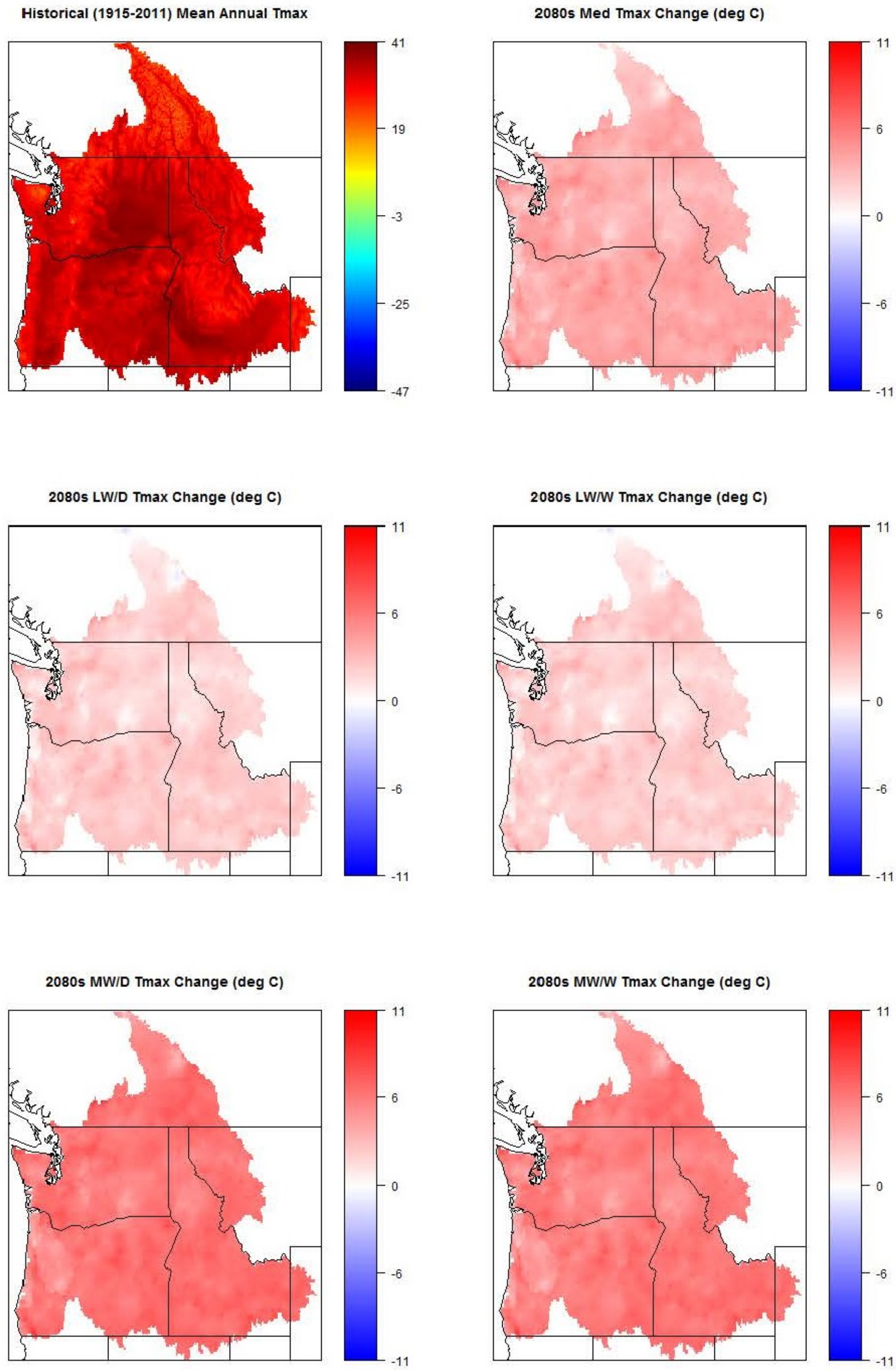


Figure 3.3 Mean annual maximum temperature for the period of January 1915 through December 2011 (from Livneh et al. 2013) and maps of the change in degrees Celsius between historical and 2080 period averages for each Hybrid-Delta climate scenario.

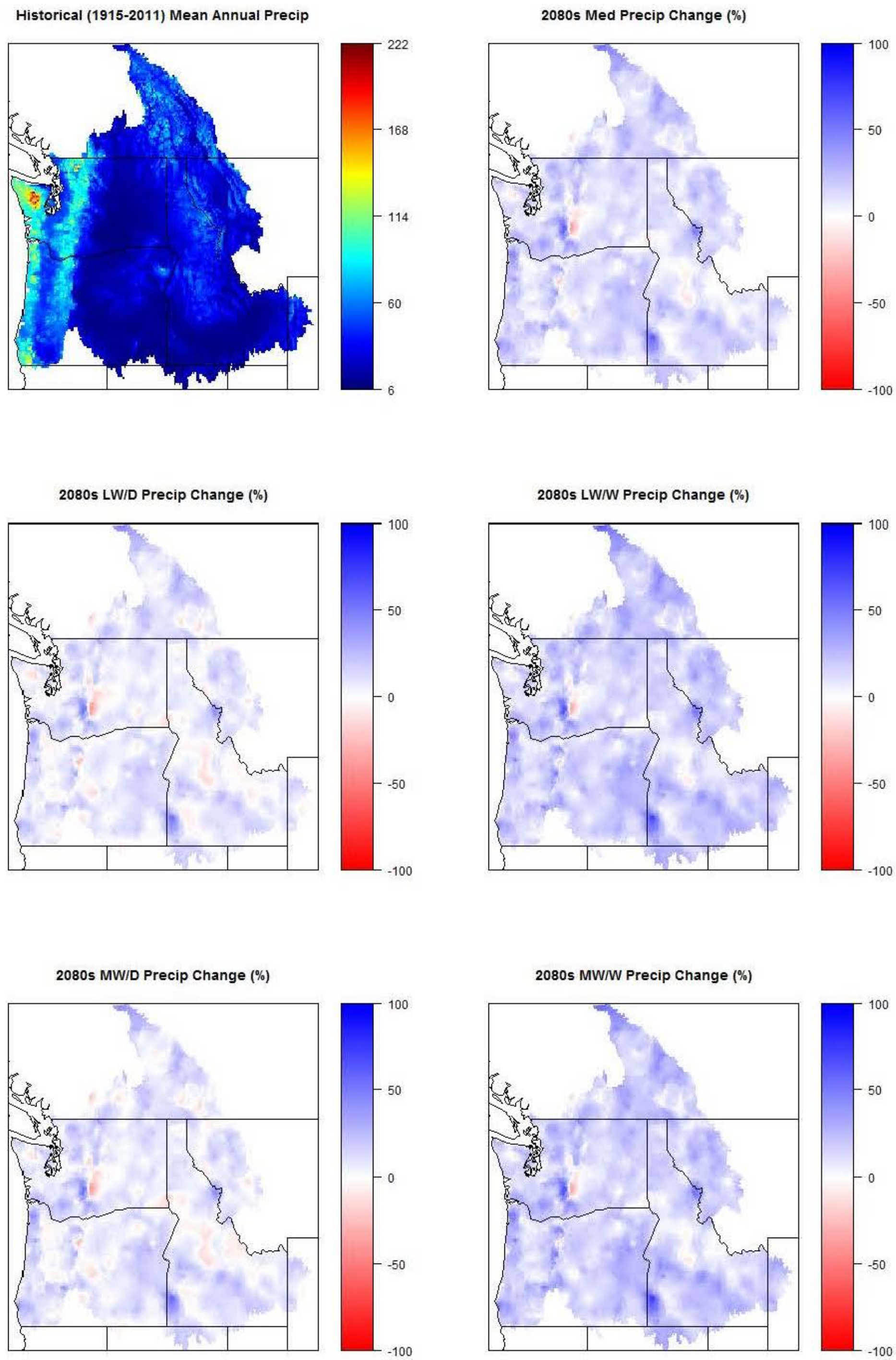


Figure 3.4 Mean annual precipitation for the period of January 1915 through December 2011 (from Livneh et al. 2013) and maps of percent change between historical and 2080 period averages for each Hybrid-Delta climate scenario.

It is worth noting that most reservoir systems have been designed based on historical hydrologic patterns and these patterns are changing. Many reservoir systems in the Columbia River Basin were designed under the assumption that snowpack would serve as a large upstream reservoir, accumulating and storing water through the winter and gradually releasing it during the spring and summer melt. In many locations, changes to seasonal runoff may pose challenges to water management as more water comes down the river during the flood control period when excess water is considered a hazard, and less water comes down the river during the irrigation season when water is an important economic and ecological asset.

Sections 3.1.1 through 3.1.4 highlight these changes for select locations (in upstream to downstream order) within the Columbia River Basin. These locations are illustrated in Figure 3.5.

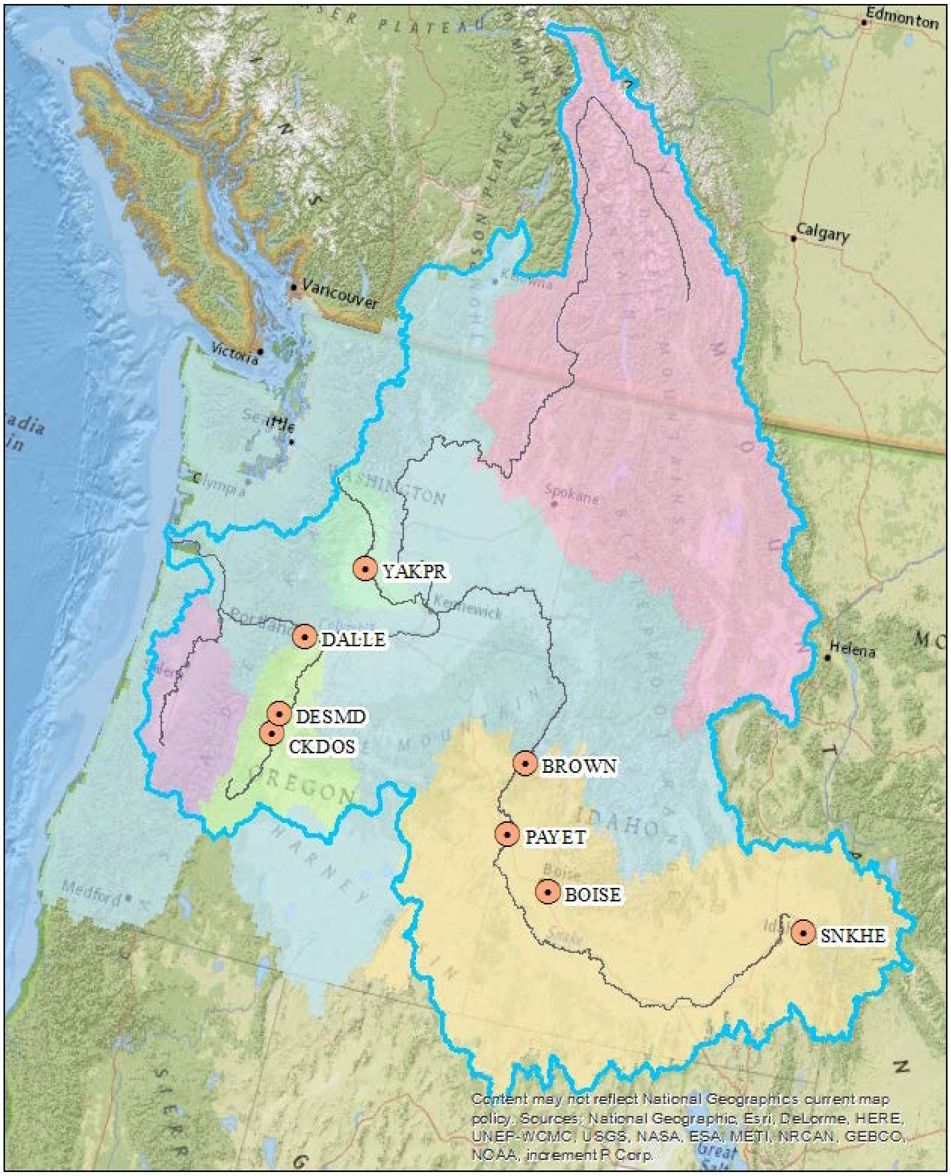


Figure 3.5 Map of select locations that are discussed in further detail in Sections 3.1.1 through 3.1.4.

3.1.1 Yakima River Basin

Similar to the patterns exhibited in the other parts of the Columbia River Basin, all five scenarios suggest increasing temperatures in the Yakima subbasin over the next century, with the largest increases in temperature projected to occur during the summer months. Figure 3.6 illustrates the 2080s monthly 50^{th}-percentile changes in temperature and precipitation (relative to the historical 1980 through 2009 period) that are projected over the Yakima River subbasin for each climate change scenario. Precipitation projections are more varied between scenarios, but generally suggest a pattern of wetter conditions through the spring, winter, and fall and drier conditions during the summer months, with the exception of the Less Warming/Wet scenario (which showed increasing precipitation in all months, excluding July).

Interestingly, the “dry” scenarios (Less Warming/Dry and More Warming/Dry) exhibited larger increases in temperature during the summer months compared to their “wet” counterparts. Comparison of the projected precipitation changes between the Less Warming and More Warming scenarios also revealed interesting patterns, with the “dry” scenarios (Less Warming/Dry and More Warming/Dry) showing “wetter” (or “less-dry”) conditions under the More Warming scenario during the late-spring (May and June) and late-fall (November and December) compared to its Less Warming counterpart, and “drier” (or “less-wet”) conditions during the winter and summer months. The pattern was similar for the “wet” scenarios (Less Warming/Wet and More Warming/Wet), with the More Warming scenario showing “wetter” (or “less-dry”) conditions in early spring (March and April) as well as in October and December compared to its Less Warming counterpart.

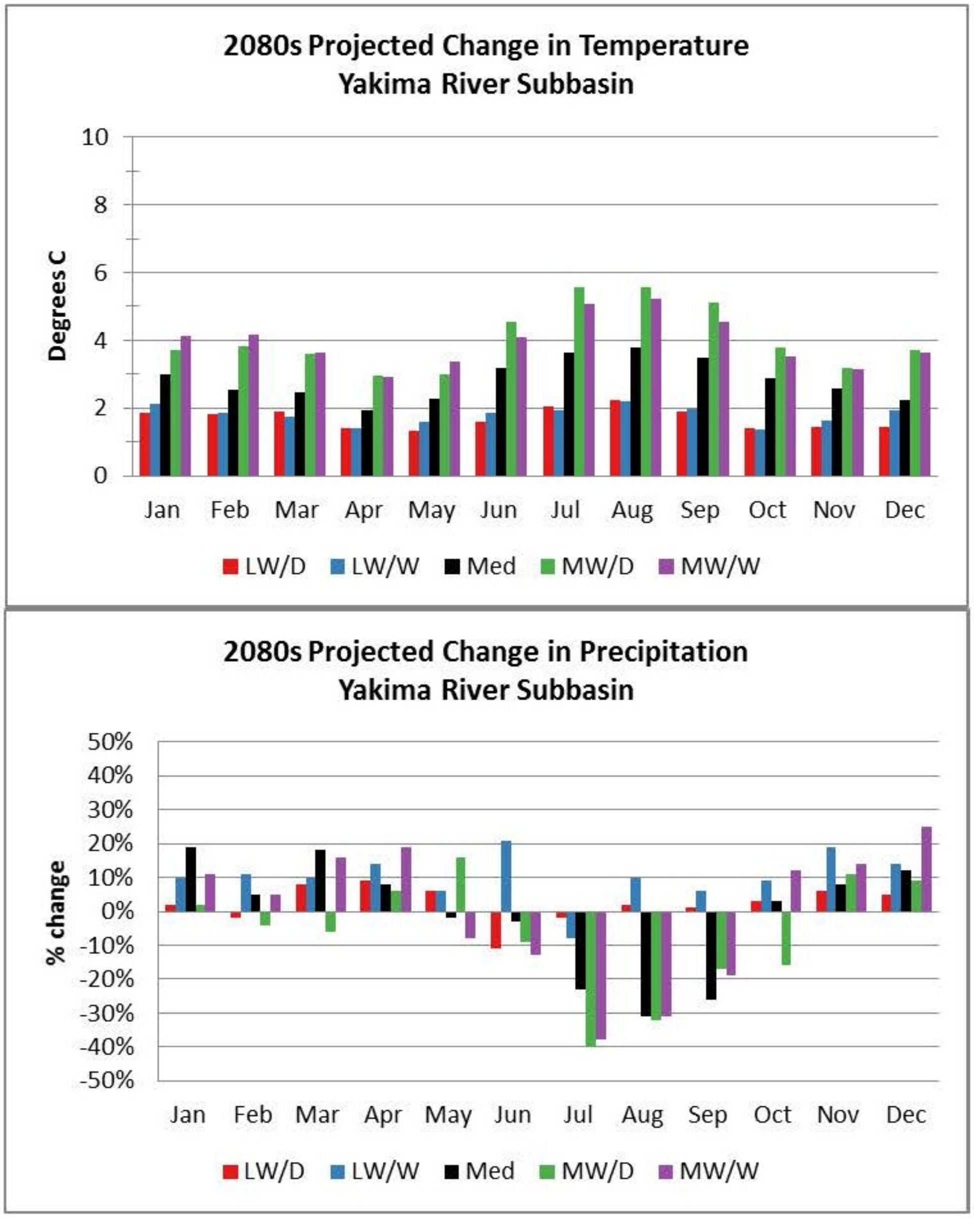


Figure 3.6 Projected 2080s monthly 50th-percentile change in temperature (top) and precipitation (bottom) for five scenarios (Less Warming/Dry, Less Warming/Wet, Median, More Warming/Dry, and More Warming/Wet) relative to the historical 1980-2009 period.

3.1.1.1 Yakima River near Parker, WA

As shown in Figure 3.7, which illustrates the simulated mean annual runoff volume and the percent change in mean annual runoff volume for each period and scenario, the results of this Assessment suggest relatively small changes in annual runoff volume for the Yakima River near Parker, WA (YAKPR) location over the course of this century (-10.8% to 6.5% during the 2020s, -10.2% to 8.2% by the 2040s, -11.8% to 11.9% by the 2060s, and -11.6% to 12.7% by the 2080s). Despite these rather small changes in annual runoff volume, changes to the magnitude and timing of peak runoff in the basin are likely to be significant. Figure 3.8 through Figure 3.9 present the simulated mean monthly flows and percent change in mean monthly flow (relative to the historical baseline period) for each scenario and future period. Under all scenarios, unregulated flows at YAKPR increase substantially during the winter and decrease during the spring and summer. In the Median and More-Warming scenarios, peak runoff occurs as much as 3 months earlier with peak flows occurring during February, rather than in May. Such changes are consistent with the projected increases in temperature and precipitation during the winter and spring and may be indicative of decreased winter snowpack accumulation as more precipitation falls as rain rather than snow.

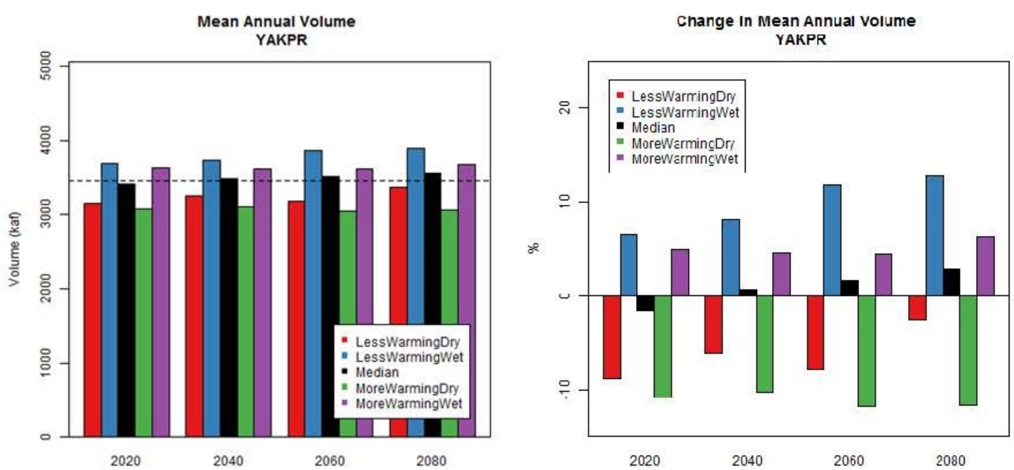


Figure 3.7 Mean annual volume (left) and change in mean annual volume (right) at YAKPR.

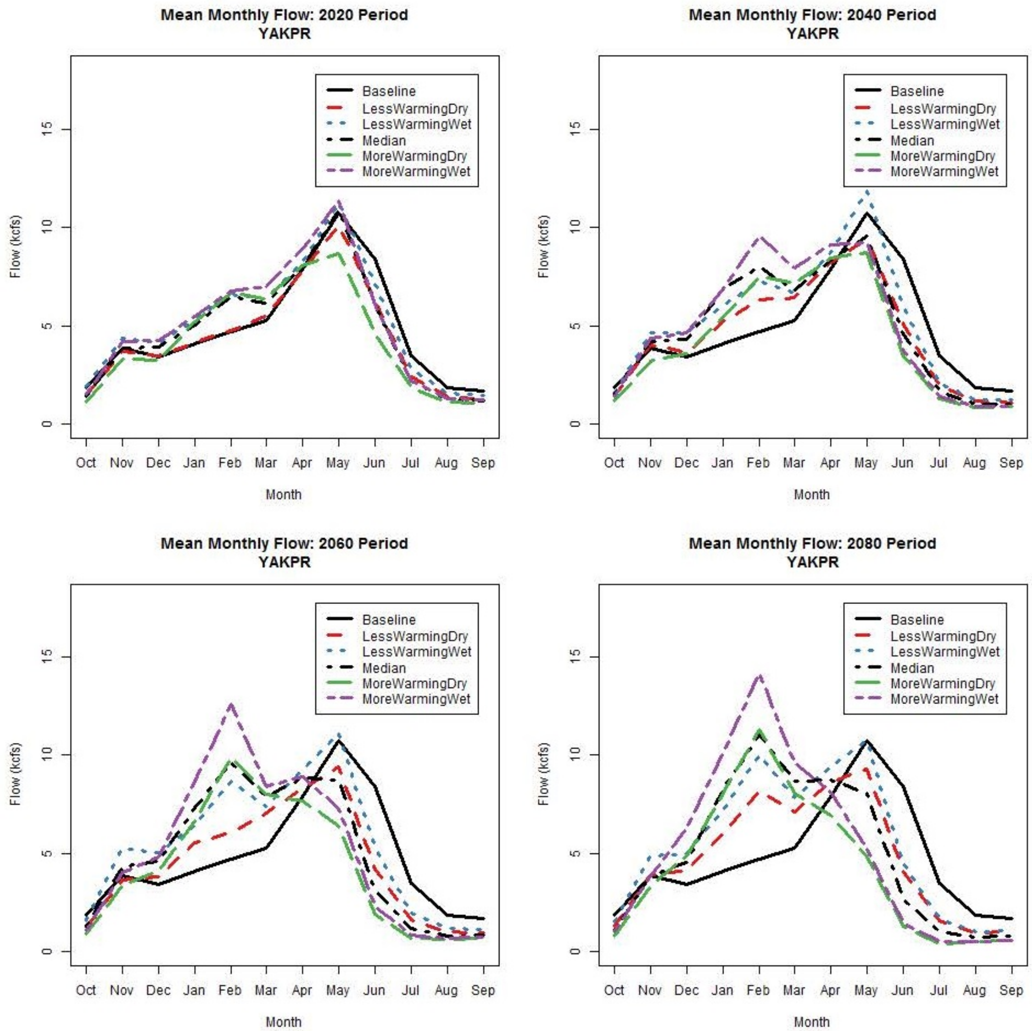


Figure 3.8 Mean monthly flow at YAKPR.

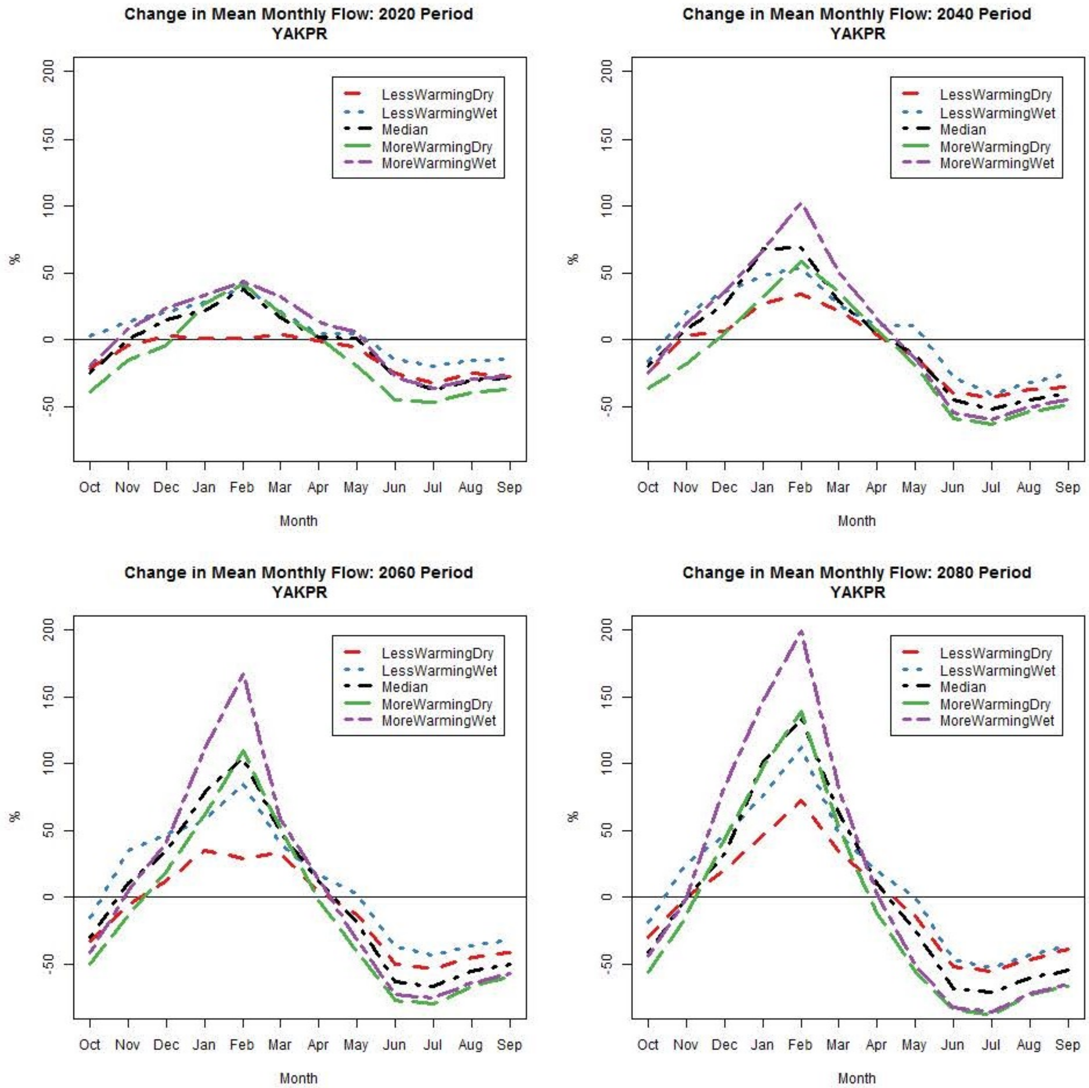


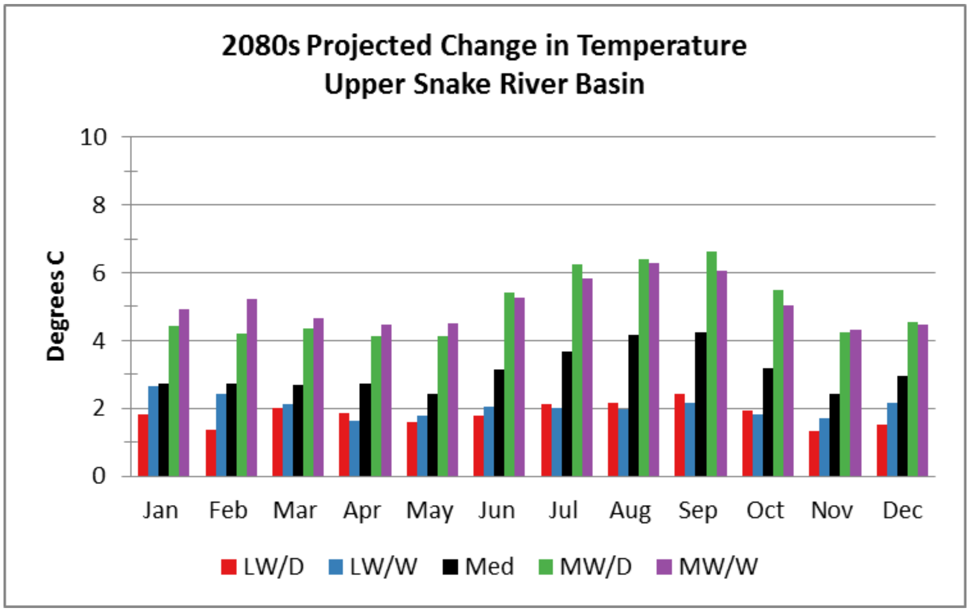
Figure 3.9 Change in mean monthly flow at YAKPR.

3.1.2 *Upper Snake River Basin*

This section presents a summary of the simulated changes in climate and runoff for the Snake River at Brownlee Dam (BROWN), the Snake River near Heise, ID (SNKHE), the Boise River at Lucky Peak (BOISE), and the Payette River near Payette, ID (PAYET). As compared to temperature changes projected for the other subbasins considered in this Assessment, the Snake River Basin exhibited the largest increases in temperature and followed the pattern seen in the other subbasins with the largest increases occurring during the summer months. Almost all scenarios project increased precipitation during the winter and early-spring. Projected conditions for the remainder of the year (May through October) were more varied, but generally indicate drier conditions (decreased precipitation) during those months. Only the Less Warming/Wet scenario projected year-round increases in precipitation. These results are illustrated in Figure 3.10.

Comparison of the More Warming scenarios (More Warming/Dry and More Warming/Wet) revealed an interesting pattern with the “dry” scenario showing larger increases in temperature during the summer and early-fall (June through October) compared to its “wet” counterpart, and smaller increases in temperature during the winter and spring (January through May). Comparison of the Less Warming scenarios (Less Warming/Dry and Less Warming/Wet) showed a similar pattern.

The Upper Snake subbasin also showed interesting differences in projected precipitation changes between the Less Warming and More Warming scenarios. Closer inspection of the “dry” scenarios (Less Warming/Dry and More Warming/Dry) shows the More Warming scenario to be “wetter” (or “less-dry”) during the winter and summer months compared to its Less Warming counterpart, and “drier” (or “less-wet”) during the spring (April and May) and fall (September through November) months. Comparison of the “wet” scenarios (Less Warming/Wet and More Warming/Wet) showed the More Warming scenario to be “wetter” (or “less-dry”) during the winter and early spring (December through April) and “drier” (or “less-wet”) during the summer and fall (June through November) compared to its Less Warming counterpart. It is also interesting to note that while the Less Warming/Wet scenario shows increases in precipitation for all months, the More Warming/Wet scenario shows decreases during June and July.



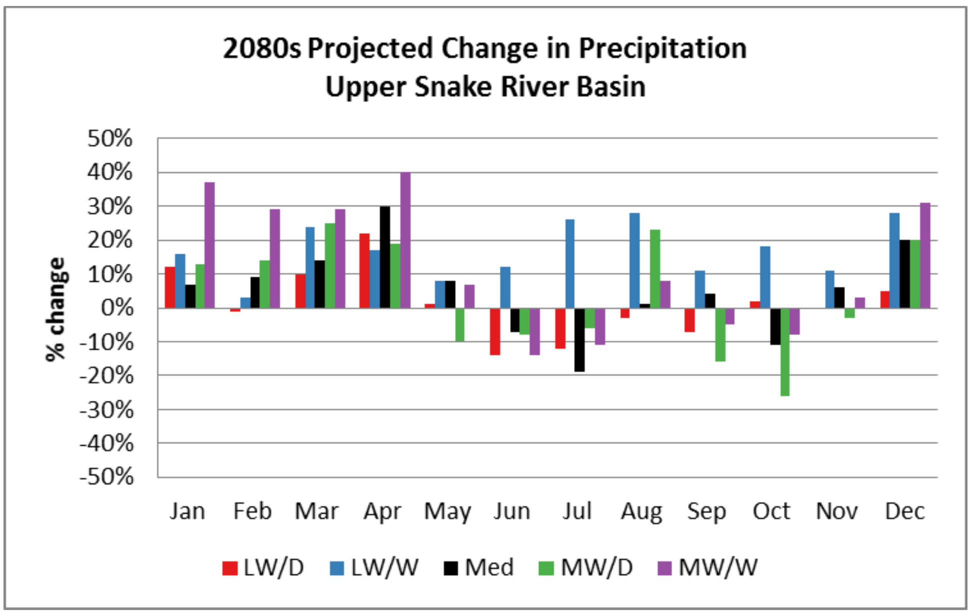


Figure 3.10 Projected 2080s monthly 50th-percentile change in temperature (top) and precipitation (bottom) for five scenarios (Less Warming/Dry, Less Warming/Wet, Median, More Warming/Dry, and More Warming/Wet) relative to the historical 1980-2009 period.

3.1.2.1 Snake River at Brownlee Dam

The results of this Assessment suggest that the total annual runoff above BROWN will increase by the end of the century under all of the scenarios considered; however, simulations for the earlier periods (2020s, 2040s, and 2060s) were more varied with the "dry" scenarios indicating decreases in annual runoff volumes. Figure 3.11 (left) illustrates the simulated mean annual volume at BROWN for all periods and scenarios relative to the historical mean annual volume (horizontal dashed line). The percent change in mean annual volume relative to historical values is shown by the plot on the right side of this figure. As shown in these figures, the results of this Assessment suggest that the annual runoff volume at BROWN will change by -6.1% to 9.6% during the 2020s, -4.9% to 10.8% by the 2040s, -1.6% to 12.9% by the 2060s, and 4.2% to 18.4% by the 2080s relative to the historical period (1980 through 2009).

This trend is consistent with the increased winter precipitation shown in Figure 3.10. While some months do show decreases in precipitation, the magnitude of the decreases is small relative to the increases during the wetter months. It is interesting to note that the "less warming" scenarios (Less Warming/Wet and Less Warming/Dry) resulted in larger volumes compared to their "more warming" counterparts (More Warming/Wet and More Warming/Dry). This may be attributed to increased evapotranspiration (ET) in the warmer scenarios.

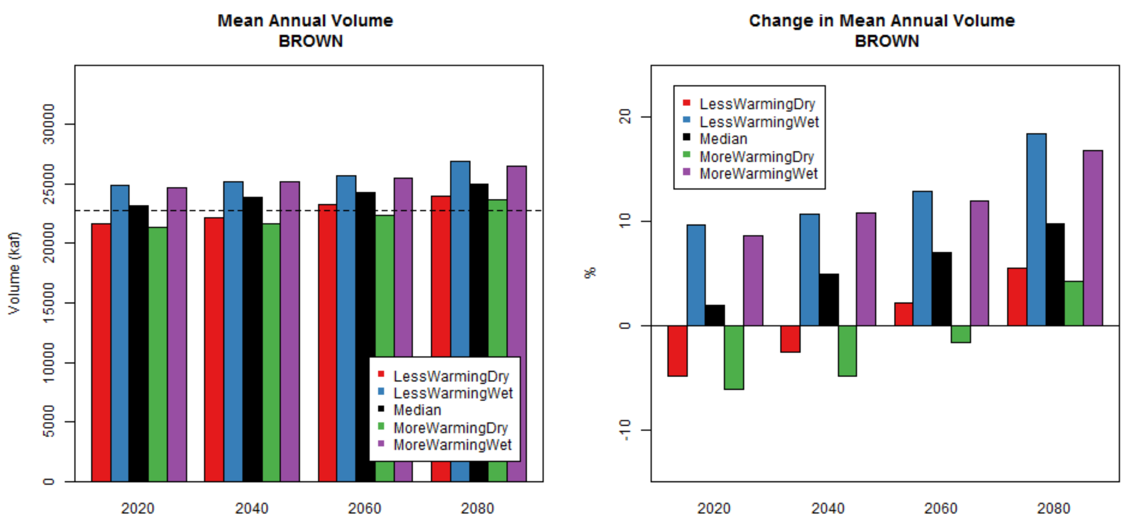


Figure 3.11 Mean annual volume (left) and change in mean annual volume (right) at BROWN.

While this Assessment suggests there will be an overall increase in annual volume at BROWN, conditions are likely to vary by season. The results of this Assessment indicate there will be increased runoff during the winter and spring months and decreased runoff through the summer and fall. Figure 3.12 and Figure 3.13 depict the simulated mean monthly flows for each scenario and period and illustrate the shift towards earlier runoff and larger peak flows, as well as decreased flow during the summer and fall.

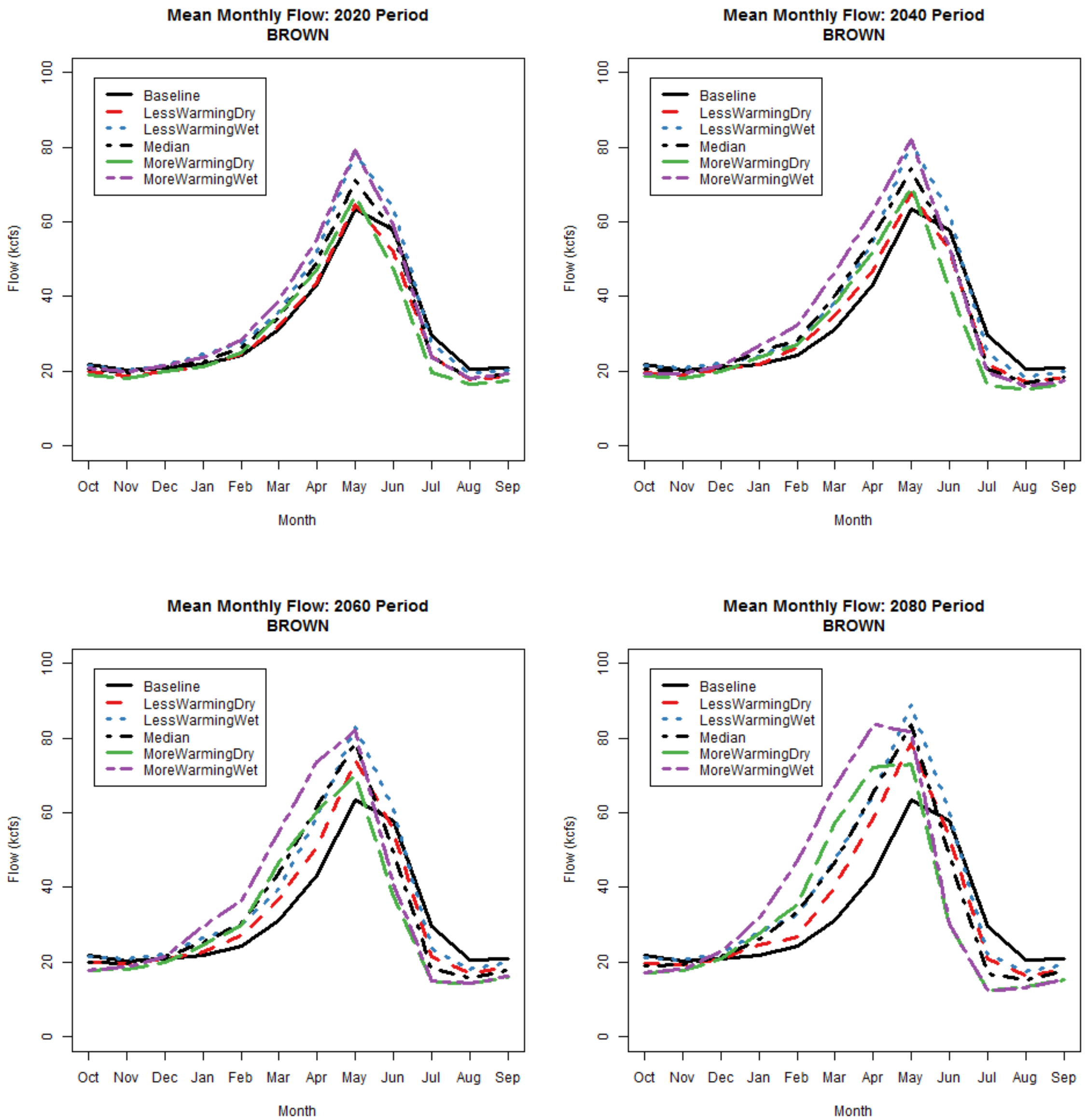


Figure 3.12 Mean monthly flow at BROWN.

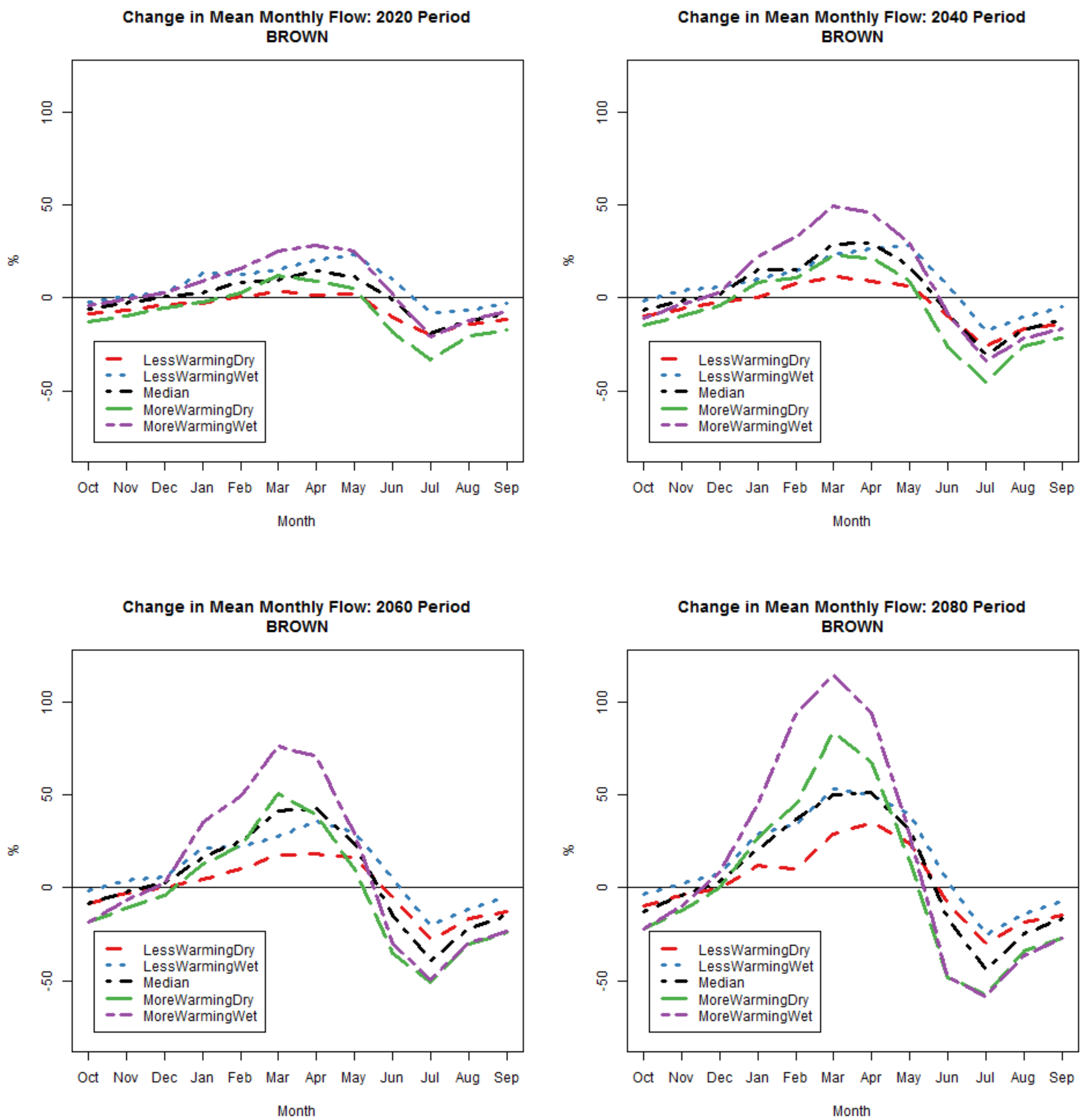


Figure 3.13 Change in mean monthly flow at BROWN.

3.1.2.2 Snake River near Heise, ID

Similar to the trends shown for the Snake River at Brownlee, the results of this study suggest that the total annual runoff above the Snake River near Heise, ID (SNKHE) will increase by the end of the century. Only the More-Warming/Dry scenario shows annual runoff volumes to be similar to the historic period. The left panel of Figure 3.14 illustrates the simulated mean annual volume at point SNKHE for all periods and scenarios as well as the historical mean annual volume (horizontal dashed line), while the percent change from historical is shown on the right. As shown in this figure, the results of this Assessment suggest that the annual runoff volume at SNKHE will change by -6.6% to 9.2% during the 2020s, -7.1% to 11.4% by the 2040s, -3.8% to 14.7% by the 2060s, and -0.1% to 19.5% by the 2080s relative to the historical period (1980 through 2009). Similar to the results shown for the Snake River at Brownlee Dam, the “less warming” scenarios (Less Warming/Wet and Less Warming/Dry) resulted in larger volumes compared to their “more warming” counterparts (More Warming/Wet and More Warming/Dry). This may be attributed to increased ET in the warmer scenarios.

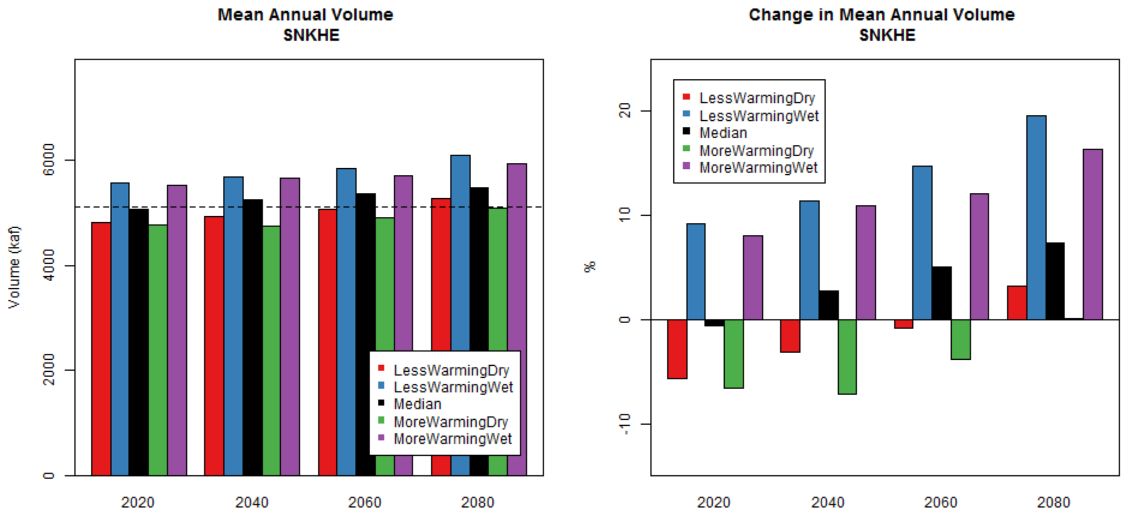


Figure 3.14 Mean annual volume (left) and change in mean annual volume (right) at SNKHE.

Figure 3.15 and Figure 3.16 illustrate the seasonal variation of the simulated climate change impacts to runoff at SNKHE. As shown in these figures, the results of this Assessment suggest a shift towards earlier runoff and larger peak flows, with early spring runoff increasing substantially by the end of the century and late summer runoff decreasing. This trend is consistent with the warming and increased winter/spring precipitation shown in Figure 3.10, the combination of which would promote earlier snowmelt and larger peak flows. These figures also illustrate how the “more warming” scenarios result in earlier peak flows (occurring in May, rather than June) in all periods (2020s through 2080s), while the “less warming” scenarios show a more gradual shift towards an earlier peak.

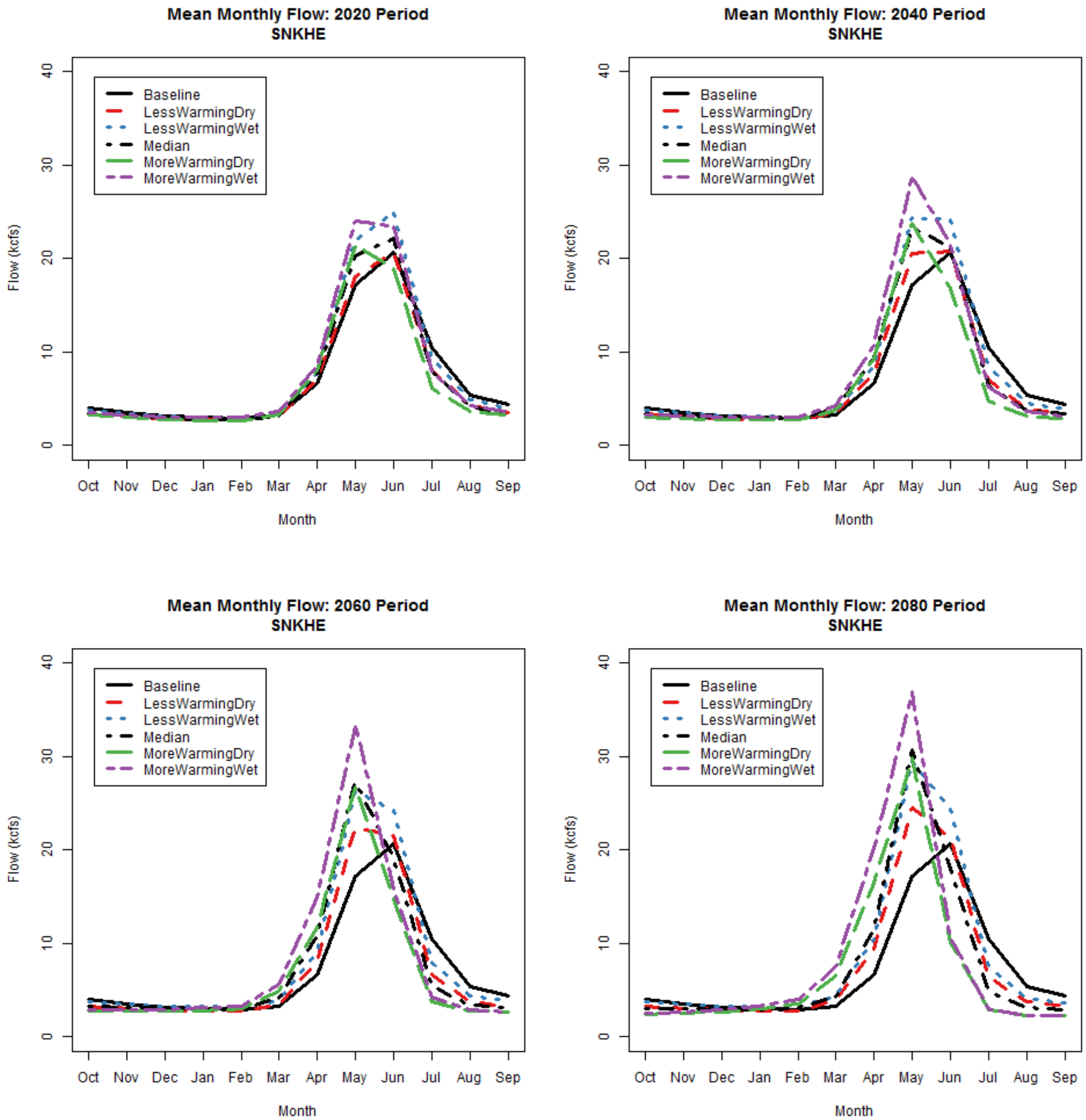


Figure 3.15 Mean monthly flow at SNKHE.

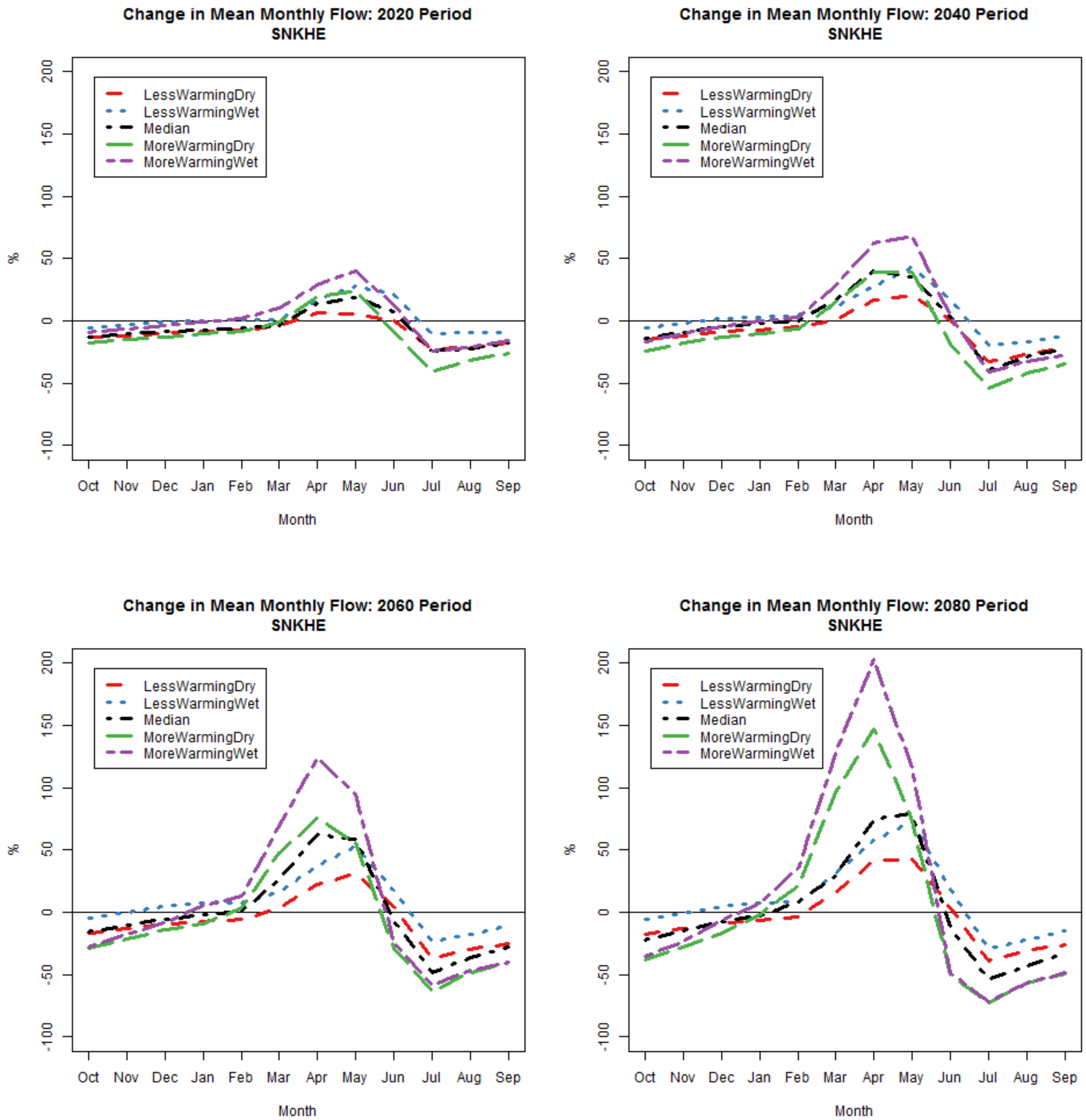


Figure 3.16 Change in mean monthly flow at SNKHE.

3.1.2.3 Boise River at Lucky Peak

Similar to the results for the Snake River at Brownlee Dam downstream, the results of this study suggest that the total annual runoff at the location Boise River at Lucky Peak (BOISE) will increase (relative to the historical baseline) by the end of the century under all of the scenarios considered, with simulated runoff for the earlier periods (2020s, 2040s, and 2060s) showing more varied results. As illustrated in Figure 3.17, the results of this Assessment suggest that the annual runoff volume at BOISE will change by -8.9% to 11.8% during the 2020s, -6.3% to 13.2% by the 2040s, -3.1% to 15.7% by the 2060s, and 2.5% to 20.5% by the 2080s relative to the historical period (1980 through 2009).

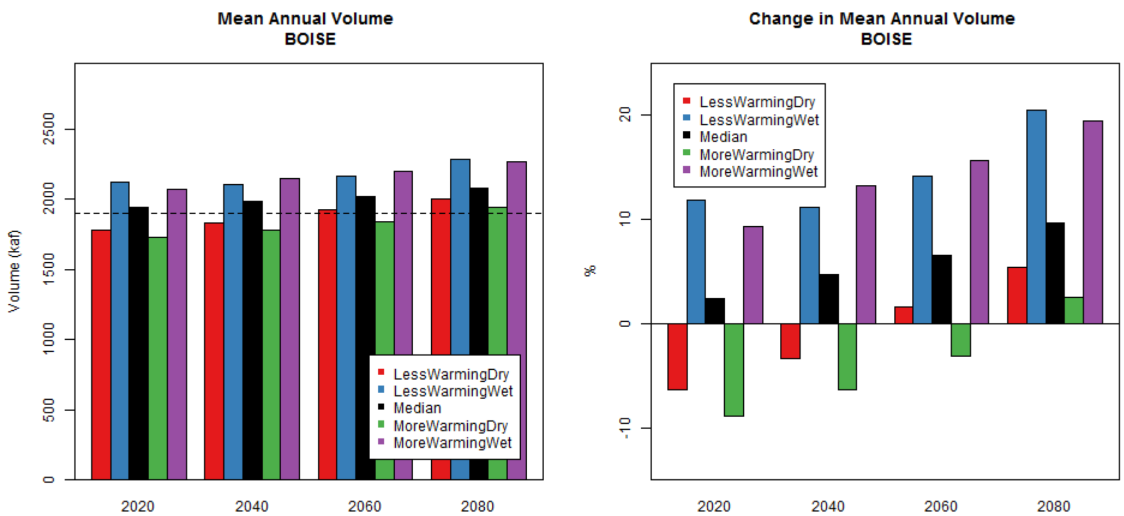


Figure 3.17 Mean annual volume (left) and change in mean annual volume (right) at BOISE.

While this Assessment suggests an overall increase in annual volume at BOISE by the end of the century, seasonal variations are apparent with the warm season (May through September) showing decreases in mean monthly flow and the cool season (January through April) showing potentially large increases in flow. Figure 3.18 and Figure 3.19 depict these changes in terms of mean monthly flow and help to illustrate the shift towards earlier runoff and larger peak flows during the cool season and decreased flows during the summer and fall.

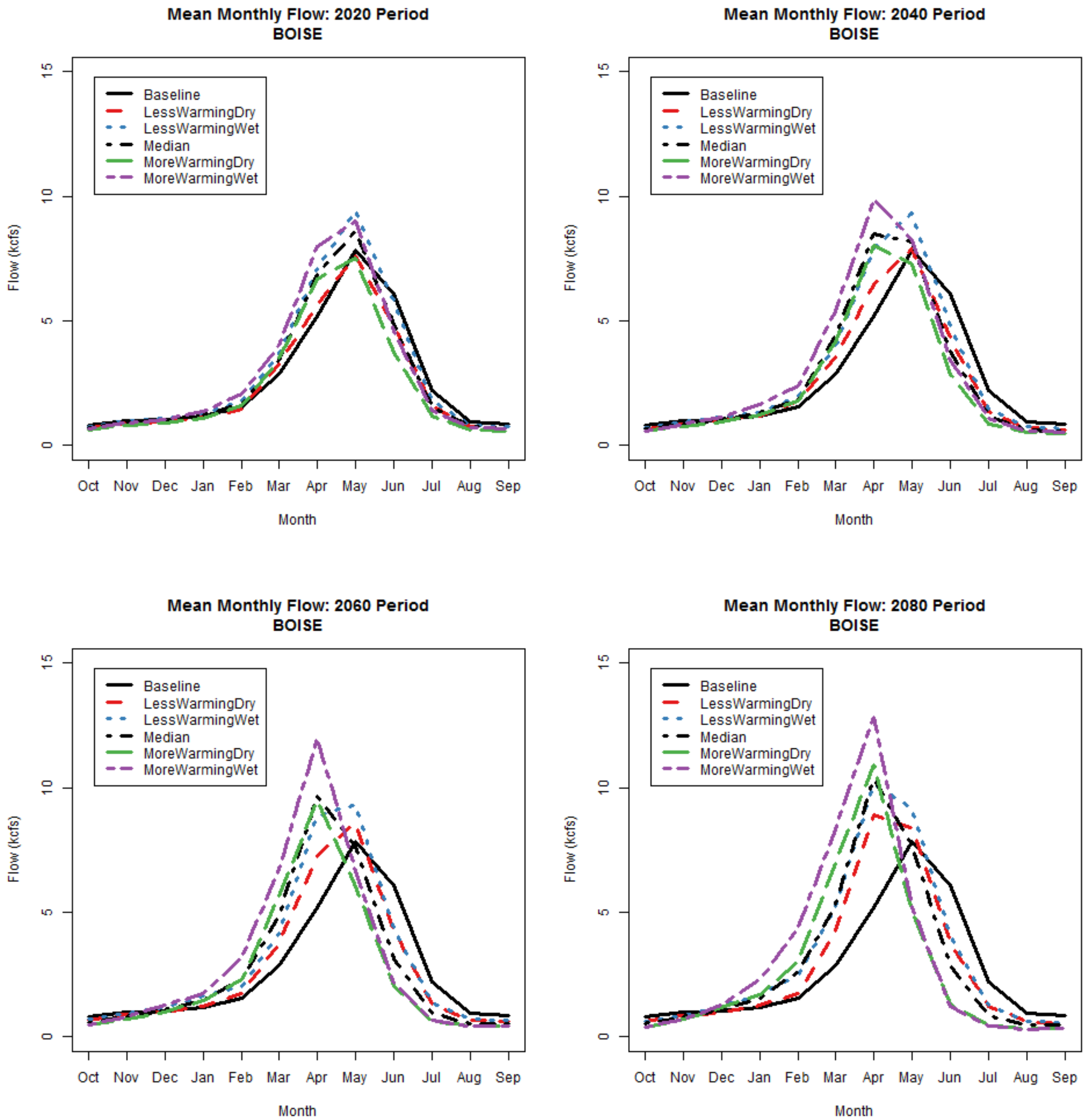


Figure 3.18 Mean monthly flow at BOISE.

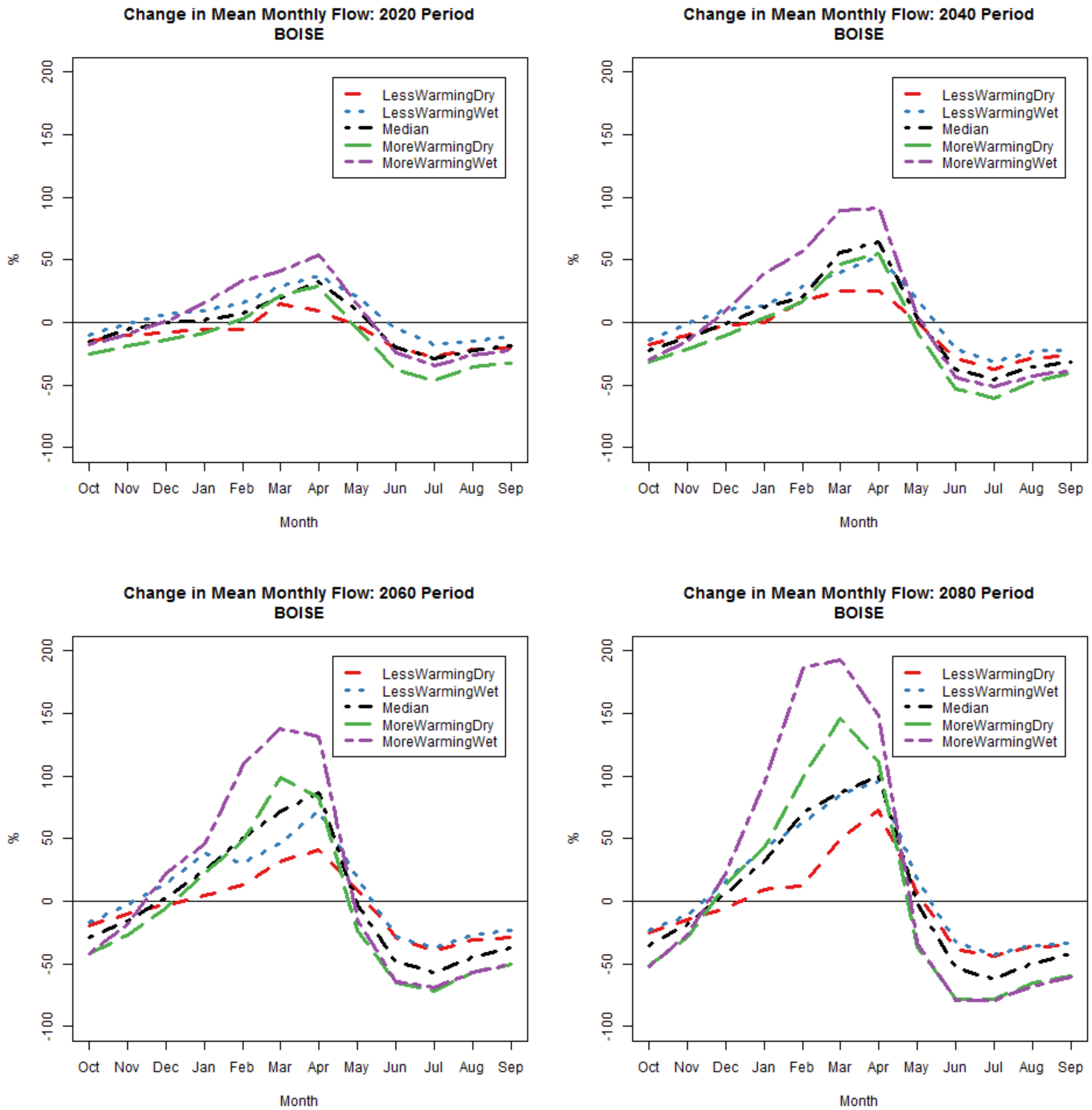


Figure 3.19 Change in mean monthly flow at BOISE.

3.1.2.4 Payette River near Payette, ID

As with the other locations presented here for the Snake River Basin, the results of this study suggest that the total annual runoff above the Payette River near Payette, ID (PAYET) will increase by the end of the century for all but one of the scenarios considered (only the More Warming/Dry scenario suggests that annual runoff will remain below the historical baseline volume). The left panel of Figure 3.20 illustrates the simulated mean annual volume at point PAYET for all periods and scenarios along with the historical mean annual volume (horizontal dashed line), while the percent change from historical is shown on the right. As illustrated in this figure, the results of this Assessment suggest that the annual runoff volume at PAYET will change by -8.8% to 11.2% during the 2020s, -8.0% to 11.3% by the 2040s, -6.6% to 12.7% by the 2060s, and -2.6% to 17.7% by the 2080s relative to the historical period (1980 through 2009).

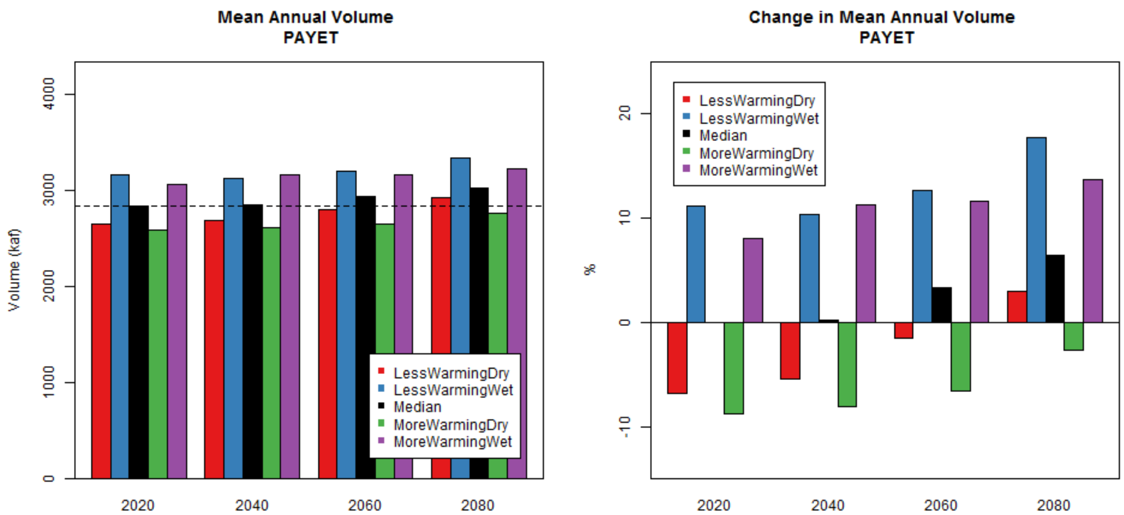


Figure 3.20 Mean annual volume (left) and change in mean annual volume (right) at PAYET.

Monthly flow simulations for PAYET suggest the potential for significant increases in winter and early-spring flows and large decreases in flow during the summer and fall months. Figure 3.21 and Figure 3.22 illustrate these patterns for all scenarios and periods. As with the other Snake River Basin sites, these changes are consistent with the projected warming and increased early-spring precipitation shown in Figure 3.10, as well as the potential effects of increased temperature on ET rates.

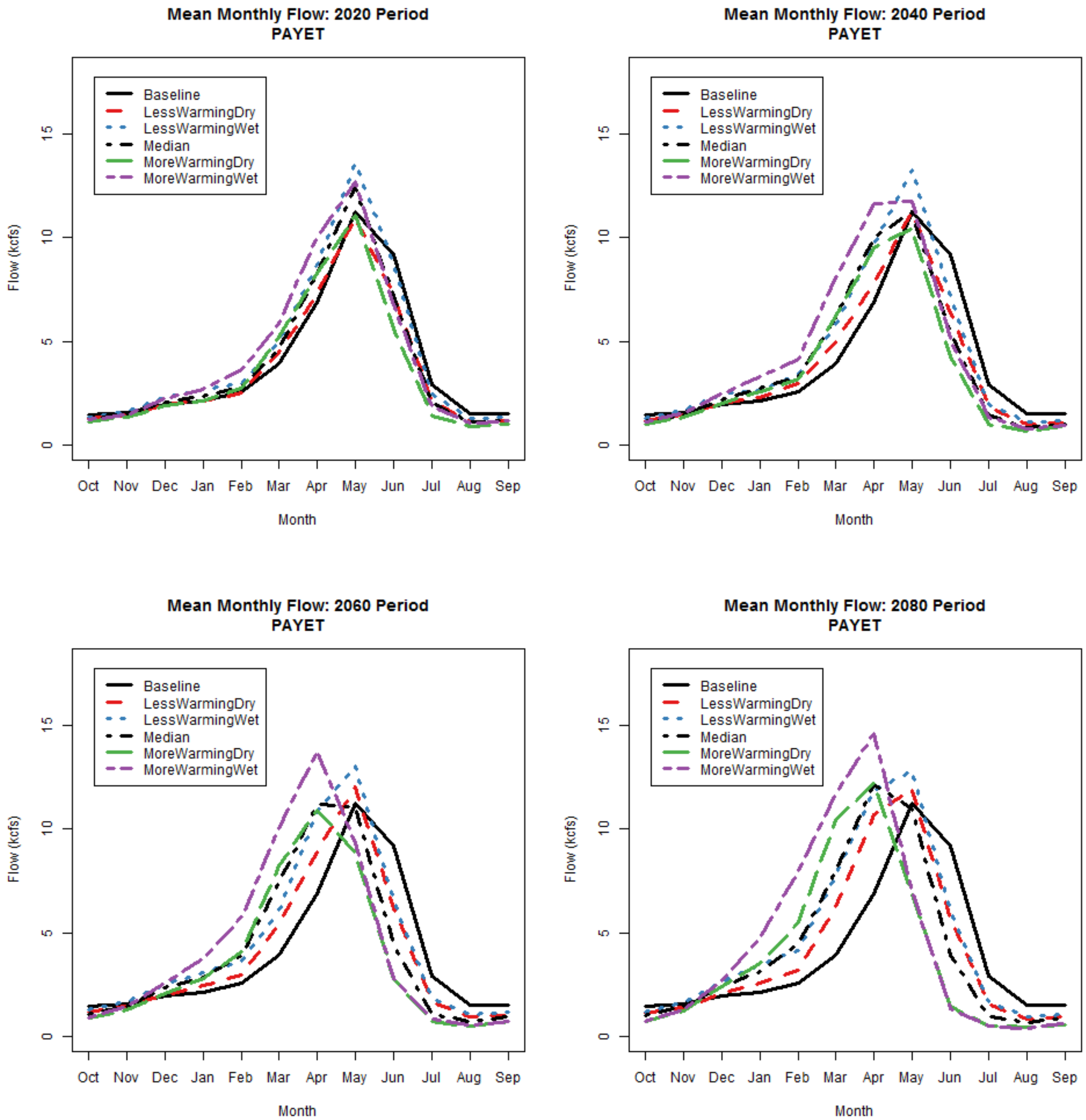


Figure 3.21 Mean monthly flow at PAYET.

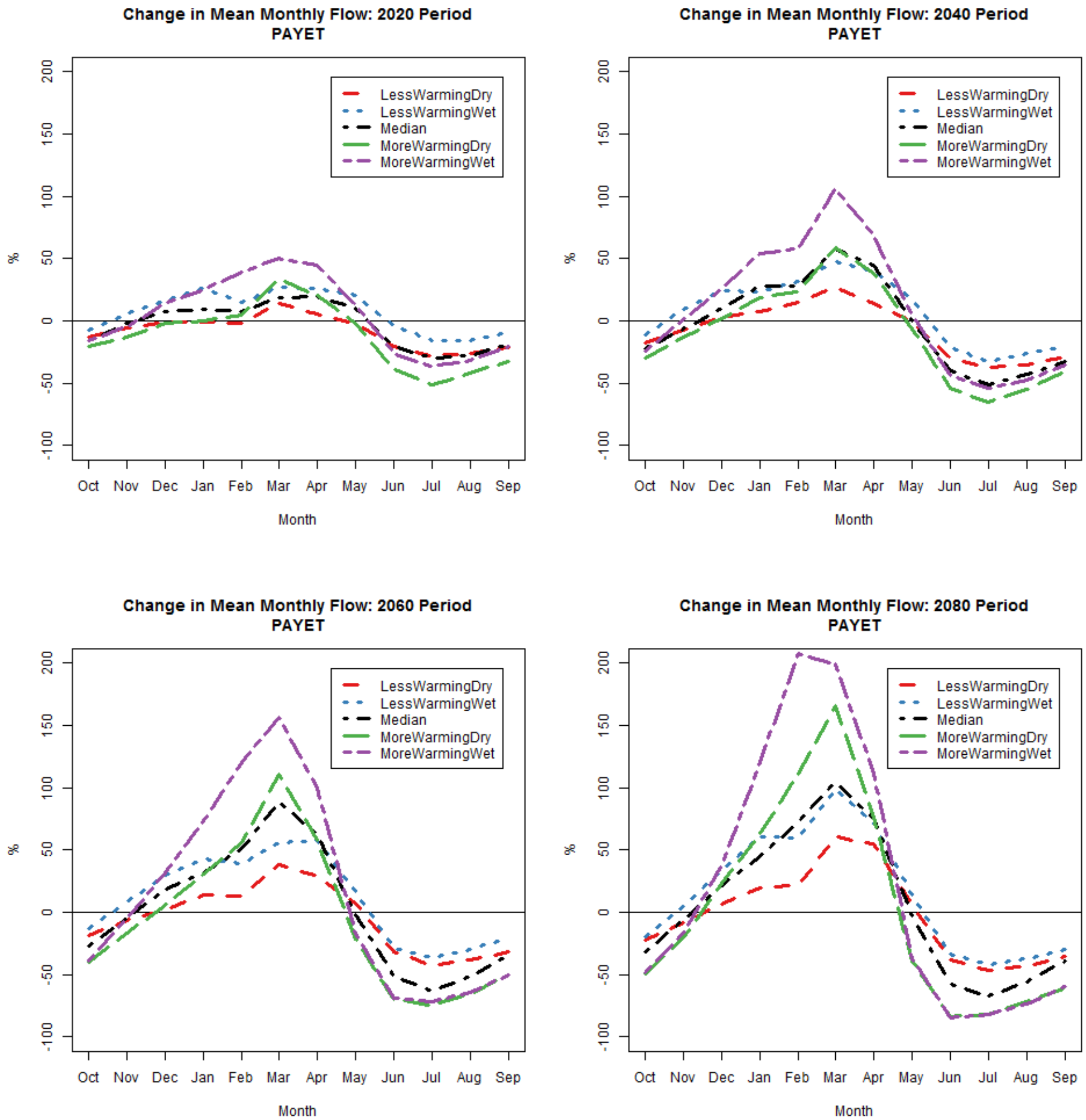
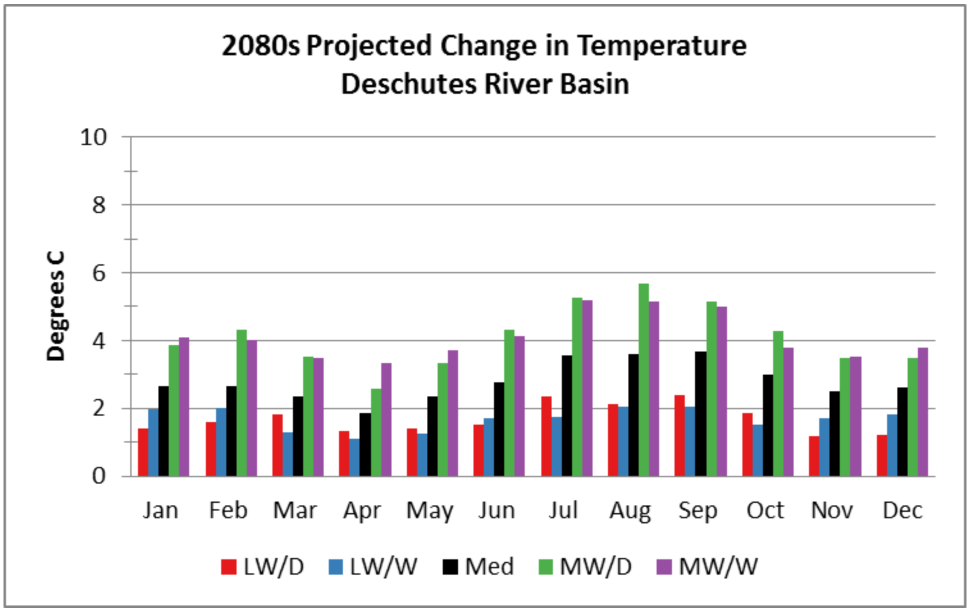


Figure 3.22 Change in mean monthly flow at PAYET.

3.1.3 Deschutes River Basin

This section presents a summary of the climate projections generated for the Deschutes River Basin as well as the simulated hydrologic impacts at two locations within the basin, including the Deschutes River near Madras, OR (DSMD) and the Crooked River below Opal Springs near Culver, OR (CKDOS). As with the other subbasins considered in this Assessment, all scenarios projected increases in temperature for the Deschutes River Basin, with the largest increases occurring during the summer months. Projected changes in precipitation were more varied than those for temperature; however, the results suggest a trend towards increased precipitation during the cool season and decreased precipitation during the warmer season. Only the Less Warming/Wet scenario projected a year-round increase in precipitation. While this scenario projects rather large increases in precipitation during the summer months, it should be noted that small increases in precipitation during dry conditions can equate to large increases in terms of percentages. Figure 3.23 illustrates these changes in temperature and precipitation relative to baseline conditions.



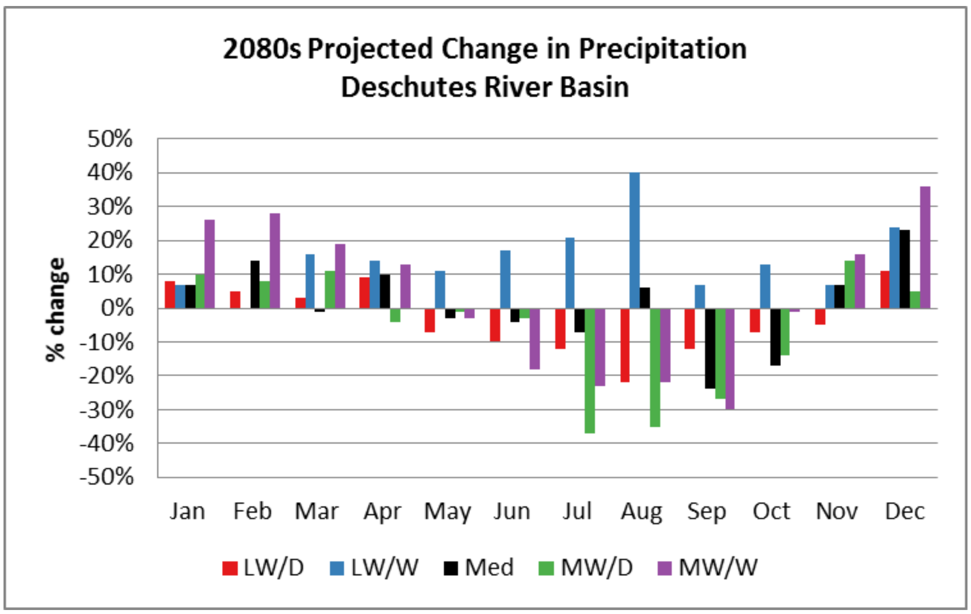


Figure 3.23 Projected 2080s monthly 50th-percentile change in temperature (top) and precipitation (bottom) for five scenarios (More Warming/Dry, More Warming/Wet, Median, Less Warming/Dry, and Less Warming/Wet) relative to the historical 1980-2009 period.

3.1.3.1 Deschutes River near Madras, OR

Of all of the locations presented here, the simulated runoff volumes for the Deschutes River near Madras, OR (DESMD) showed the smallest changes relative to the historical baseline annual volume. Changes ranged from -2.9% to 3.5% for the 2020s and gradually increase over the century to range from -1.7% to 7.8% by the 2080s. These changes are illustrated in Figure 3.24, where mean annual runoff for each scenario and period is plotted in the left-hand panel (baseline conditions are represented by the black dashed line) and percent change from baseline is plotted in the right-hand panel.

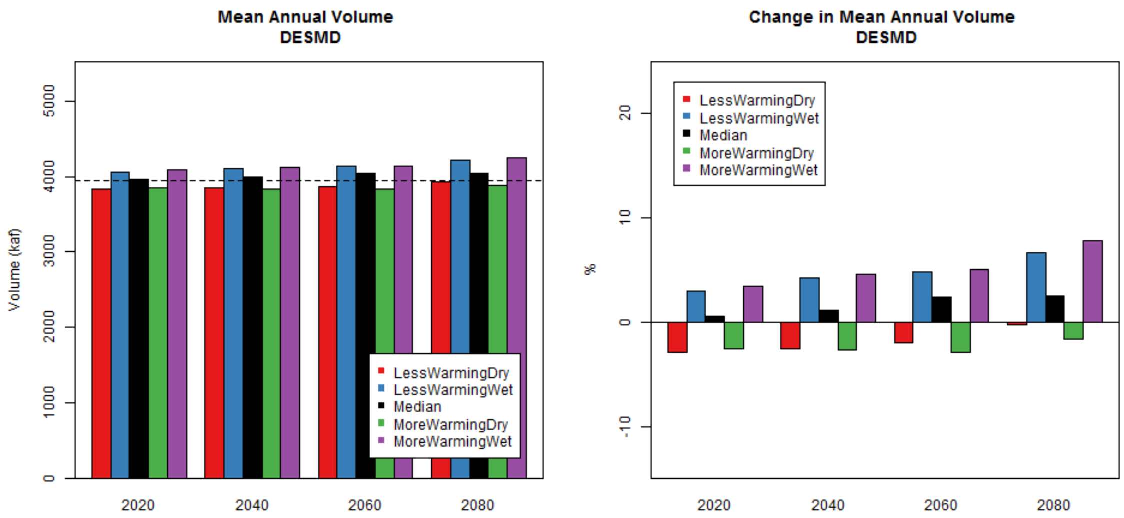


Figure 3.24 Mean annual volume (left) and change in mean annual volume (right) at DESMD.

While this study found little change in the overall annual volume of runoff at DESMD, results suggest that winter and spring flows will increase over the next century, while summer and fall flows will decrease. These changes are consistent with the projected increases in temperature and precipitation during the winter and spring and may be indicative of decreased winter snowpack accumulation as more precipitation falls as rain rather than snow. That said, the performance of the VIC model in the Deschutes subbasin was poor and the results presented here relied heavily on bias correction. As discussed further in Section 3.2, VIC is not able to reproduce the significant interactions between surface water and groundwater in this subbasin. It is possible that increased precipitation during the winter and spring would increase groundwater recharge, which in turn could increase (or maintain) summer low flows. More investigation is needed to determine whether the changes shown here are actually an artifact of hydrologic model performance.

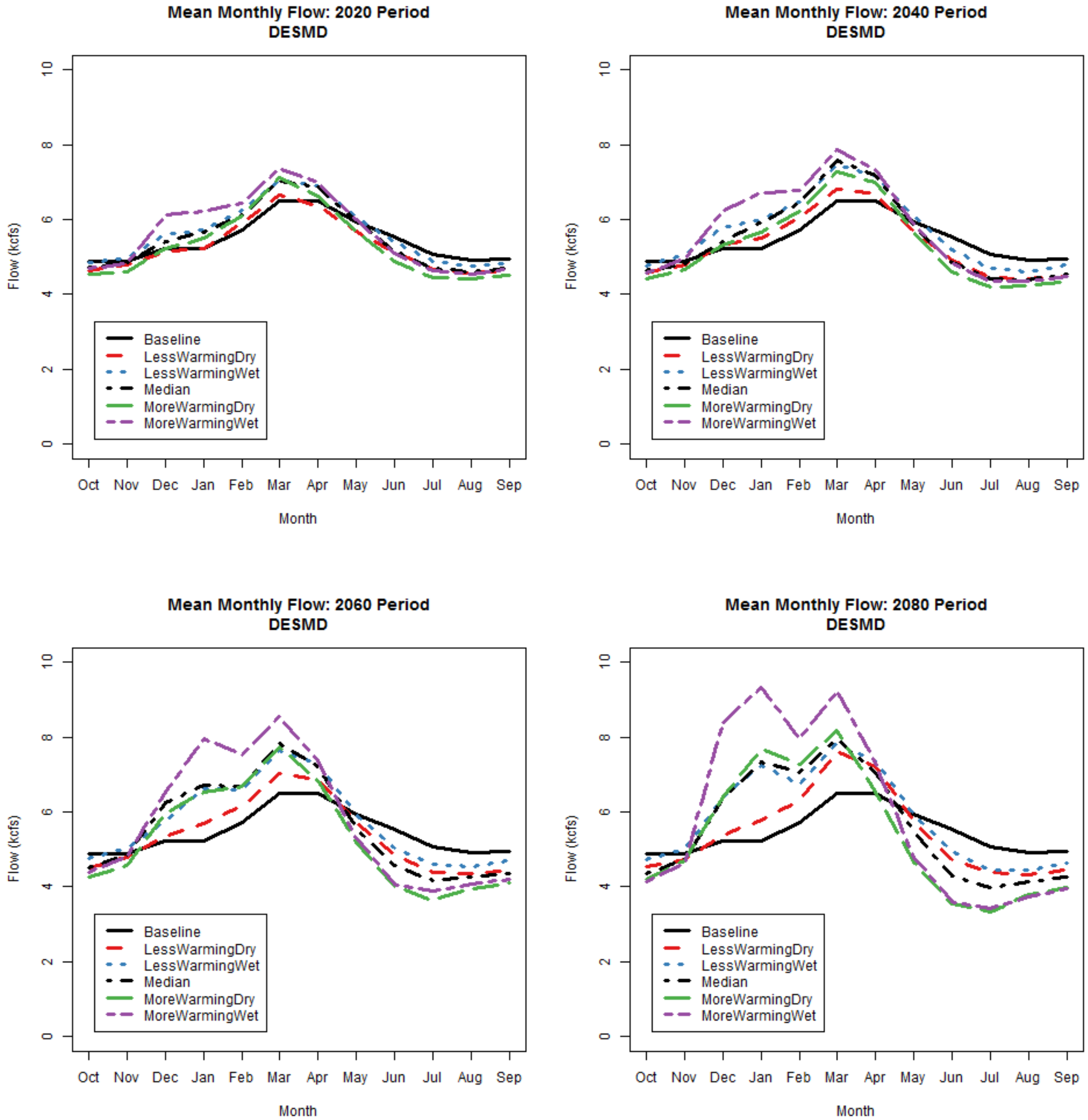


Figure 3.25 Mean monthly flow at DESMD.

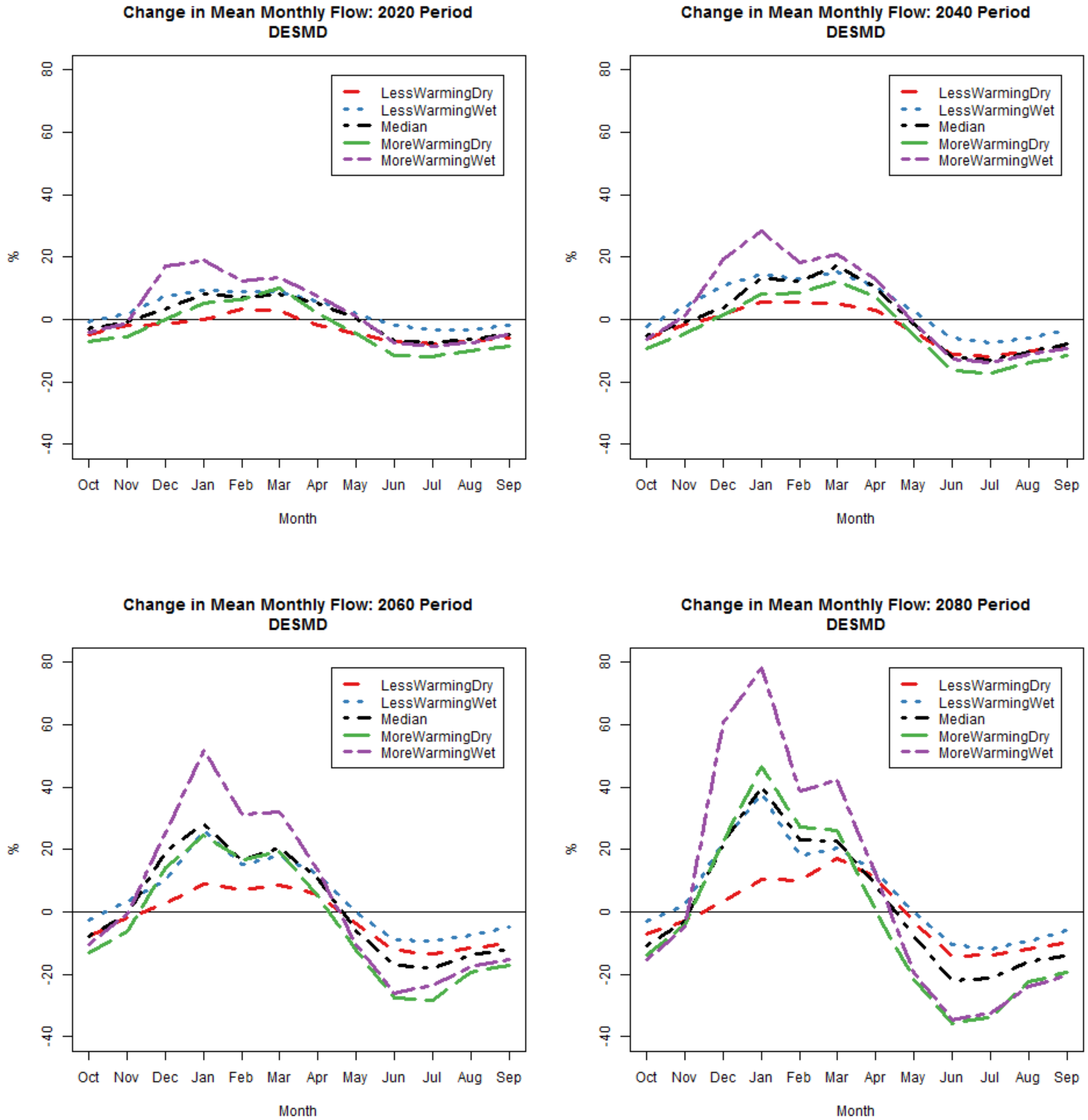


Figure 3.26 Change in mean monthly flow at DESMD.

3.1.3.2 Crooked River below Opal Springs near Culver, OR

In contrast to the Deschutes River near Madras, OR, the Crooked River area has relatively less surface-groundwater interaction and the VIC model performed much better at the Crooked River below Opal Springs near Culver, OR (CKDOS) location. Simulated changes to mean annual runoff were still very similar to those generated for DESMD, with all changes falling within -2.8% to 10.2% of historical. These changes are illustrated in Figure 3.27, where mean annual runoff for each scenario and period is plotted in the left-hand panel (historical baseline conditions are represented by the black dashed line) and percent change from baseline is plotted in the right-hand panel.

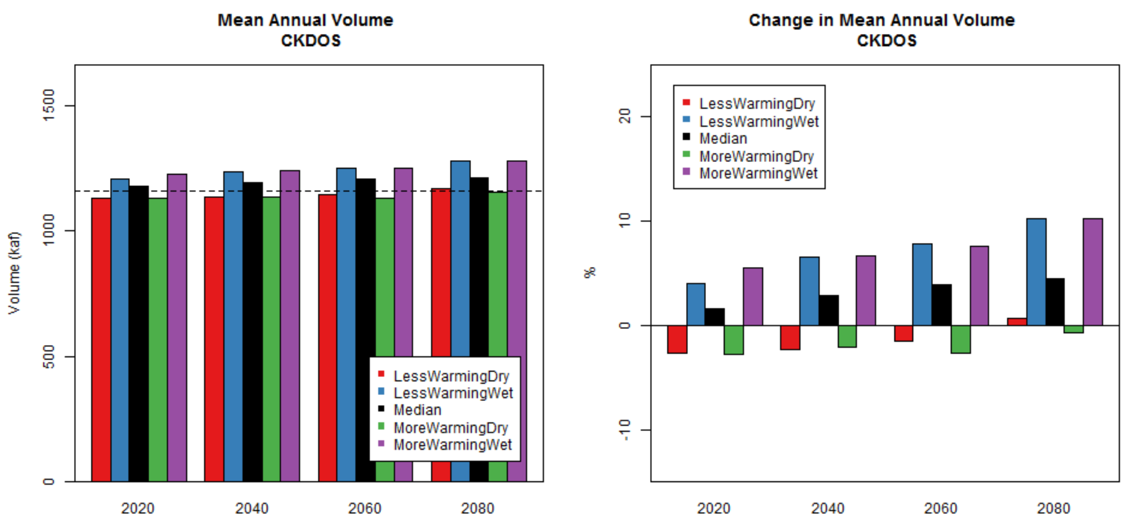


Figure 3.27 Mean annual volume (left) and change in mean annual volume (right) at CKDOS.

The seasonal changes simulated by this Assessment for CKDOS show trends similar to those seen for sites in the Upper Snake River Basin (Section 3.1.2). These sites currently exhibit snowmelt-driven peaks during the spring season and simulations indicate that these peaks will increase in magnitude over the next century. The results of this study also suggest there will be an increase in winter flows and a decrease in spring and early-summer flows at this location; however, these changes are relatively small compared to the seasonal changes simulated at other locations. Figure 3.28 and Figure 3.29 illustrate these changes in terms of both mean monthly flow and percent change in mean monthly flow relative to the historical period.

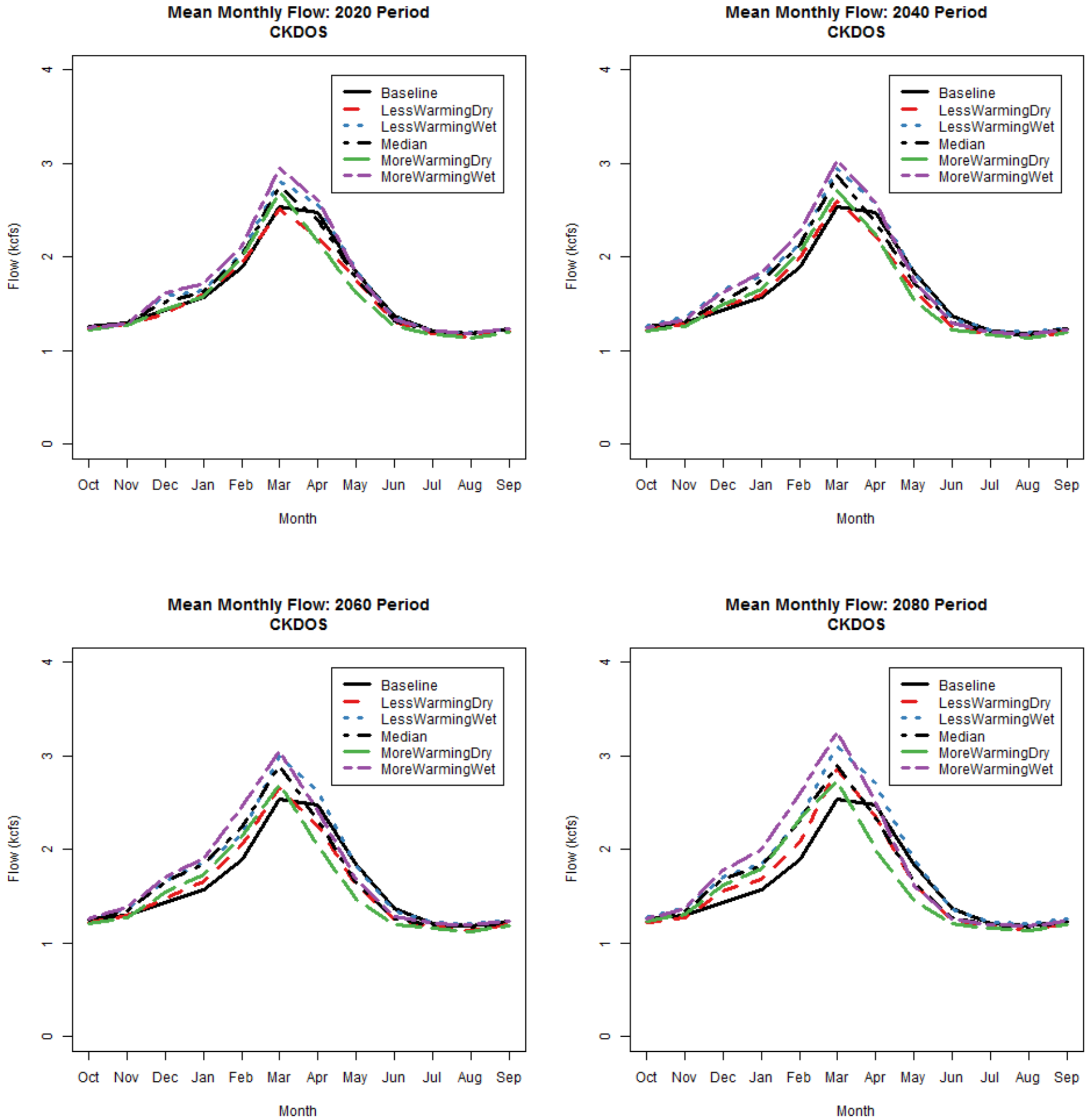


Figure 3.28 Mean monthly flow at CKDOS.

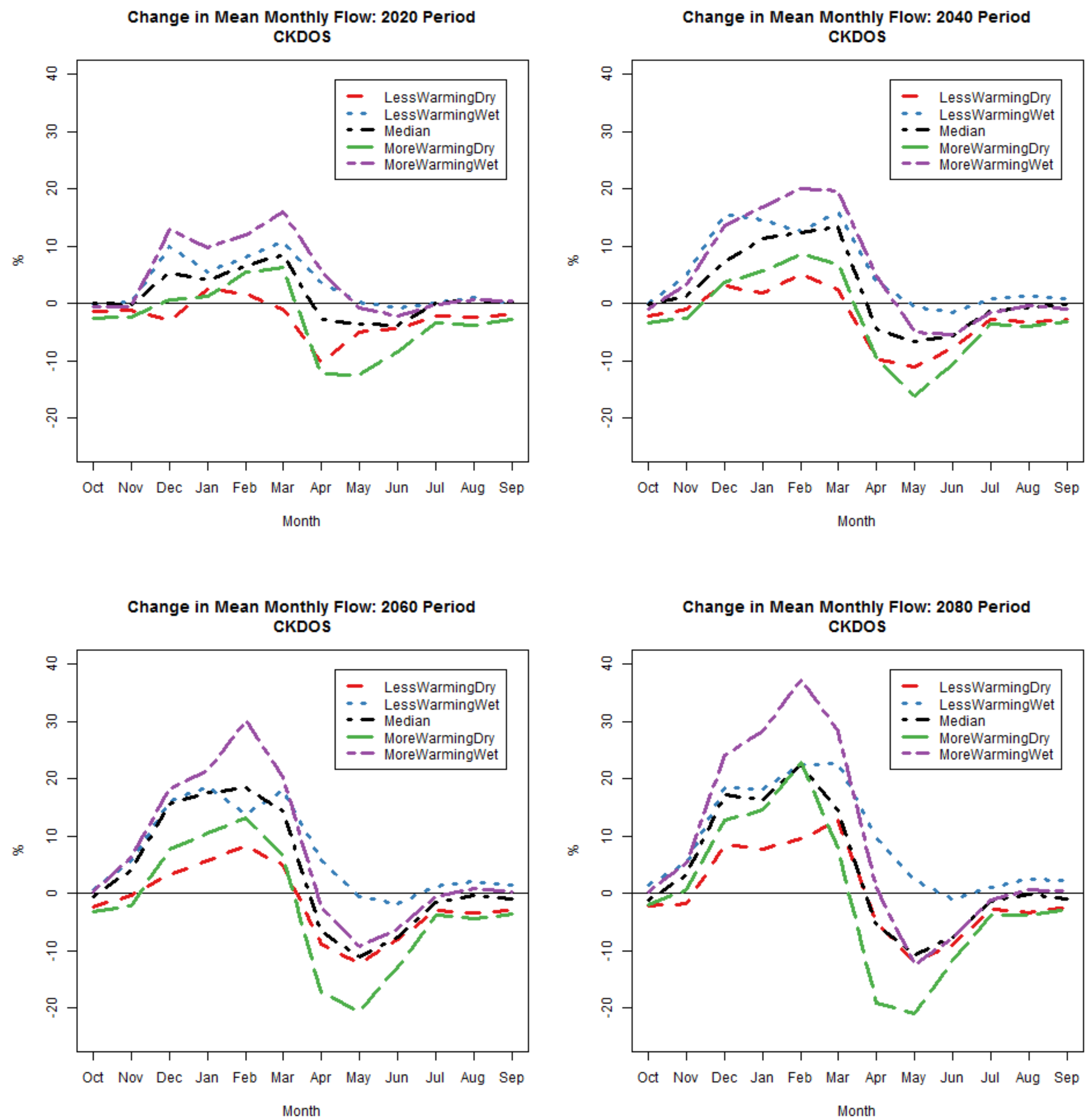


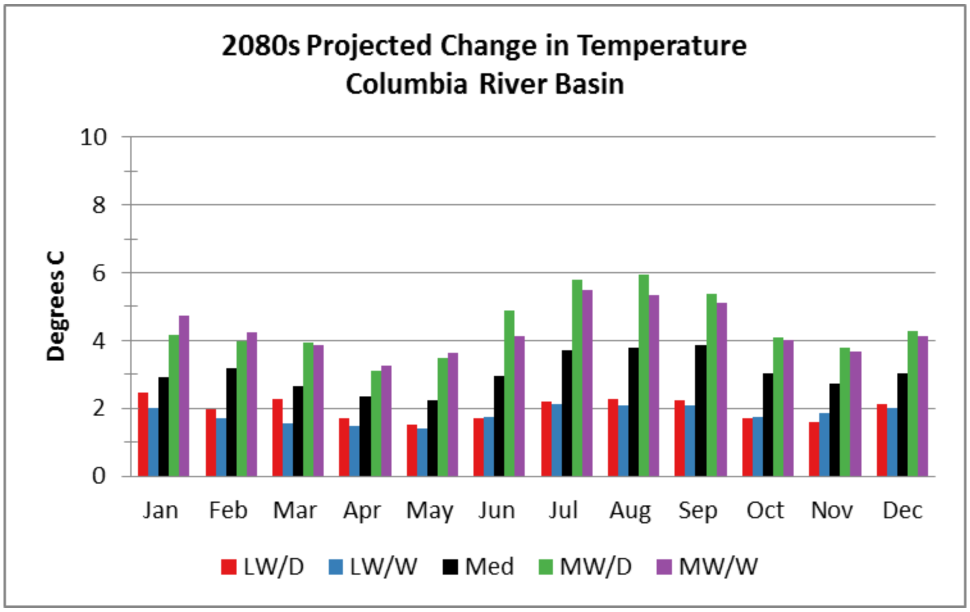
Figure 3.29 Change in mean monthly flow at CKDOS.

3.1.4 Mainstem Columbia River

3.1.4.1 Columbia River above The Dalles

Figure 3.30 depicts the monthly 50th percentile changes in temperature and precipitation projected for the 2080s period under each climate change scenario for the larger Columbia River Basin. This figure highlights the seasonality of these changes with the largest increases in temperature occurring in mid-summer and mid-winter (smaller increases in the spring and fall) and a general trend towards increased cool season precipitation and decreased warm season precipitation. Only the Less Warming/Wet scenario projected year-round increases in precipitation. It should be noted; however, that changes in precipitation are presented in terms of percent change from historical conditions and small decreases in precipitation during months that already (historically) receive very little precipitation can correspond to large percent change values.

Comparison of the More Warming scenarios (More Warming/Dry and More Warming/Wet) revealed an interesting pattern with the “dry” scenario showing larger increases in temperature June through December compared to its “wet” counterpart, and smaller increases in temperature during the winter and spring (January through May). Comparison of the Less Warming scenarios (Less Warming/Dry and Less Warming/Wet) showed a pattern that was similar, but less pronounced.



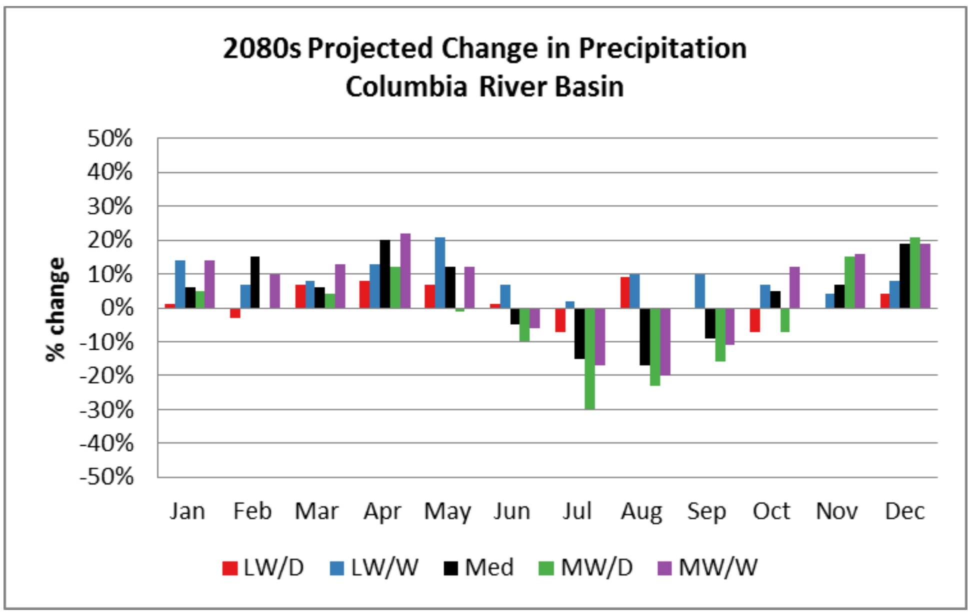


Figure 3.30 Projected 2080s monthly median change in temperature (top) and precipitation (bottom) for five scenarios (More Warming/Dry, More Warming/Wet, Median, Less Warming/Dry, and Less Warming/Wet) relative to the historical 1980-2009 period.

Figure 3.31 illustrates the simulated mean annual runoff volume and percent change in mean annual runoff (from historical) above The Dalles (DALLE). As shown in this figure, simulated changes varied in both direction and magnitude; however, all but one scenario suggest an increase in volume by the end of the century. Only the More Warming/Dry scenario produced consistently lower volumes for all of the simulated periods. As illustrated, the results of this Assessment suggest that annual volume at DALLE will change by -5% to 7.7% during the

2020s, -5.5% to 10.1% by the 2040s, -6.4% to 12.3% by the 2060s, and -4.2% to 14.5% by the 2080s relative to the historical period (1980 through 2009). It is interesting to note that the "less warming" scenarios show a larger increase in volume over time compared to the "more warming" scenarios. This is likely due in part to increases in ET associated with rising temperatures.

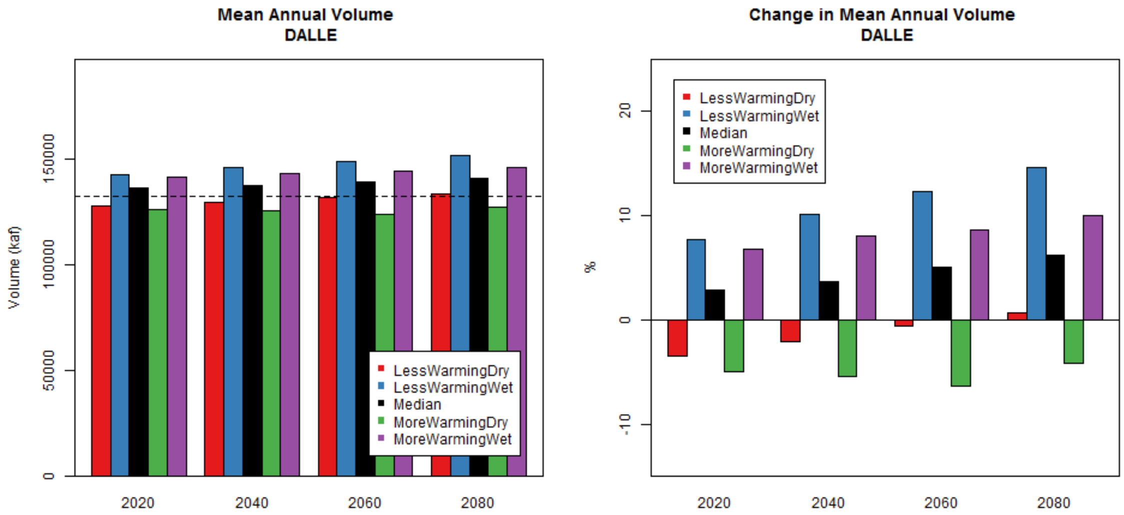


Figure 3.31 Mean annual volume (left) and change in mean annual volume (right) at DALLE.

Figure 3.32 and Figure 3.33 illustrate the seasonal variation in simulated runoff in terms of mean monthly flow. As shown in these figures, the results of this Assessment indicate a shift towards earlier peak runoff (shifting from June to May), as well as the potential for significant increases in late-winter and early-spring flows. During the summer and fall months, all scenarios suggest that flows will decline over the remainder of the century. These trends are not only consistent with the results of the upstream locations discussed previously, but also with the general trends in warming, increased winter/spring precipitation, and decreased summer precipitation shown in Figure 3.30.

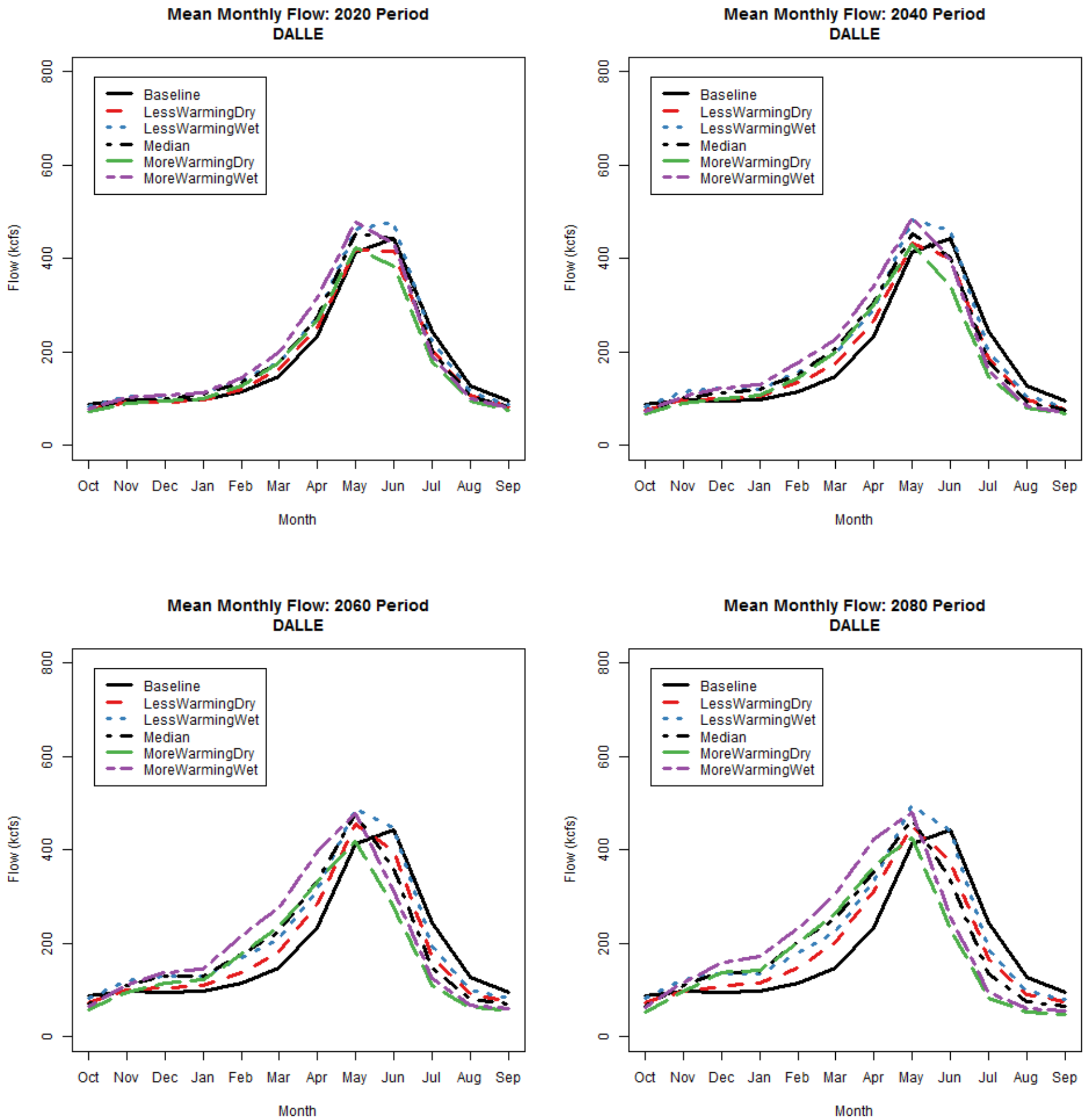


Figure 3.32 Mean monthly flow at DALLE.

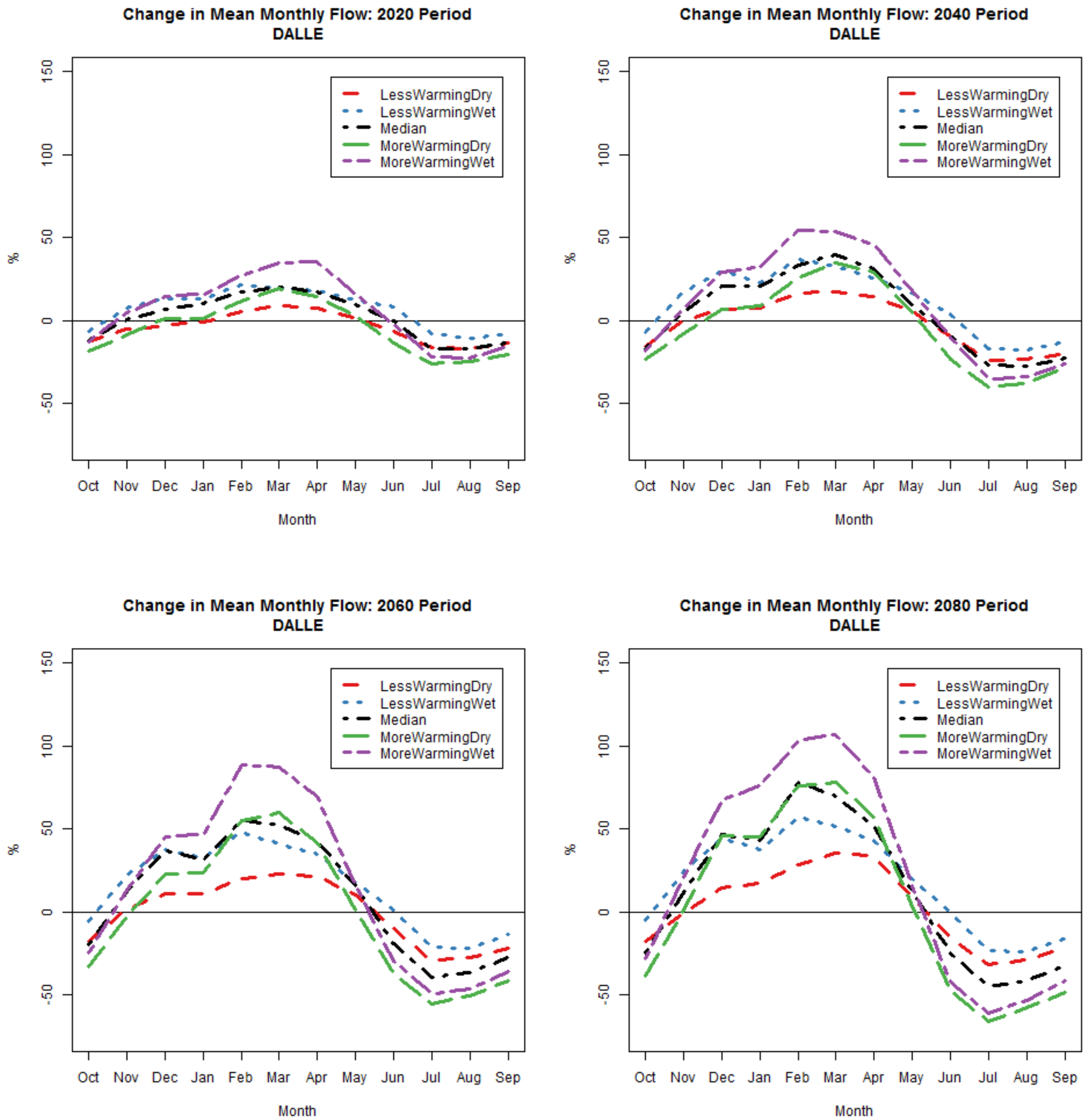


Figure 3.33 Change in mean monthly flow at DALLE.

3.2 Limitations in Groundwater-Dominant Watersheds

One limitation of VIC is that, although it calculates the volume of water that becomes baseflow on a cell-by-cell basis, it is limited in its ability to simulate groundwater flow. For this reason, basins where streamflow conditions are highly dependent on groundwater-surface water interactions may not be well simulated by VIC. This behavior is particularly apparent in the Deschutes River Basin where baseflow dominates the annual hydrograph resulting in a shape that appears more flat compared to the shape associated with a snowmelt dominated basin, like the Boise River Basin. Figure 3.34 illustrates the historical naturalized flows (solid lines) and the simulated flows provided by VIC for the Deschutes (left panel) and Boise (right panel) Basins. As shown by these plots, VIC performs much better at simulating flows in a snowmelt dominated basin like the Boise than it does in a baseflow dominated basin like the Deschutes.

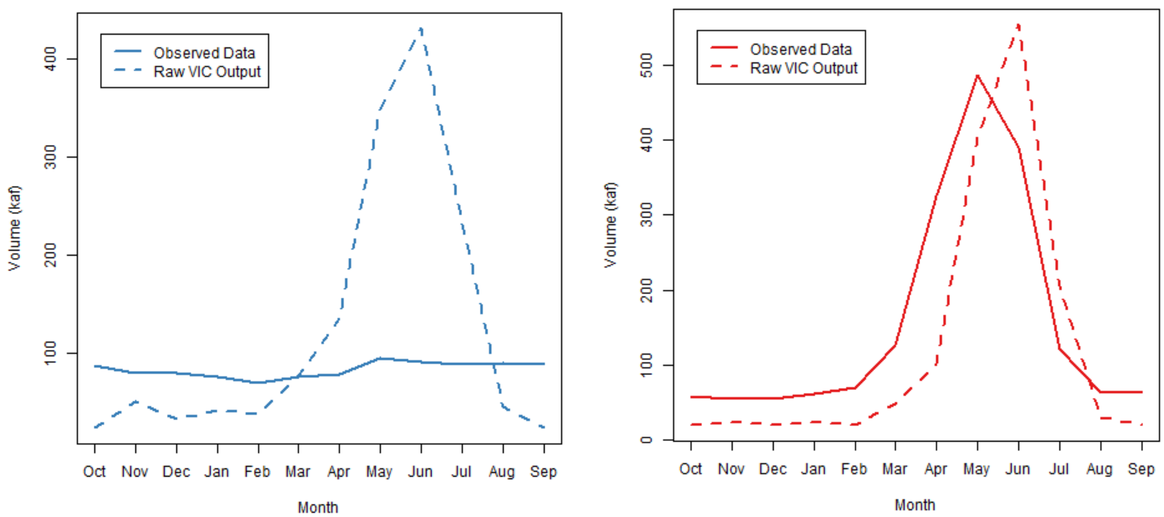


Figure 3.34 Monthly mean volume for the historical period of (1) observed naturalized flow (solid line) and (2) raw VIC output (dashed line) for the Deschutes River at Benham Falls (left) and the Boise River at Glenwood Bridge (right).

One approach for handling the difference between VIC simulated flow and observed flow is the use of bias correction post-processing (described further in Section 2.3) where simulated flows are adjusted to more closely match observations using a statistical quantile mapping technique. Another, perhaps obvious, approach for addressing this issue is to determine whether the basin hydrographs are likely to be well simulated by VIC *prior* to choosing a hydrologic model for use in the study. If the hydrographs for a particular basin tend to be more flat (indicating that streamflow is highly influenced by baseflow), it may indicate the need for a model that simulates groundwater flow, in addition to surface flow. Such a model would produce more accurate flow simulations and require less bias correction.

A high level assessment was conducted for the streamflow locations included in this study to determine whether any of these locations might benefit from the use of a hydrologic model with better groundwater representation. Two types of streamflow data were available for this study: naturalized and unregulated flow data. Naturalized flow data represents the flow that would be in the river without regulation by reservoirs, without diversions, without groundwater return flows that result from irrigation deep percolation, and without streamflow depletions that result from groundwater pumping. Unregulated flow data, on the other hand, represents the flow that would be in the river without regulation by reservoirs and without diversions; however, groundwater return flows and streamflow depletions remain a factor in the dataset. This difference is often due to a simple lack of information regarding groundwater returns and groundwater pumping. In many cases, unregulated data is the best that is available.

Using both naturalized and unregulated average annual hydrographs, ratios of the annual low flow volume to the annual peak flow volume were calculated. It should be noted that the use of unregulated data for this calculation has the potential to create an upward bias in the ratio value due to the fact that groundwater return flows may be augmenting low flows in the late-summer and winter. Figure 3.35 illustrates the ratios that were calculated for each measurement location. Points outlined with a circle depict locations where ratios were calculated using unregulated data.

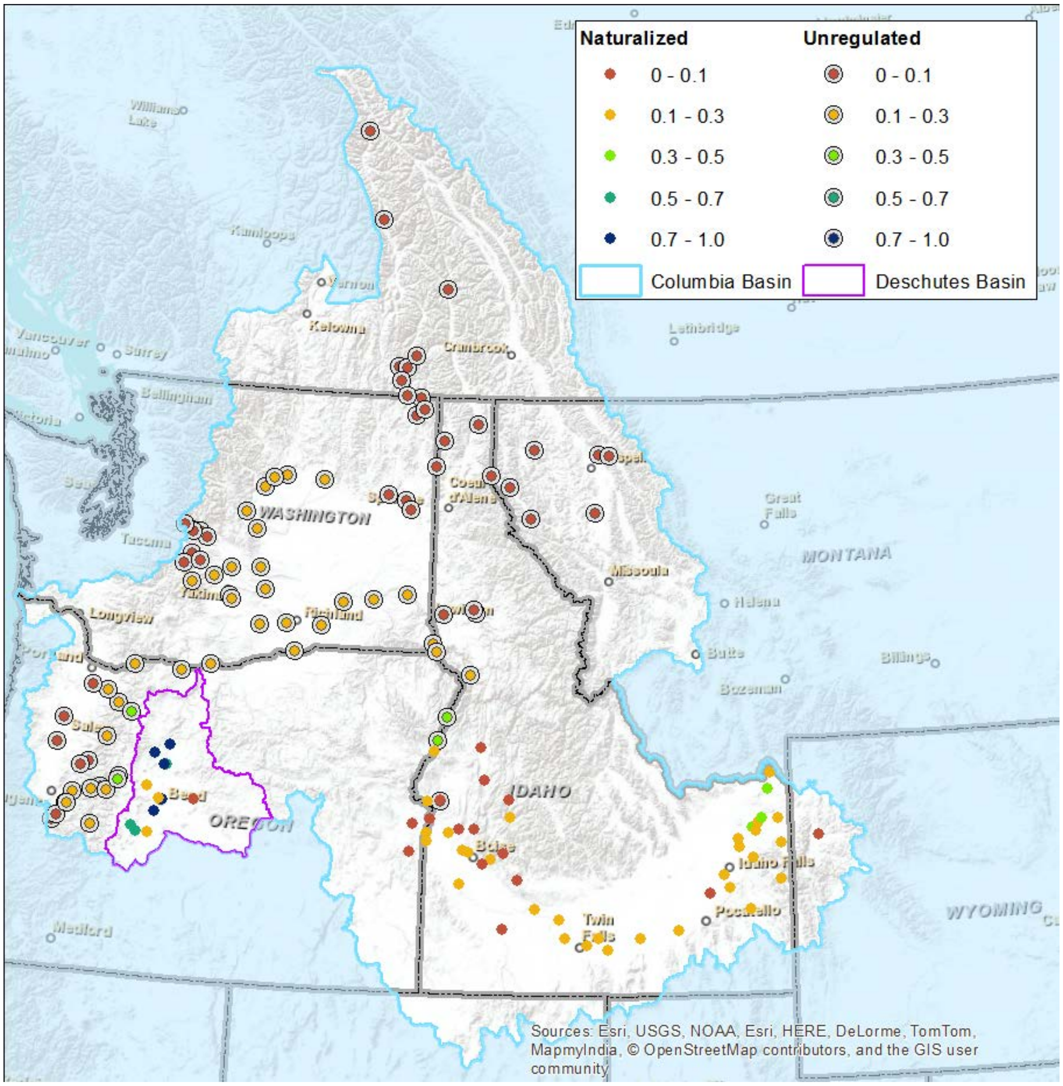


Figure 3.35: Map of calculated ratios representing the average annual low flow divided by the average annual peak flow. The data with grey outlines are ratios calculated using unregulated data.

Higher ratios are indicative of conditions where the average annual hydrograph is more flat and suggests more significant influence from baseflow (as in the Deschutes River Basin), while lower ratios suggest that the hydrograph is more strongly influenced by a snowmelt runoff pattern (characterized by higher peaks and lower lows, as in the Boise River Basin). As expected, the locations within the Deschutes River Basin (outlined in purple) exhibit the highest ratio values when compared to the rest of the locations considered.

This screening approach shows promise for informing hydrologic model selection; however, more research is needed to identify a cutoff ratio above which a model with lateral groundwater transport should be considered.

3.3 Comparison with Previous RMJOC-1 Climate Change Study Results

This section presents a side-by-side comparison of the results generated by this Assessment and those produced by the RMJOC-1 Climate Change Study (RMJOC-1 2011) at five locations within the Columbia River Basin. Generally speaking, this Assessment produced results similar to those generated by the RMJOC-1 Climate Change Study with some nuances. While the two studies showed similar shifts in peak flow timing and reductions in summer flows, the results of this Assessment demonstrated larger peak runoff values and less pronounced increases in winter flows. Figure 3.36 through Figure 3.40 provide side-by-side illustrations of the Assessment (left side of each figure, identified as CRBIA) and the RMJOC-1 Climate Change Study (right side of each figure) simulated monthly runoff for the 2020s and 2040s under each climate scenario. The source of these differences was not investigated in detail; however, they may be the result of a number of factors, including the following:

- CMIP5 climate change projections were used for this Assessment while CMIP3 projections were used for the RMJOC-1 Climate Change Study.
- This Assessment selected projections for each scenario at the subbasin-scale while the RMJOC-1 Climate Change Study selected projections for the Columbia River Basin as a whole.
- This Assessment used the Hybrid Delta Ensemble methodology (discussed in Section 2) to develop climate change scenarios while the RMJOC-1 Climate Change Study used the Hybrid Delta method and single GCM projections.

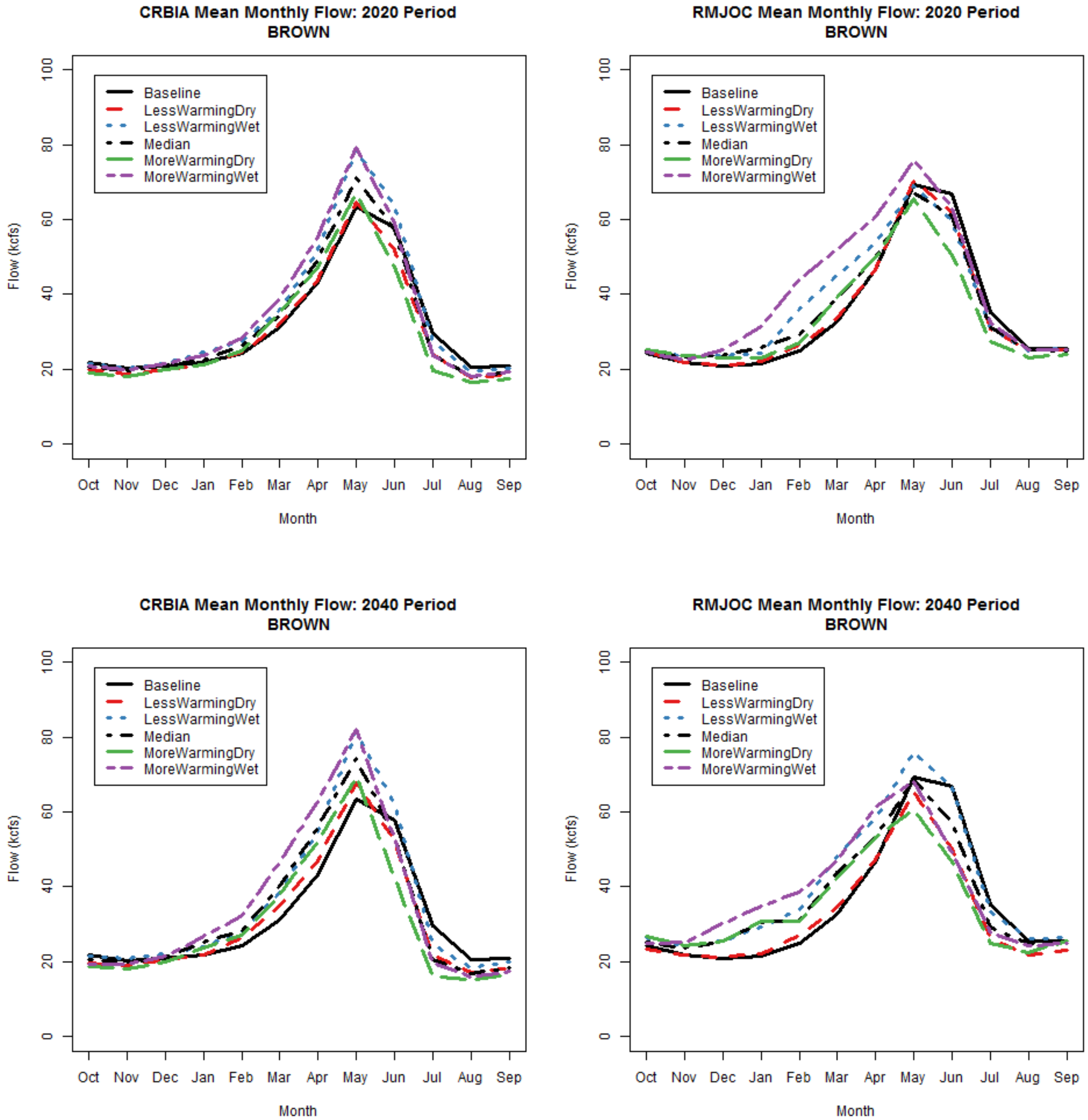


Figure 3.36 CRBIA (left) and RMJOC (right) simulated mean monthly runoff volumes for the Snake River at Brownlee (BROWN) for the 2020s (top) and 2040s (bottom).

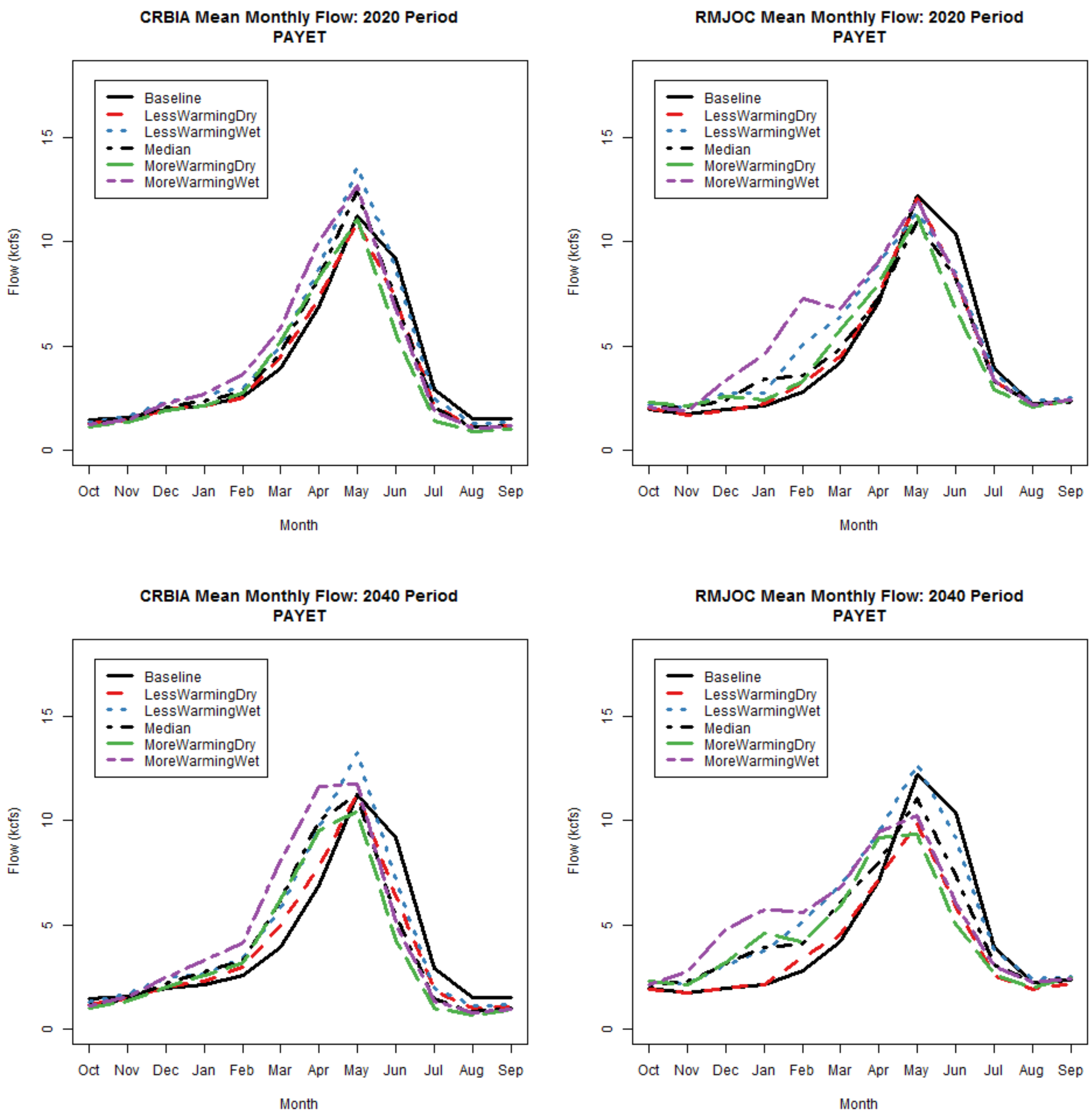


Figure 3.37 CRBIA (left) and RMJOC (right) simulated mean monthly runoff volumes for the Payette River near Payette, Idaho (PAYET) for the 2020s (top) and 2040s (bottom).

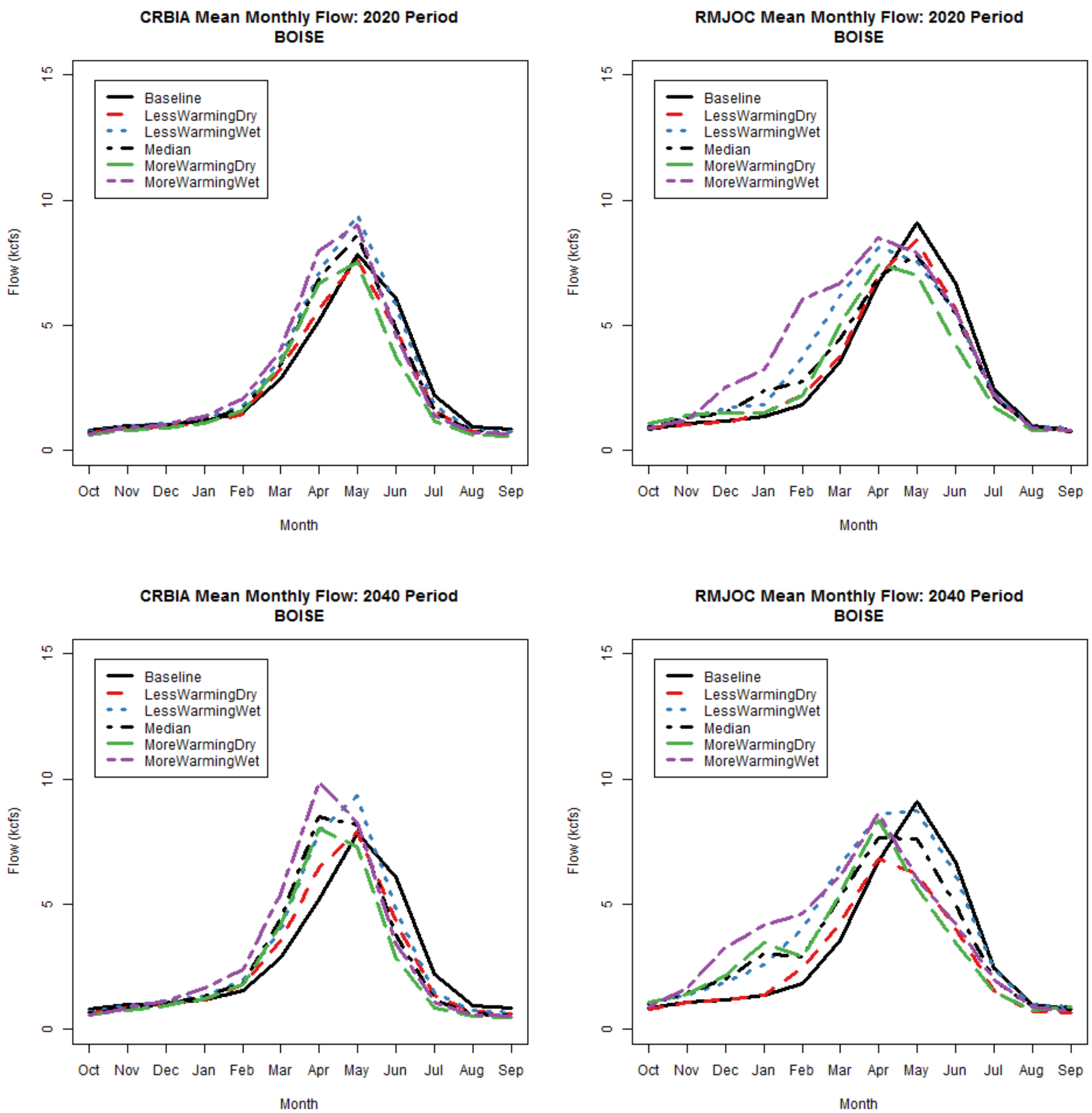


Figure 3.38 CRBIA (left) and RMJOC (right) simulated mean monthly runoff volumes for the Boise River at Lucky Peak (BOISE) for the 2020s (top) and 2040s (bottom).

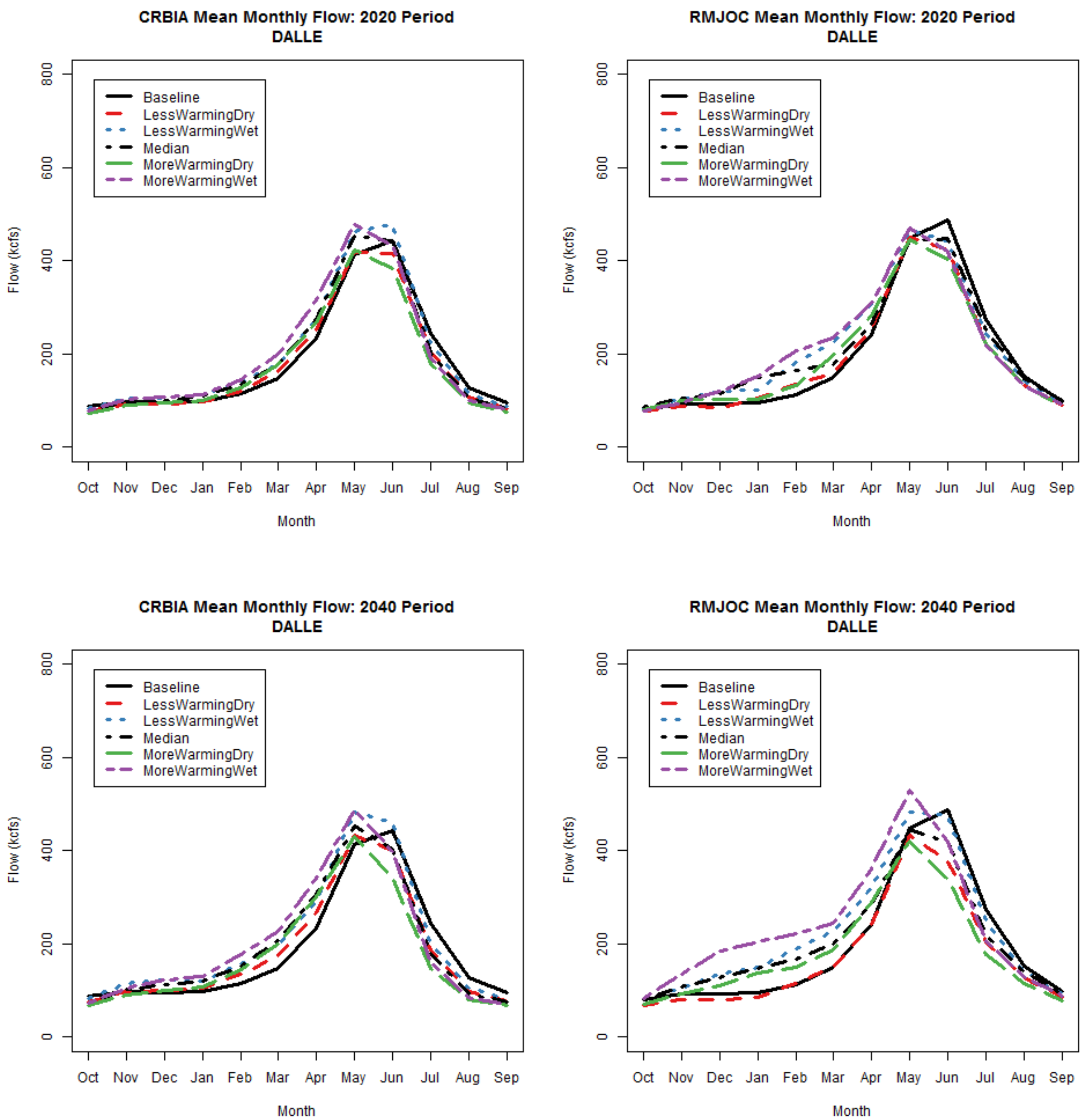


Figure 3.39 CRBIA (left) and RMJOC (right) simulated mean monthly runoff volumes for the Columbia River at The Dalles (DALLE) for the 2020s (top) and 2040s (bottom).

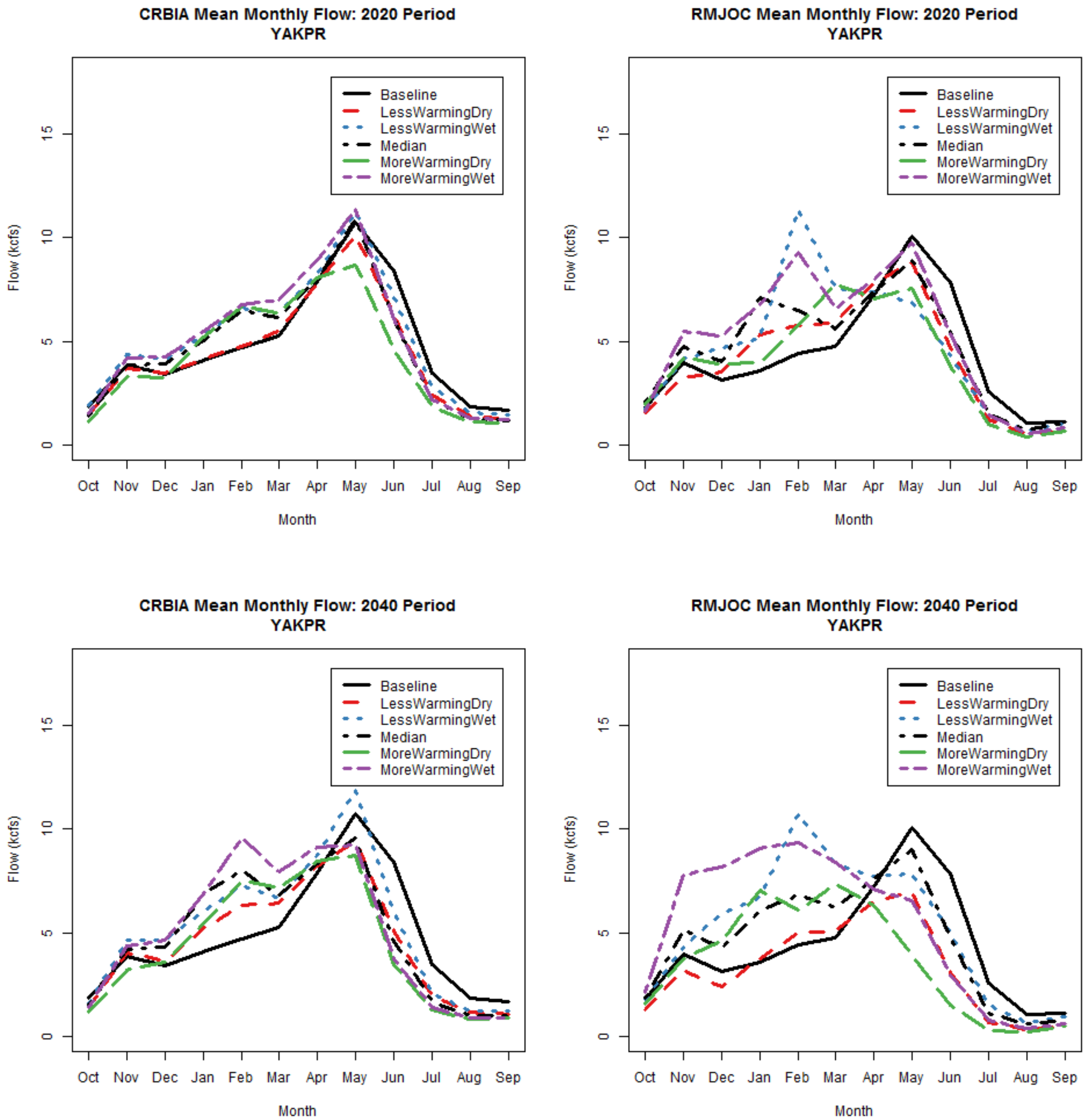


Figure 3.40 CRBIA (left) and RMJOC (right) simulated mean monthly runoff volumes for the Yakima River near Parker (YAKPR) for the 2020s (top) and 2040s (bottom).

4 Literature Cited

Parenthetical Reference	Bibliographic Citation
Bureau of Reclamation. See Reclamation.	
Liang et al. 1994	Liang, X., D.P. Lettenmaier, E.F. Wood, and S.J. Burges. 1994. *A Simple Hydrologically Based Model of Land Surface Water and Energy Fluxes for General Circulation Models.* Journal of Geophysical Research, 99(D7), 14415-14428.
Livneh et al. 2013	Livneh, B., E.A. Rosenberg, C. Lin, B. Nijssen, V. Mishra, K. Andreadis, E. Maurer, D.P. Lettenmaier. 2013. *A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States: Updates and Extensions.* Journal of Climate, 26(23), 9384-9392. Retrieved from http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-12-00508.1 (last accessed January 27, 2016)
Lohmann et al. 1996	Lohmann, D., R. Nolte-Holube, and E. Raschke. 1996. *A Large-Scale Horizontal Routing Model to be Coupled to Land Surface Parametrization Schemes.* Tellus, 48(A), 708-721.
Lohmann et al. 1998	Lohmann, D., E. Raschke, B. Nijssen and D.P. Lettenmaier. 1998. *Regional Scale Hydrology: I. Formulation Of The VIC-2L Model Coupled to a Routing Model.* Hydrological Sciences Journal, 43:1, 131-141.
Reclamation 2010	Bureau of Reclamation. 2010. *Climate Change and Hydrology Scenarios for Oklahoma Yield Studies.* Prepared by the U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver, Colorado. 71 pp.
Reclamation 2014	Bureau of Reclamation. 2014. *Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections: Release of Hydrology Projections, Comparison with Preceding Information, and Summary of User Need.* Prepared by U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver, Colorado. 110 pp.

Parenthetical Reference	Bibliographic Citation
RMJOC-1 2011	River Management Joint Operating Committee Climate Change Study Reports, Parts I–IV. 2011. U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, and Bonneville Power Administration. *Climate and Hydrology Datasets for Use in the RMJOC-1 Climate Agencies' Longer-Term Planning Studies.* 2010–2011.
Snover et al. 2003	Snover A.K., A.F. Hamlet, D.P. Lettenmaier. 2003. *Climate Change Scenarios for Water Planning Studies.* Bulletin of the American Meteorological Society, 84 (11): 1513-151.

5 APPENDIX

5.1 Simulated Streamflow Locations

Table 1. List of CRBIA simulated streamflow locations.

Site Full Name	POINT NAME	Subbasin	Latitude	Longitude
Crooked River Below Opal Springs, Near Culver, OR	CKDOS	Deschutes	44.4925	-121.2833
Crooked River Near Prineville, OR	CKDPV	Deschutes	44.1133	-120.7944
Cresent Cr At Cresent Lake Nr Crecent, OR	CRSCR	Deschutes	43.5030	-121.9722
Deschutes River Below Bend, OR	DESBD	Deschutes	44.0831	-121.3067
Deschutes R At Benham Falls Nr Bend, OR	DESBH	Deschutes	43.9382	-121.4120
Deschutes R Bl Crane Prairie Res Nr Pine, OR	DESCP	Deschutes	43.7556	-121.7833
Deschutes River Near Culver, OR	DESCV	Deschutes	44.4989	-121.3200
Deschutes R Bl Wickiup Res Nr La Pine, OR	DESLP	Deschutes	43.6861	-121.6869
Deschutes River Near Madras, OR	DESMD	Deschutes	44.7289	-121.2572
Little Deschutes River Near La Pine, OR	LDESL	Deschutes	43.6892	-121.5017
Metolius River Near Grandview, OR	METGV	Deschutes	44.6264	-121.4828
Ochoco Cr Bl Ochoco Rs Nr Prineville, OR	OCHPV	Deschutes	44.2986	-120.7250
Tumalo Creek Bl Tumalo Feed Canal Nr Bend, OR	TUMBD	Deschutes	44.0878	-121.3717

Site Full Name	POINT NAME	Subbasin	Latitude	Longitude
Whychus Creek Near Sisters, OR	WHYSI	Deschutes	44.2339	-121.5658
Albeni Falls	ALBEN	Grand Coulee	48.1822	-117.0333
Hugh Keenleyside (Arrow)	ARROW	Grand Coulee	49.3394	-117.7719
Beaver River Near the Mouth	BEAVE	Grand Coulee	51.5097	-117.4617
Bonners Ferry	BONFE	Grand Coulee	48.6981	-116.3125
Boundary	BOUND	Grand Coulee	48.9872	-117.3475
Box	BOXCA	Grand Coulee	48.7811	-117.4153
Brilliant	BRILL	Grand Coulee	49.3244	-117.6203
Cabinet	CABIN	Grand Coulee	48.0881	-116.0728
Coeur D'Alene	CDALK	Grand Coulee	47.6661	-116.7706
Chief Joseph	CHIEF	Grand Coulee	47.9944	-119.6347
Columbia Falls	COLFA	Grand Coulee	48.3619	-114.1839
Corra Linn	CORRA	Grand Coulee	49.4669	-117.4669
Duncan	DUNCA	Grand Coulee	50.2667	-116.9464
Kerr	FLAPO	Grand Coulee	47.6803	-114.2458
Hungry Horse	FLASF	Grand Coulee	48.3417	-114.0083

Site Full Name	POINT NAME	Subbasin	Latitude	Longitude
Grand Coulee	GCOUL	Grand Coulee	47.9656	-118.9817
Libby	LIBBY	Grand Coulee	48.4117	-115.3094
Long Lake	LLAKE	Grand Coulee	47.8367	-117.8403
Mica	MICAA	Grand Coulee	52.0778	-118.5664
Murphy Creek	MUCXX	Grand Coulee	49.1778	-117.7164
Nine Mile	NINXX	Grand Coulee	47.7760	-117.5450
Noxon Rapids	NOXON	Grand Coulee	47.9611	-115.7328
Post Falls	PFALL	Grand Coulee	47.7031	-116.9778
Priest Rapids	PRIRA	Grand Coulee	46.6289	-119.8636
Priest Lake	PRSTL	Grand Coulee	48.4903	-116.9042
Revelstoke	REVEL	Grand Coulee	51.0494	-118.1939
Rock Island	RISLA	Grand Coulee	47.3325	-120.0800
Rocky Reach	ROCKY	Grand Coulee	47.5244	-120.3011
Monroe Street	SPOKA	Grand Coulee	47.6594	-117.4481
Sullivan Lake	SUVXX	Grand Coulee	48.8450	-117.2867
Thompson Falls	THOMF	Grand Coulee	47.5950	-115.3600

Site Full Name	POINT NAME	Subbasin	Latitude	Longitude
Wanapum	WANAP	Grand Coulee	46.8881	-119.9836
Waneta	WANET	Grand Coulee	49.0039	-117.6114
Wells	WELLS	Grand Coulee	47.9467	-119.8656
Anatone	ANATO	Columbia	46.0972	-116.9767
Orofino	CLEAR	Columbia	46.4783	-116.2575
The Dalles	DALLE	Columbia	45.6075	-121.1722
Dworshak	DWORS	Columbia	46.5153	-116.2961
Galloway	GALXX	Columbia	44.2550	-116.7730
Troy	GROND	Columbia	45.9458	-117.4500
Hells Canyon	HCANY	Columbia	45.2514	-116.6972
Ice Harbor	ICEHA	Columbia	46.2506	-118.8819
John Day	JNDAY	Columbia	45.7147	-120.6936
Little Goose	LGOOS	Columbia	46.5872	-118.0258
Lower Granite	LGRAN	Columbia	46.6678	-117.4439
Lime Point	LIMXX	Columbia	46.0031	-116.9169
Lower Monumental	LMONU	Columbia	46.5502	-118.5335

Site Full Name	POINT NAME	Subbasin	Latitude	Longitude
Oxbox	OXBOW	Columbia	44.9728	-116.8333
Round Butte	RNDBB	Columbia	44.6039	-121.2778
White Bird	SALMO	Columbia	45.7503	-116.3239
Spalding	SPALD	Columbia	46.4486	-116.8264
Snake River at Neeley American Falls Inflow	AMERI	Upper Snake	42.7675	-112.8794
Henrys Fork at St. Anthony, ID	ANTIX	Upper Snake	43.9667	-111.6725
Boise River at Glenwood Bridge nr Boise, ID	BIGIX	Upper Snake	43.6603	-116.2783
Blackfoot Reservoir Inflow	BLKIX	Upper Snake	43.0058	-111.7156
SF Boise River at Anderson Ranch	BOAND	Upper Snake	43.3436	-115.4775
Boise River Arrowrock Inflow	BOARK	Upper Snake	43.5942	-115.9222
Boise River Lucky Peak Inflow	BOISE	Upper Snake	43.5278	-116.0586
Boise River nr Middleton, ID	BOMIX	Upper Snake	43.6837	-116.3788
Boise River nr Twin Springs, ID	BOTWI	Upper Snake	43.6594	-115.7272
Snake River at Brownlee Dam Inflow	BROWN	Upper Snake	44.8364	-116.8994
Bruneau River nr Hot Spring, ID	BRUNE	Upper Snake	42.7711	-115.7203
Blackfoot River nr Shelley, ID	BSHIX	Upper Snake	43.2628	-112.0478

Site Full Name	POINT NAME	Subbasin	Latitude	Longitude
Snake River nr Buhl, ID	BUHLX	Upper Snake	42.6658	-114.1722
Burnt River at Huntington, OR	BURNT	Upper Snake	44.3583	-117.2722
Falls River nr Chester, ID	CHEIX	Upper Snake	44.0183	-111.5666
Deadwood River Deadwood Reservoir Inflow	DEADR	Upper Snake	44.2919	-115.6419
Teton River abv S Leigh Creek	DGGIX	Upper Snake	43.7819	-111.2092
Payette River Black Canyon Reservoir Inflow	EMMXX	Upper Snake	43.9306	-116.4417
Falls River nr Squirrel, ID	FALIX	Upper Snake	44.0686	-111.2414
Grassy Lake Inflow	GRSYX	Upper Snake	44.1238	-110.8181
Henrys Lake Inflow	HENRY	Upper Snake	44.5972	-111.3536
Henrys Fork nr Ashton, ID	HFAIX	Upper Snake	44.0697	-111.5106
Henrys Fork nr Rexburg, ID	HFORK	Upper Snake	43.8258	-111.9050
Payette River nr Horseshoe Bend, ID	HRSIX	Upper Snake	43.9450	-116.1969
Henrys Fork nr Island Park, ID Island Park Inflow	IPARK	Upper Snake	44.4167	-111.3947
Jackson Lake Inflow	JLAKE	Upper Snake	43.8578	-110.5900
Snake River nr Kimberly, ID	KIMIX	Upper Snake	42.5908	-114.3602
Boise River nr Parma, ID	LBOIS	Upper Snake	43.7817	-116.9728

Site Full Name	POINT NAME	Subbasin	Latitude	Longitude
Snake River at Lorenzo, ID	LORIX	Upper Snake	43.7358	-111.8781
Malheur River blw Nevada Dam nr Vale, OR	MALHE	Upper Snake	43.9875	-117.2189
Snake River at Milner, ID	MILNE	Upper Snake	42.5281	-114.0178
Snake River nr Minidoka, ID	MINAD	Upper Snake	42.6728	-113.5003
Malad River nr Gooding, ID	MRGIX	Upper Snake	42.8863	-114.8031
NF Payette River nr Banks, ID	NPBIX	Upper Snake	44.1142	-116.1072
NF Payette River Cascade Dam Inflow	NPCSC	Upper Snake	44.5250	-116.0458
Owyhee Reservoir Inflow	OWYHE	Upper Snake	43.6544	-117.2558
Snake River nr Irwin Palisades Inflow	PALIS	Upper Snake	43.3508	-111.2189
Payette River nr Payette, ID	PAYET	Upper Snake	44.0422	-116.9253
NF Payette River at McCall	PAYIX	Upper Snake	44.9072	-116.1192
South Fork Payette River at Lowman, ID	PAYLO	Upper Snake	44.0853	-115.6222
Payette River nr Leatha, ID	PLEIX	Upper Snake	43.8964	-116.6258
Powder River nr Richland, OR	POWDE	Upper Snake	44.7778	-117.2917
Willow Cr blw Ririe Dam Ririe Dam Inflow	RIRXX	Upper Snake	43.5808	-111.7419
Owyhee River nr Rome, OR	ROMOX	Upper Snake	43.6544	-117.2558

Site Full Name	POINT NAME	Subbasin	Latitude	Longitude
Snake River at King Hill, ID	SKHIX	Upper Snake	43.0022	-115.2025
Snake River blw Lower Salmon Falls nr Hagerman, ID	SLSIX	Upper Snake	42.7694	-114.9039
Snake River nr Blackfoot, ID	SNAIX	Upper Snake	43.1975	-112.3698
Snake River nr Heise, ID	SNKHE	Upper Snake	43.6125	-111.6600
Snake River nr Shelley, ID	SNSHY	Upper Snake	43.4131	-112.1350
Snake River at Nyssa, OR	SNYIX	Upper Snake	43.8761	-116.9825
Snake River nr Murphy, ID	SWAIX	Upper Snake	43.2919	-116.4200
Teton River nr St. Anthony, ID	TEAIX	Upper Snake	43.9275	-111.6139
Teton River at Mouth	TTNMT	Upper Snake	42.6658	-114.7122
Snake River nr Weiser, ID	WEIIX	Upper Snake	44.2456	-116.9808
Willow Cr at mouth nr Idaho Falls, ID	WFWIX	Upper Snake	43.5808	-111.7419
Weiser River nr Weiser, ID	WSRIX	Upper Snake	44.2700	-116.7722
Blue River	BLUXX	Willamette	44.1625	-122.3319
Cottage Grove	COTXX	Willamette	43.7208	-123.0486
Falls Creek	FALXX	Willamette	43.9271	-122.8625
Green Peter	GPRXX	Willamette	44.4493	-122.5497

Site Full Name	POINT NAME	Subbasin	Latitude	Longitude
Leaburg	LEAXX	Willamette	44.1250	-122.4694
Cougar	MCKEN	Willamette	44.1333	-122.2333
North Fork	NFORK	Willamette	45.1672	-122.1550
River Mill	RMILL	Willamette	45.3000	-122.3528
Dorena	ROCOT	Willamette	43.7847	-122.9847
Foster	SANFO	Willamette	44.4014	-122.6847
Detroit	SANNI	Willamette	44.7500	-122.2833
Smith R. Reservoir	SMHXX	Willamette	44.3056	-122.0444
Timothy Meadows	TMYXX	Willamette	45.0714	-121.9394
Fern Ridge	TOMAL	Willamette	44.1181	-123.2847
Trail Bridge	TRBXX	Willamette	44.2681	-122.0486
Walterville	WAVXX	Willamette	44.0700	-122.7700
Willamette River at Albany (Nwp)	WILAL	Willamette	44.6333	-123.1000
Dexter	WILDE	Willamette	43.9347	-122.8333
T.W. Sullivan	WILFA	Willamette	45.3486	-122.6189
Hills Creek	WILLS	Willamette	43.7183	-122.4339

Site Full Name	POINT NAME	Subbasin	Latitude	Longitude
Salem	WILSA	Willamette	44.9333	-123.0333
Ahtanum Creek at Union Gap	AHTNM	Yakima	46.5361	-120.4722
American River Near Nile, WA	AMRNL	Yakima	46.9778	-121.1675
Bumping Reservoir	BMPGD	Yakima	46.8728	-121.2917
Cle Elum Reservoir	CLELD	Yakima	47.2447	-121.0667
Kachess Reservoir	KCHSD	Yakima	47.2614	-121.2033
Naches River Near Cliffdell, WA	NCHCD	Yakima	46.9067	-121.0258
Naches River Near Naches, WA	NCHNA	Yakima	46.7456	-120.7681
Rimrock Reservoir - Tieton River	RMRKD	Yakima	46.6628	-121.1236
Yakima River at Cle Elum, WA	YAKCE	Yakima	47.1914	-120.9458
Yakima River at Easton, WA	YAKEN	Yakima	47.2389	-121.1778
Yakima River at Euclid Rd Br Near Grandview, WA	YAKGV	Yakima	46.2169	-119.9167
Yakima River at Kiona, WA	YAKKI	Yakima	46.2536	-119.4769
Keechelus Reservoir - Yak at Martin	YAKMN	Yakima	47.3214	-121.3361
Yakima River Near Parker, WA	YAKPR	Yakima	46.4972	-120.4417
Yakima River at Umtanum, WA	YAKUM	Yakima	46.8628	-120.4789

5.2 Deschutes Ensemble Selection

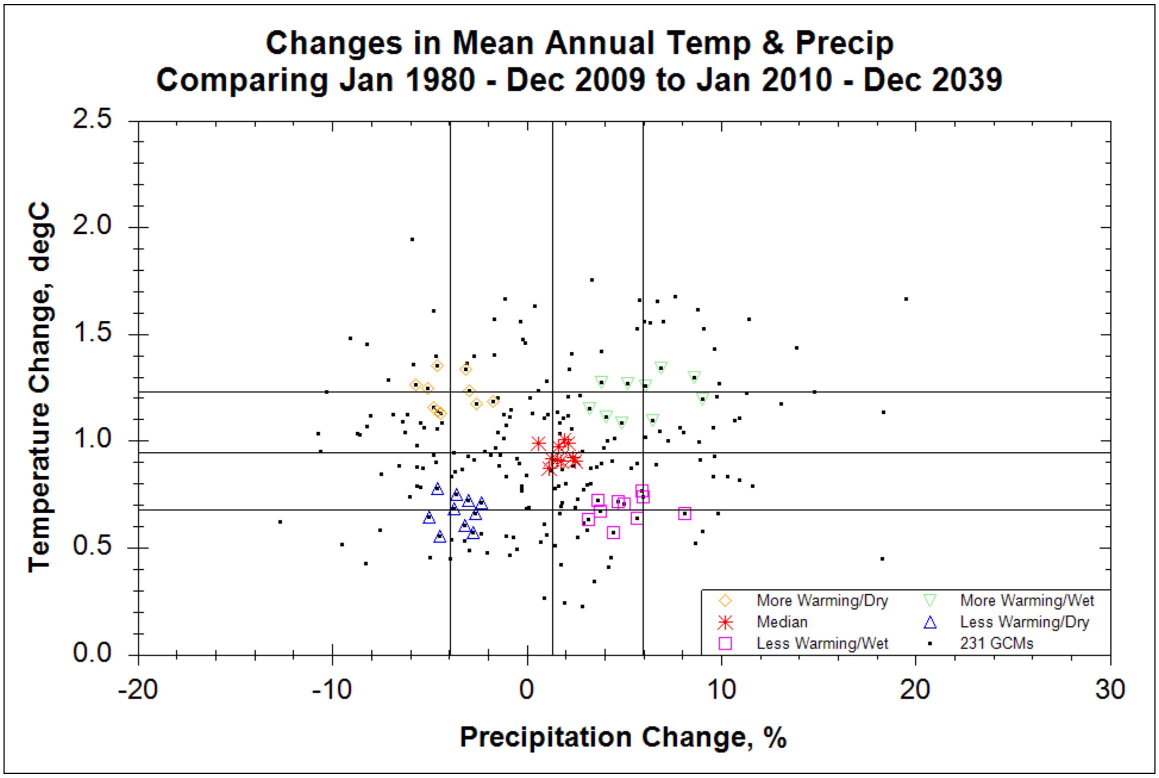


Figure 5.1 Deschutes 2020s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 2. Deschutes 2020s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
gfdl-cm3.1.rcp26	-2.968319	1.232797	1
gfdl-cm3.1.rcp85	-5.072804	1.244242	2
cesm1-cam5.3.rcp45	-4.788455	1.156708	3
csiro-mk3-6-0.6.rcp26	-4.593396	1.139953	4
bcc-csm1-1.1.rcp26	-2.58689	1.169594	5
access1-3.1.rcp85	-4.421612	1.128328	6
hadgem2-ao.1.rcp26	-5.708271	1.263283	7
miroc-esm.1.rcp26	-3.107116	1.335928	8
hadgem2-ao.1.rcp85	-4.618509	1.350858	9
csiro-mk3-6-0.1.rcp26	-1.729368	1.184839	10
More Warming/Wet			
hadgem2-es.1.rcp45	6.107185	1.253331	1
cesm1-cam5.2.rcp45	5.18681	1.267861	2
cesm1-cam5.2.rcp85	6.883016	1.337906	3
ipsl-cm5a-lr.3.rcp45	3.863316	1.271464	4
ccsm4.1.rcp85	6.475651	1.093117	5
hadgem2-es.4.rcp26	4.126486	1.109147	6
miroc5.1.rcp26	4.863739	1.080603	7
access1-0.1.rcp85	8.626164	1.292239	8
miroc5.1.rcp85	3.266391	1.150286	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
ccsm4.5.rcp85	9.029257	1.1948	10
Median			
mpi-esm-lr.2.rcp85	1.647855	0.968814	1
cmcc-cm.1.rcp45	1.294738	0.914206	2
mpi-esm-mr.1.rcp85	1.573335	0.907847	3
ipsl-cm5a-lr.1.rcp60	1.747561	0.906328	4
cmcc-cm.1.rcp85	0.598082	0.987297	5
mpi-esm-lr.1.rcp85	2.111143	0.988014	6
ccsm4.1.rcp26	1.928198	1.00225	7
csiro-mk3-6-0.1.rcp85	2.374073	0.920283	8
cnrm-cm5.4.rcp85	1.153849	0.868269	9
gfdl-esm2g.1.rcp60	2.476955	0.903192	10
Less Warming/Dry			
csiro-mk3-6-0.8.rcp45	-3.742465	0.683595	1
csiro-mk3-6-0.3.rcp85	-2.983722	0.717339	2
ccsm4.3.rcp26	-3.624224	0.7494	3
csiro-mk3-6-0.8.rcp26	-5.029957	0.640314	4
giss-e2-r.1.rcp85	-2.635814	0.661295	5
csiro-mk3-6-0.2.rcp45	-3.170127	0.602086	6
ccsm4.3.rcp60	-2.340976	0.710656	7
csiro-mk3-6-0.9.rcp45	-4.581352	0.774836	8
csiro-mk3-6-0.4.rcp85	-4.482628	0.552478	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
csiro-mk3-6-0.3.rcp45	-2.733105	0.569289	10
Less Warming/Wet			
fio-esm.1.rcp85	5.689897	0.635119	1
ccsm4.2.rcp60	5.983755	0.73875	2
giss-e2-r.1.rcp60	5.042949	0.703581	3
bcc-csm1-1-m.1.rcp45	4.695065	0.713203	4
ccsm4.3.rcp85	5.962252	0.7642	5
noresm1-me.1.rcp85	3.808367	0.672203	6
ipsl-cm5b-lr.1.rcp85	8.162838	0.660167	7
fio-esm.1.rcp26	4.474477	0.5685	8
csiro-mk3-6-0.2.rcp85	3.696853	0.719033	9
cesm1-cam5.1.rcp26	3.187141	0.63295	10

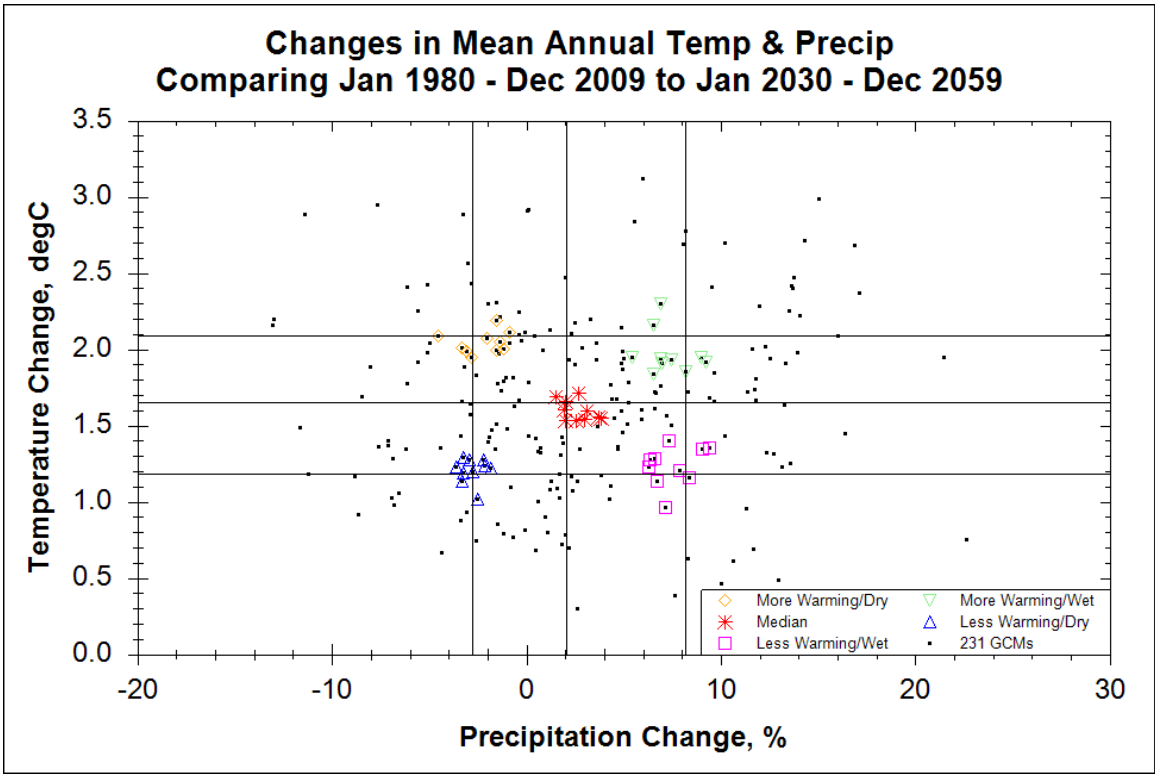


Figure 5.2 Deschutes 2040s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 3. Deschutes 2040s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
cnrm-cm5.6.rcp85	-2.041866	2.070664	1
canesm2.2.rcp45	-3.298417	2.005378	2
fgoals-g2.1.rcp85	-3.060877	1.987356	3
mpi-esm-lr.1.rcp85	-1.370035	2.049447	4
csiro-mk3-6-0.8.rcp85	-2.796679	1.946394	5
fgoals-s2.3.rcp85	-1.55134	2.191225	6
gfdl-cm3.1.rcp45	-1.524277	1.991292	7
csiro-mk3-6-0.1.rcp85	-4.518553	2.087608	8
ipsl-cm5a-lr.1.rcp85	-0.854747	2.108186	9
ipsl-cm5a-lr.3.rcp45	-1.192659	1.998394	10
More Warming/Wet			
fgoals-s2.2.rcp85	6.571121	2.154767	1
cnrm-cm5.2.rcp85	8.979801	1.942281	2
ccsm4.5.rcp85	7.481782	1.926872	3
cesm1-cam5.2.rcp45	6.924752	1.936506	4
ipsl-cm5a-mr.1.rcp45	9.244318	1.917536	5
miroc5.1.rcp85	6.975595	1.904989	6
hadgem2-es.3.rcp26	8.167466	1.850286	7
gfdl-cm3.1.rcp85	6.893345	2.30022	8
hadgem2-es.4.rcp45	5.429776	1.947192	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
hadgem2-es.3.rcp60	6.547886	1.836483	10
Median			
hadgem2-ao.1.rcp26	2.030022	1.658297	1
csiro-mk3-6-0.5.rcp45	1.959935	1.603697	2
access1-3.1.rcp45	1.528219	1.687361	3
ec-earth.12.rcp45	2.69486	1.714931	4
ipsl-cm5a-lr.1.rcp60	3.10649	1.592975	5
mpi-esm-mr.1.rcp45	1.998918	1.531453	6
bcc-csm1-1.1.rcp45	2.570272	1.529167	7
csiro-mk3-6-0.5.rcp26	2.991856	1.540722	8
fgoals-g2.1.rcp45	3.709303	1.554914	9
cesm1-cam5.2.rcp26	3.845985	1.548839	10
Less Warming/Dry			
noresm1-me.1.rcp26	-2.768158	1.195486	1
csiro-mk3-6-0.8.rcp26	-3.245116	1.186475	2
fgoals-g2.1.rcp26	-3.283857	1.132125	3
ccsm4.3.rcp45	-2.148161	1.232244	4
mri-cgcm3.1.rcp85	-1.825358	1.219061	5
ccsm4.4.rcp26	-3.587202	1.227675	6
mpi-esm-lr.3.rcp26	-2.958701	1.271781	7
csiro-mk3-6-0.9.rcp26	-2.21633	1.275697	8
csiro-mk3-6-0.10.rcp26	-3.254317	1.2859	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
csiro-mk3-6-0.7.rcp60	-2.486506	1.014519	10
Less Warming/Wet			
gfdl-esm2g.1.rcp60	8.381487	1.159492	1
ipsl-cm5a-lr.1.rcp26	7.860844	1.207008	2
fio-esm.1.rcp85	6.755171	1.135353	3
ec-earth.12.rcp26	6.282697	1.227244	4
miroc5.1.rcp26	9.061028	1.342422	5
fio-esm.2.rcp85	6.611065	1.284831	6
ipsl-cm5b-lr.1.rcp45	6.352054	1.269992	7
ccsm4.5.rcp26	9.422567	1.351564	8
ccsm4.2.rcp26	7.183094	0.960672	9
cesm1-cam5.3.rcp60	7.330774	1.400047	10

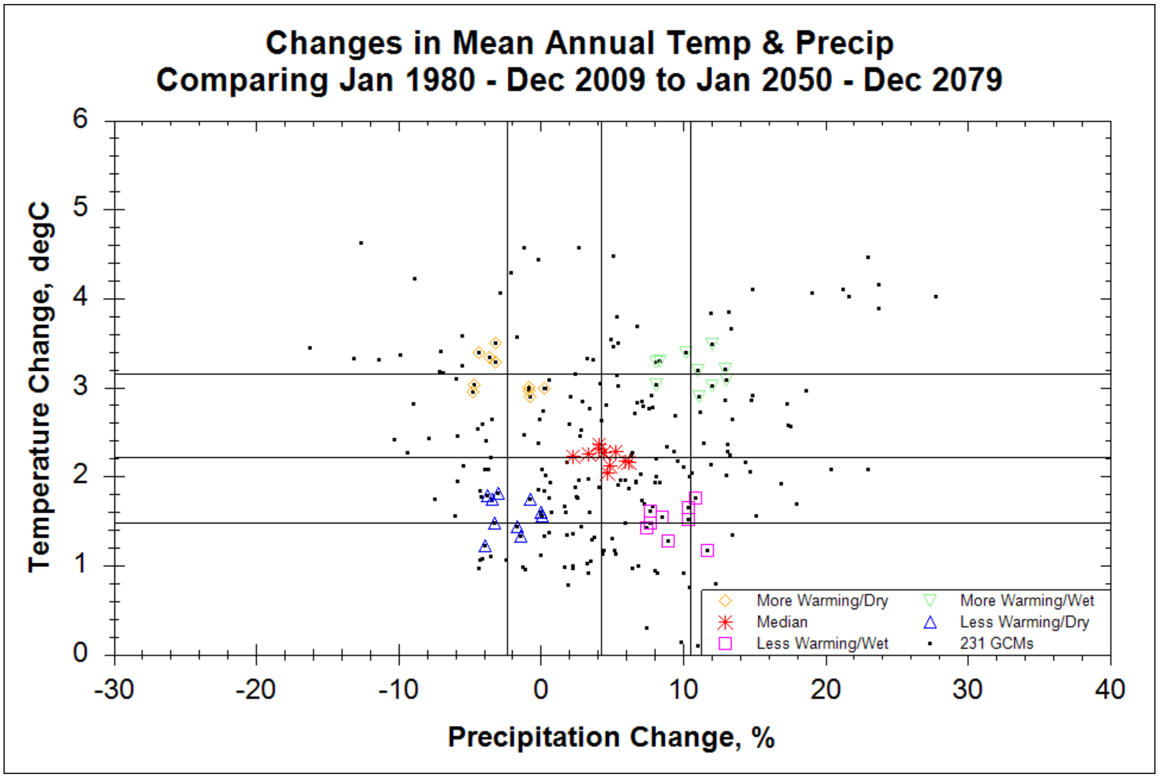


Figure 5.3 Deschutes 2060s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 4. Deschutes 2060s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
csiro-mk3-6-0.8.rcp85	-3.155158	3.276483	1
csiro-mk3-6-0.3.rcp85	-3.551991	3.33482	2
csiro-mk3-6-0.7.rcp85	-0.830663	2.998106	3
hadgem2-es.2.rcp45	-0.799387	2.964253	4
mpi-esm-mr.1.rcp85	-4.674016	3.024186	5
canesm2.2.rcp45	-0.765875	2.899578	6
hadgem2-ao.1.rcp45	-4.336661	3.384736	7
hadgem2-es.3.rcp60	-4.736672	2.950086	8
csiro-mk3-6-0.1.rcp85	-3.200248	3.489328	9
csiro-mk3-6-0.1.rcp45	0.244117	2.985639	10
More Warming/Wet			
ec-earth.12.rcp85	11.04157	3.192795	1
cnrm-cm5.1.rcp85	10.20671	3.388933	2
cnrm-cm5.4.rcp85	12.01358	3.015097	3
canesm2.3.rcp45	11.1483	2.897286	4
cnrm-cm5.2.rcp85	8.367451	3.295203	5
ccsm4.5.rcp85	8.139577	3.031639	6
canesm2.5.rcp45	12.99075	3.206072	7
cnrm-cm5.6.rcp85	8.154579	3.286003	8
hadgem2-es.1.rcp45	13.02236	3.086711	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
cesm1-cam5.1.rcp85	12.04539	3.488644	10
Median			
ec-earth.12.rcp45	4.425257	2.265283	1
noresm1-m.1.rcp45	4.120591	2.301853	2
csiro-mk3-6-0.2.rcp45	3.344295	2.255992	3
noresm1-m.1.rcp60	4.902814	2.117975	4
cesm1-cam5.1.rcp45	5.310126	2.270711	5
ipsl-cm5a-lr.1.rcp60	4.10596	2.359828	6
inmcm4.1.rcp85	4.66461	2.0352	7
ccsm4.5.rcp45	5.979717	2.17445	8
noresm1-me.1.rcp45	6.172503	2.153722	9
csiro-mk3-6-0.1.rcp60	2.256305	2.229914	10
Less Warming/Dry			
giss-e2-r.3.rcp45	-1.650858	1.427547	1
csiro-mk3-6-0.7.rcp60	-3.271087	1.474897	2
fgoals-g2.1.rcp26	-1.379083	1.325719	3
ccsm4.4.rcp60	-3.382413	1.738708	4
mri-cgcm3.1.rcp45	-3.906173	1.220622	5
csiro-mk3-6-0.9.rcp26	-0.005033	1.596192	6
ccsm4.3.rcp45	0.100591	1.557847	7
ccsm4.2.rcp45	-0.758417	1.740031	8
csiro-mk3-6-0.10.rcp26	-3.026902	1.807389	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
csiro-mk3-6-0.2.rcp60	-3.77417	1.776561	10
Less Warming/Wet			
ipsl-cm5a-lr.2.rcp26	10.38439	1.512386	1
cesm1-cam5.3.rcp26	10.40713	1.650383	2
cesm1-cam5.3.rcp85	10.40713	1.650383	3
ccsm4.3.rcp60	8.515575	1.541906	4
ec-earth.12.rcp26	8.940971	1.276467	5
fio-esm.1.rcp85	10.89573	1.755486	6
miroc5.1.rcp26	7.676465	1.476781	7
giss-e2-h-cc.1.rcp45	11.68671	1.160522	8
giss-e2-r.1.rcp60	7.457711	1.417742	9
gfdl-esm2g.1.rcp60	7.674066	1.612481	10

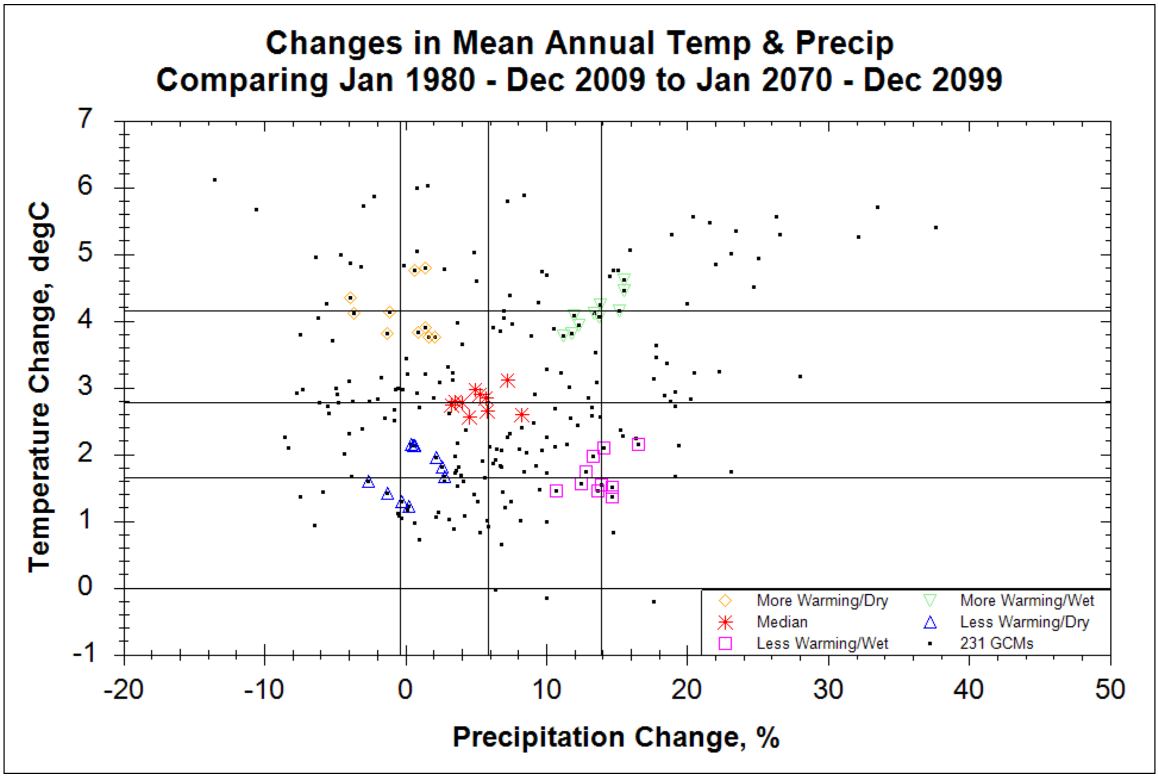


Figure 5.4 Deschutes 2080s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 5. Deschutes 2080s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
mpi-esm-lr.3.rcp85	-1.107227	4.126739	1
ccsm4.4.rcp85	-1.233976	3.807456	2
hadgem2-ao.1.rcp60	0.888909	3.817908	3
hadgem2-ao.1.rcp45	1.430507	3.889911	4
miroc-esm-chem.1.rcp60	-3.661593	4.110486	5
hadgem2-es.3.rcp60	1.651396	3.742786	6
gfdl-esm2g.1.rcp85	2.110762	3.752489	7
csiro-mk3-6-0.4.rcp85	0.702418	4.749889	8
bcc-csm1-1.1.rcp85	-3.924276	4.347005	9
gfdl-cm3.1.rcp85	1.467877	4.787314	10
More Warming/Wet			
ccsm4.5.rcp85	13.41792	4.104306	1
ec-earth.6.rcp85	13.87957	4.225033	2
cmcc-cm.1.rcp85	13.75713	4.051078	3
noresm1-me.1.rcp85	15.17916	4.144597	4
hadgem2-es.2.rcp60	11.97223	4.065122	5
cesm1-bgc.1.rcp85	12.32605	3.922806	6
cnrm-cm5.4.rcp85	15.49074	4.446333	7
fgoals-g2.1.rcp85	11.82621	3.810344	8
cnrm-cm5.6.rcp85	15.54815	4.603906	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
hadgem2-es.1.rcp60	11.23988	3.772003	10
Median			
csiro-mk3-6-0.4.rcp60	5.717112	2.840564	1
noresm1-m.1.rcp45	5.860876	2.645139	2
csiro-mk3-6-0.5.rcp45	5.296059	2.898172	3
hadgem2-es.3.rcp45	5.001501	2.966942	4
noresm1-me.1.rcp45	4.531191	2.554514	5
csiro-mk3-6-0.4.rcp45	4.066043	2.772564	6
canesm2.2.rcp45	7.294975	3.108219	7
gfdl-esm2m.1.rcp85	3.511996	2.779845	8
csiro-mk3-6-0.8.rcp45	3.310116	2.738844	9
ccsm4.5.rcp60	8.252438	2.588342	10
Less Warming/Dry			
giss-e2-r.3.rcp45	-1.229252	1.414289	1
gfdl-esm2m.1.rcp60	-2.611896	1.590589	2
giss-e2-r-cc.1.rcp45	-0.224738	1.294589	3
ccsm4.4.rcp45	2.163405	1.939092	4
mpi-esm-lr.2.rcp45	0.598623	2.125022	5
mpi-esm-lr.1.rcp45	2.61147	1.799511	6
canesm2.2.rcp26	0.699837	2.130797	7
fgoals-g2.1.rcp45	0.455194	2.141047	8

	Change in Precip (%)	Change in Temp (deg C)	Rank
giss-e2-r.4.rcp45	0.288482	1.208817	9
csiro-mk3-6-0.7.rcp26	2.749458	1.659306	10
Less Warming/Wet			
ipsl-cm5a-lr.2.rcp26	13.90345	1.543481	1
cesm1-cam5.3.rcp26	12.81997	1.732908	2
fio-esm.2.rcp60	13.65645	1.443817	3
cesm1-cam5.1.rcp26	14.68221	1.501931	4
noresm1-m.1.rcp26	12.4754	1.559203	5
csiro-mk3-6-0.5.rcp26	13.31559	1.958061	6
giss-e2-h-cc.1.rcp45	14.66968	1.352269	7
ccsm4.3.rcp60	14.11467	2.096822	8
fio-esm.1.rcp60	10.68333	1.447569	9
hadgem2-es.1.rcp26	16.51095	2.139047	10

5.3 Grand Coulee Ensemble Selection

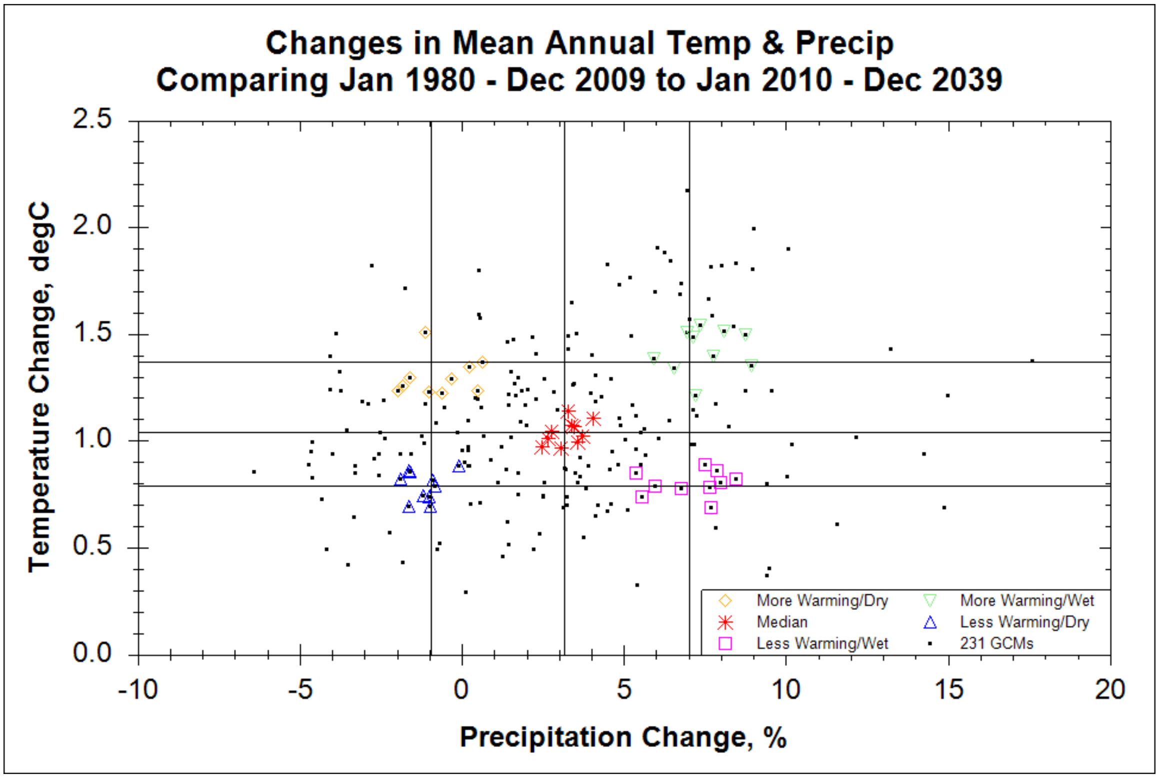


Figure 5.5 Grand Coulee 2020s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 6. Grand Coulee 2020s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
cesm1-bgc.1.rcp45	-1.612765	1.296106	1
mpi-esm-mr.1.rcp26	-0.303696	1.287239	2
cesm1-bgc.1.rcp85	0.230298	1.342594	3
hadgem2-es.3.rcp60	-1.814466	1.253839	4
hadgem2-es.3.rcp45	-1.120976	1.505514	5
cesm1-cam5.2.rcp85	0.639277	1.369383	6
ipsl-cm5a-lr.3.rcp26	-1.020361	1.227494	7
hadgem2-ao.1.rcp60	-1.959734	1.234658	8
csiro-mk3-6-0.1.rcp26	-0.623918	1.224167	9
ccsm4.5.rcp45	0.486438	1.235553	10
More Warming/Wet			
bcc-csm1-1.1.rcp26	6.551967	1.337292	1
hadgem2-cc.1.rcp45	7.749523	1.396536	2
access1-3.1.rcp85	5.922142	1.386342	3
gfdl-cm3.1.rcp85	7.139342	1.483431	4
miroc-esm-chem.1.rcp60	6.966297	1.505256	5
canesm2.2.rcp45	8.103683	1.514008	6
miroc-esm.1.rcp85	7.370943	1.537853	7
mpi-esm-mr.1.rcp45	7.208831	1.211644	8
canesm2.4.rcp85	8.940503	1.351358	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
miroc-esm.1.rcp26	8.756156	1.497633	10
Median			
ipsl-cm5a-lr.1.rcp45	3.470713	1.064225	1
ccsm4.1.rcp26	2.762038	1.043967	2
bcc-csm1-1.1.rcp60	3.409724	1.070414	3
ec-earth.6.rcp85	2.649724	1.011661	4
csiro-mk3-6-0.5.rcp26	3.712408	1.018717	5
cmcc-cm.1.rcp85	3.584682	0.991864	6
cesm1-cam5.1.rcp85	3.078321	0.963925	7
fio-esm.2.rcp85	2.472824	0.971325	8
access1-3.1.rcp45	4.048138	1.107489	9
csiro-mk3-6-0.9.rcp85	3.268283	1.136464	10
Less Warming/Dry			
gfdl-esm2m.1.rcp60	-0.817255	0.788872	1
giss-e2-r.3.rcp45	-0.889083	0.815831	2
fio-esm.1.rcp26	-1.202899	0.744667	3
fio-esm.3.rcp45	-1.026888	0.736083	4
csiro-mk3-6-0.9.rcp26	-1.903043	0.819181	5
fio-esm.1.rcp85	-1.596097	0.852639	6
csiro-mk3-6-0.8.rcp26	-0.968872	0.692611	7
inmcm4.1.rcp85	-1.650755	0.857758	8
fio-esm.3.rcp85	-1.633526	0.691278	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
cmcc-cm.1.rcp45	-0.084277	0.882264	10
Less Warming/Wet			
giss-e2-r.1.rcp26	6.763423	0.776389	1
csiro-mk3-6-0.4.rcp45	7.636284	0.782375	2
csiro-mk3-6-0.4.rcp26	7.970678	0.803753	3
gfdl-esm2m.1.rcp45	5.965174	0.787897	4
csiro-mk3-6-0.6.rcp45	7.888566	0.862247	5
noresm1-m.1.rcp60	7.508265	0.884825	6
mpi-esm-lr.1.rcp26	8.469002	0.818075	7
csiro-mk3-6-0.2.rcp26	7.689925	0.687742	8
noresm1-me.1.rcp45	5.548182	0.734608	9
ipsl-cm5a-mr.1.rcp26	5.37943	0.846494	10

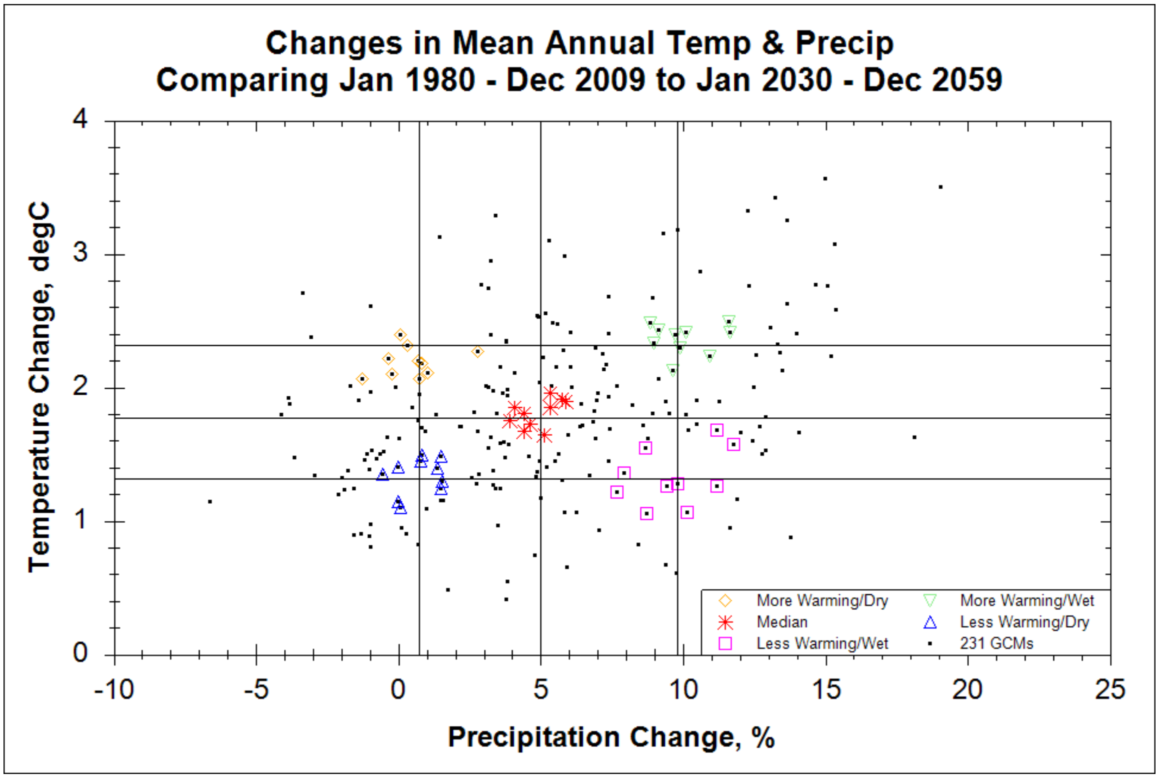


Figure 5.6 Grand Coulee 2040s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 7. Grand Coulee 2040s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
ccsm4.4.rcp85	0.336786	2.31685	1
ccsm4.5.rcp85	0.709677	2.197022	2
csiro-mk3-6-0.10.rcp85	0.061869	2.396569	3
mpi-esm-lr.3.rcp85	-0.326988	2.215531	4
csiro-mk3-6-0.1.rcp85	0.843527	2.181617	5
ipsl-cm5a-lr.1.rcp85	-0.210677	2.101433	6
mpi-esm-mr.1.rcp85	1.027649	2.109978	7
ccsm4.2.rcp85	0.725606	2.058414	8
mpi-esm-lr.2.rcp85	2.781658	2.272492	9
ipsl-cm5a-lr.3.rcp45	-1.268237	2.062997	10
More Warming/Wet			
cesm1-cam5.1.rcp85	9.897999	2.294142	1
access1-3.1.rcp85	9.737837	2.392189	2
miroc5.1.rcp85	10.12425	2.408892	3
hadgem2-cc.1.rcp45	8.983903	2.327703	4
fgoals-s2.3.rcp85	9.13871	2.42503	5
gfdl-cm3.1.rcp60	10.9483	2.236264	6
miroc-esm.1.rcp60	9.663527	2.127136	7
canesm2.2.rcp26	11.64057	2.407133	8
bcc-csm1-1.1.rcp85	8.863511	2.481783	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
ipsl-cm5a-lr.2.rcp85	11.61161	2.492942	10
Median			
ccsm4.5.rcp60	4.6166	1.723622	1
csiro-mk3-6-0.2.rcp85	5.340447	1.84785	2
hadgem2-es.3.rcp60	4.435783	1.800778	3
ccsm4.5.rcp26	4.433833	1.665867	4
csiro-mk3-6-0.1.rcp26	3.92959	1.749767	5
hadgem2-es.4.rcp26	5.865014	1.890917	6
cmcc-cm.1.rcp45	5.135631	1.641661	7
hadgem2-es.3.rcp26	5.775181	1.9141	8
miroc5.1.rcp26	4.073551	1.851939	9
hadgem2-es.1.rcp60	5.359294	1.956264	10
Less Warming/Dry			
ccsm4.1.rcp60	1.379154	1.38995	1
fio-esm.3.rcp85	1.556758	1.296103	2
ccsm4.1.rcp45	0.768045	1.450417	3
csiro-mk3-6-0.8.rcp60	0.006643	1.398856	4
giss-e2-r.3.rcp45	1.489568	1.244253	5
csiro-mk3-6-0.1.rcp60	1.482808	1.482914	6
csiro-mk3-6-0.6.rcp60	-0.03029	1.142869	7
mpi-esm-lr.2.rcp26	0.838209	1.495475	8
inmcm4.1.rcp85	-0.569744	1.352792	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
mri-cgcm3.1.rcp45	0.080666	1.101156	10
Less Warming/Wet			
fgoals-g2.1.rcp26	9.819604	1.277058	1
csiro-mk3-6-0.4.rcp26	9.418676	1.259358	2
giss-e2-r.1.rcp45	11.2109	1.258411	3
noresm1-m.1.rcp60	7.912099	1.356953	4
ccsm4.3.rcp60	7.661114	1.213139	5
csiro-mk3-6-0.5.rcp60	8.734483	1.055394	6
csiro-mk3-6-0.2.rcp60	10.13897	1.061067	7
gfdl-esm2g.1.rcp45	11.76779	1.57335	8
cesm1-cam5.1.rcp60	8.678832	1.541894	9
bcc-csm1-1.1.rcp26	11.21169	1.677083	10

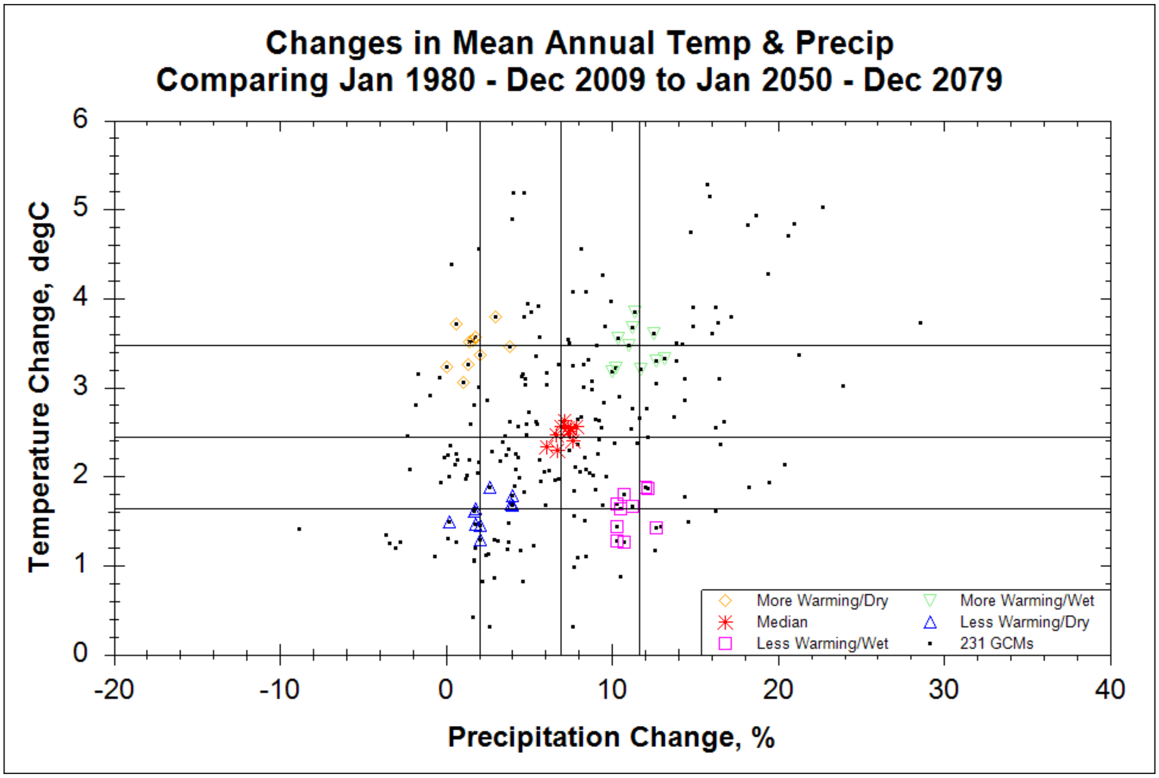


Figure 5.7 Grand Coulee 2060s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 8. Grand Coulee 2060s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
ccsm4.1.rcp85	2.076493	3.366211	1
mpi-esm-lr.3.rcp85	1.613351	3.527483	2
ccsm4.4.rcp85	1.763464	3.55875	3
ccsm4.3.rcp85	1.433519	3.511972	4
hadgem2-cc.1.rcp45	1.328428	3.255842	5
cesm1-bgc.1.rcp85	2.971239	3.788103	6
ccsm4.5.rcp85	3.884639	3.459353	7
hadgem2-es.4.rcp60	0.084544	3.229439	8
access1-0.1.rcp45	1.047548	3.0568	9
hadgem2-ao.1.rcp45	0.643646	3.705608	10
More Warming/Wet			
canesm2.2.rcp45	11.03217	3.463778	1
csiro-mk3-6-0.3.rcp85	12.5211	3.607594	2
miroc-esm-chem.1.rcp45	11.2104	3.668683	3
canesm2.4.rcp45	10.38654	3.543256	4
mpi-esm-lr.1.rcp85	11.72805	3.197008	5
hadgem2-es.1.rcp45	10.23786	3.212144	6
miroc-esm.1.rcp60	12.69093	3.299086	7
bcc-csm1-1-m.1.rcp85	10.03708	3.174822	8
csiro-mk3-6-0.2.rcp85	13.18818	3.326467	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
canesm2.5.rcp45	11.39493	3.841444	10
Median			
cmcc-cm.1.rcp45	6.627614	2.469675	1
cesm1-cam5.3.rcp60	7.46594	2.5001	2
noresm1-me.1.rcp45	7.399123	2.539167	3
bcc-csm1-1.1.rcp60	6.923041	2.557522	4
canesm2.5.rcp26	7.539582	2.527039	5
hadgem2-es.1.rcp26	6.729725	2.293656	6
ec-earth.12.rcp45	6.103308	2.327133	7
csiro-mk3-6-0.8.rcp45	7.643755	2.395258	8
miroc5.1.rcp45	7.887327	2.562628	9
ipsl-cm5a-lr.4.rcp45	7.175379	2.631622	10
Less Warming/Dry			
noresm1-me.1.rcp26	1.817516	1.637983	1
ccsm4.5.rcp26	1.704409	1.613164	2
giss-e2-r.3.rcp45	1.781758	1.462747	3
mri-cgcm3.1.rcp45	2.05395	1.44885	4
csiro-mk3-6-0.10.rcp26	2.675295	1.874414	5
csiro-mk3-6-0.7.rcp60	0.230788	1.490456	6
gfdl-esm2g.1.rcp60	3.92952	1.690178	7
noresm1-me.1.rcp60	4.03616	1.777464	8
csiro-mk3-6-0.3.rcp60	3.991869	1.674892	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
ipsl-cm5a-lr.1.rcp26	2.089207	1.291019	10
Less Warming/Wet			
csiro-mk3-6-0.9.rcp26	11.24807	1.667403	1
bcc-csm1-1.1.rcp26	10.50829	1.631717	2
noresm1-m.1.rcp26	12.16229	1.855439	3
ec-earth.8.rcp45	12.02514	1.881597	4
csiro-mk3-6-0.4.rcp26	10.32637	1.435136	5
cesm1-cam5.2.rcp26	10.74835	1.799764	6
csiro-mk3-6-0.3.rcp26	10.28197	1.693711	7
fgoals-g2.1.rcp26	12.70039	1.423633	8
mpi-esm-lr.1.rcp26	10.71081	1.259931	9
ec-earth.12.rcp26	10.29859	1.267447	10

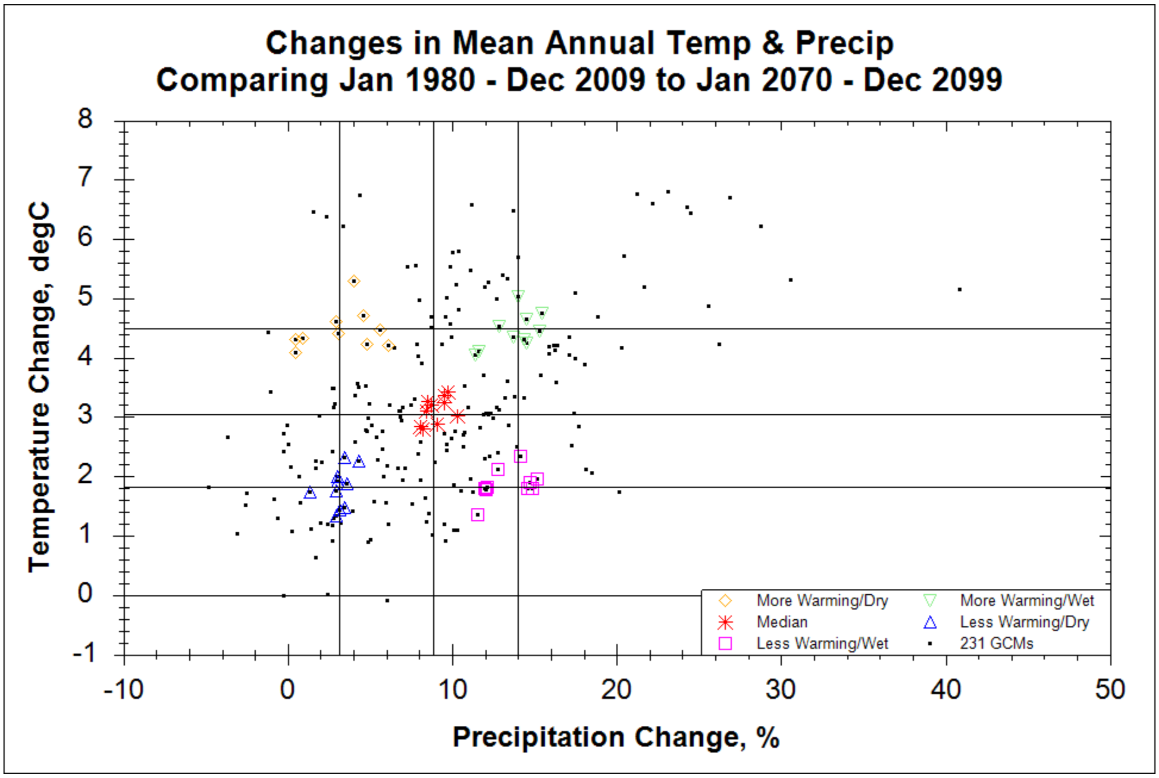


Figure 5.8 Grand Coulee 2080s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 9. Grand Coulee 2080s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
ccsm4.4.rcp85	3.123223	4.412325	1
ccsm4.1.rcp85	2.968052	4.597625	2
ccsm4.3.rcp85	4.608751	4.707022	3
hadgem2-ao.1.rcp60	0.946952	4.317753	4
hadgem2-ao.1.rcp45	0.468803	4.310511	5
hadgem2-es.3.rcp60	0.469676	4.08192	6
mpi-esm-mr.1.rcp85	4.798807	4.222972	7
cnrm-cm5.1.rcp85	5.589725	4.471694	8
csiro-mk3-6-0.10.rcp85	4.033842	5.282105	9
hadgem2-es.4.rcp60	6.133632	4.20935	10
More Warming/Wet			
bcc-csm1-1-m.1.rcp85	13.76237	4.3381	1
miroc-esm-chem.1.rcp60	14.53455	4.653969	2
mpi-esm-lr.1.rcp85	14.40378	4.302656	3
ec-earth.12.rcp85	12.84894	4.527061	4
noresm1-me.1.rcp85	15.43854	4.740281	5
ec-earth.6.rcp85	15.31289	4.436186	6
hadgem2-es.2.rcp60	14.55011	4.239867	7
canesm2.5.rcp45	11.62159	4.096305	8
csiro-mk3-6-0.4.rcp85	14.05203	5.034158	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
cnrm-cm5.6.rcp85	11.43652	4.050528	10
Median			
miroc5.1.rcp45	8.478532	3.093022	1
bcc-csm1-1.1.rcp60	8.702233	3.203828	2
cesm1-cam5.1.rcp45	9.525433	3.241517	3
csiro-mk3-6-0.8.rcp45	9.065068	2.887261	4
cmcc-cm.1.rcp45	8.05355	2.841653	5
csiro-mk3-6-0.8.rcp60	8.228343	2.800328	6
csiro-mk3-6-0.1.rcp45	8.483061	3.264392	7
miroc-esm-chem.1.rcp26	9.545157	3.367656	8
cesm1-cam5.3.rcp60	9.754472	3.417645	9
ipsl-cm5a-mr.1.rcp45	10.31926	3.019789	10
Less Warming/Dry			
fio-esm.2.rcp60	2.973784	1.746122	1
mri-cgcm3.1.rcp45	3.626727	1.873792	2
ipsl-cm5a-lr.3.rcp26	3.03637	1.922831	3
miroc5.1.rcp26	3.037913	1.990872	4
ipsl-cm5a-mr.1.rcp26	1.377993	1.741714	5
giss-e2-r-cc.1.rcp45	3.437634	1.4716	6
ipsl-cm5a-lr.1.rcp26	3.184031	1.436186	7
cesm1-bgc.1.rcp45	4.286654	2.256586	8
giss-e2-r.4.rcp45	2.935699	1.340522	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
ccsm4.4.rcp45	3.481248	2.308536	10
Less Warming/Wet			
noresm1-m.1.rcp26	14.5818	1.799258	1
csiro-mk3-6-0.2.rcp26	14.74759	1.892817	2
giss-e2-r.1.rcp60	14.88778	1.783472	3
csiro-mk3-6-0.6.rcp26	15.16694	1.948408	4
csiro-mk3-6-0.3.rcp26	12.11631	1.816367	5
csiro-mk3-6-0.8.rcp26	12.02899	1.775594	6
cesm1-cam5.3.rcp26	11.98516	1.784094	7
hadgem2-es.2.rcp26	12.7503	2.104411	8
cesm1-cam5.3.rcp85	14.1322	2.331814	9
giss-e2-r.1.rcp45	11.56191	1.346506	10

5.4 Columbia River Basin Ensemble Selection

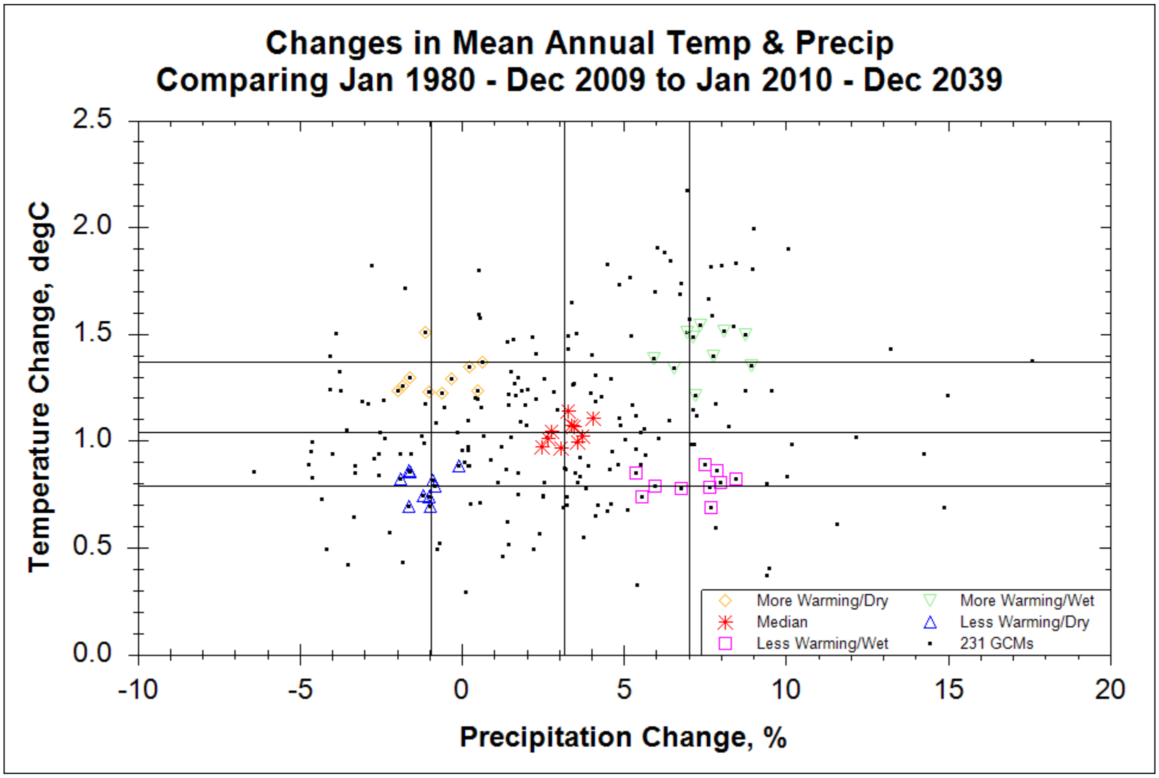


Figure 5.9 Columbia River Basin 2020s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 10. Columbia River Basin 2020s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
cesm1-cam5.2.rcp45	-0.891431	1.328311	1
cnrm-cm5.1.rcp85	-1.617564	1.278664	2
mpi-esm-mr.1.rcp26	-1.271342	1.247522	3
miroc5.1.rcp45	0.036779	1.410119	4
cnrm-cm5.10.rcp85	-0.069415	1.2893	5
ipsl-cm5a-lr.3.rcp26	-0.338403	1.261703	6
csiro-mk3-6-0.1.rcp26	-0.180307	1.2635	7
csiro-mk3-6-0.6.rcp26	0.114843	1.2463	8
cesm1-bgc.1.rcp85	0.088778	1.242928	9
hadgem2-es.2.rcp45	0.11987	1.481956	10
More Warming/Wet			
hadgem2-es.1.rcp60	5.790939	1.316653	1
ccsm4.5.rcp85	6.015962	1.328747	2
ipsl-cm5a-lr.4.rcp85	4.934762	1.418694	3
canesm2.2.rcp45	4.502998	1.404631	4
access1-0.1.rcp45	3.976461	1.323253	5
noresm1-m.1.rcp26	5.036365	1.226844	6
access1-0.1.rcp85	5.983083	1.474519	7
hadgem2-es.4.rcp85	4.170018	1.443431	8
ipsl-cm5a-mr.1.rcp45	6.23315	1.229903	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
hadgem2-es.1.rcp45	3.426827	1.386356	10
Median			
ec-earth.2.rcp45	2.612679	1.093828	1
noresm1-m.1.rcp45	2.897801	1.083117	2
ccsm4.1.rcp26	2.347681	1.096389	3
gfdl-esm2g.1.rcp26	3.031054	1.068711	4
csiro-mk3-6-0.6.rcp85	3.00653	1.024758	5
cesm1-cam5.1.rcp85	2.568173	0.993561	6
ec-earth.6.rcp85	3.481759	1.063478	7
access1-3.1.rcp45	1.468818	1.095433	8
ccsm4.5.rcp45	2.907497	1.166353	9
hadgem2-es.4.rcp45	3.249299	1.157458	10
Less Warming/Dry			
csiro-mk3-6-0.8.rcp60	-0.965349	0.835303	1
csiro-mk3-6-0.3.rcp85	-1.118579	0.849842	2
csiro-mk3-6-0.3.rcp45	-0.895361	0.686845	3
ccsm4.1.rcp60	0.092328	0.764228	4
fio-esm.1.rcp85	0.297496	0.782619	5
ccsm4.2.rcp45	0.319981	0.826119	6
csiro-mk3-6-0.8.rcp26	-2.184314	0.713267	7
csiro-mk3-6-0.4.rcp85	0.286817	0.746989	8
gfdl-esm2m.1.rcp60	-0.028938	0.697917	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
fio-esm.3.rcp45	-0.309887	0.675922	10
Less Warming/Wet			
mpi-esm-lr.1.rcp26	5.302028	0.802756	1
ipsl-cm5b-lr.1.rcp45	5.236961	0.749528	2
csiro-mk3-6-0.4.rcp45	5.336291	0.73182	3
giss-e2-r.1.rcp45	4.601749	0.7763	4
gfdl-esm2m.1.rcp45	4.884658	0.841269	5
giss-e2-r.1.rcp26	4.517477	0.727711	6
noresm1-m.1.rcp60	6.024269	0.825325	7
noresm1-me.1.rcp45	4.256109	0.810317	8
ipsl-cm5b-lr.1.rcp85	4.071758	0.752861	9
ec-earth.12.rcp26	5.678737	0.886464	10

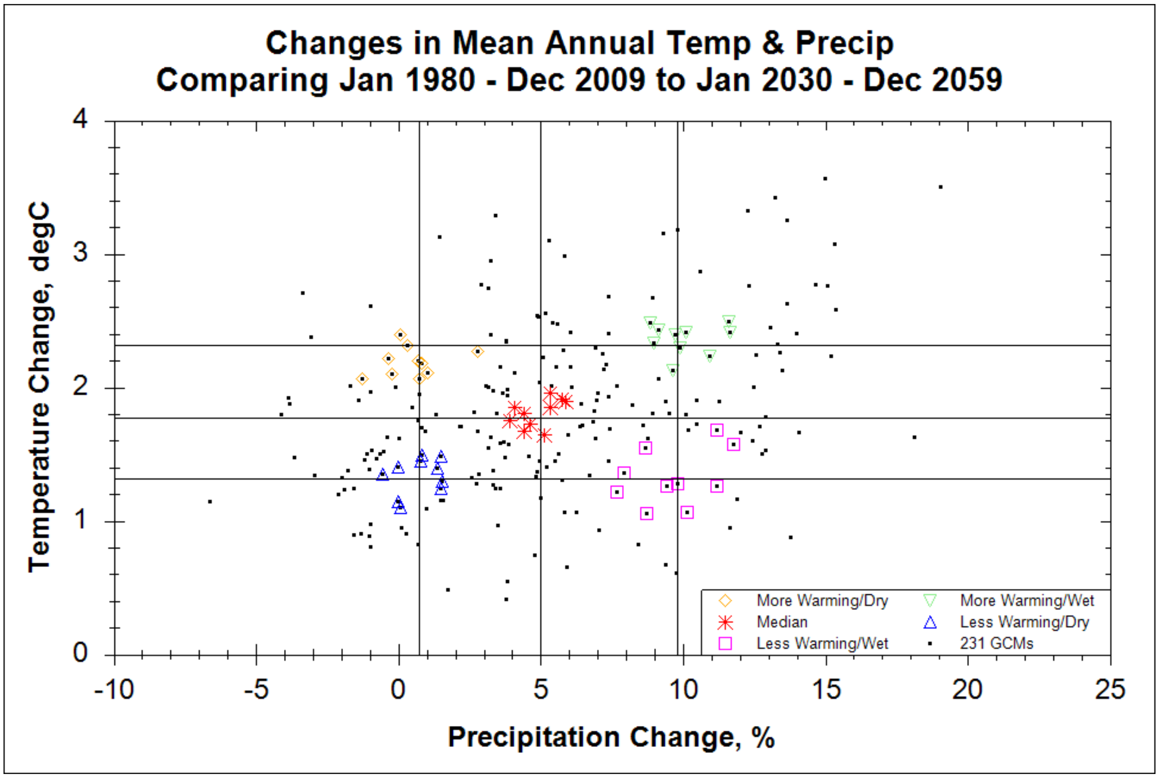


Figure 5.10 Columbia River Basin 2040s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 11. Columbia River Basin 2040s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
hadgem2-es.2.rcp26	0.680803	2.273664	1
csiro-mk3-6-0.1.rcp85	0.175822	2.17628	2
mpi-esm-lr.2.rcp85	0.561581	2.187958	3
ipsl-cm5a-lr.1.rcp85	0.137377	2.151764	4
canesm2.2.rcp45	1.510215	2.335039	5
ipsl-cm5a-lr.3.rcp45	-0.416712	2.031503	6
mpi-esm-lr.3.rcp85	-1.082721	2.068467	7
ipsl-cm5a-lr.1.rcp45	0.220198	2.028156	8
hadgem2-es.2.rcp45	2.316085	2.4055	9
mpi-esm-mr.1.rcp85	-0.208957	2.002192	10
More Warming/Wet			
gfdl-cm3.1.rcp45	7.433584	2.317411	1
miroc5.1.rcp85	8.516849	2.367286	2
access1-3.1.rcp85	7.598231	2.392581	3
miroc-esm.1.rcp60	6.826901	2.162167	4
fgoals-g2.1.rcp85	8.220912	2.165581	5
cesm1-cam5.2.rcp85	7.509408	2.415897	6
gfdl-cm3.1.rcp60	7.054463	2.084083	7
ec-earth.12.rcp85	6.417534	2.146975	8
canesm2.2.rcp26	6.095894	2.349444	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
ipsl-cm5a-lr.3.rcp85	8.470448	2.545889	10
Median			
ec-earth.12.rcp45	4.391348	1.761786	1
csiro-mk3-6-0.4.rcp85	4.50483	1.788075	2
cesm1-cam5.3.rcp45	4.442377	1.802583	3
ipsl-cm5a-mr.1.rcp60	4.346484	1.810608	4
bcc-csm1-1.1.rcp45	3.957106	1.762389	5
mpi-esm-lr.1.rcp45	4.40048	1.689075	6
ipsl-cm5b-lr.1.rcp85	4.49752	1.845583	7
csiro-mk3-6-0.2.rcp45	4.60341	1.862883	8
hadgem2-ao.1.rcp26	4.149041	1.854456	9
hadgem2-es.3.rcp60	5.276142	1.81455	10
Less Warming/Dry			
csiro-mk3-6-0.8.rcp26	-0.215143	1.300478	1
fio-esm.3.rcp85	1.04451	1.263233	2
fio-esm.1.rcp85	-0.424351	1.349664	3
ccsm4.1.rcp60	1.26607	1.407481	4
ccsm4.2.rcp26	0.819072	1.146803	5
noresm1-me.1.rcp60	-0.879978	1.203281	6
csiro-mk3-6-0.10.rcp26	-0.676347	1.353536	7
ccsm4.3.rcp45	-0.357472	1.40925	8
gfdl-esm2m.1.rcp85	0.521381	1.480217	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
csiro-mk3-6-0.7.rcp26	1.28949	1.141497	10
Less Warming/Wet			
ipsl-cm5a-mr.1.rcp26	7.739889	1.3589	1
cesm1-cam5.1.rcp26	7.017225	1.328808	2
csiro-mk3-6-0.2.rcp60	6.786025	1.1273	3
gfdl-esm2g.1.rcp60	6.283944	1.185267	4
mpi-esm-lr.1.rcp26	7.993594	1.097261	5
ec-earth.12.rcp26	6.178054	1.113808	6
cesm1-cam5.1.rcp60	9.289045	1.453325	7
csiro-mk3-6-0.6.rcp26	7.798216	1.509056	8
csiro-mk3-6-0.2.rcp26	8.620196	1.516108	9
ipsl-cm5a-lr.1.rcp26	5.863596	1.187314	10

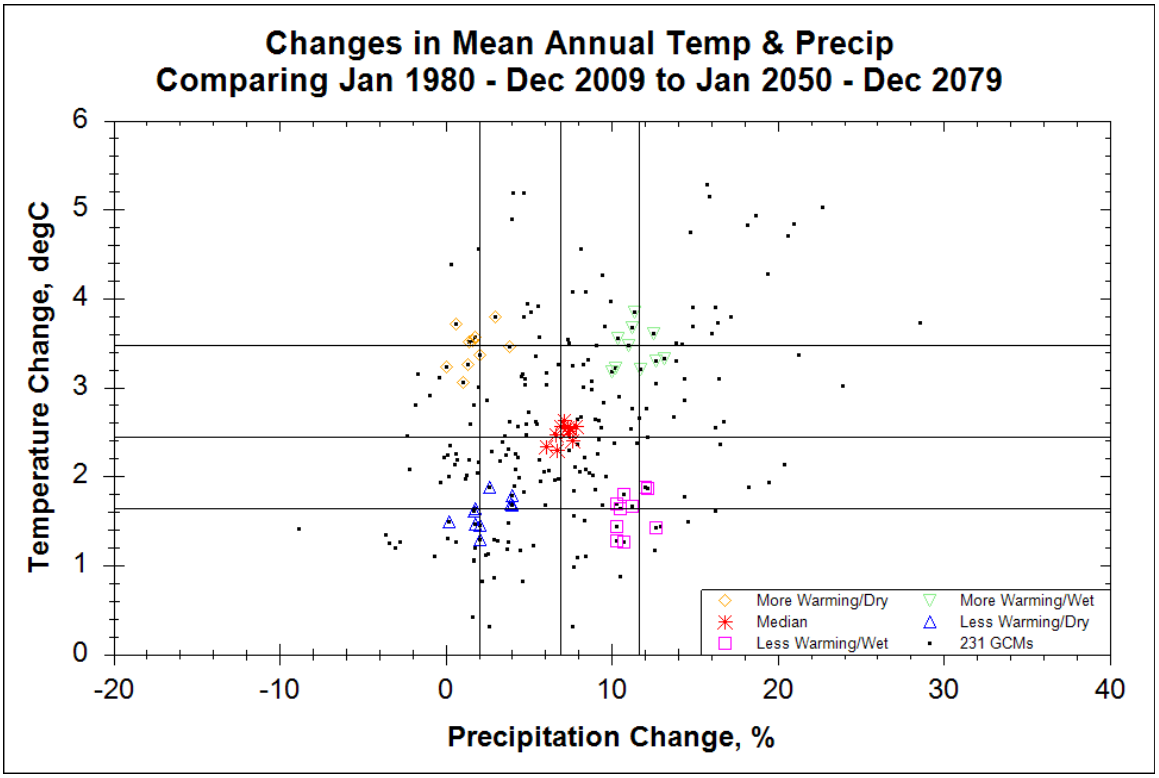


Figure 5.11 Columbia River Basin 2060s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 12. Columbia River Basin 2060s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
csiro-mk3-6-0.8.rcp85	2.566518	3.38413	1
cesm1-bgc.1.rcp85	2.408803	3.526269	2
ccsm4.1.rcp85	2.558999	3.182361	3
ccsm4.3.rcp85	3.104753	3.2904	4
csiro-mk3-6-0.6.rcp85	1.375004	3.543328	5
csiro-mk3-6-0.4.rcp85	3.59655	3.444514	6
mpi-esm-mr.1.rcp85	2.749907	3.156605	7
miroc-esm-chem.1.rcp26	2.044444	3.059931	8
mpi-esm-lr.2.rcp85	2.932667	3.160231	9
access1-0.1.rcp45	2.140065	3.047008	10
More Warming/Wet			
csiro-mk3-6-0.2.rcp85	10.33195	3.412703	1
noresm1-m.1.rcp85	11.25903	3.510417	2
canesm2.5.rcp45	10.99215	3.629228	3
bcc-csm1-1.1.rcp85	9.924042	3.720097	4
cmcc-cm.1.rcp85	8.593355	3.043508	5
cnrm-cm5.4.rcp85	10.30993	3.014494	6
csiro-mk3-6-0.1.rcp45	8.453824	3.039231	7
canesm2.3.rcp45	11.92696	3.295436	8
ec-earth.12.rcp85	12.01484	3.317108	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
gfdl-cm3.1.rcp45	10.84026	3.01665	10
Median			
gfdl-cm3.1.rcp26	6.226747	2.492775	1
cesm1-cam5.3.rcp45	6.143245	2.486675	2
cmcc-cm.1.rcp45	6.992748	2.431347	3
csiro-mk3-6-0.1.rcp60	6.800003	2.316014	4
cesm1-cam5.1.rcp45	6.616426	2.586367	5
ccsm4.5.rcp60	6.331871	2.194478	6
ec-earth.12.rcp45	5.070863	2.335689	7
noresm1-me.1.rcp45	7.4217	2.472472	8
ccsm4.5.rcp45	5.235451	2.47437	9
canesm2.5.rcp26	7.498187	2.430222	10
Less Warming/Dry			
noresm1-me.1.rcp26	1.928996	1.565019	1
ccsm4.5.rcp26	2.544028	1.491289	2
giss-e2-r.3.rcp45	1.397882	1.462075	3
noresm1-me.1.rcp60	2.808566	1.757028	4
ipsl-cm5a-lr.1.rcp26	1.87717	1.344667	5
csiro-mk3-6-0.3.rcp60	1.043927	1.626958	6
ccsm4.3.rcp45	2.119263	1.848228	7
csiro-mk3-6-0.10.rcp60	3.305138	1.82068	8
ccsm4.2.rcp60	2.466263	1.895164	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
mri-cgcm3.1.rcp45	0.699409	1.367036	10
Less Warming/Wet			
csiro-mk3-6-0.6.rcp26	10.24371	1.581942	1
noresm1-m.1.rcp26	10.06729	1.73913	2
giss-e2-r.1.rcp45	9.808444	1.364839	3
cesm1-cam5.3.rcp85	9.008471	1.730958	4
cesm1-cam5.3.rcp26	9.008471	1.730958	5
csiro-mk3-6-0.2.rcp26	11.77368	1.786247	6
ec-earth.12.rcp26	9.508507	1.213644	7
ccsm4.3.rcp60	9.34662	1.854922	8
hadgem2-es.4.rcp26	11.36907	1.991322	9
ipsl-cm5a-lr.2.rcp26	8.056944	1.560617	10

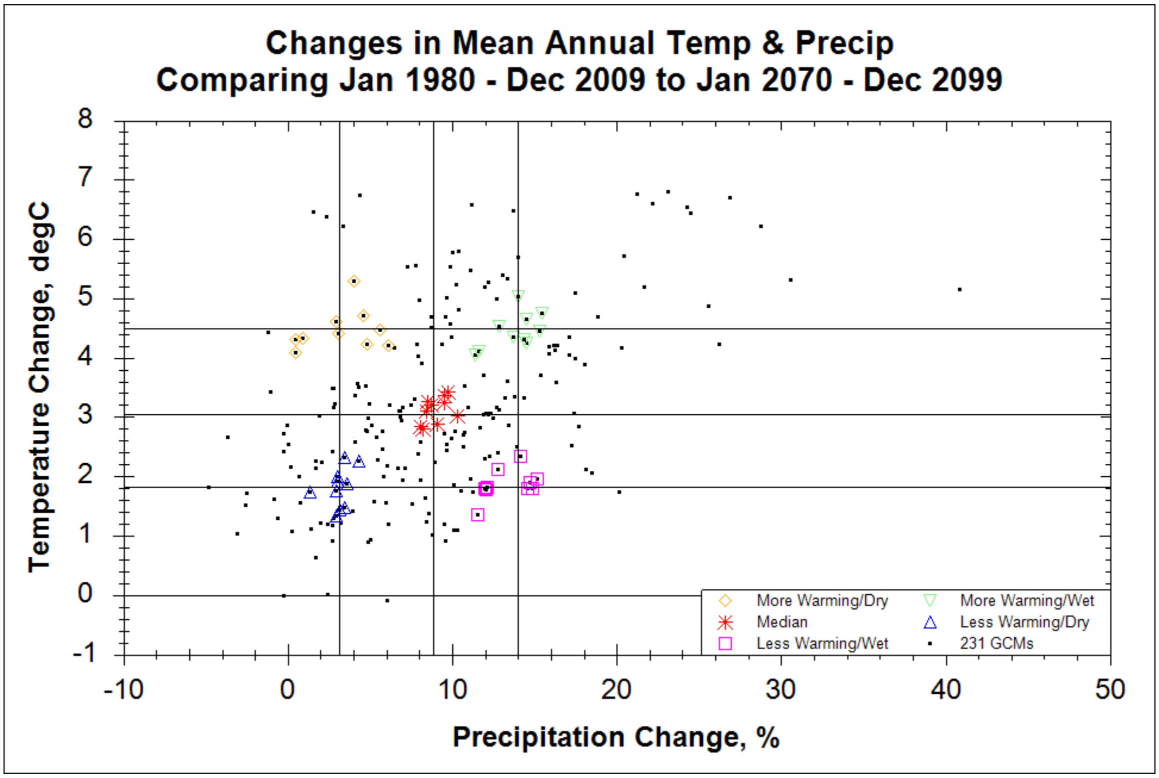


Figure 5.12 Columbia River Basin 2080s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 13. Columbia River Basin 2080s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
ccsm4.1.rcp85	3.073712	4.39765	1
hadgem2-ao.1.rcp60	3.382655	4.314128	2
hadgem2-ao.1.rcp45	4.008592	4.345878	3
ccsm4.2.rcp85	2.205436	4.254653	4
ccsm4.4.rcp85	1.87329	4.255169	5
hadgem2-es.3.rcp60	2.04948	3.995811	6
ccsm4.3.rcp85	5.778275	4.441264	7
mpi-esm-mr.1.rcp85	0.360593	4.144725	8
csiro-mk3-6-0.7.rcp85	6.469172	4.942608	9
csiro-mk3-6-0.9.rcp85	6.369063	5.026294	10
More Warming/Wet			
cesm1-bgc.1.rcp85	12.35868	4.430617	1
ccsm4.5.rcp85	11.42095	4.563558	2
ec-earth.6.rcp85	13.26281	4.519484	3
cnrm-cm5.4.rcp85	10.783	4.394508	4
ec-earth.12.rcp85	11.1629	4.568572	5
mpi-esm-lr.1.rcp85	10.60662	4.254972	6
hadgem2-es.4.rcp60	10.71418	4.100636	7
cnrm-cm5.6.rcp85	13.47869	4.366575	8
bcc-csm1-1-m.1.rcp85	9.924411	4.233442	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
ipsl-cm5b-lr.1.rcp85	11.23612	3.884156	10
Median			
csiro-mk3-6-0.6.rcp60	8.256987	3.089986	1
inmcm4.1.rcp85	8.527534	3.262308	2
csiro-mk3-6-0.4.rcp45	8.924033	2.992605	3
cmcc-cm.1.rcp45	8.387432	2.805903	4
miroc-esm.1.rcp26	6.97473	2.969795	5
csiro-mk3-6-0.2.rcp60	8.838124	2.893281	6
noresm1-me.1.rcp45	9.114074	2.964972	7
csiro-mk3-6-0.8.rcp45	6.732251	2.891114	8
cesm1-cam5.1.rcp45	9.684453	3.13712	9
csiro-mk3-6-0.4.rcp60	9.724798	3.053306	10
Less Warming/Dry			
ipsl-cm5a-mr.1.rcp26	3.101415	1.698056	1
ipsl-cm5a-lr.3.rcp26	4.230427	1.842017	2
cesm1-bgc.1.rcp45	3.777919	2.078683	3
mpi-esm-lr.2.rcp45	4.311103	2.126397	4
ccsm4.2.rcp45	3.867873	2.144781	5
miroc5.1.rcp26	2.373323	1.890333	6
hadgem2-es.3.rcp26	2.990499	2.063883	7
fio-esm.2.rcp60	4.283977	1.666383	8
hadgem2-ao.1.rcp26	3.385887	2.14835	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
ccsm4.4.rcp45	3.764019	2.226789	10
Less Warming/Wet			
giss-e2-r.1.rcp60	11.8704	1.721981	1
csiro-mk3-6-0.2.rcp26	12.6579	1.815022	2
csiro-mk3-6-0.8.rcp26	11.41541	1.821336	3
cesm1-cam5.1.rcp26	11.29209	1.694511	4
hadgem2-es.2.rcp26	12.04042	2.042467	5
csiro-mk3-6-0.6.rcp26	11.26988	1.977033	6
giss-e2-h-cc.1.rcp45	11.4623	1.399386	7
cesm1-cam5.3.rcp26	10.56176	1.818972	8
csiro-mk3-6-0.3.rcp26	10.37585	1.810825	9
ipsl-cm5a-lr.2.rcp26	10.12831	1.582408	10

5.5 Upper Snake Ensemble Selection

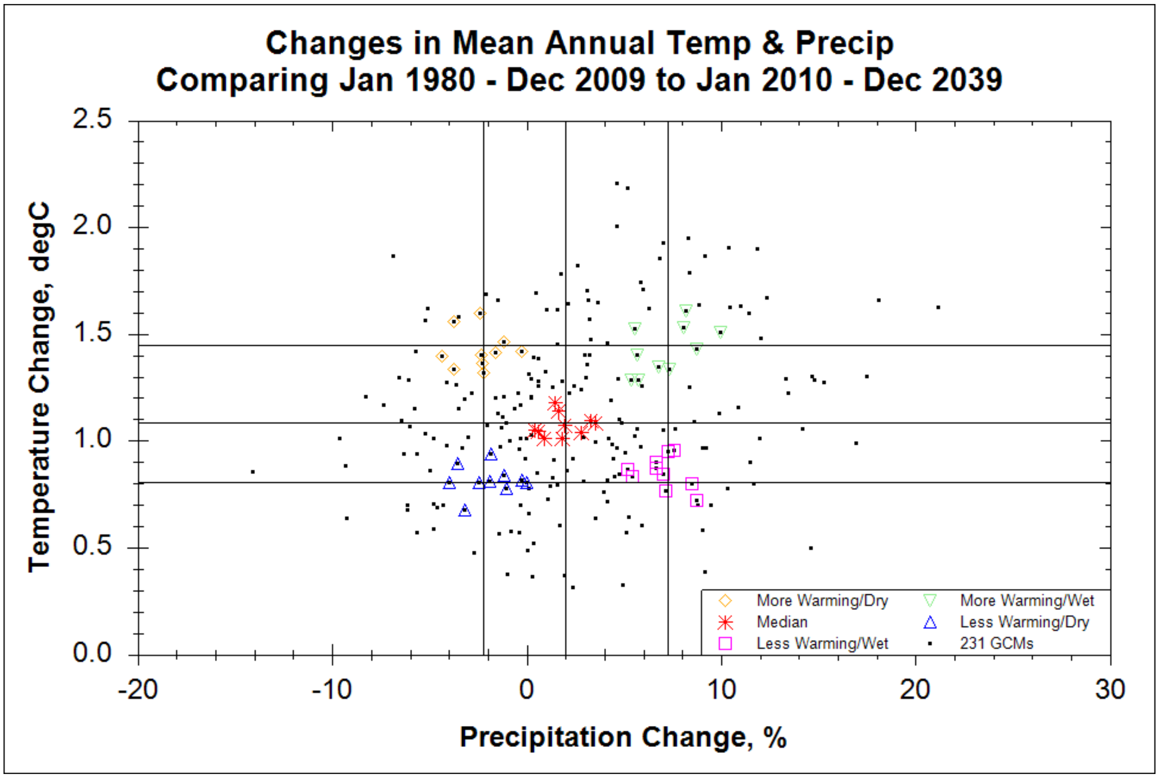


Figure 5.13 Upper Snake 2020s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 14. Upper Snake 2020s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
miroc5.1.rcp60	-2.30185	1.403161	1
hadgem2-es.3.rcp26	-1.595452	1.409172	2
cnrm-cm5.10.rcp85	-1.176144	1.464314	3
fgoals-g2.1.rcp85	-2.263363	1.362936	4
ec-earth.2.rcp45	-2.188846	1.316131	5
cesm1-bgc.1.rcp45	-3.724227	1.333022	6
bcc-csm1-1.1.rcp26	-4.362854	1.393994	7
cesm1-cam5.3.rcp45	-0.237524	1.414744	8
miroc5.1.rcp45	-2.407475	1.595483	9
hadgem2-es.2.rcp45	-3.765682	1.559672	10
More Warming/Wet			
ipsl-cm5a-lr.4.rcp85	8.051558	1.531614	1
ccsm4.1.rcp85	8.772219	1.430228	2
hadgem2-es.1.rcp45	5.676116	1.400822	3
cnrm-cm5.1.rcp85	6.809981	1.342708	4
cesm1-cam5.2.rcp26	7.340526	1.332156	5
gfdl-cm3.1.rcp45	5.579646	1.525097	6
cesm1-cam5.2.rcp85	8.197251	1.604708	7
ccsm4.5.rcp85	9.943126	1.508106	8
ec-earth.6.rcp85	5.756034	1.285567	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
hadgem2-es.1.rcp60	5.396701	1.283522	10
Median			
ipsl-cm5a-lr.1.rcp26	1.969649	1.071094	1
cesm1-cam5.1.rcp85	1.631153	1.137828	2
gfdl-esm2g.1.rcp26	1.834328	1.007881	3
cnrm-cm5.4.rcp85	2.791042	1.039269	4
csiro-mk3-6-0.1.rcp85	3.291236	1.093508	5
csiro-mk3-6-0.6.rcp45	0.919019	1.011017	6
cmcc-cm.1.rcp45	0.59475	1.042983	7
mpi-esm-mr.1.rcp45	0.441826	1.047439	8
ccsm4.4.rcp45	1.473758	1.174869	9
mpi-esm-lr.1.rcp45	3.527944	1.083661	10
Less Warming/Dry			
csiro-mk3-6-0.8.rcp60	-2.461144	0.805333	1
csiro-mk3-6-0.8.rcp26	-1.893302	0.807519	2
csiro-mk3-6-0.3.rcp85	-1.1627	0.837442	3
csiro-mk3-6-0.3.rcp45	-1.03366	0.775983	4
mri-cgcm3.1.rcp85	-3.999641	0.805356	5
mpi-esm-lr.2.rcp26	-1.858701	0.935256	6
csiro-mk3-6-0.4.rcp26	-3.551358	0.89025	7
giss-e2-r.3.rcp45	-0.235546	0.814025	8
fio-esm.2.rcp26	-3.205631	0.676906	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
fio-esm.1.rcp85	0.017733	0.80617	10
Less Warming/Wet			
ipsl-cm5b-lr.1.rcp45	7.137187	0.766247	1
gfdl-esm2g.1.rcp45	7.027884	0.843008	2
noresm1-m.1.rcp60	6.67066	0.869792	3
gfdl-esm2g.1.rcp60	8.520341	0.796417	4
mpi-esm-mr.1.rcp85	6.667426	0.898631	5
csiro-mk3-6-0.1.rcp60	5.435772	0.82985	6
gfdl-esm2m.1.rcp85	8.723324	0.719208	7
ipsl-cm5a-lr.2.rcp45	7.256271	0.950872	8
ipsl-cm5a-mr.1.rcp26	7.604591	0.954842	9
csiro-mk3-6-0.7.rcp26	5.200548	0.863381	10

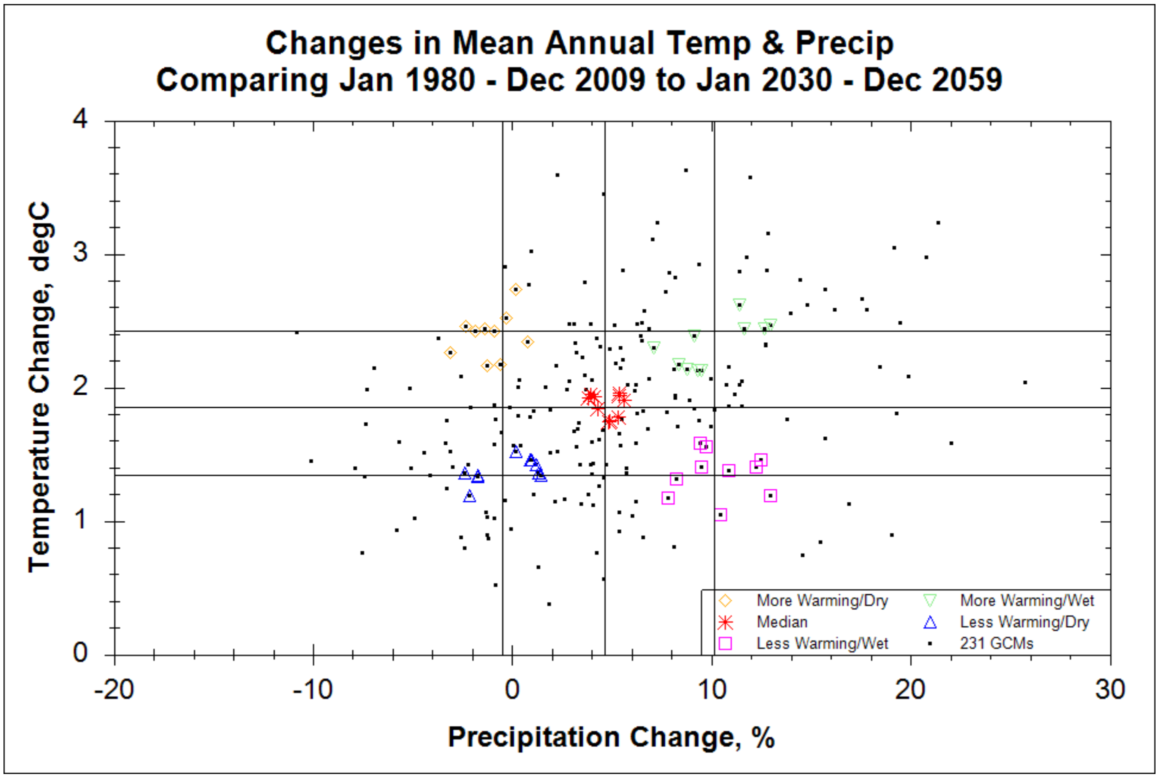


Figure 5.14 Upper Snake 2040s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 15. Upper Snake 2040s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
ccsm4.4.rcp85	-0.907884	2.42328	1
canesm2.2.rcp45	-1.388819	2.439694	2
hadgem2-es.2.rcp45	-0.324483	2.518744	3
hadgem2-es.3.rcp45	-1.843856	2.421822	4
mpi-esm-lr.1.rcp85	0.794819	2.342564	5
canesm2.2.rcp26	-2.312741	2.456972	6
mpi-esm-lr.2.rcp85	-0.609987	2.170458	7
hadgem2-es.2.rcp60	-1.244871	2.157428	8
ec-earth.2.rcp45	-3.116764	2.258375	9
fgoals-s2.3.rcp85	0.153409	2.731028	10
More Warming/Wet			
ccsm4.5.rcp85	9.157184	2.388253	1
canesm2.3.rcp26	11.62156	2.433753	2
noresm1-m.1.rcp85	11.40772	2.619119	3
miroc-esm.1.rcp60	12.6873	2.435722	4
access1-0.1.rcp45	8.391418	2.167017	5
ipsl-cm5a-lr.2.rcp85	12.93393	2.460797	6
hadgem2-es.4.rcp45	8.782138	2.138339	7
ccsm4.1.rcp85	9.34567	2.128394	8
noresm1-m.1.rcp45	9.521102	2.126825	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
cnrm-cm5.1.rcp85	7.109227	2.295389	10
Median			
csiro-mk3-6-0.2.rcp45	4.304825	1.842044	1
ipsl-cm5a-lr.3.rcp26	5.351869	1.934511	2
ipsl-cm5a-mr.1.rcp60	5.602136	1.905606	3
csiro-mk3-6-0.1.rcp26	4.098306	1.92885	4
miroc5.1.rcp26	5.361222	1.951586	5
noresm1-m.1.rcp26	4.883625	1.749975	6
cmcc-cm.1.rcp45	5.331249	1.779447	7
ec-earth.12.rcp45	3.805981	1.916964	8
csiro-mk3-6-0.4.rcp45	4.852024	1.741542	9
mpi-esm-mr.1.rcp85	3.925494	1.946292	10
Less Warming/Dry			
csiro-mk3-6-0.10.rcp26	-1.719747	1.332478	1
fio-esm.3.rcp85	-1.729757	1.341356	2
fio-esm.2.rcp85	0.923837	1.458722	3
mpi-esm-lr.2.rcp26	0.963059	1.453175	4
csiro-mk3-6-0.8.rcp60	1.218939	1.423081	5
csiro-mk3-6-0.1.rcp60	0.174443	1.521814	6
fio-esm.1.rcp85	1.290307	1.356764	7
csiro-mk3-6-0.7.rcp26	-2.14702	1.192006	8
ccsm4.4.rcp26	-2.362913	1.361269	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
mpi-esm-lr.3.rcp26	1.44518	1.339058	10
Less Warming/Wet			
ccsm4.2.rcp60	10.85133	1.373106	1
cesm1-cam5.1.rcp26	9.478354	1.401006	2
noresm1-me.1.rcp26	8.241319	1.308822	3
ipsl-cm5a-mr.1.rcp26	12.27208	1.401722	4
cesm1-cam5.1.rcp60	12.47505	1.460033	5
ccsm4.5.rcp26	9.747016	1.554797	6
ec-earth.12.rcp26	7.835332	1.168806	7
cesm1-cam5.3.rcp60	9.454907	1.580967	8
gfdl-esm2g.1.rcp60	10.44198	1.043078	9
giss-e2-r.1.rcp45	12.98613	1.183836	10

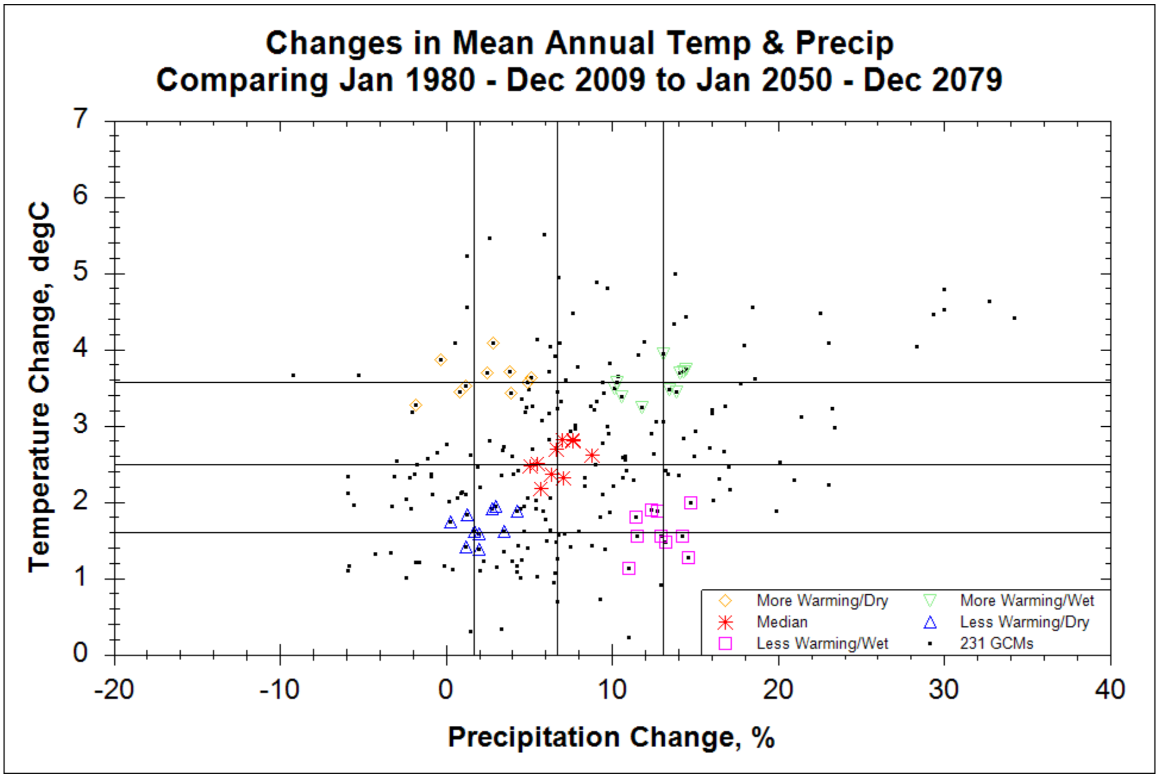


Figure 5.15 Upper Snake 2060s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 16. Upper Snake 2060s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
csiro-mk3-6-0.4.rcp85	1.228749	3.509292	1
mpi-esm-lr.3.rcp85	0.860515	3.435783	2
ccsm4.4.rcp85	2.533999	3.695503	3
bcc-csm1-1.1.rcp85	3.876073	3.699742	4
hadgem2-es.2.rcp60	3.902892	3.427767	5
csiro-mk3-6-0.10.rcp85	-0.286958	3.852142	6
csiro-mk3-6-0.3.rcp85	4.905844	3.559111	7
miroc-esm.1.rcp45	2.876906	4.080144	8
cesm1-bgc.1.rcp85	5.158479	3.621458	9
mpi-esm-lr.2.rcp85	-1.789978	3.261089	10
More Warming/Wet			
fgoals-g2.1.rcp85	13.44865	3.465778	1
ccsm4.5.rcp85	14.12112	3.683286	2
cnrm-cm5.1.rcp85	14.33253	3.708214	3
cnrm-cm5.4.rcp85	13.92037	3.430567	4
noresm1-m.1.rcp85	14.44502	3.734383	5
gfdl-cm3.1.rcp45	11.79111	3.237603	6
cnrm-cm5.10.rcp85	10.62252	3.369214	7
miroc5.1.rcp85	13.09107	3.9404	8
ec-earth.12.rcp85	10.33953	3.565606	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
ec-earth.8.rcp85	10.14696	3.4795	10
Median			
csiro-mk3-6-0.1.rcp60	6.338243	2.357861	1
ipsl-cm5a-lr.1.rcp60	5.509274	2.497008	2
gfdl-cm3.1.rcp26	6.691842	2.683408	3
fgoals-g2.1.rcp45	7.108603	2.320264	4
ec-earth.12.rcp45	5.053534	2.469975	5
ccsm4.5.rcp45	8.789625	2.613003	6
ipsl-cm5b-lr.1.rcp85	7.666028	2.798828	7
ipsl-cm5a-lr.3.rcp45	7.669656	2.806975	8
mpi-esm-lr.3.rcp45	5.751458	2.170083	9
cesm1-cam5.1.rcp45	7.037309	2.811955	10
Less Warming/Dry			
csiro-mk3-6-0.3.rcp60	1.694673	1.603108	1
giss-e2-r.3.rcp45	2.003163	1.573464	2
bcc-csm1-1.1.rcp26	1.197598	1.412114	3
csiro-mk3-6-0.7.rcp26	2.001515	1.368769	4
csiro-mk3-6-0.10.rcp60	1.270628	1.833047	5
csiro-mk3-6-0.6.rcp26	3.488353	1.6069	6
csiro-mk3-6-0.9.rcp26	0.278557	1.731561	7
csiro-mk3-6-0.8.rcp60	2.812502	1.913828	8
ipsl-cm5a-lr.3.rcp26	2.977466	1.93785	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
csiro-mk3-6-0.5.rcp26	4.293295	1.871383	10
Less Warming/Wet			
cesm1-cam5.1.rcp26	12.98306	1.543456	1
ipsl-cm5a-mr.1.rcp26	13.21995	1.465072	2
giss-e2-r.1.rcp60	14.26622	1.550397	3
gfdl-esm2g.1.rcp60	11.52249	1.549681	4
gfdl-esm2g.1.rcp45	12.74816	1.882911	5
ccsm4.3.rcp60	12.40391	1.891328	6
noresm1-m.1.rcp26	11.44619	1.801797	7
mpi-esm-mr.1.rcp45	14.74111	1.989811	8
giss-e2-h-cc.1.rcp45	14.58266	1.261358	9
ec-earth.12.rcp26	11.00547	1.123092	10

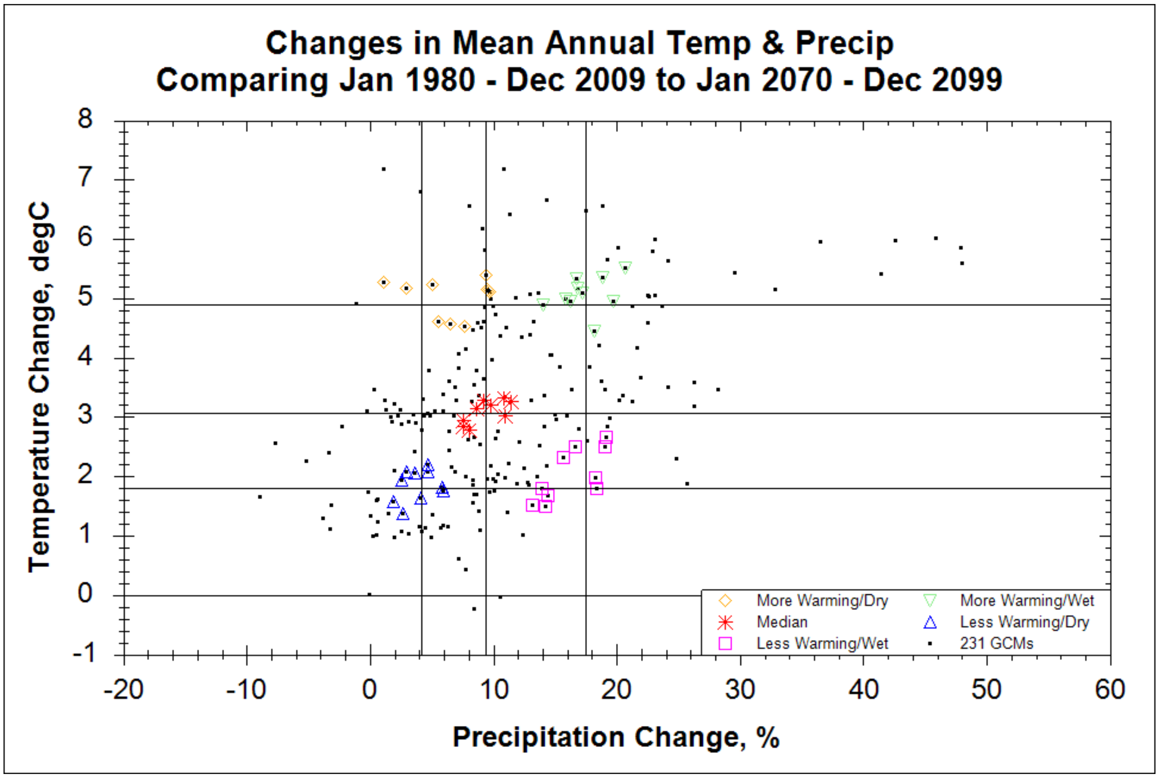


Figure 5.16 Upper Snake 2080s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 17. Upper Snake 2080s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
csiro-mk3-6-0.9.rcp85	5.039541	5.218147	1
csiro-mk3-6-0.3.rcp85	2.9236	5.167156	2
miroc-esm.1.rcp45	5.574594	4.604717	3
ccsm4.4.rcp85	6.497872	4.560575	4
csiro-mk3-6-0.10.rcp85	1.115872	5.276389	5
csiro-mk3-6-0.6.rcp85	9.376901	5.380192	6
hadgem2-ao.1.rcp60	7.682746	4.524694	7
csiro-mk3-6-0.4.rcp85	9.547504	5.154947	8
miroc5.1.rcp85	9.599806	5.128228	9
csiro-mk3-6-0.8.rcp85	9.742563	5.110458	10
More Warming/Wet			
csiro-mk3-6-0.5.rcp85	17.2708	5.082014	1
fgoals-g2.1.rcp85	16.30744	4.942997	2
cnrm-cm5.4.rcp85	15.86382	4.977042	3
access1-3.1.rcp85	16.86489	5.161058	4
cnrm-cm5.10.rcp85	19.77394	4.944172	5
ipsl-cm5a-lr.2.rcp85	18.86863	5.358272	6
csiro-mk3-6-0.1.rcp85	16.79126	5.320117	7
hadgem2-es.2.rcp60	18.24181	4.43515	8
miroc-esm-chem.1.rcp60	14.06247	4.891858	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
cesm1-cam5.1.rcp85	20.71807	5.50562	10
Median			
csiro-mk3-6-0.6.rcp60	9.796964	3.1896	1
noresm1-me.1.rcp45	9.766064	3.193486	2
csiro-mk3-6-0.4.rcp60	8.628911	3.140414	3
mri-cgcm3.1.rcp85	9.213834	3.284205	4
cesm1-cam5.1.rcp45	10.89399	3.328344	5
gfdl-cm3.1.rcp26	8.092439	2.775092	6
csiro-mk3-6-0.8.rcp45	7.584067	2.931281	7
csiro-mk3-6-0.7.rcp60	7.594664	2.843311	8
ccsm4.5.rcp60	10.98443	3.016114	9
miroc-esm.1.rcp26	11.48673	3.258864	10
Less Warming/Dry			
csiro-mk3-6-0.7.rcp26	4.111441	1.630617	1
miroc5.1.rcp26	4.65646	2.073078	2
mpi-esm-lr.1.rcp45	3.642373	2.047767	3
mri-cgcm3.1.rcp45	5.820144	1.812572	4
csiro-mk3-6-0.9.rcp26	2.558079	1.926297	5
mpi-esm-lr.2.rcp45	4.660801	2.192025	6
csiro-mk3-6-0.4.rcp26	5.937731	1.748556	7
giss-e2-r.3.rcp45	1.854715	1.565767	8
hadgem2-ao.1.rcp26	2.973164	2.071853	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
giss-e2-r.4.rcp45	2.68801	1.366825	10
Less Warming/Wet			
fgoals-s2.2.rcp45	18.26746	1.980892	1
noresm1-m.1.rcp26	18.39454	1.799008	2
cesm1-cam5.1.rcp26	14.42714	1.682414	3
giss-e2-h-cc.1.rcp45	14.27545	1.500414	4
csiro-mk3-6-0.8.rcp26	13.99082	1.78735	5
cesm1-cam5.3.rcp85	19.03865	2.500314	6
ipsl-cm5a-lr.2.rcp26	13.15258	1.507792	7
gfdl-esm2g.1.rcp60	15.70261	2.313464	8
ec-earth.8.rcp45	19.19658	2.654992	9
canesm2.3.rcp26	16.68056	2.495631	10

5.6 Willamette Ensemble Selection

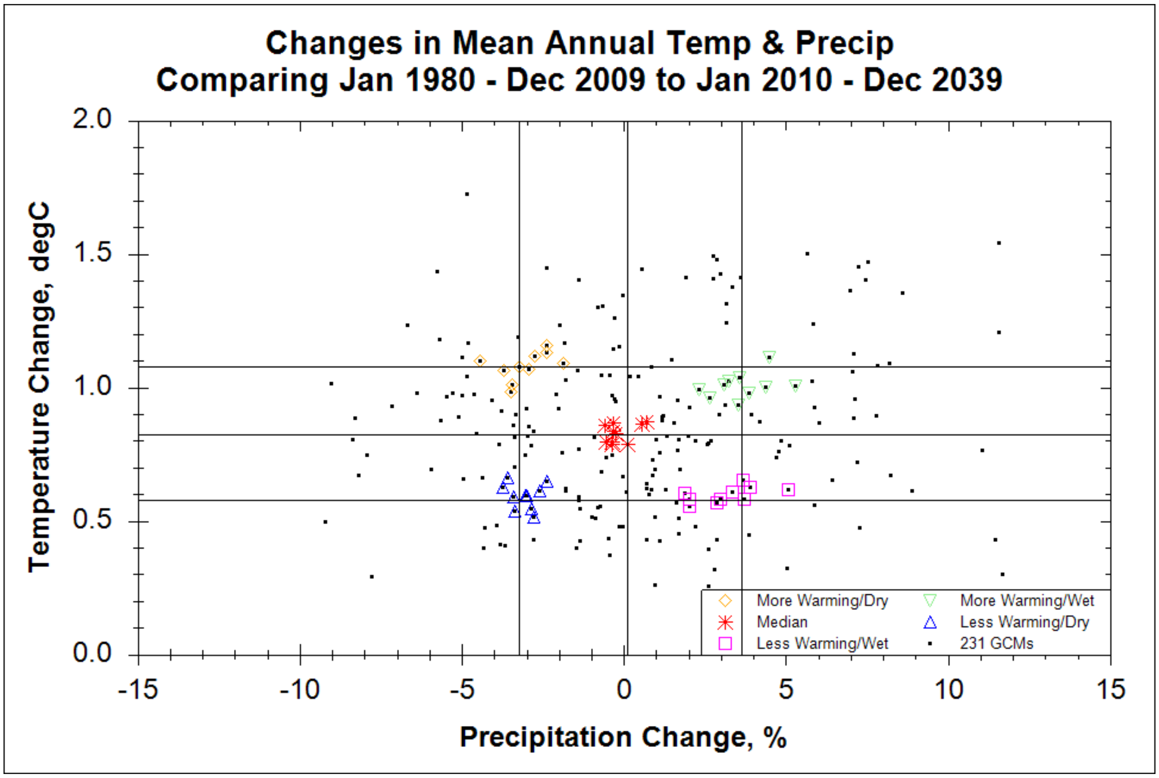


Figure 5.17 Willamette 2020s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 18. Willamette 2020s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
cnrm-cm5.1.rcp85	-3.207393	1.075303	1
gfdl-cm3.1.rcp85	-2.946268	1.065914	2
access1-3.1.rcp85	-3.682631	1.063419	3
cnrm-cm5.10.rcp85	-2.74011	1.1175	4
mpi-esm-lr.2.rcp85	-3.43125	1.0082	5
hadgem2-es.2.rcp45	-2.375399	1.129656	6
hadgem2-es.3.rcp60	-4.451818	1.096175	7
csiro-mk3-6-0.6.rcp26	-3.472353	0.984133	8
miroc-esm-chem.1.rcp45	-2.39449	1.155053	9
hadgem2-ao.1.rcp26	-1.858315	1.091144	10
More Warming/Wet			
cesm1-cam5.2.rcp85	3.583333	1.036808	1
gfdl-esm2g.1.rcp26	3.228343	1.023311	2
hadgem2-es.1.rcp45	4.470183	1.112742	3
ec-earth.12.rcp45	3.091448	1.009011	4
ccsm4.5.rcp60	4.392316	1.001689	5
miroc5.1.rcp85	3.856803	0.979797	6
mpi-esm-lr.1.rcp45	2.312595	0.990722	7
ipsl-cm5a-lr.1.rcp45	2.663026	0.958822	8
ccsm4.5.rcp85	5.28883	1.005889	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
ipsl-cm5a-mr.1.rcp60	3.528713	0.932803	10
Median			
miroc5.1.rcp60	-0.2397	0.82382	1
noresm1-m.1.rcp26	-0.33625	0.8349	2
ccsm4.2.rcp60	0.109992	0.785786	3
csiro-mk3-6-0.6.rcp85	-0.34795	0.795417	4
mpi-esm-mr.1.rcp45	0.576039	0.860339	5
mpi-esm-lr.1.rcp26	-0.355079	0.78475	6
cnrm-cm5.1.rcp45	-0.54551	0.794	7
csiro-mk3-6-0.3.rcp26	-0.316723	0.868164	8
csiro-mk3-6-0.8.rcp85	-0.584541	0.855842	9
cesm1-cam5.2.rcp45	0.710411	0.871236	10
Less Warming/Dry			
csiro-mk3-6-0.8.rcp45	-3.403486	0.591628	1
csiro-mk3-6-0.9.rcp45	-3.050265	0.594097	2
ccsm4.4.rcp45	-3.019823	0.593428	3
gfdl-esm2m.1.rcp60	-3.368587	0.533792	4
giss-e2-r.1.rcp85	-2.859448	0.544125	5
ccsm4.3.rcp26	-2.594602	0.61145	6
csiro-mk3-6-0.3.rcp85	-3.753854	0.6262	7
csiro-mk3-6-0.2.rcp45	-2.78713	0.515492	8
gfdl-esm2m.1.rcp85	-3.595442	0.661875	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
cesm1-cam5.1.rcp60	-2.36049	0.649019	10
Less Warming/Wet			
giss-e2-r.1.rcp60	3.710216	0.579464	1
csiro-mk3-6-0.7.rcp26	3.366007	0.607745	2
fio-esm.1.rcp26	2.978471	0.579694	3
ccsm4.3.rcp85	3.887847	0.624061	4
noresm1-m.1.rcp60	2.865491	0.5658	5
ipsl-cm5b-lr.1.rcp85	3.693683	0.6513	6
csiro-mk3-6-0.2.rcp85	5.085904	0.614028	7
fio-esm.2.rcp26	2.025062	0.578439	8
noresm1-me.1.rcp85	2.038066	0.553003	9
csiro-mk3-6-0.6.rcp60	1.867743	0.60107	10

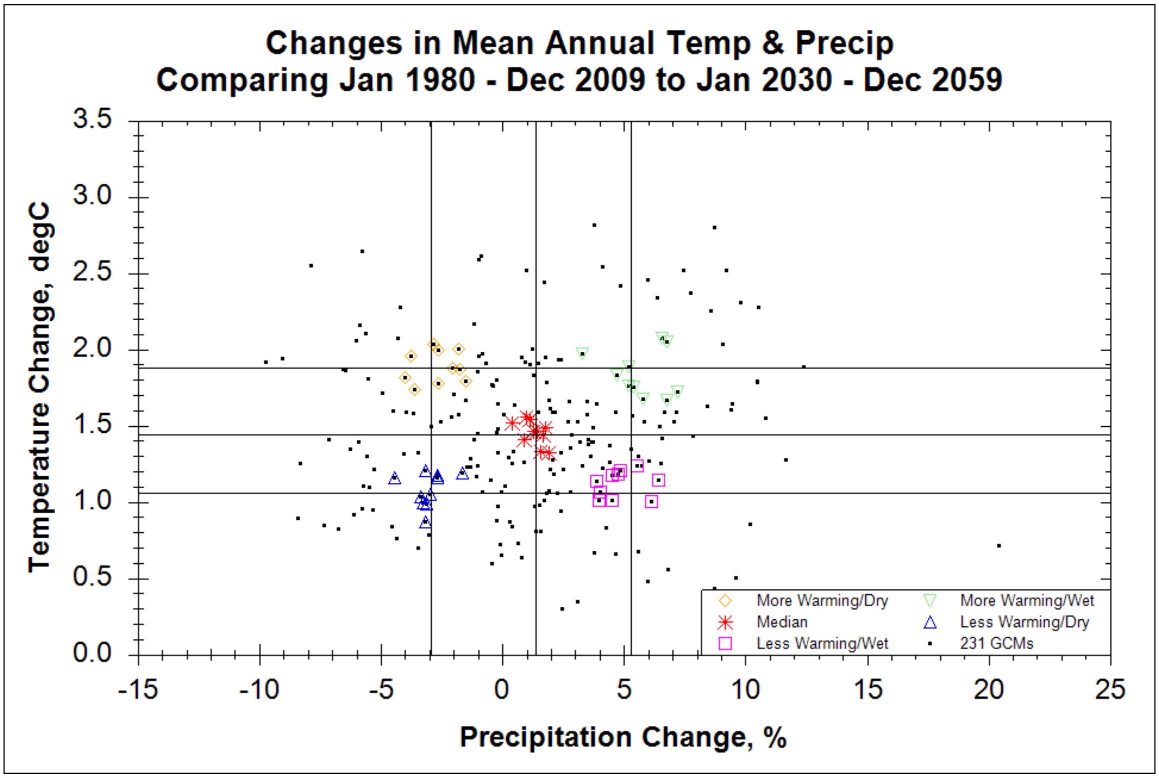


Figure 5.18 Willamette 2040s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 19. Willamette 2040s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
mpi-esm-lr.1.rcp85	-2.042384	1.872164	1
csiro-mk3-6-0.8.rcp85	-2.633314	1.773703	2
ipsl-cm5a-lr.3.rcp45	-3.727637	1.952306	3
hadgem2-es.2.rcp45	-2.633353	1.988825	4
canesm2.3.rcp45	-1.737697	1.863761	5
canesm2.2.rcp45	-4.00291	1.81065	6
ipsl-cm5a-lr.1.rcp85	-2.825433	2.030614	7
csiro-mk3-6-0.6.rcp85	-3.620851	1.7382	8
miroc-esm.1.rcp45	-1.769421	1.999053	9
gfdl-cm3.1.rcp45	-1.481114	1.790953	10
More Warming/Wet			
cesm1-cam5.2.rcp85	5.183752	1.883342	1
cesm1-cam5.1.rcp85	4.695585	1.827761	2
hadgem2-es.1.rcp60	5.19064	1.760633	3
access1-0.1.rcp85	5.393166	1.748397	4
hadgem2-es.3.rcp60	5.818971	1.671547	5
gfdl-cm3.1.rcp85	6.760235	2.048605	6
canesm2.1.rcp45	6.573751	2.072811	7
bcc-csm1-1.1.rcp85	3.279854	1.971536	8
ipsl-cm5b-lr.1.rcp85	7.226884	1.717508	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
hadgem2-es.3.rcp26	6.776825	1.6637	10
Median			
csiro-mk3-6-0.3.rcp26	1.434196	1.459539	1
ec-earth.2.rcp45	1.2867	1.459214	2
bcc-csm1-1.1.rcp45	1.682652	1.434611	3
ipsl-cm5a-lr.2.rcp26	0.896353	1.404325	4
ccsm4.2.rcp85	1.796984	1.482006	5
csiro-mk3-6-0.7.rcp85	1.152479	1.538994	6
csiro-mk3-6-0.5.rcp45	1.602312	1.330122	7
access1-3.1.rcp45	0.981458	1.552369	8
ec-earth.8.rcp45	1.908775	1.322372	9
ccsm4.1.rcp85	0.404006	1.516506	10
Less Warming/Dry			
ccsm4.4.rcp26	-2.978268	1.046753	1
csiro-mk3-6-0.8.rcp26	-3.379616	1.034331	2
ccsm4.3.rcp45	-3.247144	0.993331	3
fgoals-g2.1.rcp26	-3.13635	0.983708	4
csiro-mk3-6-0.7.rcp45	-2.660824	1.15345	5
ccsm4.1.rcp60	-2.665949	1.168905	6
csiro-mk3-6-0.8.rcp45	-3.180339	1.205733	7
mpi-esm-lr.3.rcp26	-1.644362	1.191611	8
csiro-mk3-6-0.8.rcp60	-4.453869	1.158217	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
ccsm4.3.rcp26	-3.146185	0.864258	10
Less Warming/Wet			
giss-e2-r-cc.1.rcp45	4.530893	1.005236	1
fio-esm.1.rcp85	6.161836	0.999506	2
csiro-mk3-6-0.2.rcp60	4.029575	1.062192	3
ipsl-cm5a-lr.1.rcp26	4.783138	1.183775	4
gfdl-esm2g.1.rcp60	6.41098	1.137461	5
noresm1-m.1.rcp26	4.512804	1.174314	6
ec-earth.12.rcp26	3.963134	1.008444	7
fio-esm.2.rcp85	4.870416	1.201661	8
cesm1-cam5.1.rcp60	3.908977	1.131167	9
miroc5.1.rcp26	5.538177	1.230814	10

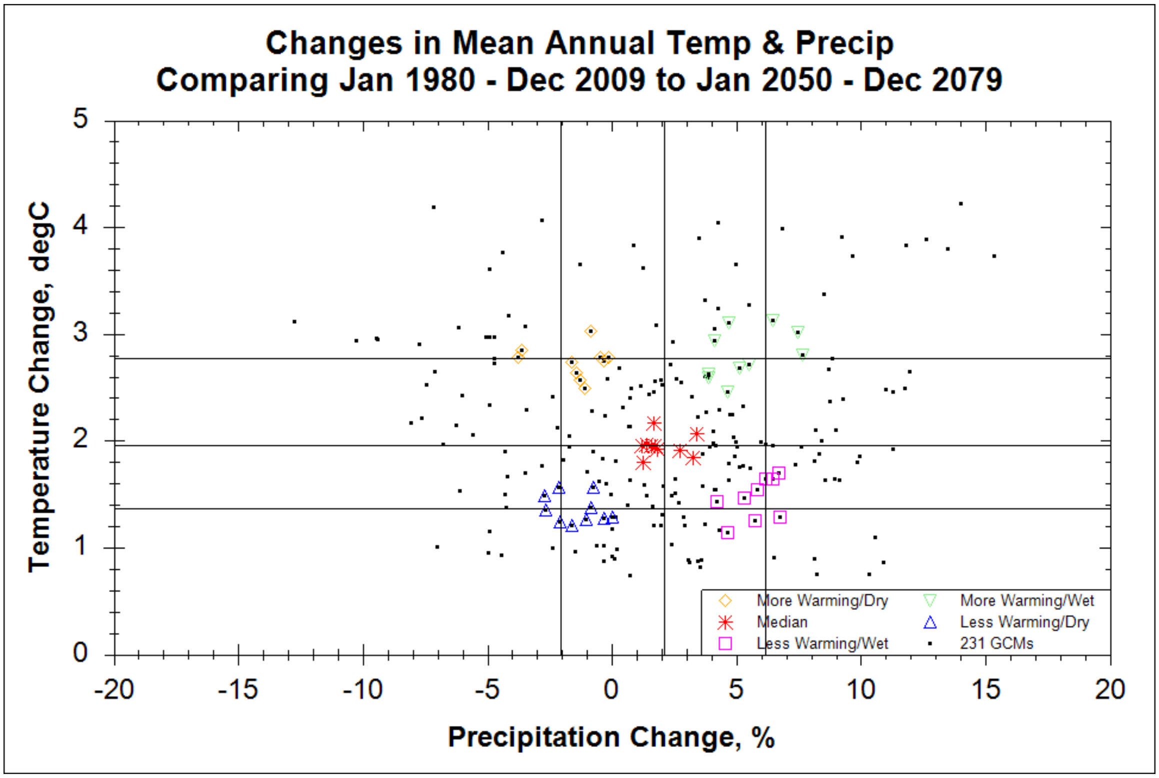


Figure 5.19 Willamette 2060s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 20. Willamette 2060s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
cesm1-bgc.1.rcp85	-1.586451	2.729703	1
hadgem2-es.3.rcp60	-1.397572	2.6341	2
hadgem2-es.2.rcp45	-1.262542	2.572664	3
mpi-esm-lr.2.rcp85	-3.623118	2.843683	4
hadgem2-es.2.rcp60	-0.463288	2.783508	5
miroc-esm.1.rcp60	-3.737194	2.776086	6
hadgem2-ao.1.rcp45	-0.31222	2.745511	7
csiro-mk3-6-0.1.rcp45	-0.14967	2.783636	8
csiro-mk3-6-0.3.rcp85	-0.84962	3.020975	9
ccsm4.3.rcp85	-1.065078	2.487461	10
More Warming/Wet			
ec-earth.12.rcp85	5.530077	2.709364	1
canesm2.3.rcp45	5.119617	2.674978	2
hadgem2-es.1.rcp45	7.678771	2.806756	3
canesm2.5.rcp45	7.477128	3.012214	4
cesm1-cam5.2.rcp85	6.445592	3.129358	5
csiro-mk3-6-0.2.rcp85	4.147966	2.933503	6
hadgem2-es.1.rcp60	3.88887	2.617519	7
hadgem2-cc.1.rcp45	4.630808	2.451905	8
bcc-csm1-1.1.rcp85	4.68888	3.105183	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
cnrm-cm5.2.rcp85	3.909566	2.585028	10
Median			
bcc-csm1-1.1.rcp45	1.731761	1.953492	1
ipsl-cm5a-lr.3.rcp26	1.844657	1.918831	2
gfdl-cm3.1.rcp26	1.602063	1.949089	3
noresm1-m.1.rcp45	1.418288	1.964131	4
cesm1-cam5.3.rcp45	2.728375	1.912906	5
ec-earth.12.rcp45	1.227664	1.957392	6
cesm1-cam5.3.rcp60	1.68936	2.162572	7
ccsm4.1.rcp60	1.258863	1.802622	8
noresm1-m.1.rcp60	3.274978	1.840853	9
csiro-mk3-6-0.2.rcp45	3.391159	2.07	10
Less Warming/Dry			
ccsm4.3.rcp45	-2.642198	1.352739	1
mpi-esm-lr.2.rcp26	-2.084069	1.235839	2
ccsm4.4.rcp60	-2.707673	1.480389	3
fgoals-g2.1.rcp26	-1.59591	1.201169	4
cesm1-bgc.1.rcp45	-2.136206	1.566389	5
mpi-esm-mr.1.rcp26	-1.025914	1.266956	6
ipsl-cm5a-lr.1.rcp26	-0.860288	1.367817	7
csiro-mk3-6-0.10.rcp60	-0.767825	1.56775	8
giss-e2-r.3.rcp45	-0.312318	1.268678	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
csiro-mk3-6-0.7.rcp60	0.013347	1.286472	10
Less Warming/Wet			
giss-e2-r.1.rcp60	6.75236	1.287108	1
ipsl-cm5a-mr.1.rcp26	5.730588	1.253986	2
cesm1-cam5.3.rcp26	5.32208	1.467839	3
cesm1-cam5.3.rcp85	5.32208	1.467839	4
gfdl-esm2g.1.rcp60	5.849693	1.545853	5
ipsl-cm5b-lr.1.rcp45	6.165162	1.64525	6
csiro-mk3-6-0.2.rcp26	6.478158	1.642922	7
ipsl-cm5a-lr.2.rcp26	4.199331	1.427622	8
giss-e2-r.1.rcp45	4.642469	1.142944	9
miroc5.1.rcp45	6.705867	1.695117	10

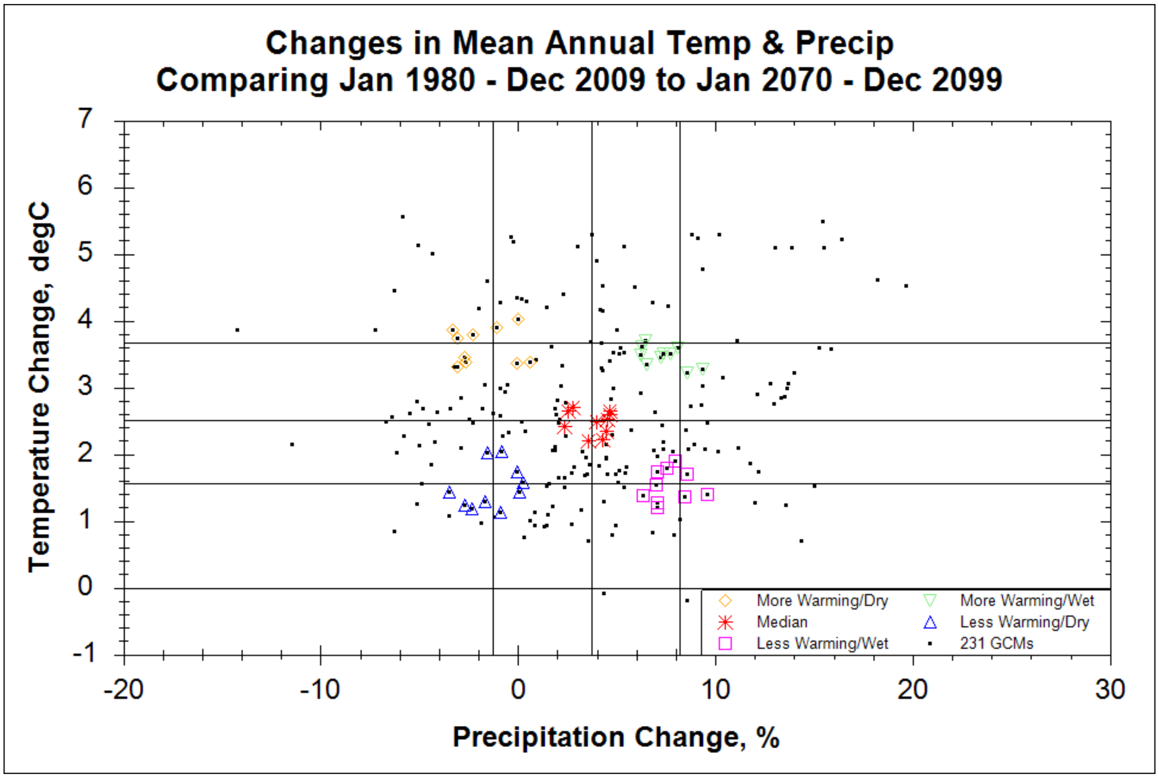


Figure 5.20 Willamette 2080s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 21. Willamette 2080s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
mpi-esm-lr.2.rcp85	-1.080976	3.901111	1
miroc-esm.1.rcp60	-2.26927	3.79445	2
ccsm4.1.rcp85	-2.681485	3.453531	3
miroc-esm-chem.1.rcp60	-3.034437	3.731686	4
miroc-esm.1.rcp45	-2.637472	3.371139	5
hadgem2-es.3.rcp60	-0.021683	3.3657	6
bcc-csm1-1.1.rcp85	0.034306	4.011775	7
mpi-esm-lr.1.rcp85	-3.301421	3.860722	8
miroc-esm-chem.1.rcp45	-3.080583	3.301656	9
ccsm4.2.rcp85	0.624358	3.372075	10
More Warming/Wet			
noresm1-me.1.rcp85	8.065081	3.58532	1
cesm1-bgc.1.rcp85	7.75342	3.500592	2
hadgem2-es.1.rcp60	7.383739	3.494669	3
cnrm-cm5.4.rcp85	7.23486	3.448494	4
hadgem2-es.2.rcp60	6.469916	3.703317	5
cnrm-cm5.6.rcp85	6.276954	3.613058	6
ec-earth.6.rcp85	6.223226	3.478881	7
hadgem2-es.4.rcp60	6.521387	3.343614	8
ipsl-cm5a-mr.1.rcp60	8.602576	3.208997	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
canesm2.3.rcp45	9.352449	3.2731	10
Median			
ipsl-cm5a-lr.2.rcp45	4.022141	2.4827	1
csiro-mk3-6-0.4.rcp45	4.547591	2.515164	2
csiro-mk3-6-0.4.rcp60	4.654651	2.582669	3
csiro-mk3-6-0.5.rcp45	4.666392	2.635606	4
cesm1-cam5.1.rcp45	4.481524	2.339031	5
hadgem2-es.3.rcp45	2.811079	2.688875	6
csiro-mk3-6-0.7.rcp45	2.524031	2.644572	7
csiro-mk3-6-0.7.rcp60	2.336361	2.409636	8
canesm2.5.rcp26	3.596638	2.196517	9
miroc5.1.rcp60	4.308329	2.221994	10
Less Warming/Dry			
giss-e2-r.3.rcp45	-1.690282	1.284125	1
mpi-esm-lr.1.rcp45	-0.042018	1.734203	2
mpi-esm-mr.1.rcp26	0.064117	1.436686	3
cesm1-bgc.1.rcp45	0.284111	1.568989	4
mpi-esm-lr.2.rcp26	-2.328919	1.176242	5
inmcm4.1.rcp45	-2.714763	1.227758	6
mpi-esm-lr.1.rcp26	-0.911614	1.129156	7
canesm2.2.rcp26	-1.578883	2.023725	8
mpi-esm-mr.1.rcp45	-0.83754	2.032094	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
miroc5.1.rcp26	-3.482799	1.434442	10
Less Warming/Wet			
csiro-mk3-6-0.2.rcp26	8.551715	1.7017	1
noresm1-m.1.rcp26	8.430978	1.358756	2
ipsl-cm5a-lr.2.rcp26	7.035567	1.527983	3
ec-earth.2.rcp45	7.571754	1.785978	4
csiro-mk3-6-0.8.rcp26	7.059947	1.741508	5
hadgem2-es.2.rcp26	7.9737	1.900947	6
fio-esm.1.rcp60	9.576292	1.396	7
giss-e2-r.1.rcp45	7.054367	1.262497	8
noresm1-me.1.rcp26	7.090462	1.200819	9
giss-e2-r.1.rcp60	6.346041	1.368244	10

5.7 Yakima Ensemble Selection

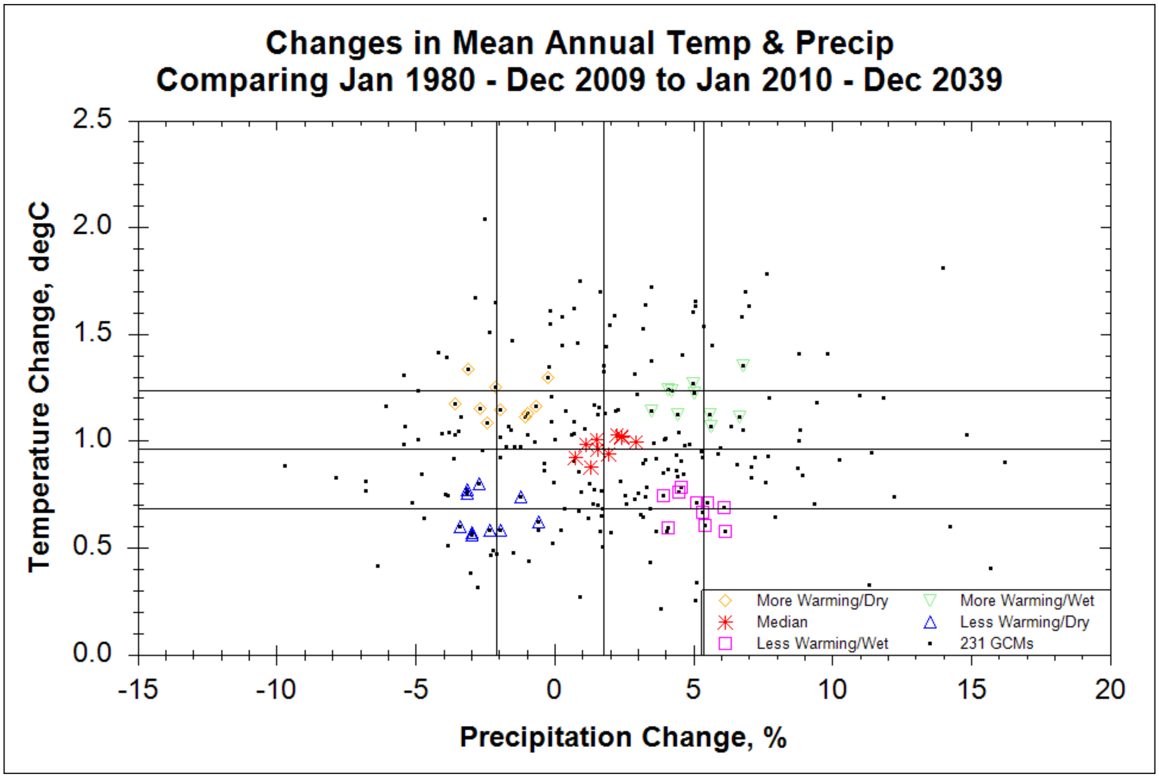


Figure 5.21 Yakima 2020s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 22. Yakima 2020s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
miroc-esm-chem.1.rcp60	-2.124281	1.248067	1
cnrm-cm5.10.rcp85	-1.94999	1.142633	2
hadgem2-ao.1.rcp60	-2.659047	1.149367	3
ipsl-cm5a-lr.4.rcp45	-3.558682	1.172783	4
hadgem2-es.3.rcp60	-3.097672	1.333344	5
gfdl-cm3.1.rcp26	-0.677287	1.159522	6
csiro-mk3-6-0.10.rcp85	-0.939456	1.129572	7
fgoals-g2.1.rcp85	-1.031348	1.109547	8
ipsl-cm5a-lr.3.rcp26	-0.231801	1.292061	9
cesm1-cam5.2.rcp45	-2.417979	1.081139	10
More Warming/Wet			
canesm2.4.rcp85	5.040179	1.222328	1
ec-earth.12.rcp45	4.998275	1.265547	2
bcc-csm1-1.1.rcp26	4.244265	1.233592	3
ipsl-cm5a-lr.3.rcp45	4.092865	1.237533	4
hadgem2-es.4.rcp26	5.59414	1.1215	5
hadgem2-es.4.rcp45	4.433722	1.121531	6
hadgem2-es.1.rcp60	6.798385	1.353089	7
ccsm4.5.rcp85	6.68299	1.113206	8
miroc5.1.rcp85	3.487996	1.138308	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
ec-earth.12.rcp85	5.622068	1.066231	10
Median			
csiro-mk3-6-0.6.rcp85	1.57952	0.957672	1
csiro-mk3-6-0.5.rcp26	1.940178	0.938917	2
ccsm4.5.rcp45	1.523905	1.007328	3
noresm1-m.1.rcp45	1.135303	0.979522	4
ec-earth.8.rcp85	2.428388	1.016269	5
gfdl-esm2g.1.rcp60	2.264891	1.027544	6
ec-earth.8.rcp45	2.438154	1.021275	7
csiro-mk3-6-0.8.rcp85	0.774242	0.921772	8
miroc5.1.rcp60	2.921994	0.992089	9
mpi-esm-lr.3.rcp45	1.289563	0.874569	10
Less Warming/Dry			
noresm1-me.1.rcp85	-1.199798	0.736417	1
giss-e2-r.1.rcp85	-1.961521	0.583183	2
csiro-mk3-6-0.3.rcp60	-2.340659	0.579639	3
gfdl-esm2m.1.rcp60	-3.156189	0.755608	4
csiro-mk3-6-0.9.rcp45	-3.145651	0.771989	5
ccsm4.4.rcp26	-2.737386	0.799289	6
csiro-mk3-6-0.8.rcp26	-2.981466	0.571997	7
fio-esm.1.rcp45	-3.399726	0.596297	8
inmcm4.1.rcp85	-0.5929	0.621647	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
csiro-mk3-6-0.9.rcp26	-2.966596	0.557442	10
Less Warming/Wet			
noresm1-m.1.rcp60	5.341824	0.666856	1
ipsl-cm5b-lr.1.rcp45	5.523055	0.707158	2
ipsl-cm5b-lr.1.rcp85	5.138309	0.706436	3
csiro-mk3-6-0.6.rcp60	6.111423	0.684303	4
giss-e2-r-cc.1.rcp45	5.427394	0.604989	5
mpi-esm-lr.1.rcp26	4.495219	0.761311	6
cesm1-cam5.1.rcp45	4.566833	0.783314	7
csiro-mk3-6-0.4.rcp45	6.141737	0.577	8
ccsm4.3.rcp60	3.942482	0.744008	9
csiro-mk3-6-0.2.rcp26	4.106984	0.594275	10

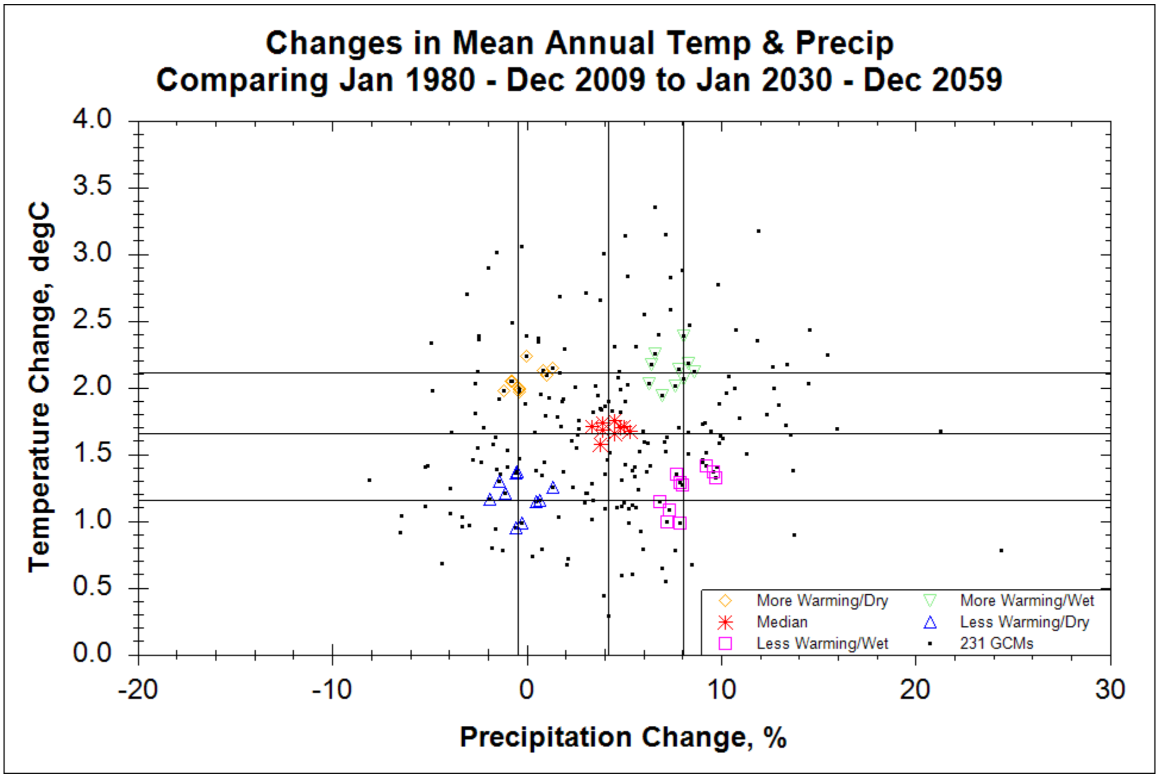


Figure 5.22 Yakima 2040s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 23. Yakima 2040s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
ipsl-cm5a-lr.3.rcp45	-0.794711	2.045989	1
ipsl-cm5a-lr.1.rcp85	-0.75791	2.041795	2
canesm2.2.rcp45	-0.398242	1.995114	3
csiro-mk3-6-0.10.rcp85	-0.01377	2.236569	4
csiro-mk3-6-0.6.rcp85	-0.362841	1.982381	5
mpi-esm-lr.2.rcp85	0.837729	2.125536	6
ipsl-cm5a-lr.1.rcp45	-0.350638	1.961356	7
noresm1-m.1.rcp45	-1.144833	1.96905	8
hadgem2-es.2.rcp60	1.037142	2.093628	9
canesm2.3.rcp45	1.328928	2.143153	10
More Warming/Wet			
fgoals-s2.3.rcp85	7.842942	2.134681	1
hadgem2-es.4.rcp45	8.046051	2.062492	2
canesm2.2.rcp26	8.59715	2.113958	3
hadgem2-cc.1.rcp45	8.295938	2.178047	4
hadgem2-es.1.rcp60	7.675993	2.007469	5
canesm2.1.rcp26	6.428478	2.168056	6
fgoals-g2.1.rcp85	6.995633	1.940022	7
hadgem2-es.3.rcp26	6.273304	2.028572	8
cesm1-cam5.2.rcp85	6.595407	2.253128	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
canesm2.1.rcp45	8.095988	2.386456	10
Median			
ec-earth.12.rcp45	4.521294	1.652119	1
ccsm4.5.rcp45	3.91957	1.678958	2
bcc-csm1-1.1.rcp45	4.856225	1.692883	3
csiro-mk3-6-0.1.rcp26	3.890514	1.735478	4
ec-earth.2.rcp45	4.529259	1.746186	5
cesm1-cam5.3.rcp26	3.778642	1.57525	6
cesm1-cam5.3.rcp85	3.778642	1.57525	7
gfdl-cm3.1.rcp60	5.004089	1.708289	8
ccsm4.2.rcp85	3.388113	1.707342	9
ipsl-cm5a-mr.1.rcp60	5.308636	1.673544	10
Less Warming/Dry			
ccsm4.3.rcp45	-1.134312	1.203692	1
csiro-mk3-6-0.8.rcp26	0.459148	1.145919	2
giss-e2-r.3.rcp45	0.685312	1.151878	3
ccsm4.4.rcp26	-1.919522	1.158756	4
csiro-mk3-6-0.7.rcp45	-1.405262	1.292211	5
mri-cgcm3.1.rcp26	-0.250962	0.978797	6
csiro-mk3-6-0.8.rcp60	-0.532845	1.354058	7
csiro-mk3-6-0.7.rcp60	-0.563773	0.950758	8
giss-e2-r.1.rcp85	-0.474814	1.362969	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
mpi-esm-mr.1.rcp26	1.346925	1.249594	10
Less Warming/Wet			
ec-earth.12.rcp26	7.32376	1.080703	1
miroc5.1.rcp60	7.990963	1.268928	2
cesm1-cam5.1.rcp26	7.911632	1.282806	3
csiro-mk3-6-0.2.rcp60	6.857066	1.146436	4
ccsm4.3.rcp60	7.865489	0.982425	5
csiro-mk3-6-0.5.rcp60	7.241655	0.989781	6
gfdl-esm2g.1.rcp60	7.730832	1.345183	7
miroc5.1.rcp26	9.718603	1.323572	8
noresm1-m.1.rcp26	9.583727	1.362192	9
cesm1-cam5.1.rcp60	9.241913	1.409672	10

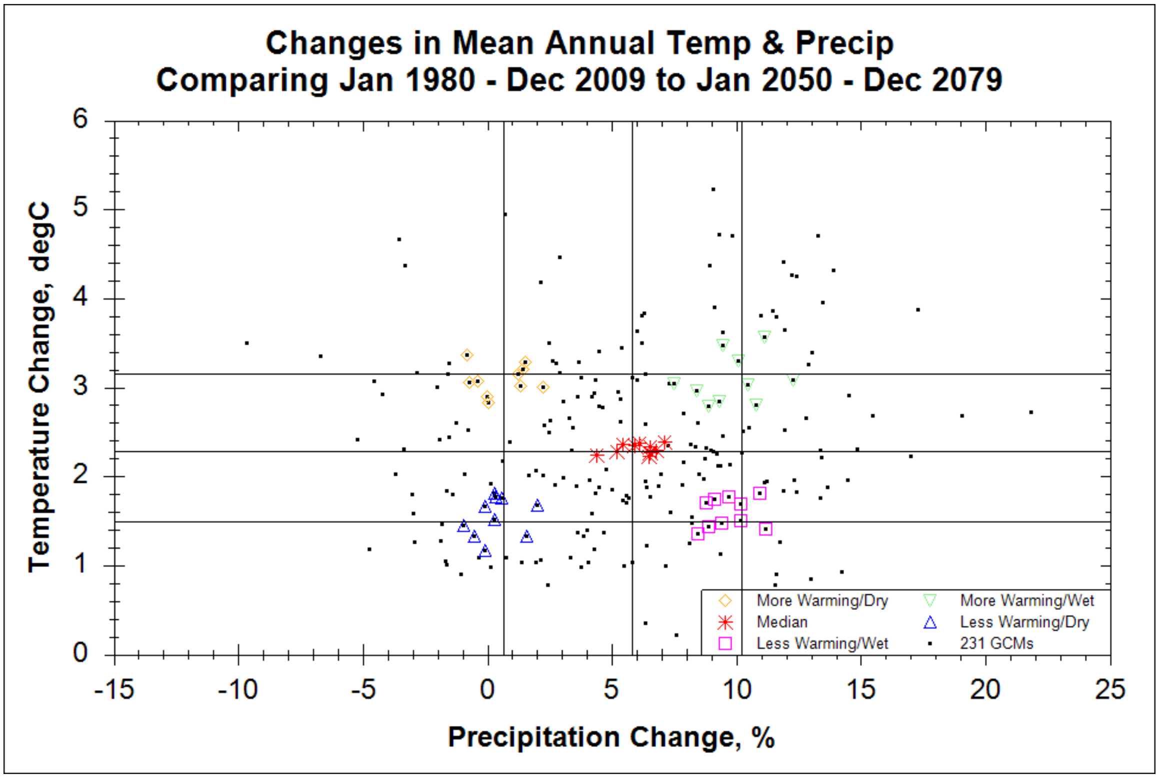


Figure 5.23 Yakima 2060s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 24. Yakima 2060s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
hadgem2-cc.1.rcp45	1.264006	3.141672	1
cesm1-bgc.1.rcp85	1.455391	3.204806	2
hadgem2-es.3.rcp45	1.333651	3.019028	3
ccsm4.4.rcp85	-0.387175	3.066103	4
csiro-mk3-6-0.4.rcp85	1.513796	3.274856	5
canesm2.2.rcp45	-0.718521	3.050564	6
ccsm4.1.rcp85	0.017963	2.887858	7
hadgem2-ao.1.rcp60	0.041053	2.820922	8
csiro-mk3-6-0.7.rcp85	2.225966	2.997156	9
csiro-mk3-6-0.6.rcp85	-0.824572	3.363811	10
More Warming/Wet			
canesm2.4.rcp45	10.48192	3.022781	1
csiro-mk3-6-0.2.rcp85	10.07235	3.289489	2
bcc-csm1-1-m.1.rcp85	9.316012	2.842639	3
fgoals-s2.3.rcp85	9.438959	3.475131	4
ccsm4.5.rcp85	8.385912	2.955975	5
gfdl-esm2g.1.rcp85	10.81568	2.793333	6
ec-earth.12.rcp85	12.27729	3.075472	7
cnrm-cm5.2.rcp85	8.901103	2.792033	8
fgoals-s2.2.rcp85	11.11725	3.55972	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
canesm2.3.rcp45	7.496632	3.044608	10
Median			
cesm1-cam5.3.rcp60	5.946314	2.342361	1
noresm1-m.1.rcp45	6.13122	2.372158	2
csiro-mk3-6-0.8.rcp45	5.440254	2.361747	3
hadgem2-es.3.rcp26	5.191369	2.283767	4
ipsl-cm5a-lr.1.rcp60	6.544255	2.327214	5
ccsm4.5.rcp45	6.543973	2.257519	6
ec-earth.12.rcp45	6.518053	2.218405	7
bcc-csm1-1.1.rcp45	6.780764	2.285092	8
canesm2.4.rcp26	7.125007	2.379669	9
noresm1-me.1.rcp45	4.411197	2.238125	10
Less Warming/Dry			
noresm1-me.1.rcp60	0.297076	1.51225	1
ccsm4.3.rcp45	-0.088497	1.65905	2
ipsl-cm5a-lr.1.rcp26	-0.529798	1.327889	3
csiro-mk3-6-0.5.rcp60	0.587942	1.7554	4
giss-e2-r.3.rcp45	1.57824	1.323403	5
ccsm4.2.rcp45	0.353767	1.771928	6
noresm1-me.1.rcp26	-0.973553	1.445089	7
ccsm4.4.rcp60	2.024669	1.678122	8
mpi-esm-lr.1.rcp45	0.287598	1.803869	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
mpi-esm-lr.2.rcp26	-0.105468	1.168664	10
Less Warming/Wet			
ipsl-cm5a-lr.2.rcp26	10.18255	1.497292	1
csiro-mk3-6-0.6.rcp26	9.415386	1.467072	2
ccsm4.3.rcp60	10.15721	1.682947	3
giss-e2-r.1.rcp60	11.19767	1.406403	4
miroc5.1.rcp26	8.892508	1.433939	5
fgoals-g2.1.rcp45	9.684656	1.76482	6
csiro-mk3-6-0.4.rcp60	9.115144	1.7352	7
gfdl-esm2g.1.rcp60	10.9551	1.806119	8
csiro-mk3-6-0.4.rcp26	8.440479	1.357258	9
cesm1-cam5.3.rcp85	8.7939	1.704953	10

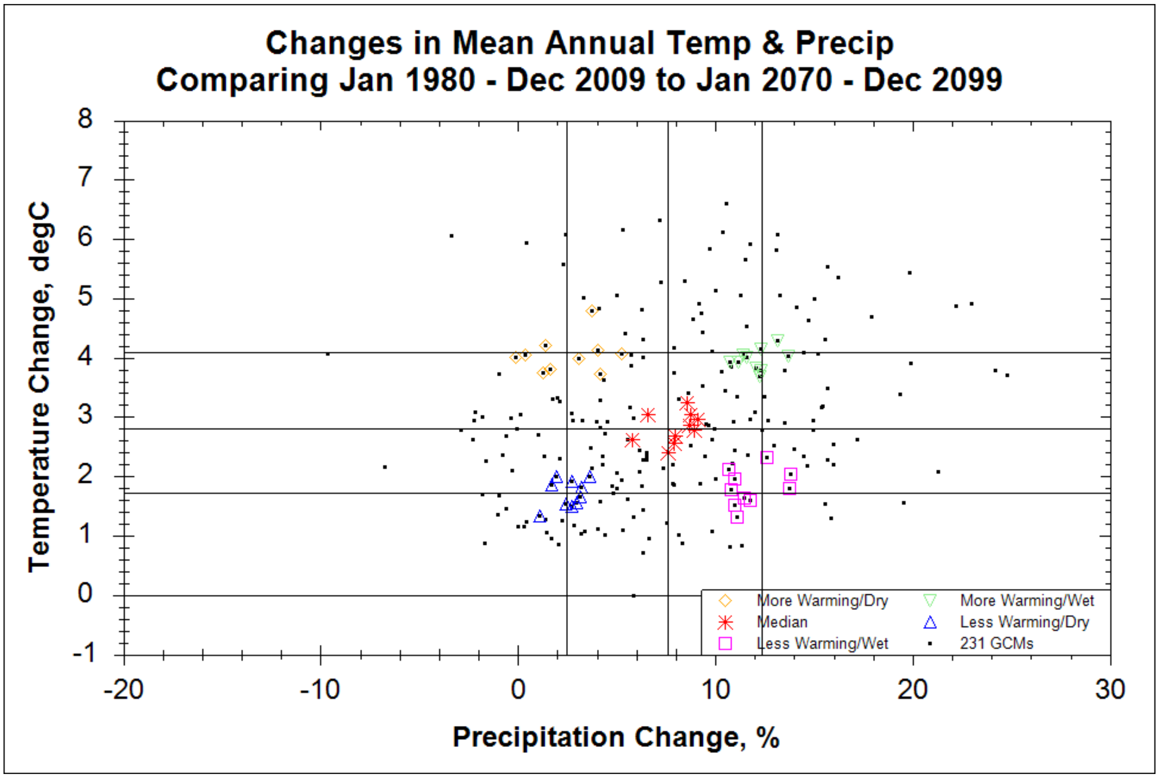


Figure 5.24 Yakima 2080s scatter-graphs of projected changes in temperature and precipitation. Vertical and horizontal lines represent the 20th, 50th, and 80th percentile changes for precipitation and temperature respectively. Points represent individual GCM projections, while colored shapes highlight the selected ensemble groups associated with each percentile combination (Less Warming/Dry, Less Warming/Wet, More Warming/Dry, More Warming/Wet, and Median).

Table 25. Yakima 2080s GCM projection ensembles.

	Change in Precip (%)	Change in Temp (deg C)	Rank
More Warming/Dry			
ccsm4.1.rcp85	3.062646	3.989339	1
miroc-esm-chem.1.rcp60	1.390729	4.194792	2
ccsm4.2.rcp85	1.670508	3.798531	3
mpi-esm-lr.3.rcp85	4.062906	4.117636	4
ccsm4.4.rcp85	1.306597	3.737108	5
miroc-esm.1.rcp60	0.403337	4.048247	6
hadgem2-es.3.rcp60	-0.090263	4.009953	7
miroc-esm.1.rcp45	4.174953	3.720486	8
mpi-esm-lr.2.rcp85	5.238118	4.055708	9
csiro-mk3-6-0.9.rcp85	3.729297	4.78968	10
More Warming/Wet			
ec-earth.12.rcp85	12.30057	4.15168	1
ec-earth.6.rcp85	11.60674	3.997175	2
hadgem2-es.4.rcp60	11.39484	4.042208	3
hadgem2-es.2.rcp60	13.1691	4.292544	4
cnrm-cm5.6.rcp85	12.09717	3.812417	5
ec-earth.8.rcp85	11.19885	3.928472	6
miroc5.1.rcp85	12.34398	3.788931	7
cesm1-bgc.1.rcp85	13.67543	4.024778	8
bcc-csm1-1-m.1.rcp85	10.74401	3.914939	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
canesm2.3.rcp45	12.24529	3.688622	10
Median			
noresm1-m.1.rcp45	7.997287	2.667528	1
noresm1-m.1.rcp60	8.705107	2.859717	2
csiro-mk3-6-0.5.rcp60	7.901412	2.549303	3
csiro-mk3-6-0.10.rcp60	8.73393	3.046545	4
csiro-mk3-6-0.2.rcp60	8.955983	2.785975	5
fio-esm.1.rcp85	6.586934	3.038445	6
gfdl-cm3.1.rcp45	9.131086	2.956158	7
hadgem2-ao.1.rcp26	7.582764	2.402289	8
cesm1-cam5.3.rcp60	8.558907	3.229694	9
noresm1-me.1.rcp45	5.799507	2.619281	10
Less Warming/Dry			
ipsl-cm5a-lr.3.rcp26	2.719723	1.910697	1
ipsl-cm5b-lr.1.rcp45	3.206872	1.818392	2
miroc5.1.rcp26	2.403483	1.528125	3
ipsl-cm5a-mr.1.rcp26	3.179353	1.643536	4
ipsl-cm5a-lr.1.rcp26	2.969141	1.543478	5
cesm1-bgc.1.rcp45	1.70933	1.856903	6
fio-esm.3.rcp60	2.717273	1.490453	7
mpi-esm-lr.2.rcp45	1.92912	2.00212	8
ccsm4.2.rcp45	3.611361	1.993653	9

	Change in Precip (%)	Change in Temp (deg C)	Rank
giss-e2-r.3.rcp45	1.128766	1.340514	10
Less Warming/Wet			
noresm1-m.1.rcp26	11.764	1.583703	1
ipsl-cm5a-lr.2.rcp26	11.44207	1.62325	2
csiro-mk3-6-0.2.rcp26	13.78138	1.802278	3
fio-esm.2.rcp60	10.99234	1.513789	4
cesm1-cam5.1.rcp26	10.81408	1.781489	5
cesm1-cam5.2.rcp26	13.83427	2.026333	6
fgoals-g2.1.rcp45	10.97966	1.956661	7
giss-e2-r.1.rcp45	11.0855	1.313989	8
gfdl-esm2g.1.rcp45	12.63341	2.319458	9
ec-earth.2.rcp45	10.7018	2.114075	10

RECLAMATION
Managing Water in the West

APPENDIX B

West-Wide Climate Risk Assessment

Columbia River Basin

Climate Impact Assessment

Technical Memorandum Water Resources Model

U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Regional Office

March 2016

Mission Statements

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.

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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1 EXECUTIVE SUMMARY

The Columbia River Basin Impact Assessment (Assessment) (under the WaterSMART Basin Study Program West-Wide Climate Risk Assessments) was initiated to establish baseline risks to water supplies and demands in the Bureau of Reclamation (Reclamation) river basins and to establish a foundation for more in-depth analyses and the development of adaptation strategies. The Assesement will provide management with a better understanding of the potential impacts of climate change in the Columbia River Basin. This Technical Memorandum (TM) discusses the water resources modeling performed in support of the Assesement to conduct an analysis of regulated system operations using simulated historical and simulated future climate change streamflow.

A monthly water resources model (WRM) of the Snake River Basin above Brownlee Reservoir was used for this analysis. The WRM includes the Boise River Basin, Payette River Basin, Owyhee River Basin as well as the Snake River Basin from its headwaters at Jackson Lake downstream to Brownlee Reservoir. The WRM has been used in a variety of studies and for multiple purposes by Reclamation. For this analysis, the WRM was used to evaluate potential impacts to regulated system operations due to projected future climate change streamflow.

The WRM distributes flow according to water right legal constraints. The model simulates existing reservoir operating procedures and distributes natural flow and stored water ownership while simultaneously following other system constraints such as minimum flow requirements. A simplified rental pool operation included in the model allows water users to supply to and rent from a common pool of contracted water allowing more junior water users to receive a full supply of water from more senior storage water contracts.

The WRM reservoir targets were adjusted to calibrate to historical system reservoir storage contents. The historical calibration period used in this analysis was from October 1, 1980 through September 30, 2008.

Twenty-one, 30 year ensemble informed Hybrid-Delta (HDe) CMIP5 climate change streamflow scenarios were run through the WRM. The climate change streamflow was projected to increase through the spring and decrease through the summer months. The increased spring inflows allowed reservoirs to refill in a higher number of years but with peak storage occurring earlier through each period due to the earlier and increased spring runoff. Modeled regulated basin outflow increased in the spring across the WRM due to the increased spring runoff and inability of the reservoir to capture the additional flow while also maintaining storage contents below flood control storage targets. Through each future period, the number of years the WRM was unable to regulate streamflow below flood stage targets increased. Irrigation delivery did not significantly decrease from the baseline between the climate change scenarios because most water users have both natural flow and stored water rights. Modeled results indicated that water users were able to rely more heavily on their stored water rights due to the increased spring runoff that consistently refilled storage contracts.

2 INTRODUCTION

2.1 Project Background

Reclamation is taking a leading role in assessing the risks and impacts of climate change to Western U.S. water resources, and in working with stakeholders to identify climate adaptation strategies. Adequate and safe water supplies are fundamental to the health of citizens, strength of the economy, and protection of the environment and ecology in the Western U.S. Global climate change poses a significant challenge to the protection of these resources.

Section 9503 of the SECURE Water Act, Subtitle F of Title IX of P.L. 111-11 (2009) (SWA), authorizes Reclamation to evaluate the risks and impacts of climate change in western river basins and to work with stakeholders to identify climate adaptation strategies. The Columbia River Basin was one of the major Reclamation river basins identified for evaluation in the SWA. The purpose of this Assessment is to generate reconnaissance-level hydrologic data and analysis on the potential effects of climate change in the basin, and how those effects relate to water supply and demand.

2.2 Purpose and Scope

The purpose of this TM is to document the Reservoir Modeling task (Task 4) included in the Assessement scope of work. The purpose of this task was to use the upper Snake River MODSIM WRM to conduct an analysis of regulated system operations using simulated historical and simulated future climate change streamflow generated during the Climate Change Analysis and Hydrologic Modeling task (Task 2) (see *Columbia River Basin Climate Impact Assessment Climate Change Analysis and Hydrologic Modeling Technical Memorandum* (Reclamation 2016)). This TM documents the updates and recalibration of the WRM in addition to providing an analysis of simulated future climate change streamflow as applied to a regulated system.

The scope of work included in the Reservoir Modeling task was to first calibrate, update, and validate the WRM. The updated WRM was then used to simulate future regulated streamflow in the Snake River Basin above Brownlee Reservoir. This was completed for both the simulated historical period (water years 1980 through 2008) and the simulated future periods (water years 2010 through 2039, 2030 through 2059, 2050 through 2079, and 2070 through 2099).

The scope of work also included time to evaluate the calibration, configuration, and control logic of the WRMs to improve the accuracy and validity of the simulations. Significant time was spent on these tasks including: updating water right data in the upper Snake and Boise basins, validating and correcting the WRM operational control logic, and adjusting reservoir targets to improve the simulation of current reservoir operations.

3 Model Development

3.1 Model Description

Reclamation's Modified Flows MODSIM WRM (Reclamation 2010) of the Snake River Basin above Brownlee Reservoir was used as a starting point for this analysis. The WRM was built using MODSIM-DSS (MODSIM)[1], a generalized river basin decision support system and network flow model developed at Colorado State University in the 1970s, and under a joint agreement with Reclamation's Pacific Northwest Regional Office (PNRO) from 1992 through 2009 and 2014 through present. The WRM represents the basin's detailed stream network and all major water management features and activities. Additionally, the WRM handles water rights accounting, via the robust MODSIM solver, to optimally distribute water across the Snake River Basin based on water right priority dates. The WRM and operational logic were configured to simulate system operations at a monthly time step.

The WRM simulates 2010 level surface irrigation diversion with patterns of demand based on hydrologic state as described in the subsequent paragraph, 2010 level groundwater pumping, and current reservoir operational logic applied to historical inflows for water years (WY) 1928 through 2008. No adjustment to this criteria was made for any individual climate change scenario. The intent was to simulate how the system might respond to projected future streamflow given current operational constraints and current level irrigation demands.

[1] http://modsim.engr.colostate.edu/

Monthly irrigation demand and reservoir targets are based on hydrologic state, a reference to the hydrologic year type (i.e., wet, average, or dry). The hydrologic state is determined monthly by the WRM using the observed or projected future runoff volumes summed through September individually for each major subbasin. The hydrologic state can change each month as the *perfect* forecast runoff volume changes. The WRM simulates hydrologic state in this way to attempt to mimic how irrigators and reservoir operators might adjust to changing conditions.

For example, the *perfect* forecast runoff volume in the Snake River Basin above Milner used the observed or projected future natural runoff at the Snake River near Heise, ID (HEII QU) to calculate the *perfect* forecast runoff volumes used by the WRM to determine the hydrologic state in this subbasin. The observed or projected future runoff at this location was summed each month starting in January and ending in June of each year. The January volume is the observed or projected future runoff that occurred from January through September, the February volume is the observed or projected future runoff that occurred from February through September, etc. The *perfect* forecast runoff volume summation process continues for each month through June. The *perfect* forecast runoff volumes from January through June for each year in the modeled period are then input into the WRM. The WRM compares these *perfect* forecast runoff volumes against known wet, average, and dry year runoff volumes to determine the current month's hydrologic state. The WRM calculated and used the hydrologic state to determine the monthly irrigation demand and reservoir targets. Consequently, irrigation demand shifts monthly in response to water supply inputs (i.e., runoff forecasts). If the water supply is very low or very high, demand volume and timing shifts to accommodate the changing conditions. If the water supply is very low, demand might increase in the spring then gradually decline as irrigators' stored water supply declines. If the water supply is very high, demand might decrease in the early spring since demand would likely be satisfied by rain. In turn, demand might increase through the summer assuming reservoirs were likely full from the high runoff and stored water is able to satisfy demand. This concept of hydrologic state will be discussed in further detail in the Results section. In particular, this Techincal Memorandum will address how hydrologic state can alter our conclusions of system irrigation impacts.

Figure 1 provides an overview of the location of the Snake River Basin above Brownlee Reservoir along with the location of the reservoirs and streamflow locations where results are presented in this TM. Table 1 and Table 2 provide a description for each reservoir and streamflow location abbreviation shown in Figure 1. The WRM includes four primary subbasins within the upper Snake River Basin above Brownlee Reservoir (BRN):

- The Snake River Basin above Milner that includes reservoir nodes:
    - JCK, PAL, HEN, ISL, GRS, RIR, BLK, AMF, and, MIN

- The Boise River Basin that includes reservoir nodes:
    - AND, ARK, and LUC
- The Payette River Basin that includes reservoir nodes:
    - PAY, DED, CSC, and EMM
- The Owyhee River Basin that includes reservoir node:
    - OWY

Not all of the reservoirs shown in Figure 1 were modeled or included in the results presented in this TM. Brownlee Reservoir (BRN) was not modeled because it is not a Reclamation managed facility and the releases from this reservoir do not impact Reclamation water delivery obligations in the Snake River Basin above BRN. Milner Dam (MIL) was not modeled due to its smaller capacity, that it does not store or accrue Reclamation storage contract water, and that it essentially acts as a run of the river project used to deliver irrigation water that diverts directly from the reservoir. Although Black Canyon Dam (EMM), Blackfoot Reservoir (BLK), and Owyhee Reservoir (OWY) were modeled, the results are not provided in this TM for brevity since the impacts at these reservoirs were similar to basin-wide impacts.

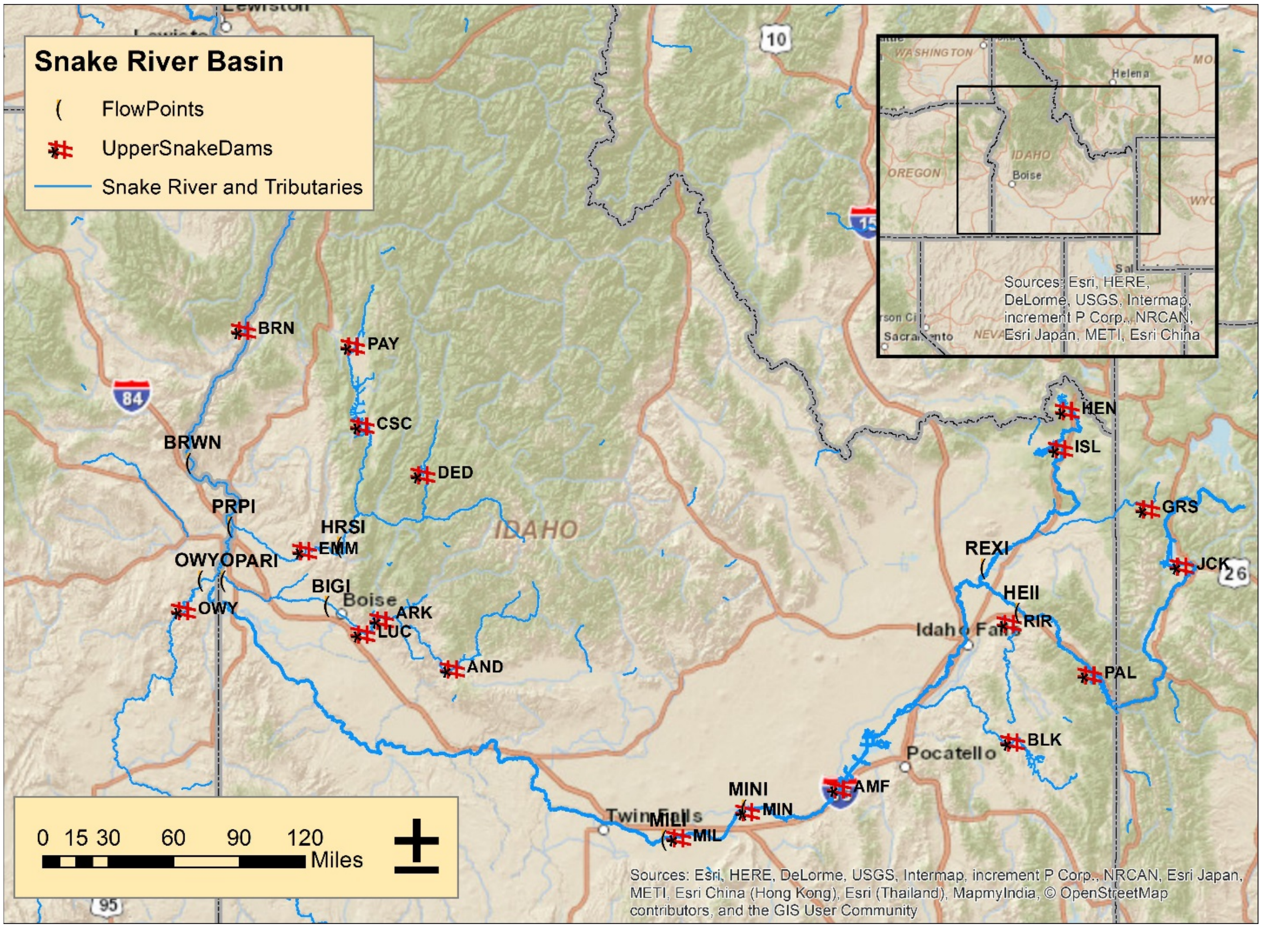


Figure 1: Location of reservoirs in the Snake River Basin above Brownlee Reservoir (BRN) and streamflow presented in this technical memorandum. Reservoir labels have three letter designations and were placed to the right of the point. Streamflow labels have four letter designations and were placed above the point.

Table 1: Reservoir node descriptions.

Reservoir node descriptions	
Snake River above Milner	
JCK	Jackson Lake Dam
PAL	Palisades Reservoir
HEN	Henrys Lake Dam

Reservoir node descriptions	
ISL	Island Park Reservoir
GRS	Grassy Lake Dam
RIR	Ririe Reservoir
BLK	Blackfoot Reservoir
AMF	American Falls Reservoir
MIN	Minidoka Dam
MIL	Milner Dam
Boise River	
AND	Anderson Ranch Dam
ARK	Arrowrock Dam
LUC	Lucky Peak Dam
Payette River	
PAY	Payette Lake Dam
DED	Deadwood Reservoir
CSC	Cascade Dam
EMM	Black Canyon Dam
Owyhee River	
OWY	Owyhee Reservoir

Table 2: Streamflow location descriptions

Streamflow location descriptions	
Snake River	
HEII	Snake River near Heise, ID
REXI	Henrys Fork near Rexburg, ID
MINI	Snake River near Minidoka, ID
MILI	Snake River at Milner, ID
BRWN	Snake River above Brownlee Reservoir
Boise River	
BIGI	Boise River at Glenwood Bridge
PARI	Boise River near Parma, ID
Payette River	
HRSI	Payette River near Horseshoe Bend, ID
PRPI	Payette River near Payette, ID
Owyhee River	
OWYO	Owyhee River at Owyhee, OR

3.2 Model Updates

Several adjustments were made to the existing WRM during this assessment. Natural flow water rights in the Snake River Basin above Milner and the Boise River Basin were updated to current Idaho Department of Water Resources (IDWR) records; this included the validation of over 1000 water rights. Stored water rights and priority refill order were validated against current Reclamation records and operations. The custom code of the WRM that provides basin specific operational control logic that is outside of the default operational control logic of MODSIM was reevaluated and validated to current operational logic. The calculation of flow augmentation was checked against current operational practices. Reservoir targets and hydrologic state forecasts were validated and calibrated. Lastly, the WRM was updated to the latest version of the MODSIM software, version 8.4.4.

3.3 Model Calibration

Significant time was spent adjusting reservoir storage target levels to best match current operational practices where the most current operational practices modeled cover the period October 1, 1980 through September 30, 2008. Although this comparison was made, it should be acknowledged that modeled reservoir contents and flow at certain river gages may not fully match observed historical data. The difference in simulated compared to historical is a result of actual operations not always following a set logical pattern unlike what is required for the WRM to exactly simulate historical conditions.

Time series plots were created showing historical end of month reservoir contents compared to modeled results over the calibration period. The same time series plots were created showing system end of month reservoir contents in the following basins: Snake River Basin above Milner, Boise River Basin, and Payette River Basin.

Table 3 summarizes the computed R-squared or coefficient of determination value for each reservoir's historical versus modeled contents over the calibration period, as well as system historical contents versus system modeled contents. R-squared is a statistical measure of how close the data are to a fitted linear regression line. R-squared is always between 0 and 1, where 0 indicates that the model explains none of the variability of the historical data, and 1 indicates that the model explains all of the variability of the historical data. In general, the higher the R-squared (closer to one), the better the model fits the historical data.

Most reservoirs had R-squared values higher than 0.6 and those at less than 0.6 were mostly due to specific historical operations that the WRM could not replicate. For example, the R-squared at Jackson Lake Dam (JCK) was 0.42; however, this is mostly due to the historical reservoir drawdown from 1984 through 1989 (Figure 2) required by safety of dams modifications. The WRM could replicate these temporary restrictions or requirements, but that is not the intent of a water resource model, so this reduces the R-squared value for some reservoirs and the R-squared value for system reservoir contents.

One of the better calibrated reservoirs was American Falls that had an R-squared value of 0.84. This value was most likely due to its larger size, consistent operational practices, and no formal flood control requirements (Figure 3). One of the least calibrated reservoirs was

Grassy Lake with an R-squared value of 0.01 which was most likely due to its smaller size and the influence of yearly operational criteria that cannot be scripted (Figure 4). R-squared gives a general sense of overall fit of simulated data to observed data, but should not be interpreted as an absolute indication of good or bad performance. While Grassy Lake has an overall low R-squared value as can be seen in Figure 4, the overall dynamics and operations of the reservoir do appear to be captured in most years. Some anomalies in operations for certain years can be seen which may be due to specific historical operations that the model is unable to capture.

An R-squared value was provided in Table 3 for subbasin system reservoir contents simply as an informative measure of how well the model captured overall subbasin operations.

Calibration plots for each reservoir and system reservoir contents can be found in the appendix.

Table 3: Summary of R-squared values for all major modeled reservoirs and system reservoir contents for each major subbasin, System.

Snake above Milner		**Boise**		**Payette**	
Reservoir	**R-squared**	**Reservoir**	**R-squared**	**Reservoir**	**R-squared**
JCK	0.42	AND	0.86	PAY	0.91
PAL	0.61	ARK	0.62	DED	0.71
RIR	0.81	LUC	0.72	CSC	0.53
AMF	0.84	**System**	**0.88**	**System**	**0.72**
MIN	0.68	N/A	N/A	N/A	N/A
HEN	0.39	N/A	N/A	N/A	N/A
ISL	0.69	N/A	N/A	N/A	N/A
GRS	0.01	N/A	N/A	N/A	N/A
System	**0.88**	N/A	N/A	N/A	N/A

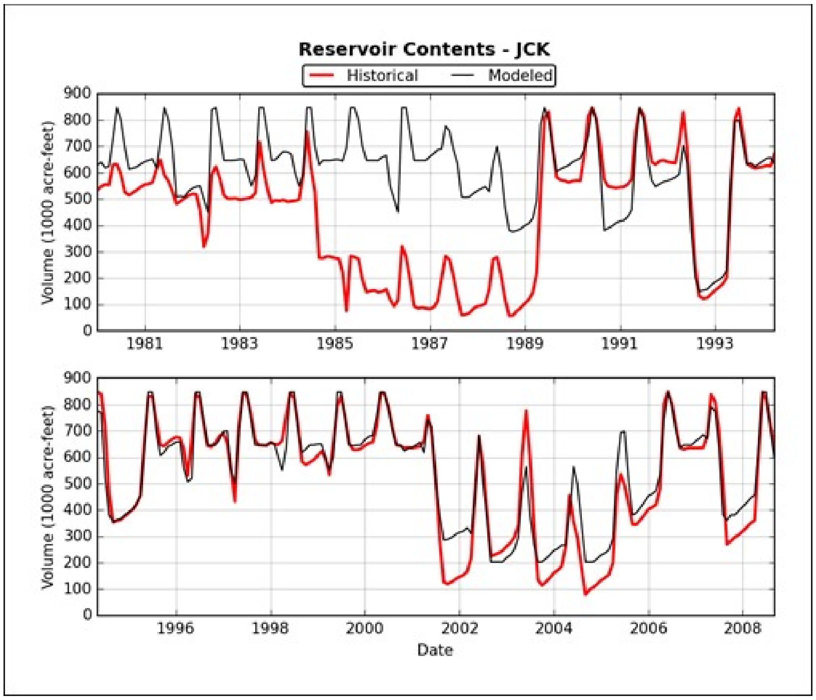


Figure 2: Historical and modeled reservoir contents at Jackson Lake (JCK). This reservoir had an R-squared value of 0.42. The difference seen during the 1984 through 1989 period was due to historical forced drawdown requirements for safety of dams modifications.

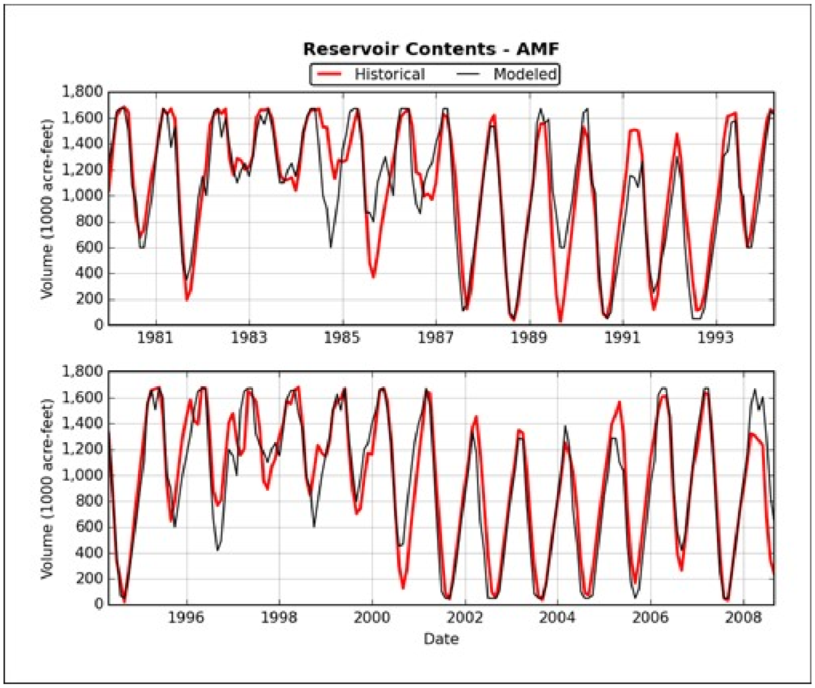


Figure 3: Historical and modeled reservoir contents at American Falls Reservoir (AMF). This reservoir was one of the best calibrated with an R-squared value of 0.84.

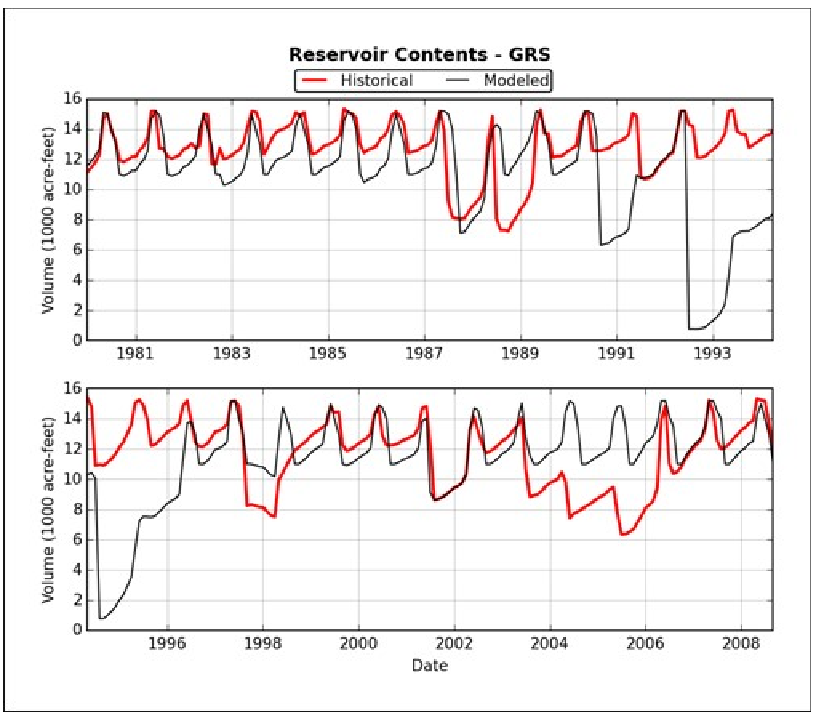


Figure 4: Historical and modeled reservoir contents at Grassy Lake (GRS). This reservoir was one of the worst calibrated with an R-squared value of 0.01.

4 CLIMATE CHANGE SCENARIO INPUTS

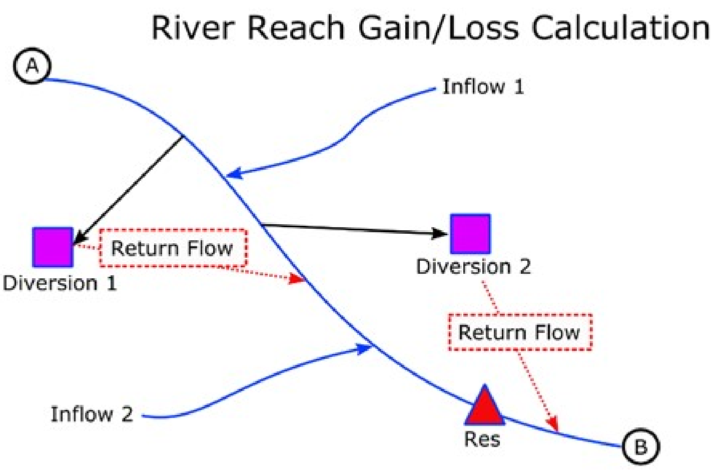
As discussed in the *Columbia River Basin Climate Impact Assessment Climate Change Analysis and Hydrologic Modeling Technical Memorandum* (Reclamation 2016), the Variable Infiltration Capacity (VIC) Macroscale Hydrologic Model was used to generate the projected future natural streamflow inputs for the WRM. Also mentioned was that ensemble informed Hybrid-Delta datasets were generated for four future periods from 2010 through 2039, 2030 through 2059, 2050 through 2079, and 2070 through 2099. These 30-year periods are referred to as being “centered around” the 2020s, 2040s, 2060s, and 2080s respectively. Five scenarios of future temperature and precipitation conditions were selected to characterize the future climate to be evaluated in each 30-year period. The five scenarios include:

- Less Warming Wetter (LW/W) – an ensemble of 10 future projections around the 20^{th} percentile of temperature and 80^{th} percentile of precipitation;
- Less Warming Drier (LW/D) – an ensemble of 10 future projections around the 20^{th} percentile of temperature and 20^{th} percentile of precipitation;
- Median (M) – an ensemble of 10 future projections around the 50^{th} percentile of temperature and 50^{th} percentile of precipitation;
- More Warming Wetter (MW/W) – an ensemble of 10 future projections around the 80^{th} percentile of temperature and 80^{th} percentile of precipitation; and,
- More Warming Drier (MW/D) – an ensemble of 10 future projections around the 80^{th} percentile of temperature and 20^{th} percentile of precipitation.

All climate change simulations are compared against a Baseline simulation. The Baseline simulation is a WRM simulation that used streamflow from a VIC simulation using simulated historical inputs of precipitation and temperature (Livneh et al. 2013). The Baseline simulation represents a regulated WRM simulation using a simulated historical water supply from VIC.

Water supply (streamflow) was the only input data needed from each climate change scenario. This is because the WRM operates in *perfect* forecast mode where the actual runoff defines the hydrologic state that determines the patterns for irrigation demand and reservoir storage targets (see Section 3.1 Model Description). To use the simulated future climate change streamflow (water supply) in the WRM the streamflow needed to be divided into reach gains or losses, and the *perfect* forecast runoff volume calculated based on the projected future streamflow at key locations.

A reach gain or loss is simply the water supply between two points in the river, where two points in the river are used to define a "reach". In a reach with known or measured inflows, diversions, and a reservoir, the reach gain or loss would be calculated using the equation shown in Figure 5.



$$\text{Reach AB gain or loss} = \text{Flow B} - \text{Flow A} - \Sigma\,\text{Inflow} + \Sigma\,\text{Diversions} - \Sigma\,\text{Diversion Return Flow} + \Delta\,\text{Res Storage} + \text{Res Evaporation}$$

Figure 5: Calculation of a reach gain or loss where diversions and a reservoir are present within a reach.

The simulated future climate change streamflow represents natural system flows where there are no reservoirs or diversions. In this case, the equation in Figure 5 simplifies to:

$$Reach\ AB\ gain\ or\ loss = Flow\ B - Flow\ A - \Sigma\, Inflow$$

This process of calculating reach gains or losses was completed for each reach included in the WRM using the simulated future climate change streamflow from each scenario. These results were input to the WRM as the new water supply.

The *perfect* forecast runoff volumes were calculated for each climate change scenario at the Snake River near Heise, the Boise River near Lucky Peak Lake, and the Payette River near Horseshoe Bend. The forecast calculated at each location was then used by the WRM to determine the hydrologic state independently for each subbasin: Snake River Basin above Milner, Boise River Basin, and the Payette River Basin. See Section 3.1 Model Description for a complete description of the *perfect* forecast runoff volume calculation.

5 RESULTS

5.1 Snake River Basin above Milner

5.1.1 System Inflow

For the Snake River Basin above Milner, all future periods inflows were projected to increase in the spring and decrease through the summer. Increases in spring inflow occur earlier through each period with peak inflow occurring in May for all periods and for all scenarios with sharp declines in June for the MW/D and MW/W scenarios beginning in the 2060 period. Median inflows were less than the Baseline for all periods and for all scenarios during the months of July, August, and September (Figure 6).

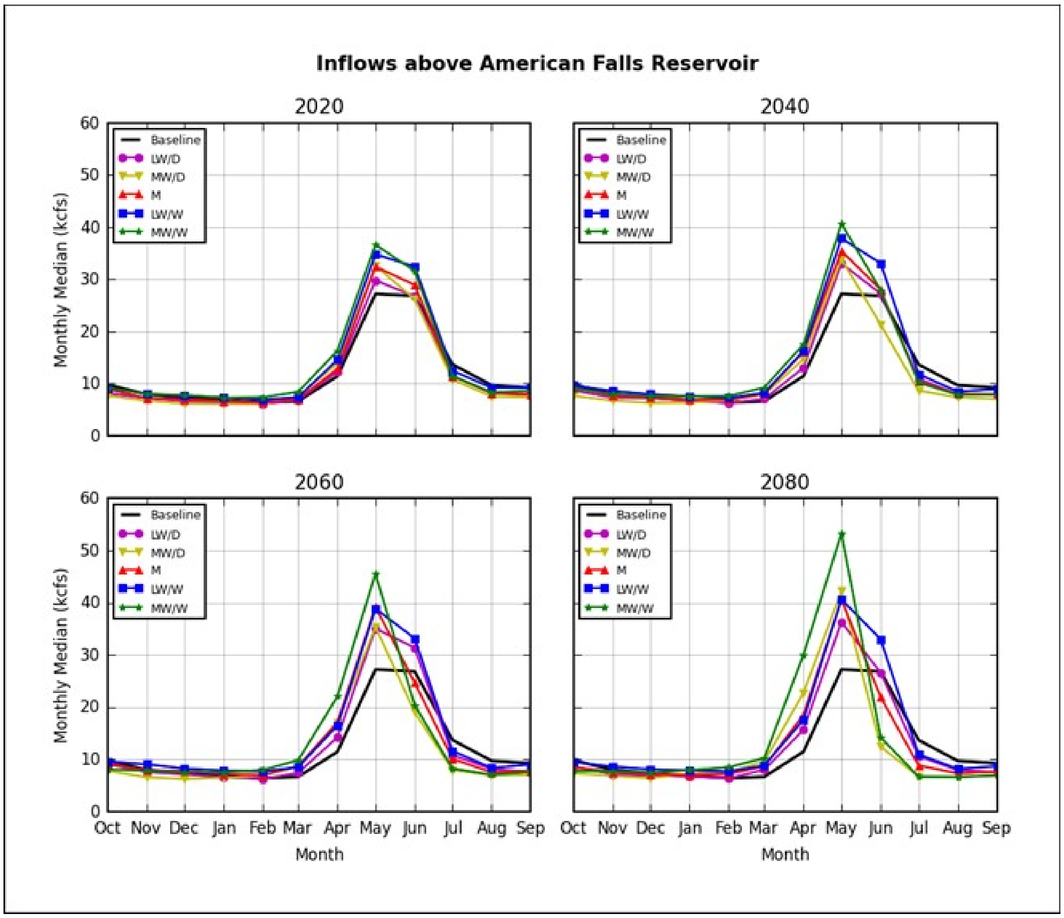


Figure 6: Monthly median unregulated inflow above American Falls Reservoir. Inflows were projected to increase through the spring and decrease through the summer.

5.1.2 System Reservoir Contents

System reservoir contents in the Snake River Basin above Milner included the reservoirs JCK, PAL, RIR, AMF, MIN, HEN, ISL, and GRS. See Figure 1 for the location of each reservoir and Table 1 for a description of the abbreviated names.

Table 4 provides a summary of the number of years the modeled reservoir system contents were greater than or equal to 4,000,000 acre-feet or the system essentially reached maximum contents. Through each period, and essentially from the drier to the wetter scenarios, the number of years the reservoir system contents were essentially at maximum contents increased across the Snake River Basin above Milner (Table 4).

Table 4: Number of years in the 30-year modeled period when the maximum reservoir system contents were greater than or equal to 4,000,000 acre-feet (maximum capacity) in the Snake River Basin above Milner.

	Baseline (years)	LW/D (years)	MW/D (years)	Median (years)	LW/W (years)	MW/W (years)
2020	18	18	18	19	25	26
2040	18	19	19	25	27	27
2060	18	20	21	26	25	28
2080	18	25	24	27	27	27

Due to the increased and earlier spring runoff (Figure 6), modeled system reservoir contents refill in a higher number of years (Table 4). These results are in spite of reduced carryover storage levels which occurred 50 percent of the time as seen in the end of October contents shown in Figure 7. Outside of the spring refill months, system reservoir contents are lower than the Baseline for nearly every scenario and every period. This is due to the reduced natural streamflow in July, August, and September that decrease the amount of irrigation water available for natural flow water rights (Figure 6). This increases irrigators dependency on stored water contracts to satisfy irrigation requests which, in turn, reduces median storage carryover levels.

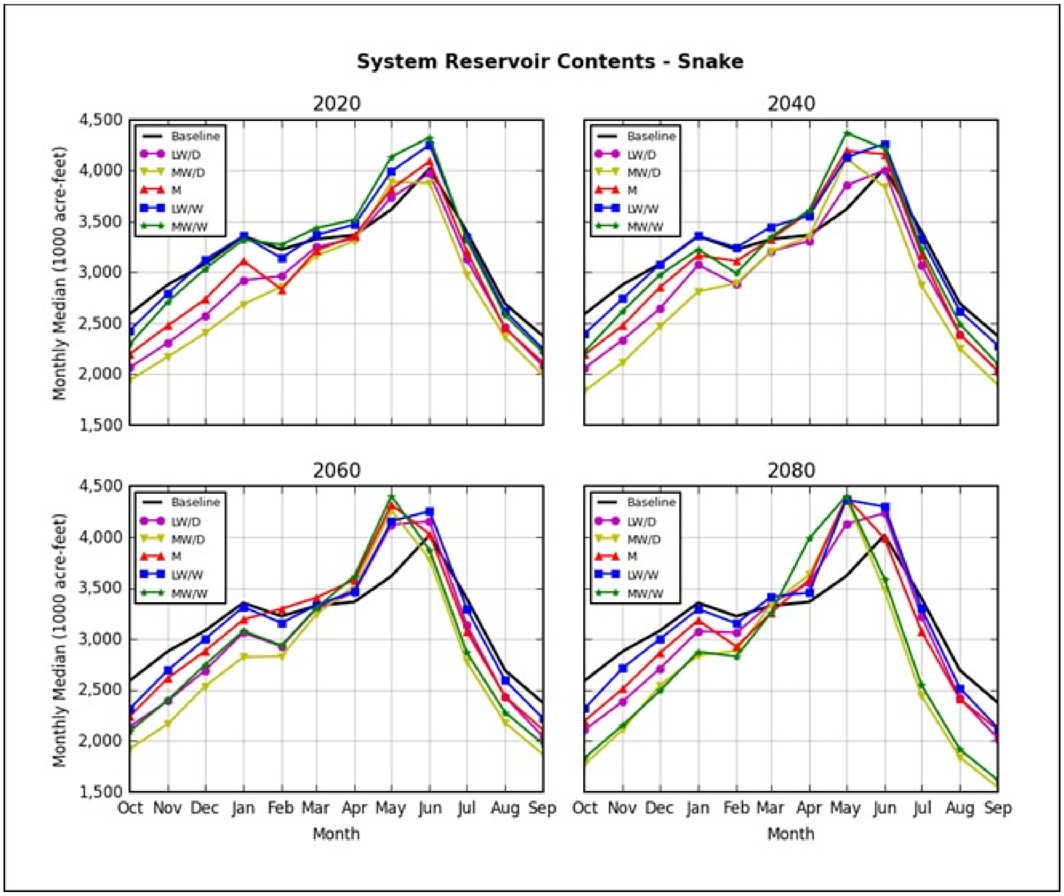


Figure 7: Monthly median system storage contents in the Snake River Basin above Milner for five simulated future climate change scenarios in four future periods: 2020s, 2040s, 2060s, and 2080s.

5.1.3 Regulated Flow

For the Snake River Basin above Milner, modeled regulated future streamflow increased in the spring months of March through May. This occurred because of the increased and earlier spring runoff (Figure 6) and because reservoirs reached maximum capacity or were constrained by flood control refill targets (Figure 7). As natural system inflows declined through the summer months, so did regulated streamflow, although not by the same amount due to the increased stored water released to satisfy irrigation demand (Figure 15).

Through each period, and essentially from drier to wetter scenarios, the number of years that flood stage targets are exceeded is projected to increase across the Snake River Basin above Milner (Table 5, Table 6, and Table 7).

Table 5: Number of years in the 30-year modeled period when regulated flows on the Snake River at Heise (HEII) were greater than a flood stage flow of 20,000 cubic feet per second (cfs).

	Baseline	LW/D	MW/D	Median	LW/W	MW/W
2020	3	2	4	5	7	7
2040	3	4	4	8	8	11
2060	3	6	7	10	8	13
2080	3	8	8	12	11	19

Table 6: Number of years in the 30-year modeled period when modeled regulated flows on the Henrys Fork at Rexburg (REXI) were greater than a flood stage flow of 12,000 cfs.

	Baseline	LW/D	MW/D	Median	LW/W	MW/W
2020	0	1	2	2	2	3
2040	0	1	3	4	4	5
2060	0	3	3	4	4	9
2080	0	4	9	7	5	12

Table 7: Number of years in the 30-year modeled period when modeled regulated flows on the Snake River below Minidoka Dam (MINI) were greater than a flood stage flow of 20,000 cfs.

	Baseline	LW/D	MW/D	Median	LW/W	MW/W
2020	4	5	4	6	9	11
2040	4	5	6	11	13	16
2060	4	9	11	15	12	20
2080	4	11	18	15	16	21

Fifty percent of the time (monthly median), regulated flows were above flood stage levels in May for the MW/W scenario in the 2060 and 2080 periods on the Snake River at Heise, ID (HEII) (Figure 8). Following the upper Snake River Basin flood control rule curves, the WRM were designed to limit flow at HEII to 20,000 cfs (the official flood stage at HEII is 24,500 cfs according to the National Weather Service). In May system reservoir contents were at their maximum levels and unable to provide any additional flood protection (Figure 7).

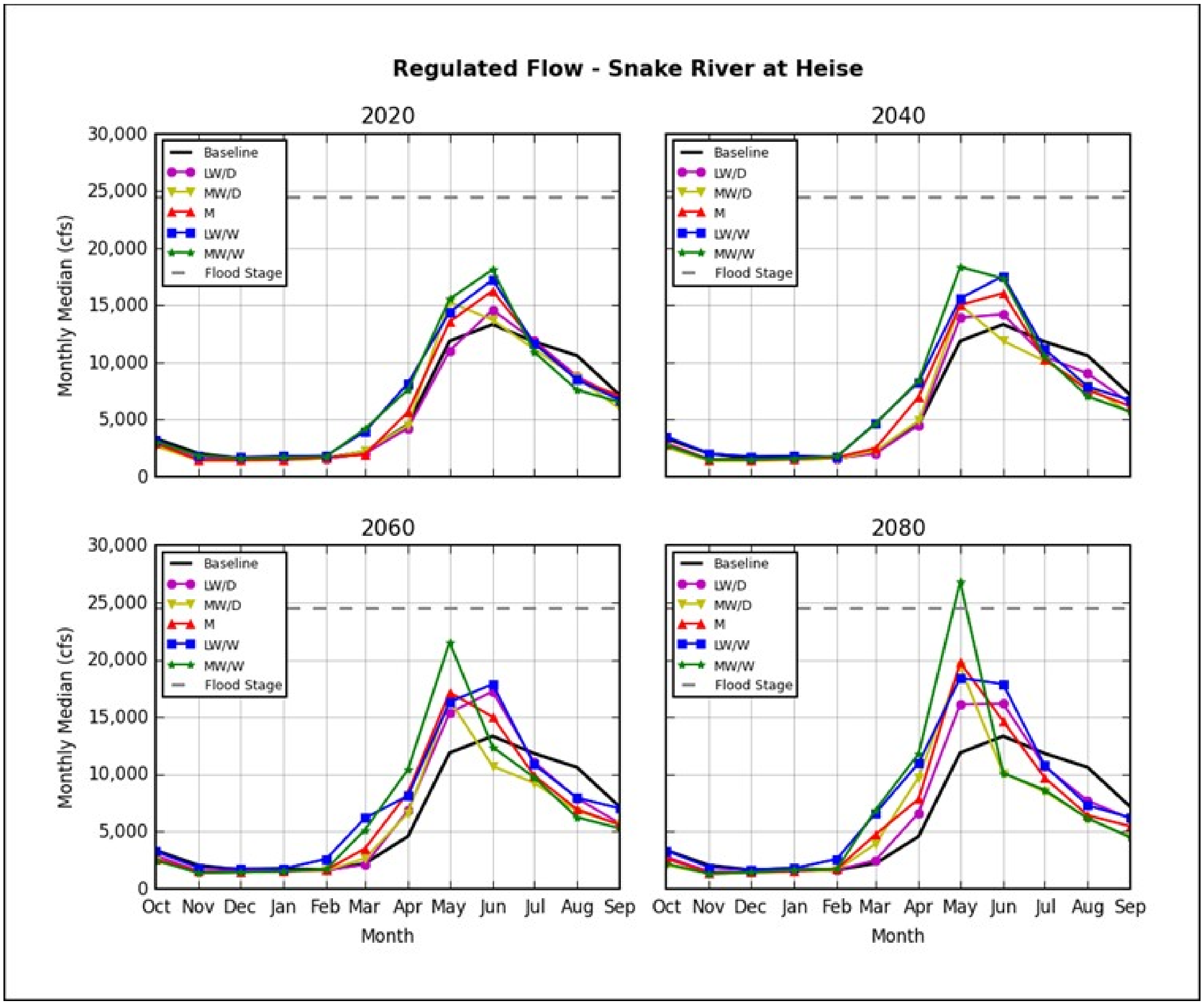


Figure 8: Monthly median regulated flow on the Snake River at Heise, ID.

As shown in Figure 9, fifty percent of the time (monthly median), regulated flows were below flood stage levels on the Henrys Fork at Rexburg, ID (REXI). Although the official flood stage at REXI is 7,800 cfs, most flooding is initially limited to lowland pastures and small amounts of cropland. As flows approach 12,000 cfs it is estimated that some infrastructure damage begins. As such, the WRM was built to attempt to constrain flows to not exceed 12,000 cfs.

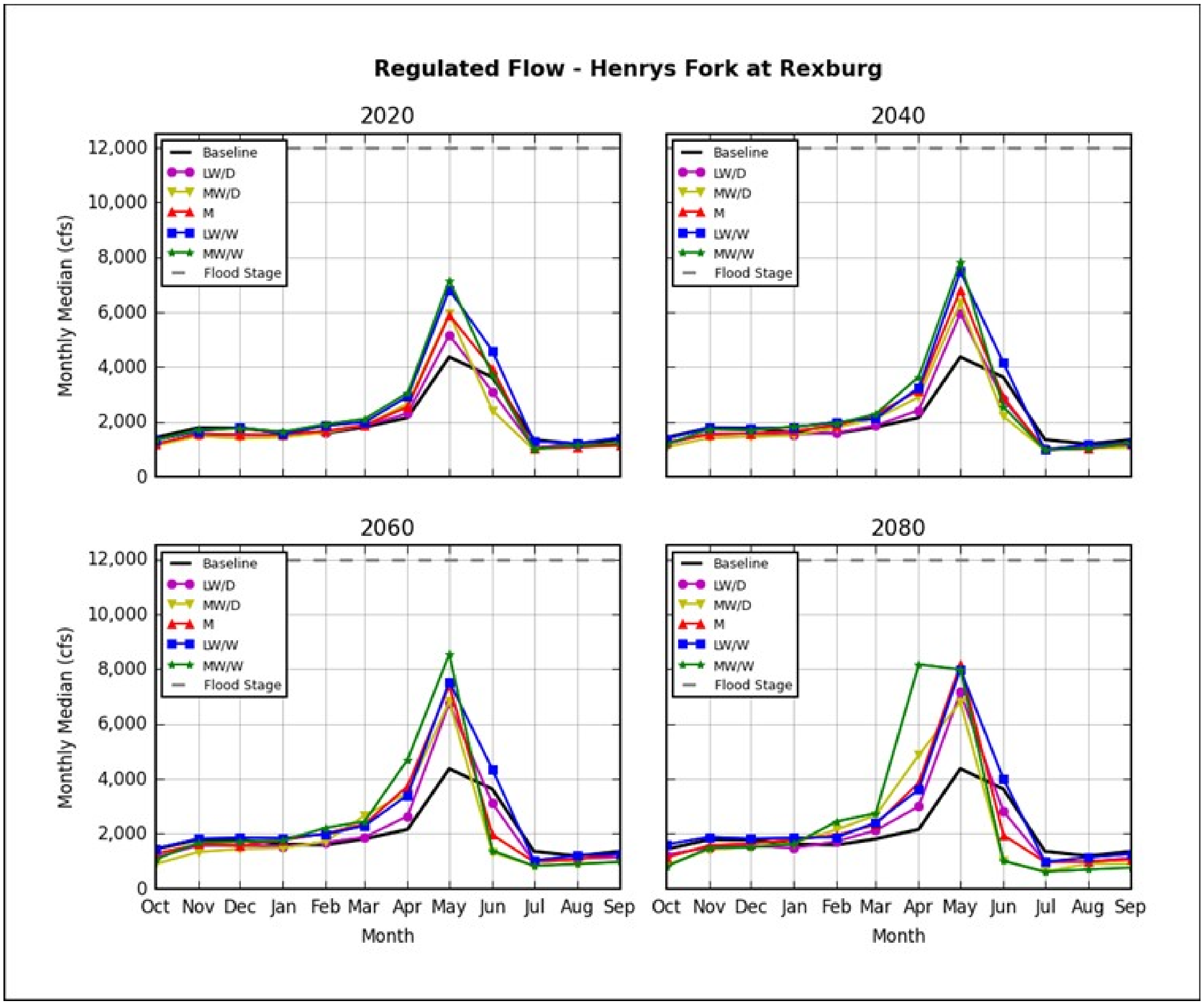


Figure 9: Monthly median regulated flow on the Henrys Fork at Rexburg, ID.

Fifty percent of the time (monthly median), regulated flows were above flood stage levels in May on the Snake River below Minidoka Dam, ID (MINI) (Figure 10). American Falls Reservoir is generally operated with the goal of limiting the discharge from Minidoka Dam to 20,000 cfs which was the modeled constraint.

As shown in Figure 10, 50 percent of the time flood stage levels were exceeded starting in the 2060 period in May for the MW/W scenario with flood stage levels exceeded for the MW/W and MW/D scenario in the 2080 period in May. In May system reservoir contents were at their maximum levels and unable to provide any additional flood protection (Figure 7).

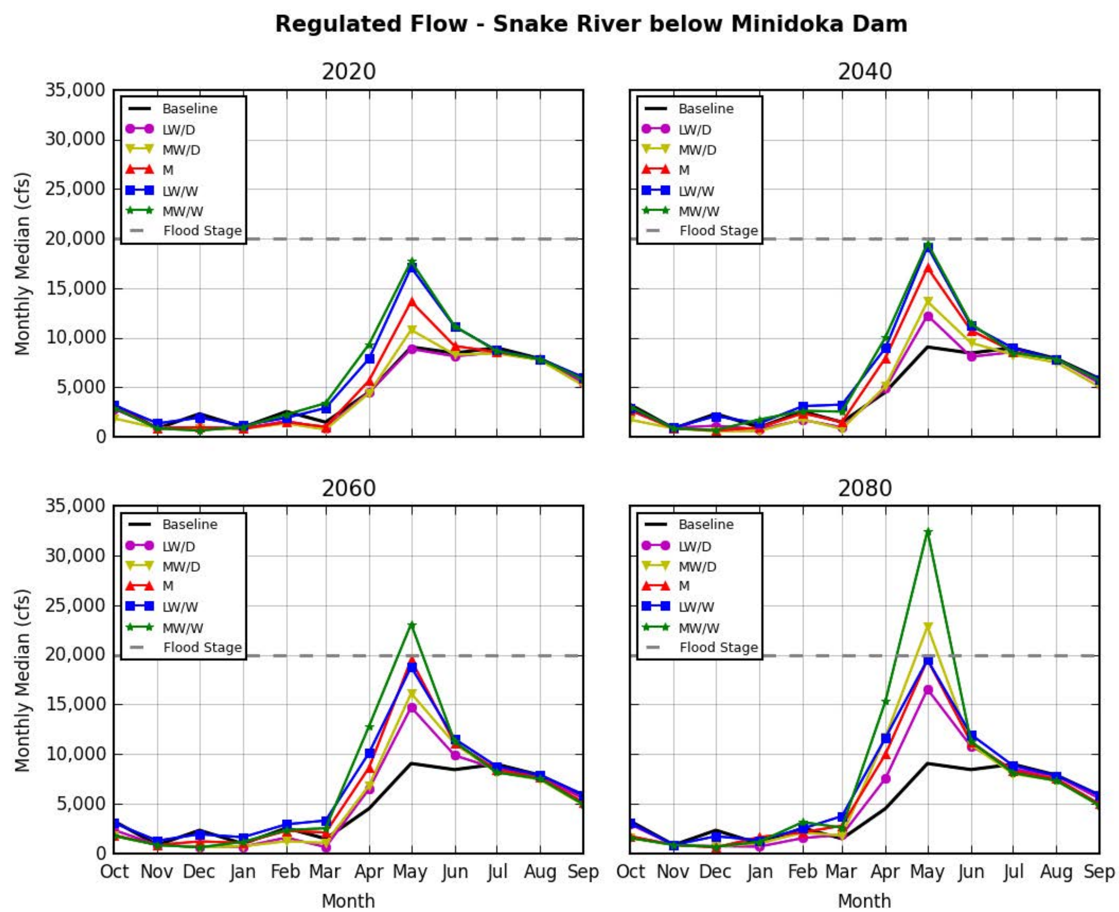


Figure 10: Monthly median regulated flow on the Snake River below Minidoka Dam, ID.

The same patterns of increased spring regulated flows are seen at Brownlee Reservoir (Figure 11), although with peak flow shifting towards April rather than May, due to regulated flows from the Boise River Basin and the Payette River Basin, and any unregulated tributary flows between Minidoka Dam and Brownlee Reservoir. Regulated flow in March, April, and May begins to rather significantly increase as early as the 2020 period for the LW/W and MW/W scenarios with April flows nearly doubling for all scenarios except for the Median and LW/D scenarios in the 2080 period. These are the median or 50 percent exceedance flows, so even higher flows would be seen in wet years.

It should be noted that no flood stage constraints were modeled from Milner Dam to Brownlee Reservoir because there is no formal flood stage requirement through this section of the Snake River. In addition, there is no downstream capacity to further regulate flows to Brownlee Reservoir. If regulated flows below Minidoka Dam are greater than flood stage, this means there is no further upstream capacity to control downstream flooding. Flood risk vulnerability was assumed to be minimal below Milner Dam.

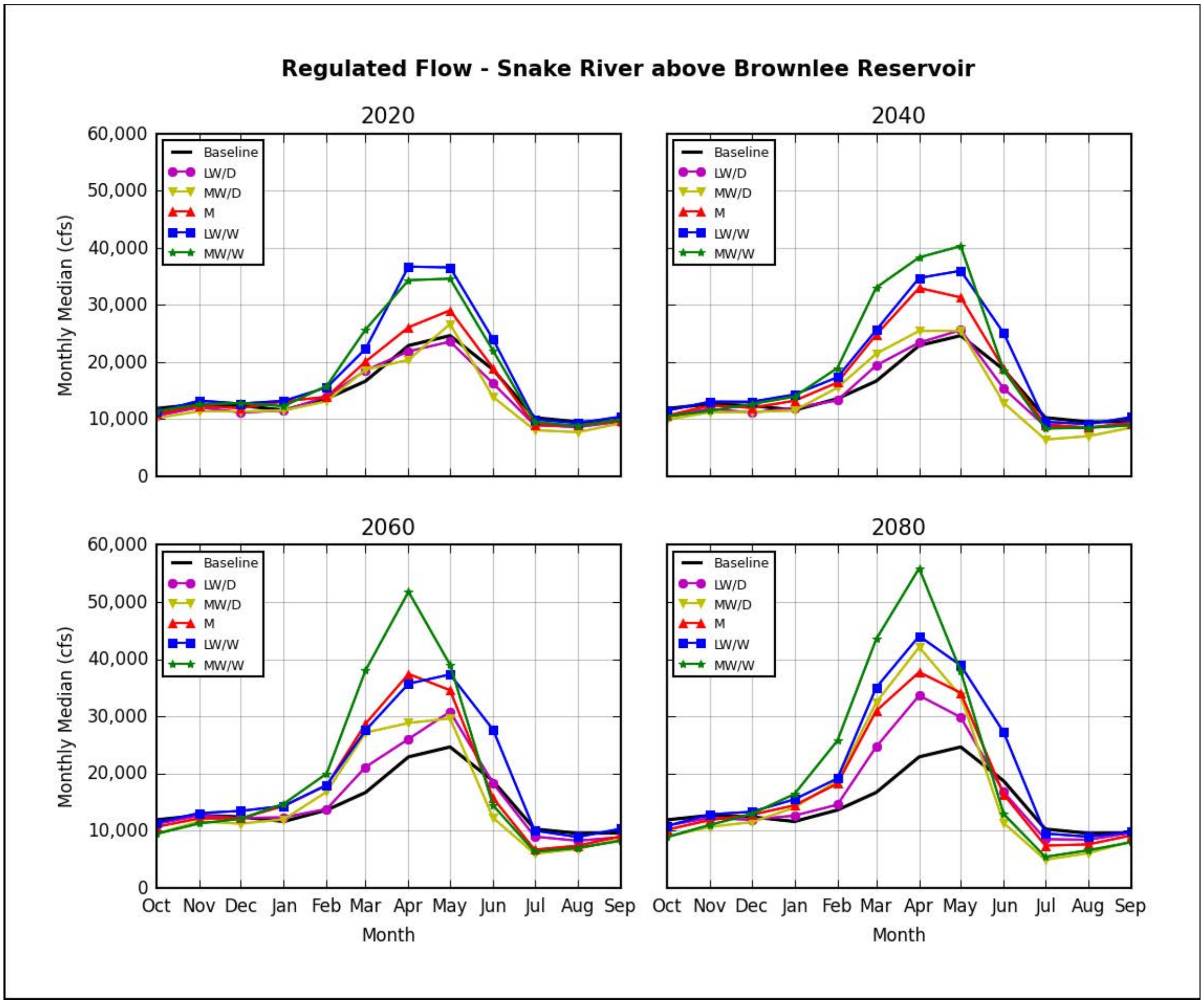


Figure 11: Monthly median regulated flow on the Snake River above Brownlee Reservoir, ID.

5.1.4 Requested Water

Water requests in the upper Snake River Basin above Milner remained similar in nearly every scenario and every period (Figure 12). Shifts in requested water are due to shifts in hydrologic state or a representation of how water users might adjust to changing climate conditions.

Figure 13 shows the projected system shortages to requests for water. Although rather significant shortage was seen in the Baseline simulation, this could have occurred for a few different reasons including:

- the modeled requested water was based on yearly patterns of average historical diversion rather than the historical timeseries

- the model implemented a simplified rental pool that does not fully capture actual rental pool exchanges
- the model does not implement private leases between irrigators
- the Baseline water supply is based on simulated historical conditions from the VIC model

While these shortages could be further investigated, what is important is the difference from the Baseline for each climate change scenario or each projected future water supply. Most shortage is seen in July and August when requests for irrigation water are high and natural flow is declining. Peak system shortage occurs in the 2080 period in July and August at approximately 150,000 acre-feet. Shortages of 50,000 acre-feet are seen as early as the 2020 period for the MW/D and LW/D scenarios.

One water user object or node in the WRM was chosen as a representative basin water user to present the impact of climate change on water rights. In the Snake River Basin above Milner this node is labeled, Northside, and represents a water user with more significant water requests as well as a water user with both natural flow water rights and stored water rights that can be used to satisfy requests. Through most periods and scenarios irrigation delivery to this representative node was satisfied less by natural flow water rights and increasingly through stored water contracts (Figure 14 and Figure 15). This occurs simply because all scenarios show natural flow water declines in July, August, and September (Figure 6). For irrigators with minimal stored water right contracts, it is expected that a moderate to significant water shortage would occur. However, most demands in the upper Snake River Basin have both natural flow and stored water contracts so a portion of the natural flow water right shortages are offset by stored water delivery.

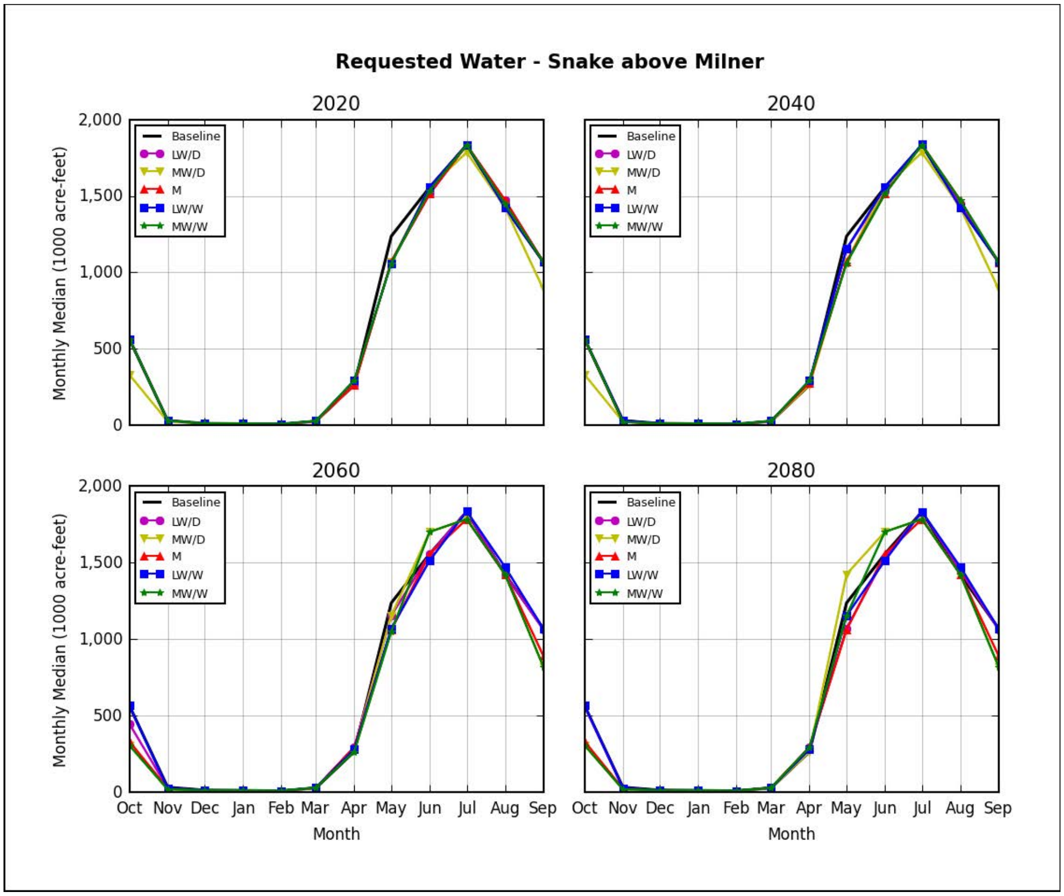


Figure 12: Monthly median of requested water in the Snake River Basin above Milner for five simulated future climate change scenarios in four future periods 2020s, 2040s, 2060s, and 2080s.

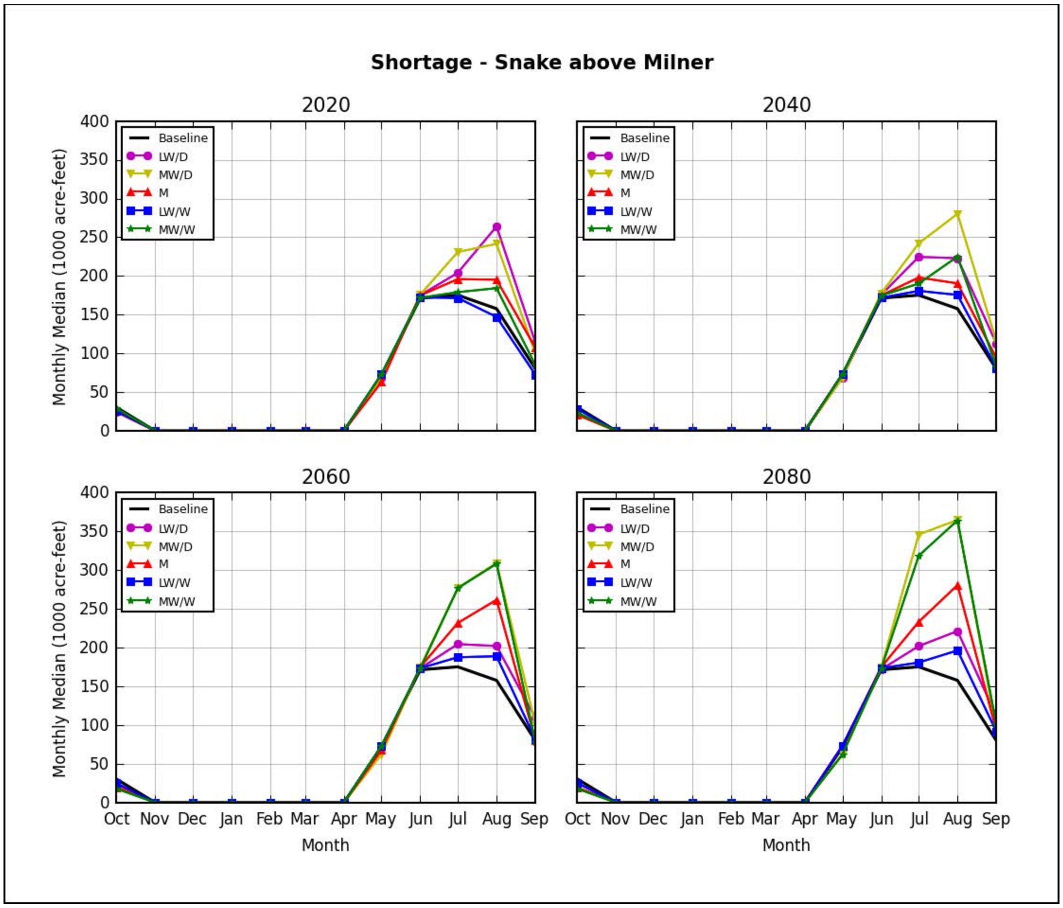


Figure 13: Monthly median of system requested water shortage in the Snake River Basin above Milner for five simulated future climate change scenarios in four future periods 2020s, 2040s, 2060s, and 2080s.

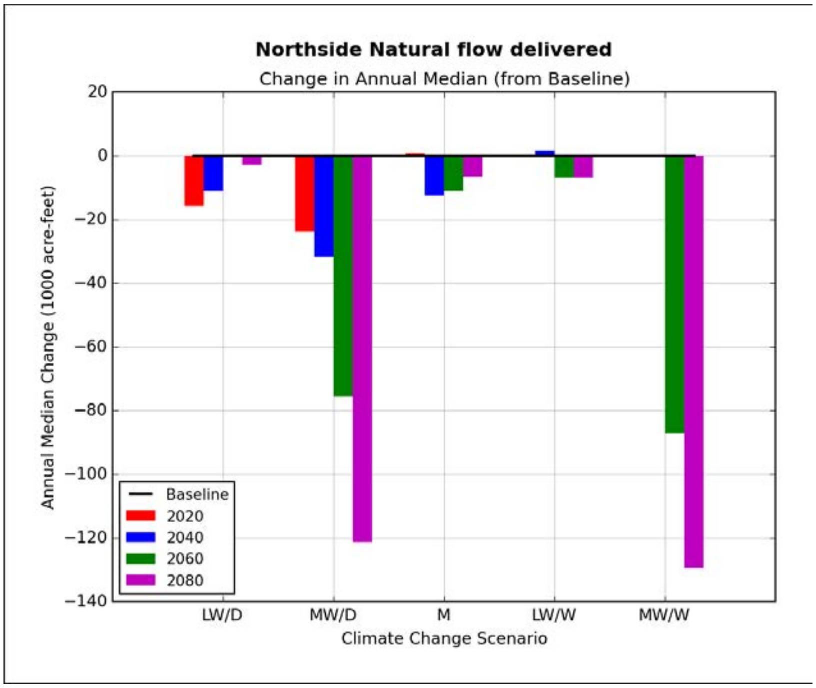


Figure 14: Annual median change in natural flow water delivery to the Northside modeled water user.

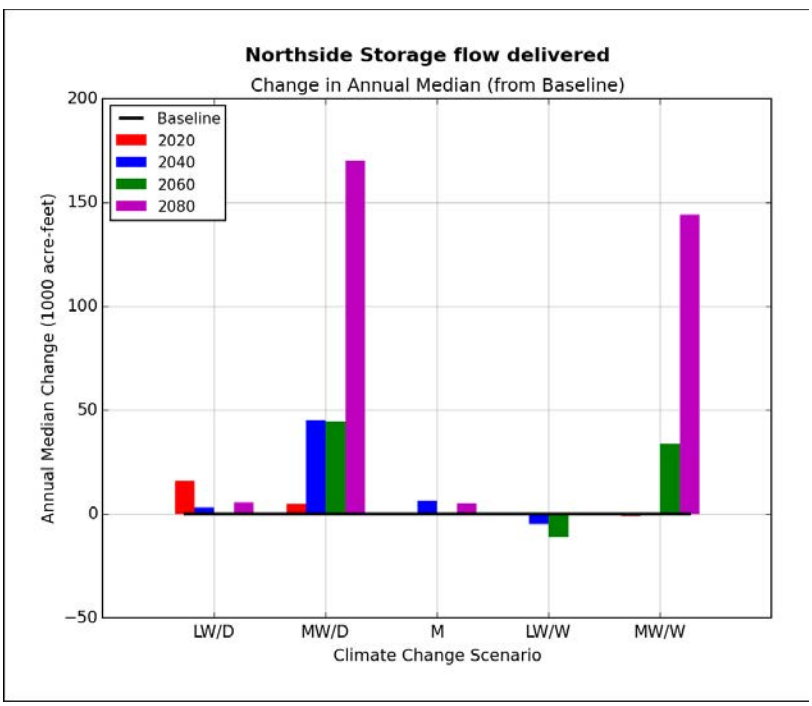


Figure 15: Annual median change in stored water delivery to the Northside modeled water user.

5.2 Boise River Basin

5.2.1 System Inflow

For all future periods in the Boise River Basin, inflows are projected to increase in the spring and decrease through the summer (Figure 16). Spring increases occur earlier through each period with peak runoff shifting from May to April by the 2080 period for all scenarios. As early as the 2040 period for the MW/W scenario and by the 2080 period for all but the LW/D scenario peak, flow increased from 7,000 cfs to over 10,000 cfs in April. Except for the LW/W scenario in the 2020 period, median inflows were less than the Baseline in the months of June, July, August, and September.

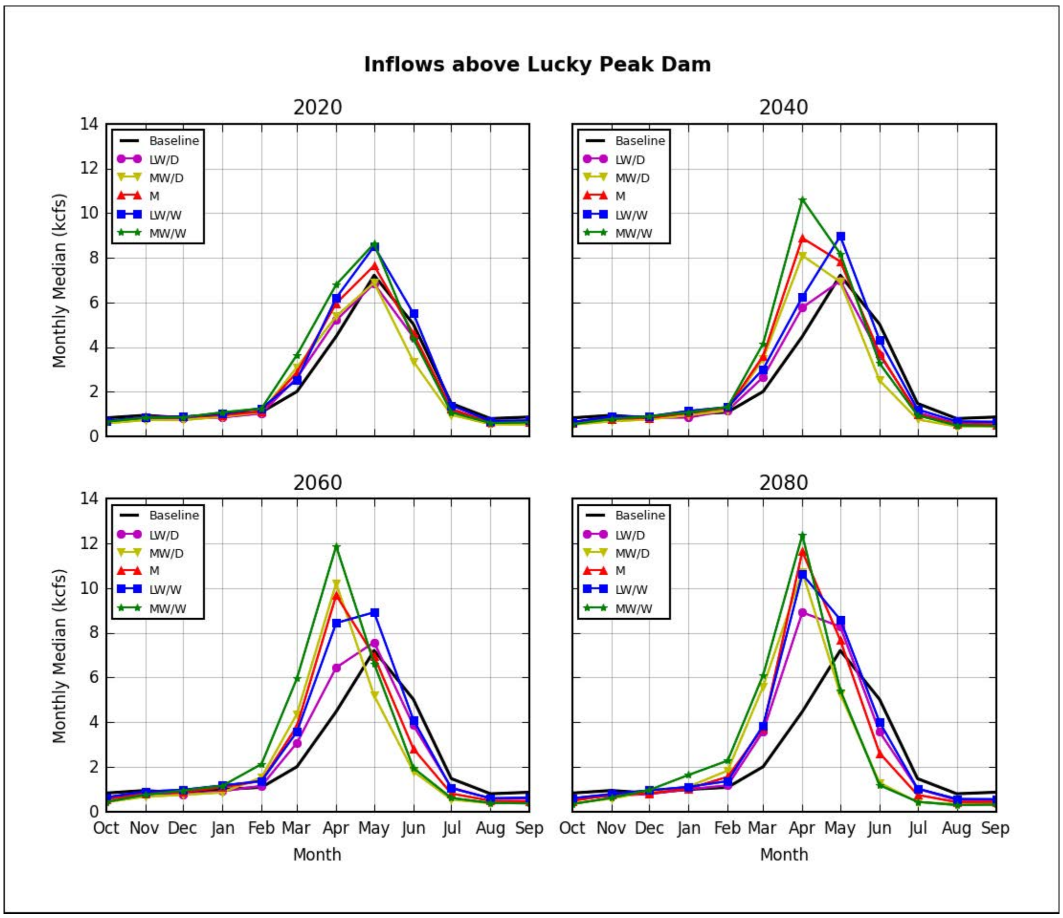


Figure 16: Monthly median unregulated inflow above Lucky Peak Dam.

5.2.2 System Reservoir Contents

System reservoir contents in the Boise River Basin included the reservoirs AND, ARK, and LUC. See Figure 1 for the location of each reservoir and Table 1 for a description of the abbreviated names.

Table 8 provides a summary of the number of years the modeled reservoir system contents were greater than or equal to 900,000 acre-feet or the system essentially reached maximum contents. Through each period, and essentially from the drier to the wetter scenarios, the number of years the reservoir system contents were essentially at maximum contents increased across the Boise River Basin (Table 8).

Table 8: Number of years in the 30-year modeled period when the maximum reservoir system contents were greater than or equal to 900,000 acre-feet (maximum capacity) in the Boise River Basin.

	Baseline	LW/D	MW/D	Median	LW/W	MW/W
2020	19	18	19	20	23	22
2040	19	18	19	21	22	24
2060	19	20	20	22	24	24
2080	19	22	21	22	27	22

Due to increased and earlier spring runoff (Figure 16) system reservoir contents continue to refill 50 percent of the time despite reduced carryover storage levels (end of October contents, Figure 17). Outside of the spring refill months system reservoir contents are generally lower than Baseline conditions due to an increasing dependency on stored water to satisfy requested water that was not satisfied by natural flow deliveries, as shown in the Settlers example below (Figure 22 and Figure 23).

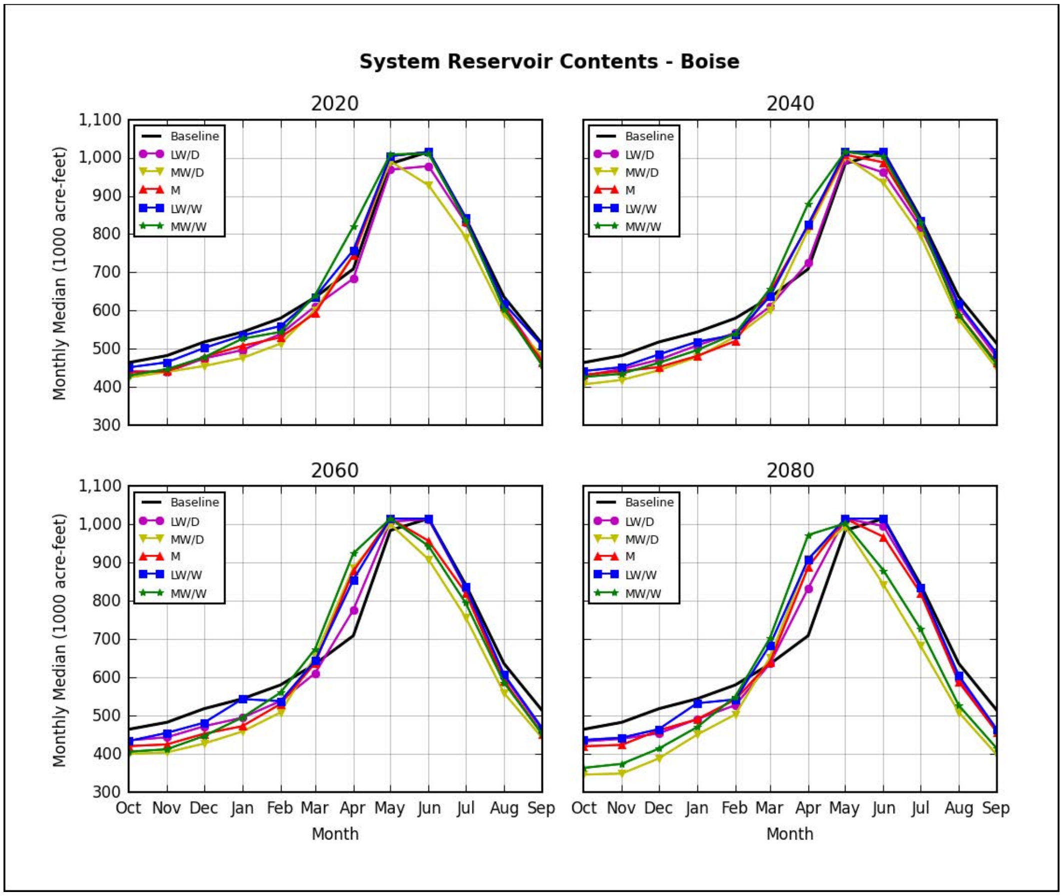


Figure 17: Monthly median of system storage contents in the Boise River Basin for five simulated future climate change scenarios in four future periods 2020s, 2040s, 2060s, and 2080s.

5.2.3 Regulated Flow

For the Boise River Basin, modeled regulated future streamflow increased in the spring months under most climate change scenarios from March through May due to the increased and earlier spring runoff (Figure 16) and reservoirs reaching maximum capacity or being constrained by flood control fill targets (Figure 17). As natural system inflows declined through the summer months so did regulated streamflow, although not by the same amount due to the increased stored water released to satisfy demand (Figure 23).

Through each period, and essentially from drier to wetter scenarios, the number of years that flood stage targets are exceeded is projected to increase across the Boise River Basin (Table 9 and Table 10). This is considered a major impact as development increasingly encroaches upon the Boise River flood plain adding to flood risk and flood management needs.

Table 9: Number of years in the 30-year modeled period when modeled regulated flows on the Boise River at the Glenwood Bridge, ID (BIGI) were greater than a flood stage flow of 7,000 cfs.

	Baseline	LW/D	MW/D	Median	LW/W	MW/W
2020	3	2	2	5	9	7
2040	3	5	4	7	10	11
2060	3	7	7	8	8	12
2080	3	9	9	10	11	15

Table 10: Number of years in the 30-year modeled period when modeled regulated flows on the Boise River near Parma, ID (PARI) were greater than a flood stage flow of 7,000 cfs.

	Baseline	LW/D	MW/D	Median	LW/W	MW/W
2020	3	4	5	7	10	10
2040	3	7	7	9	11	12
2060	3	10	12	10	12	16
2080	3	12	11	13	15	19

Fifty percent of the time (monthly median) regulated flows were below flood stage levels in any period or scenario on the Boise River at the Glenwood Bridge, ID (BIGI) (Figure 18). In the Boise River Basin, flood control rule curves were designed to limit flow at BIGI to 6,500 cfs; however, the historical operational maximum followed has been 7,000 cfs which was the modeled constraint. The MW/W scenario reached almost exactly 7,000 cfs in the 2060 and 2080 periods and the LW/W scenario reached nearly 7,000 cfs in the 2080 period. This indicates that under wetter years flood stage levels would be exceeded at this location as shown in Table 9.

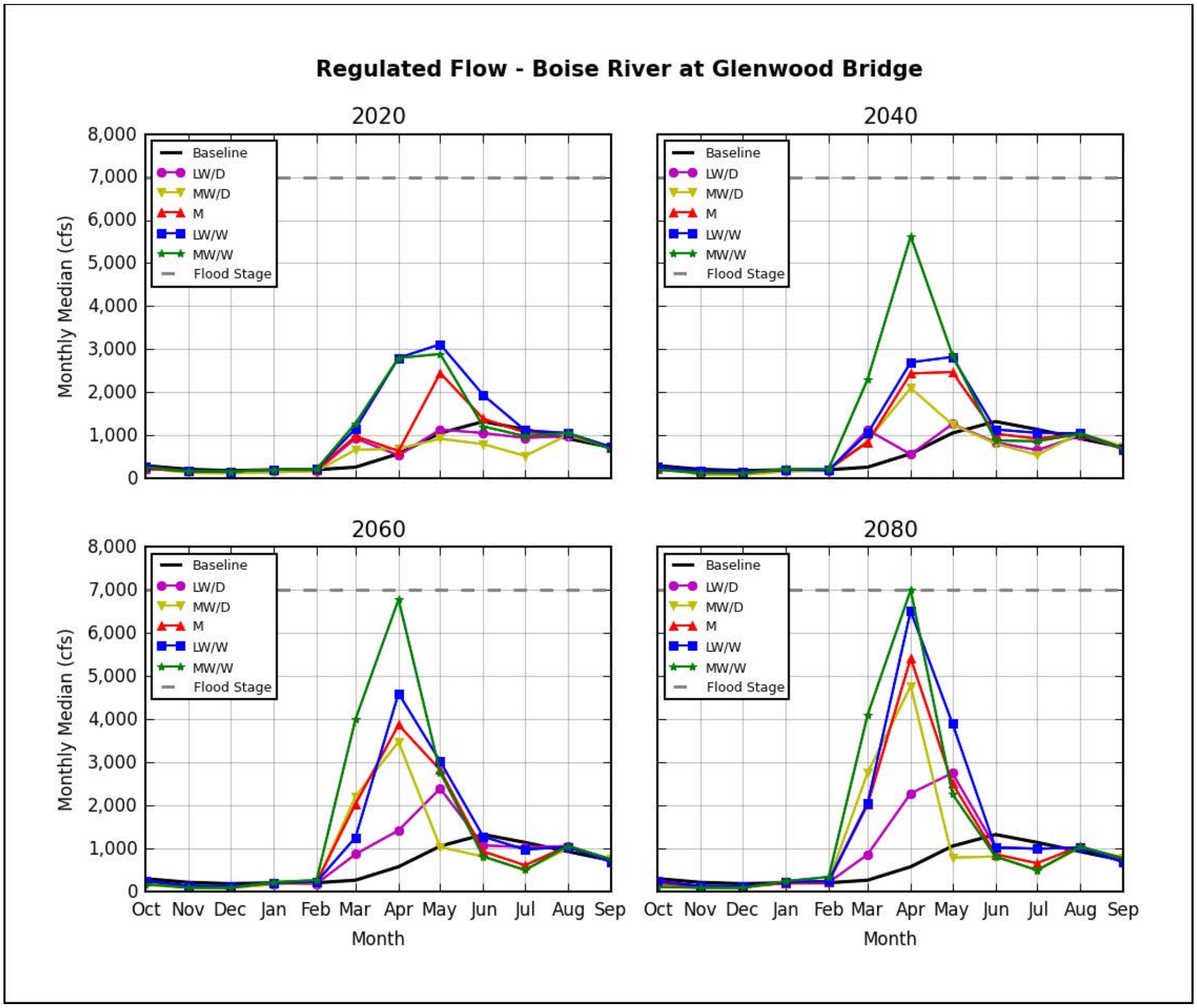


Figure 18: Monthly median regulated flow on the Boise River at the Glenwood Bridge, ID.

The Boise River flow at the Glenwood Bridge is the primary flood control objective and normally results in not exceeding a maximum flow objective of 7,000 cfs on the Boise River near Parma, ID (PARI) (Figure 19). The peak flows at PARI are nearly identical to the peak flows at BIGI as there is no regulation available between these points to further control the flow. However, as seen in Figure 19, the 7,000 cfs flood stage was exceeded under the MW/W scenario in the 2060 and 2080 periods in April. In April under the MW/W scenario local inflows between BIGI and PARI cause the flow at PARI to exceed 7,000 cfs.

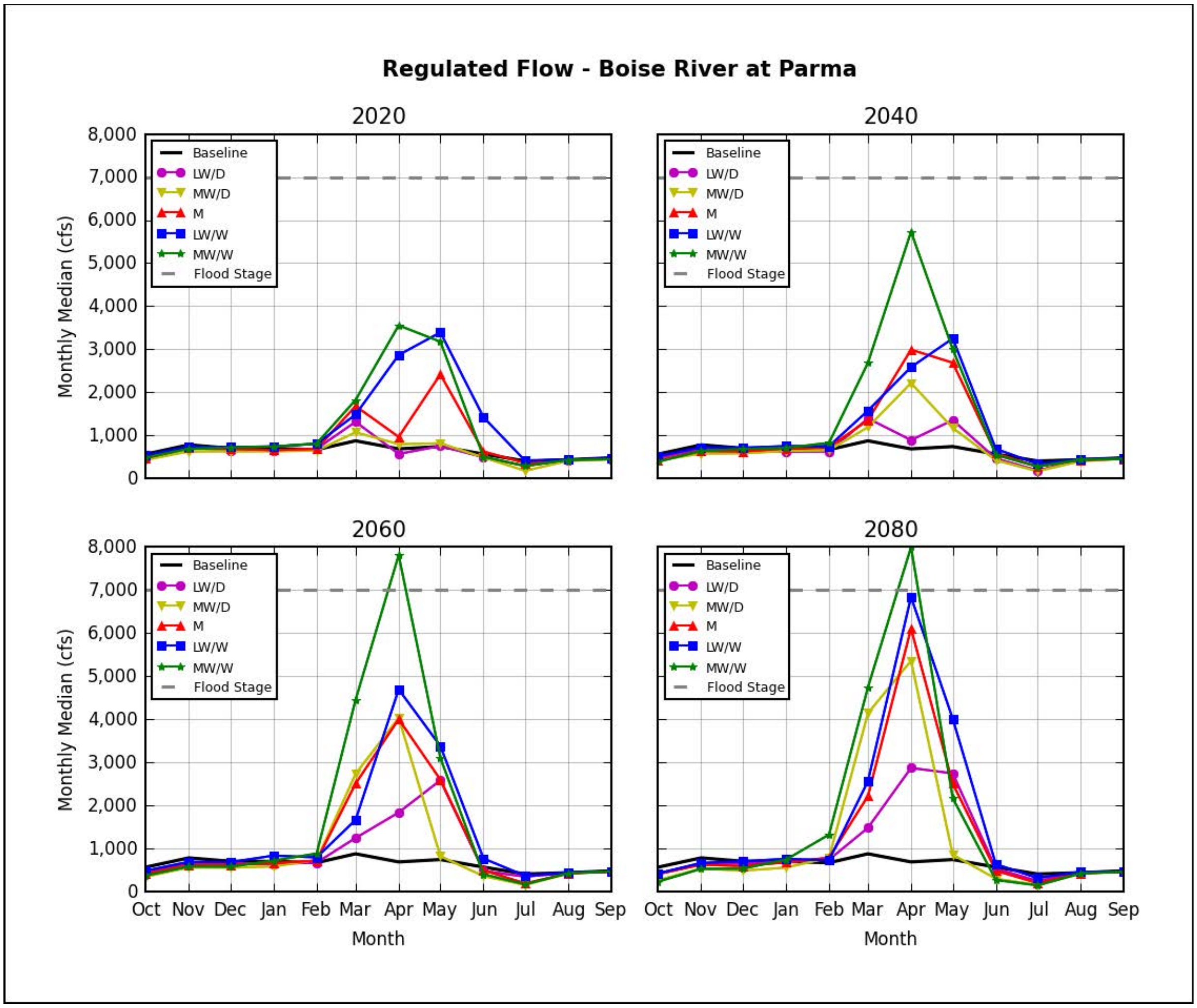


Figure 19: Monthly median regulated flow on the Boise River at Parma, ID.

5.2.4 Requested Water

In the Boise River Basin, reductions in requested water were seen for most scenarios as early as the 2020 period in the months of June, July, August, and September (Figure 20). Shifts in requested water are due to shifts in hydrologic state or a representation of how water users might adjust to changing climate conditions.

Median level requested water shortages are seen in July in all periods and for nearly all scenarios (Figure 21). Median shortages occur mostly in July due to a few factors. First, is that the natural flow supply decreased for all scenarios through all periods starting mostly in June and continuing through September so water users are more reliant on stored water earlier in the year. Second, is that the WRM has minimum flow requirements that at some locations have increased water demand in July and all minimum flow locations have priority over irrigation water requests. Third, is that some demand nodes exhaust all their available stored water in June because of the reduction in natural flow. Lastly, keep in mind that this is a plot of median conditions or conditions which occurred 50 percent of the time. So, this does not mean that there was shortage in July and no shortage in any other months but only that fifty percent of the time there was some shortage in July and fifty percent of the time there was no shortage in the other months.

One water user object or node in the WRM was chosen as a representative basin water user to present the impact of climate change on water rights. In the Boise River Basin this node is labeled “Settlers” and represents a water user with more significant water requests as well as a water user with both natural flow water rights and stored water rights that can be used to satisfy requests. Through all periods and scenarios, irrigation delivery to this representative node was satisfied less by natural flow water rights and increasingly through stored water contracts (Figure 22 and Figure 23). This occurs simply because nearly every scenario in every period shows natural flow water declines in June, July, August, and September (Figure 16).

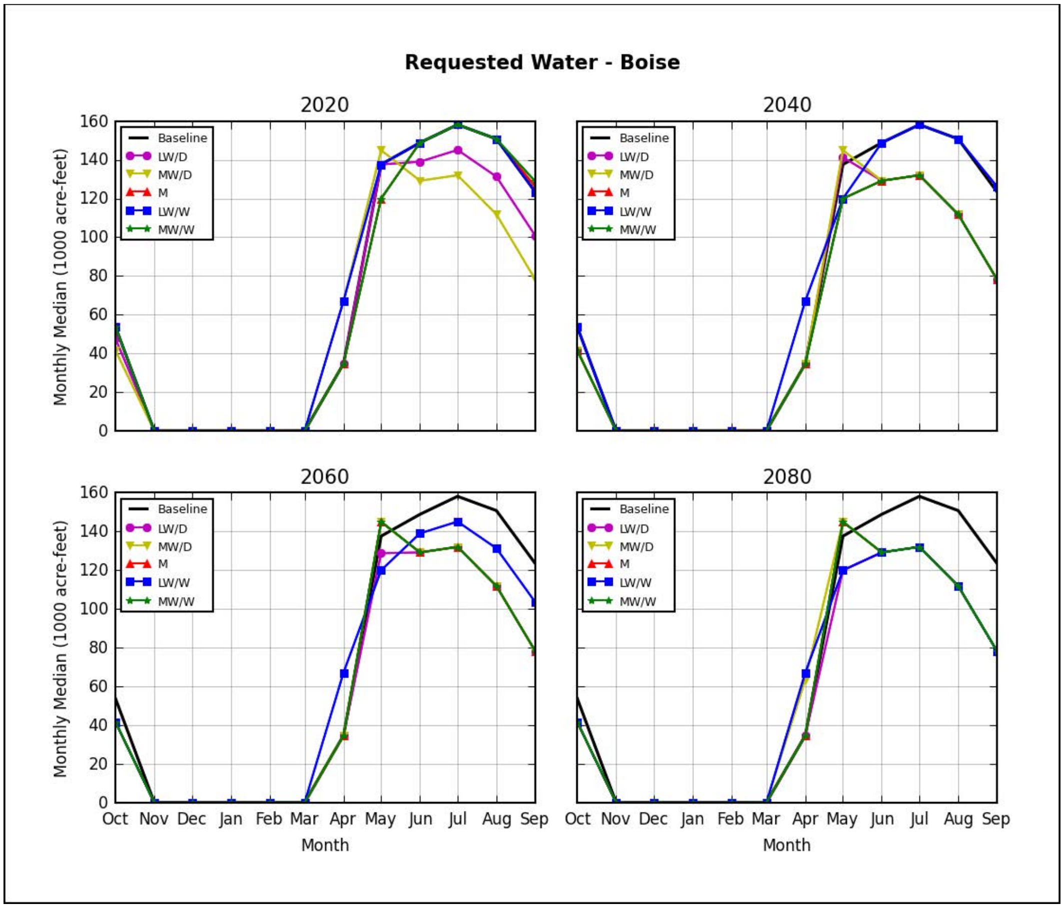


Figure 20: Monthly median of requested water in the Boise River Basin for five simulated future climate change scenarios in four future periods 2020s, 2040s, 2060s, and 2080s.

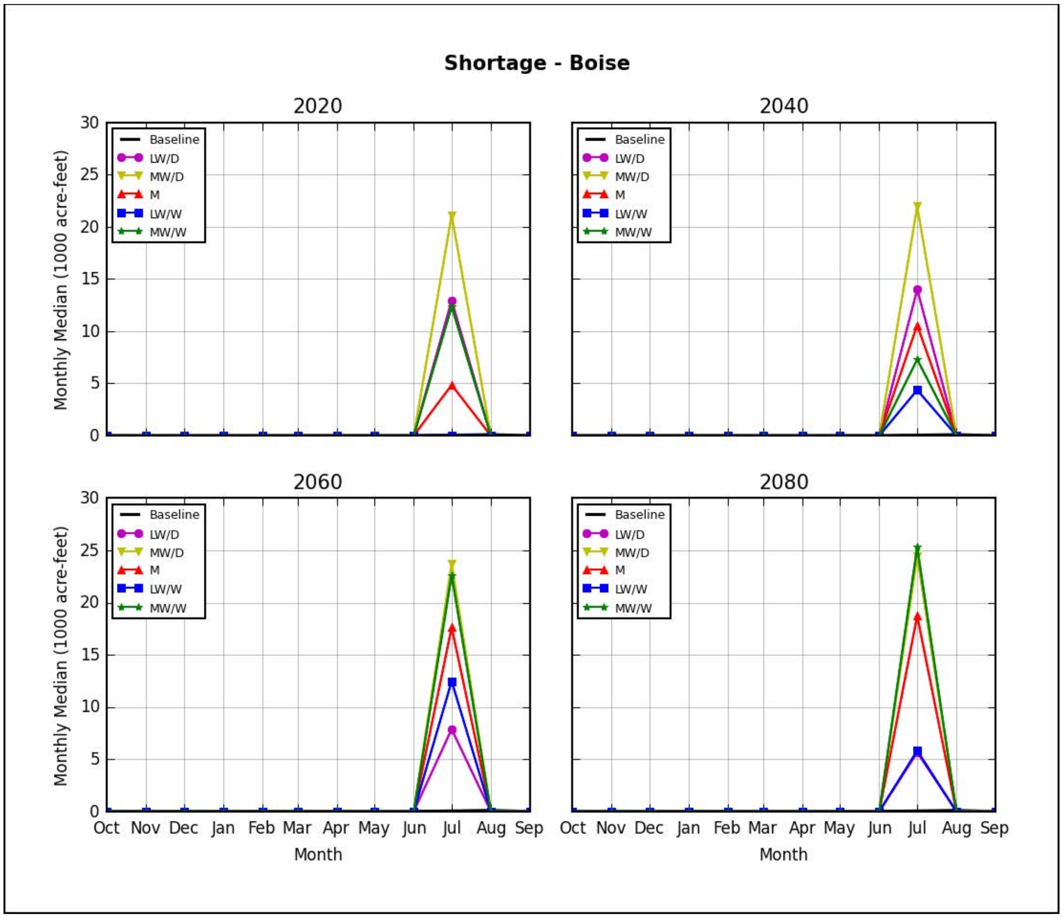


Figure 21: Monthly median of system requested water shortage in the Boise River Basin for five simulated future climate change scenarios in four future periods 2020s, 2040s, 2060s, and 2080s.

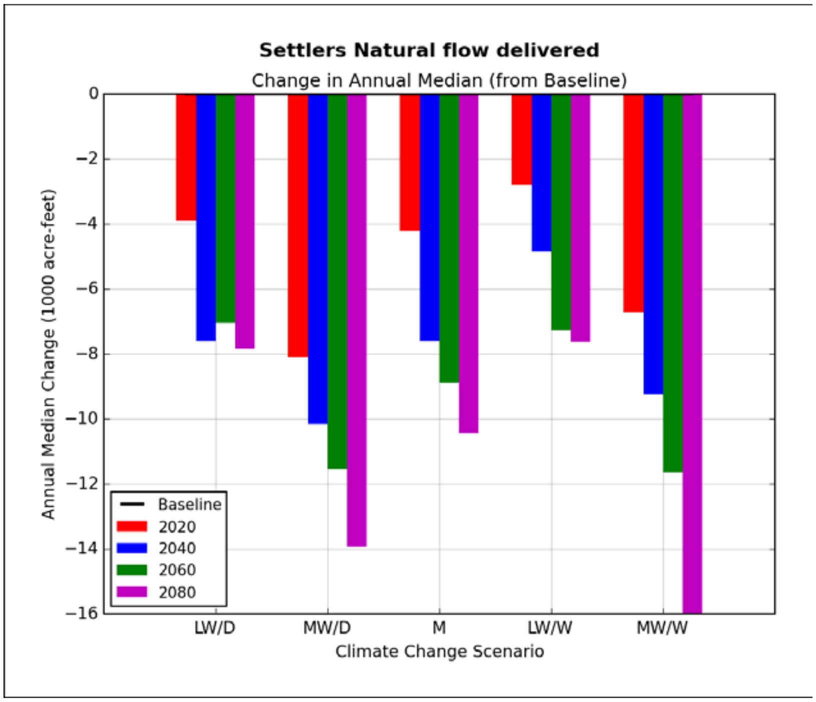


Figure 22: Annual median change in natural flow water delivery to the Settlers modeled water user.

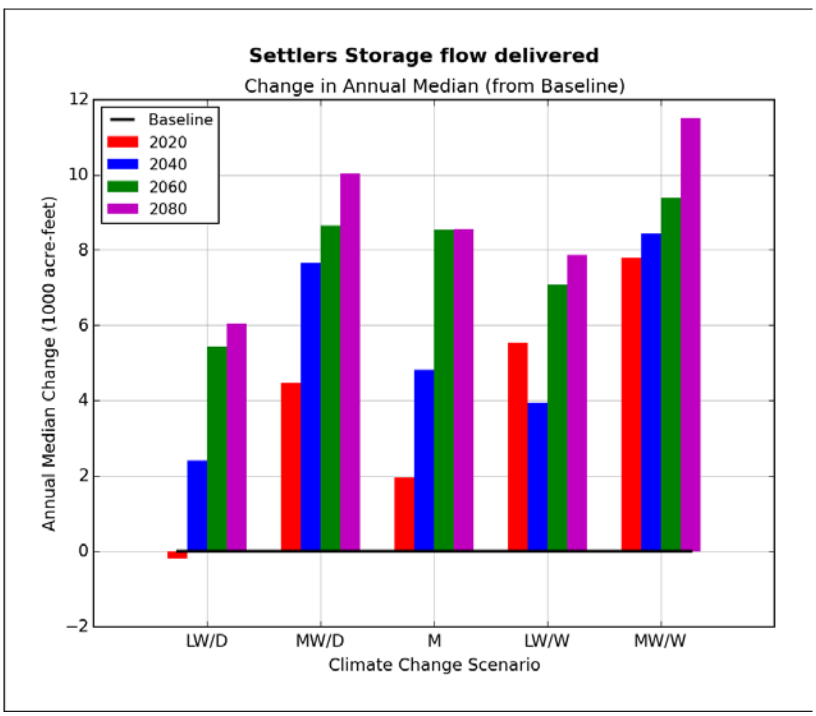


Figure 23: Annual median change in stored water delivery to the Settlers modeled water user.

5.3 Payette River Basin

5.3.1 System Inflow

For all future periods in the Payette River Basin, inflows were projected to increase in the spring and decrease through the summer. Spring increases occur earlier through each period with peak runoff shifting from May in the 2020 and 2040 period to April or May in the 2060 and 2080 periods depending on the climate change scenario. For all periods and all climate change scenarios sharp declines in June flows were simulated. Median inflows are less than the Baseline for all periods and all scenarios in the months of June, July, August, and September (Figure 24).

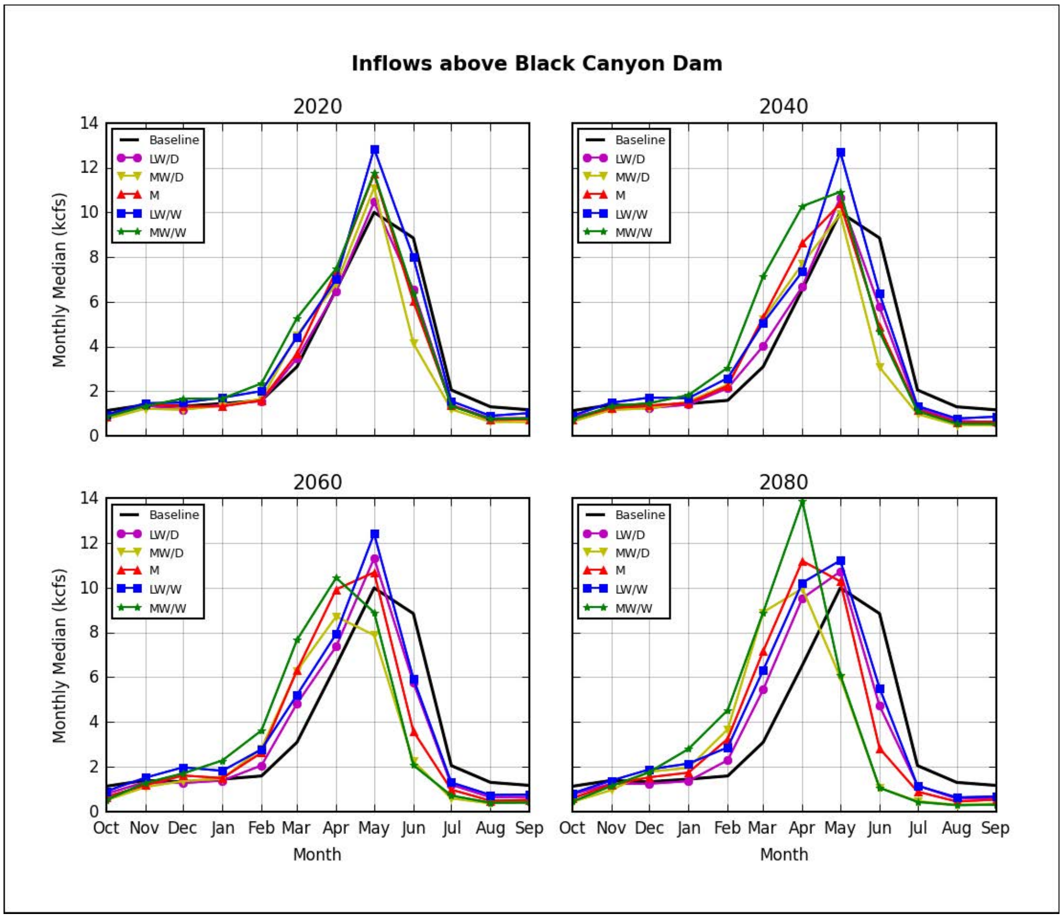


Figure 24: Monthly median unregulated inflow above Black Canyon Dam.

5.3.2 System Reservoir Contents

System reservoir contents in the Payette River Basin included the reservoirs PAY, DED, and CSC. See Figure 1 for the location of each reservoir and Table 1 for a description of the abbreviated names.

Table 11 provides a summary of the number of years the modeled reservoir system contents were greater than or equal to 850,000 acre-feet or the system essentially reached maximum contents. Through each period, and essentially from the drier to the wetter scenarios, the number of years the reservoir system contents were essentially at maximum contents increased across the Payette River Basin (Table 11).

Table 11: Number of years in the 30-year modeled period when the maximum reservoir system contents were greater than or equal to 850,000 acre-feet (maximum capacity) in the Payette River Basin.

	Baseline	LW/D	MW/D	Median	LW/W	MW/W
2020	25	23	22	24	26	26
2040	25	21	20	24	26	26
2060	25	25	20	22	26	25
2080	25	25	18	23	27	23

Due to increased and earlier spring runoff (Figure 24) system reservoir contents continue to refill 50 percent of the time despite reduced carryover storage levels (end of October contents, Figure 25). Outside of the spring refill months system reservoir contents are lower than the Baseline for every scenario and every period. This is due to the reduced natural streamflow in June, July, August, and September decreasing the amount of irrigation water available to natural flow water rights (Figure 31). This increases irrigators' dependency on stored water contracts to satisfy irrigation demand, which reduces median storage levels.

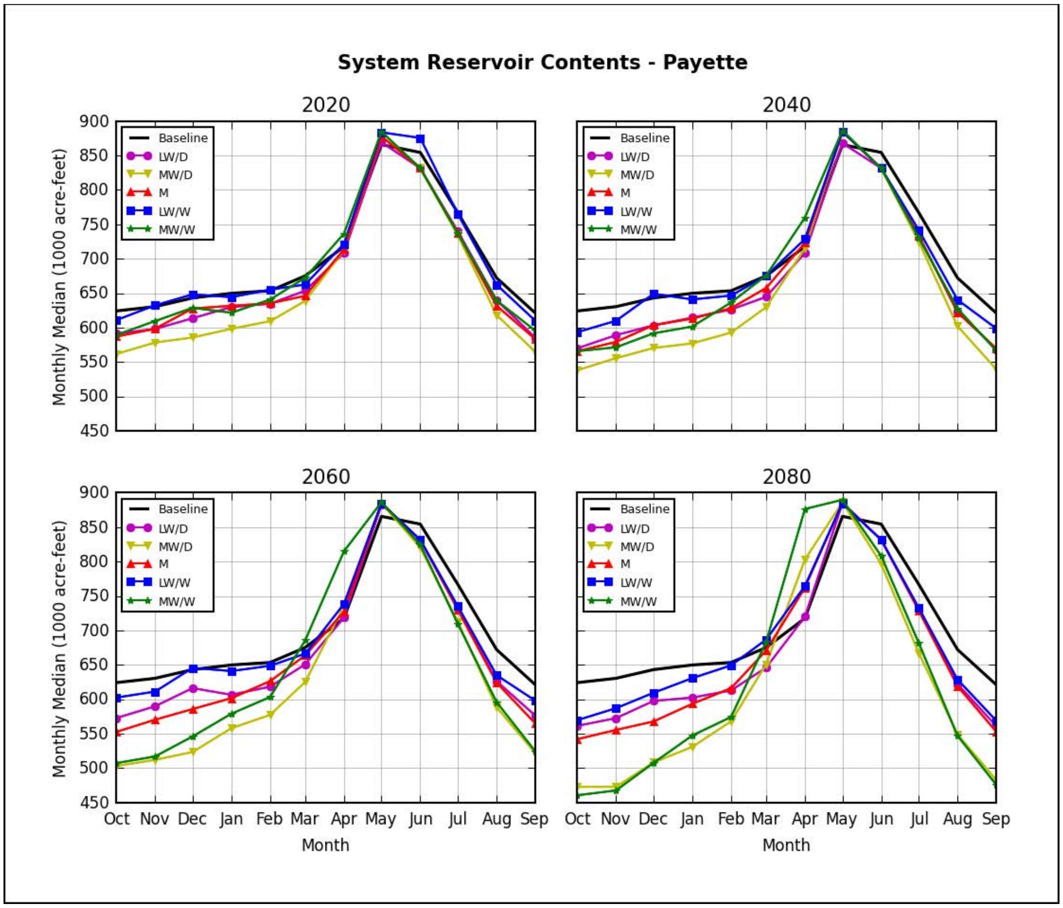


Figure 25: Monthly median of system storage contents in the Payette River Basin for five simulated future climate change scenarios in four future periods 2020s, 2040s, 2060s, and 2080s.

5.3.3 Regulated Flow

For the Payette River Basin, modeled regulated future streamflow increased from roughly February through April from the increased and earlier spring runoff (Figure 24) and reservoirs reaching maximum capacity or being constrained by flood control fill targets (Figure 25). As system inflows declined through the summer months so did regulated streamflow, although not by the same amount due to the increased stored water released to satisfy demand (Figure 31).

Through each period, and essentially from drier to wetter scenarios, the number of years that flood stage targets are exceeded is projected to increase across the Payette River Basin (Table 12).

Table 12: Number of years in the 30-year modeled period when modeled regulated flows on the Payette River at Horseshoe Bend, ID (HRSI) were greater than a flood stage flow of 12,000 cfs.

	Baseline	LW/D	MW/D	Median	LW/W	MW/W
2020	10	6	4	9	11	9
2040	10	4	3	6	10	11
2060	10	7	9	8	8	14
2080	10	7	11	11	11	15

As shown in Figure 26, fifty percent of the time (monthly median), regulated flows were below flood stage levels for all periods and all scenarios on the Payette River at Horseshoe Bend, ID. In the Payette River Basin flood control rule curves were designed to limit flow at HRSI to 12,000 cfs which was the modeled constraint. As shown in Figure 26, 50 percent of the time flood stage levels were not exceeded under any scenario or in any period.

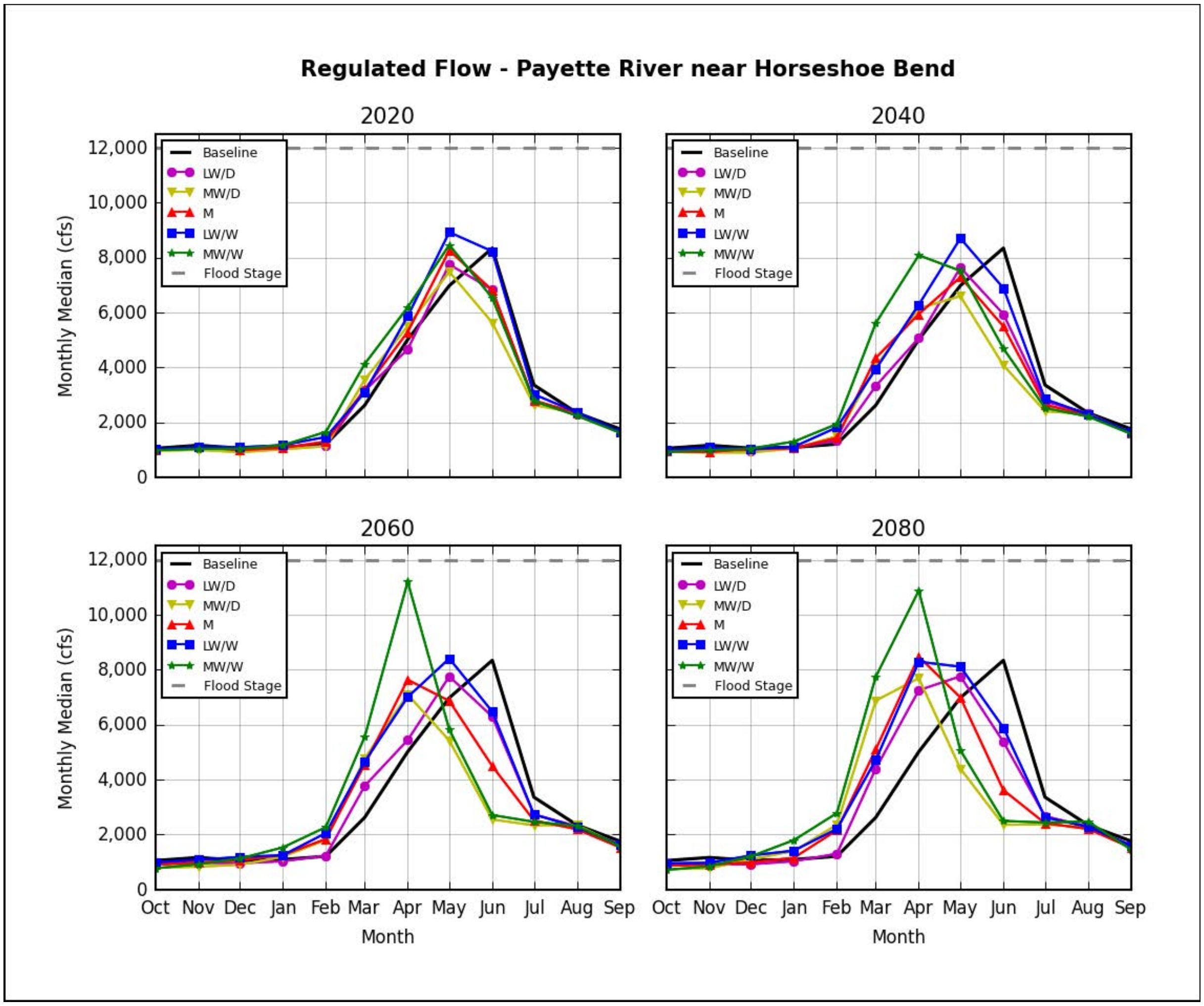


Figure 26: Monthly median regulated flow on the Payette River near Horseshoe Bend, ID.

No flood stage constraints were modeled from Horseshoe Bend to the mouth of the Payette River. Similar patterns of increased spring regulated flows are seen with larger decreases in summer flows since additional irrigation deliveries occur from Horseshoe Bend to the mouth of the Payette (Figure 27).

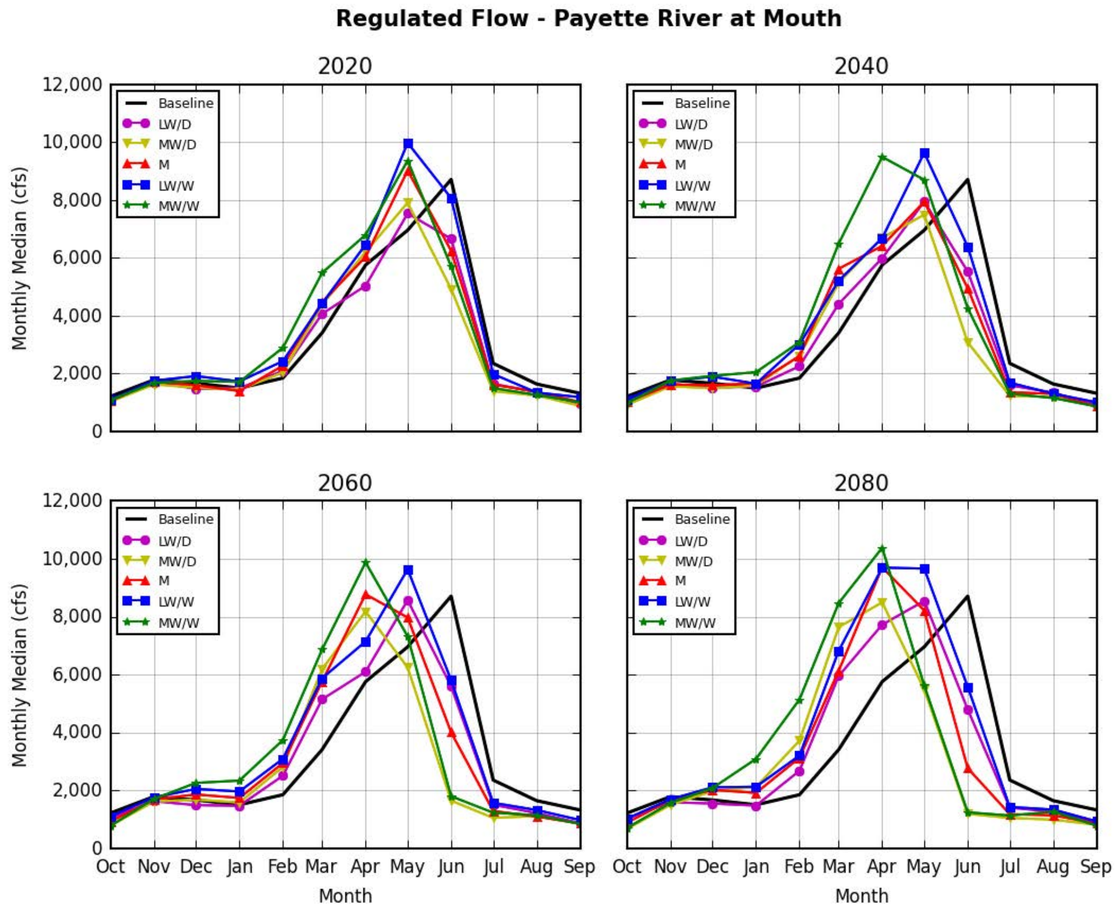


Figure 27: Monthly median regulated flow at the mouth of the Payette River, ID.

5.3.4 Requested Water

In the Payette River Basin very little change was seen in requested water for all scenarios across all periods (Figure 28). No water user shortage was seen across all periods and all scenarios. However, as seen in the other basins, demand shortage is minimized or in this case eliminated by available storage water contracts (Figure 31).

One water user object or node in the WRM was chosen as a representative basin water user to represent the impact of climate change on water rights. In the Payette River Basin this node was Northside Black Canyon and it represents a water user with more significant water requests as well as a water user with both natural flow water rights and stored water rights that can be used to satisfy requests. Through all periods and scenarios irrigation delivery to this representative node is satisfied less by natural flow water rights and increasingly through stored water contracts (Figure 30 and Figure 31). This occurs simply because all scenarios show natural flow water declines in June, July, August, and September (Figure 24).

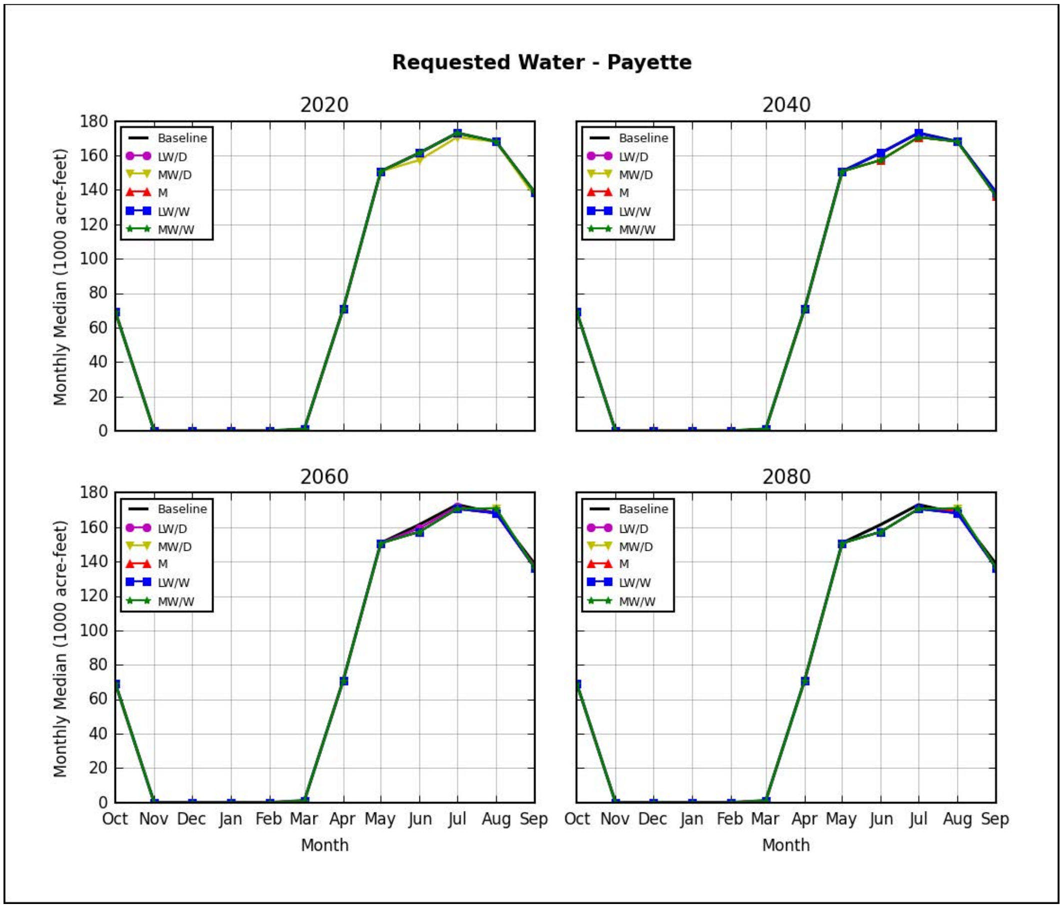


Figure 28: Monthly median of requested water in the Payette River Basin for five simulated future climate change scenarios in four future periods 2020s, 2040s, 2060s, and 2080s.

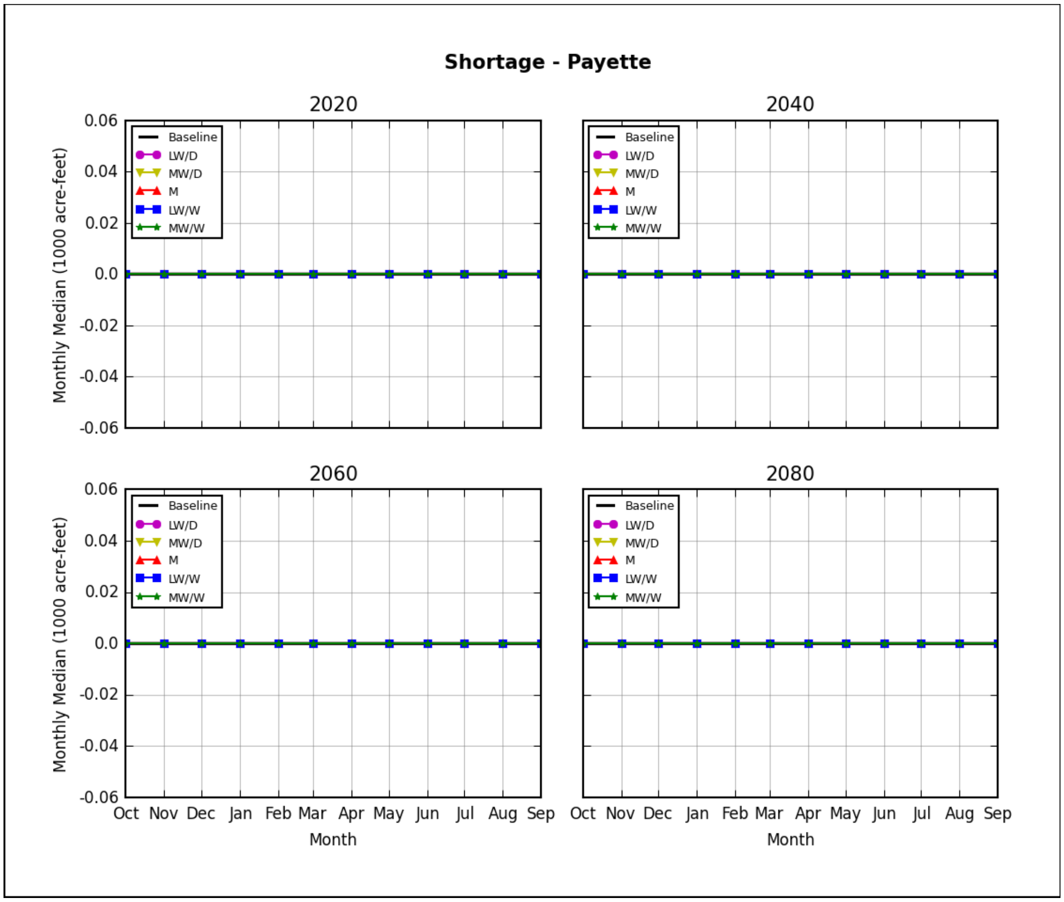


Figure 29: Monthly median of system requested water shortage in the Payette River Basin for five simulated future climate change scenarios in four future periods 2020s, 2040s, 2060s, and 2080s.

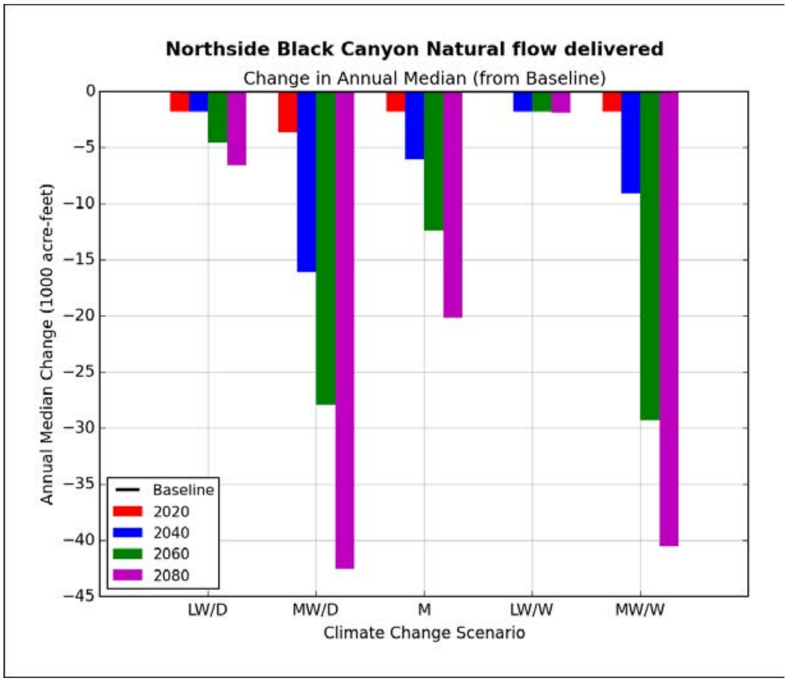


Figure 30: Annual median change in natural flow water delivery to the Northside Black Canyon modeled water user.

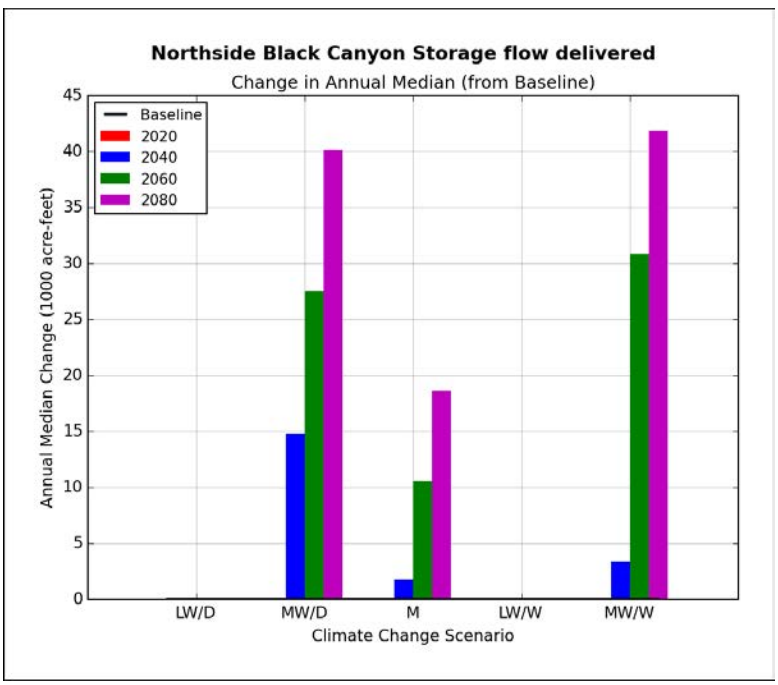


Figure 31: Annual median change in stored water delivery to the Northside Black Canyon modeled water user.

6 CONCLUSIONS

Across the entire WRM system, inflows as well as regulated streamflow were projected to increase through the spring with decreases seen in the summer months. This earlier runoff allowed reservoirs in a higher number of years than in the Baseline, but with peak storage occurring earlier through each period. The decline in system inflows in the late summer months caused lower carryover storage levels due to increased system demand on stored water delivery.

The increased system inflow in the MW/W scenario, especially pronounced in the 2080 period, projected more water than could be stored in the Snake River Basin above Milner as well as in the Boise River Basin. Because the reservoirs reach maximum storage capacity there is no further storage capacity to avoid downstream flooding under this scenario without altering the reservoirs flood control targets.

Requested water remained relatively consistent across the entire WRM (although larger request differences were seen in the Boise River Basin) due to the fact that most water users have both natural flow and stored water rights. Water users were able to rely more heavily on their stored water rights due to the increased spring runoff that refilled reservoirs at least 50 percent of the time.

It should be noted that because the WRM operates on hydrologic state with patterns of requested water, water delivery can vary between climate change scenarios yet water delivery shortage remain small. If requested water was assumed to be the same as the Baseline condition, it is expected that additional water delivery shortage would have occurred. Arguments can be made for and against this type of modeling where irrigation requests can change per scenario due to shifts in hydrologic state. One advantage to this method may be that it might provide a more realistic picture of system response given changes in water supply and how irrigators may respond to that change. One disadvantage to this method may be that it might minimize overall system impacts if it is unlikely that irrigators would respond in this manner and instead requested water remained fixed through time and independent of water supply.

7 LITERATURE CITED

Parenthetical Reference	Bibliographic Citation
Bureau of Reclamation. See Reclamation.	
Reclamation 2010	Bureau of Reclamation. 2010. *Modified and Naturalized Flows of the Snake River Basin above Brownlee*. U.S. Department of the Interior, Bureau of Reclamation, Pacific Northwest Regional Office, Boise, Idaho. May 2010.
Reclamation 2016	Bureau of Reclamation. 2016. *West-Wide Climate Risk Assessment Columbia River Basin Climate Impact Assessment, Climate Change Analysis and Hydrologic Modeling Technical Memorandum.* U.S. Department of the Interior, Bureau of Reclamation, Pacific Northwest Regional Office, Boise, Idaho.
Livneh et al. 2013	Livneh, B., E.A. Rosenberg, C. Lin, B. Nijssen, V. Mishra, K.M. Andreadis, D.P. Lettenmaier. 2013. *A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States: Updates and Extensions.* Journal of Climate, 26(23), 9384-9392. Retrieved from http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-12-00508.1 (last accessed January 28, 2016)

8 APPENDIX: WATER RESOURCES MODEL CALIBRATION

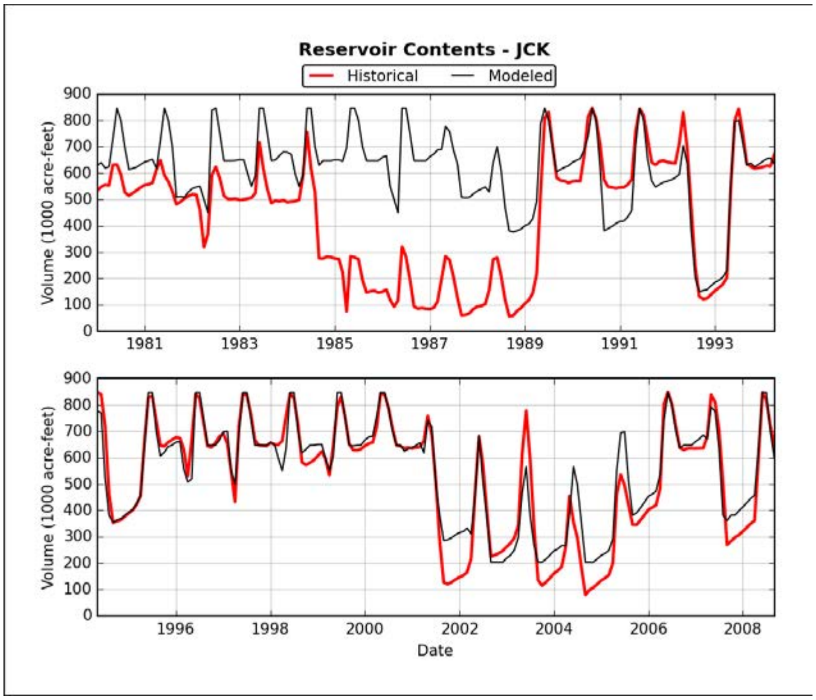


Figure 1: Historical and modeled reservoir contents at Jackson Lake (JCK).

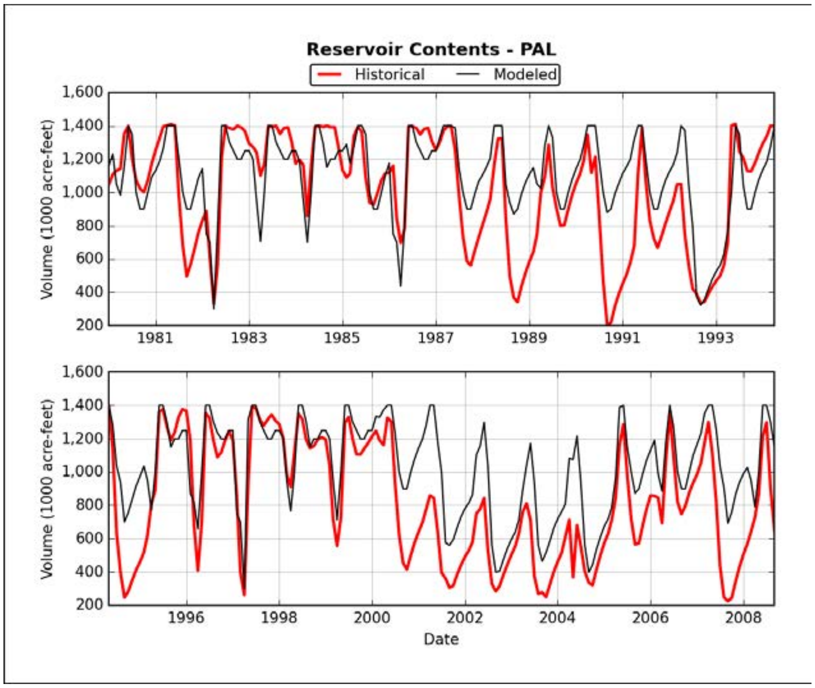


Figure 2: Historical and modeled reservoir contents at Palisades Reservoir (PAL).

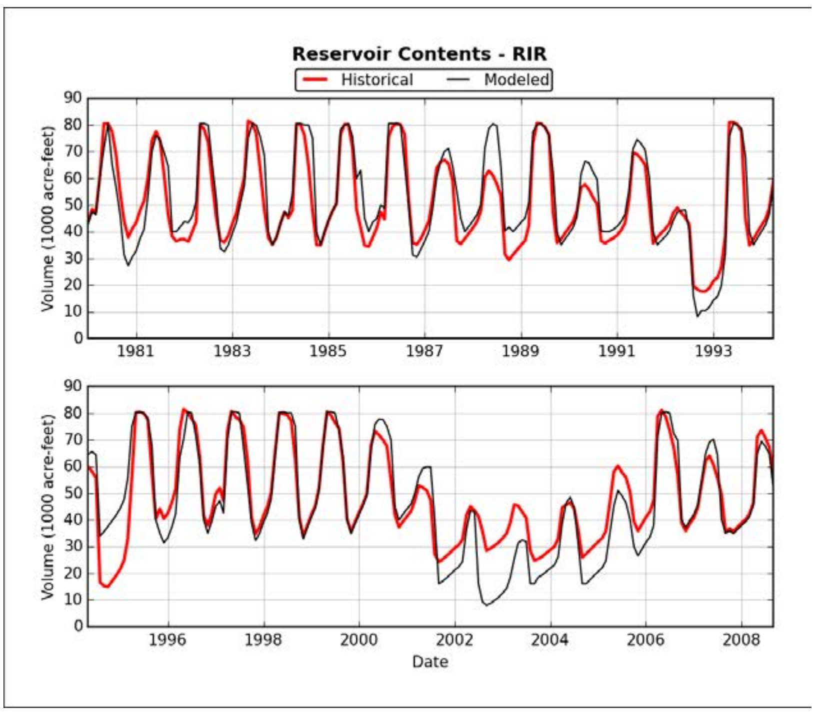


Figure 3: Historical and modeled reservoir contents at Ririe Reservoir (RIR).

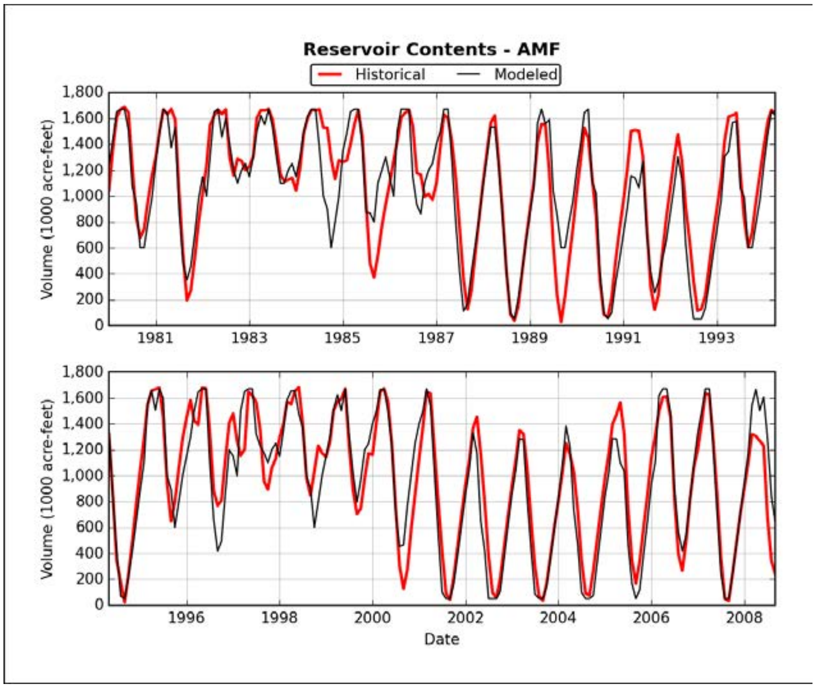


Figure 4: Historical and modeled reservoir contents at American Falls Reservoir (AMF).

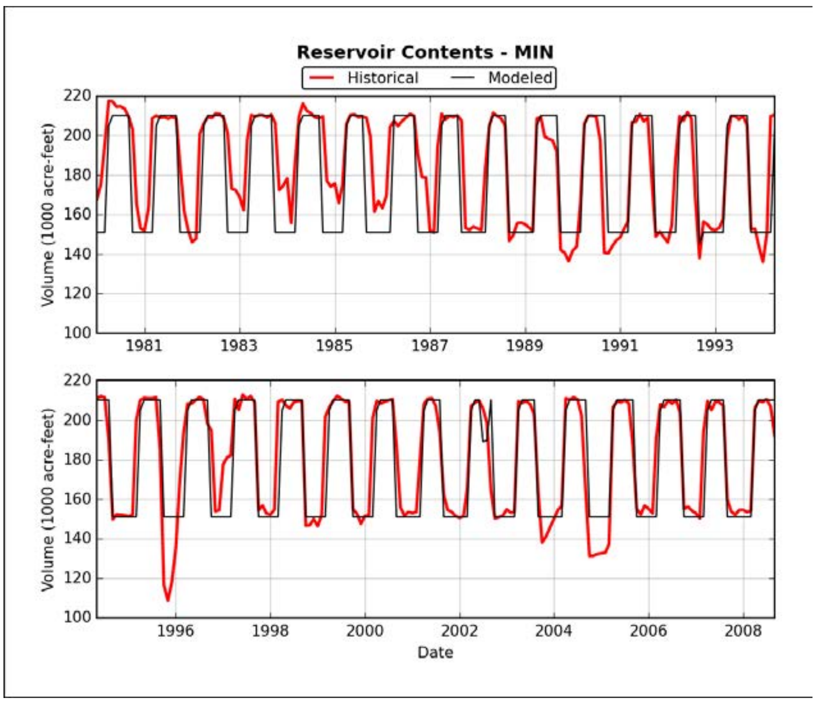


Figure 5: Historical and modeled reservoir contents at Minidoka Dam (MIN).

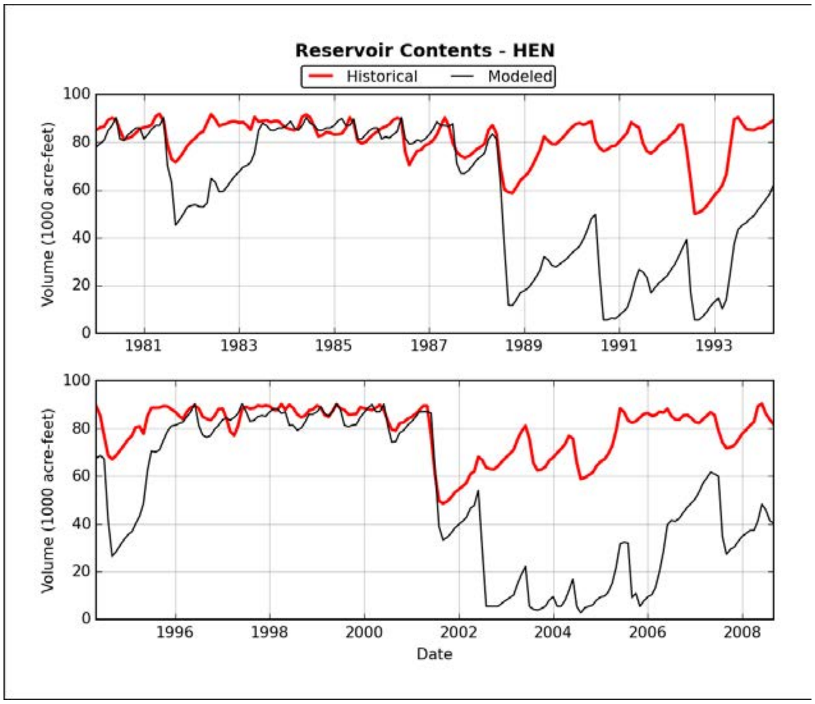


Figure 6: Historical and modeled reservoir contents at Henrys Lake (HEN).

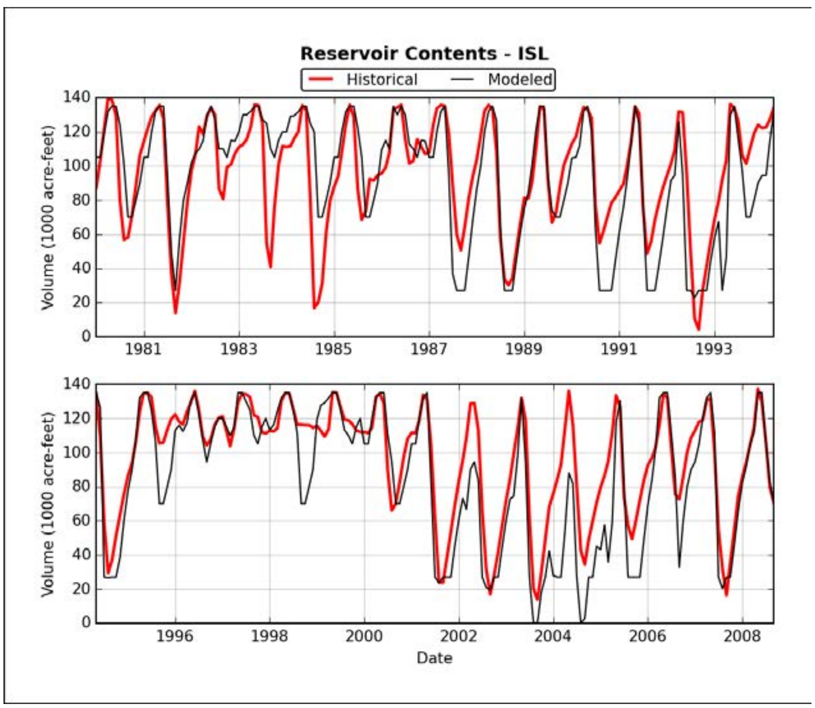


Figure 7: Historical and modeled reservoir contents at Island Park Dam (ISL).

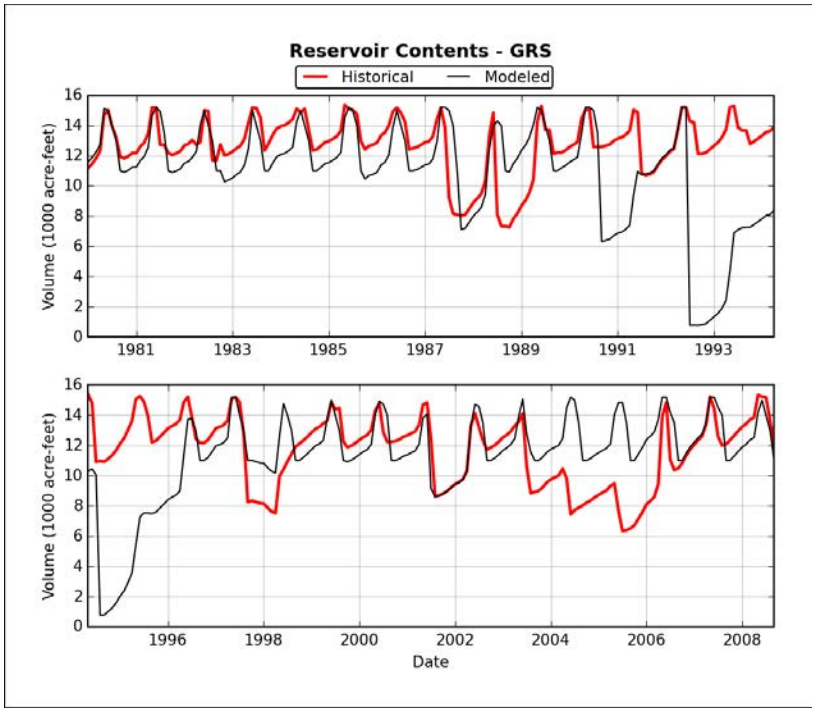


Figure 8: Historical and modeled reservoir contents at Grassy Lake (GRS).

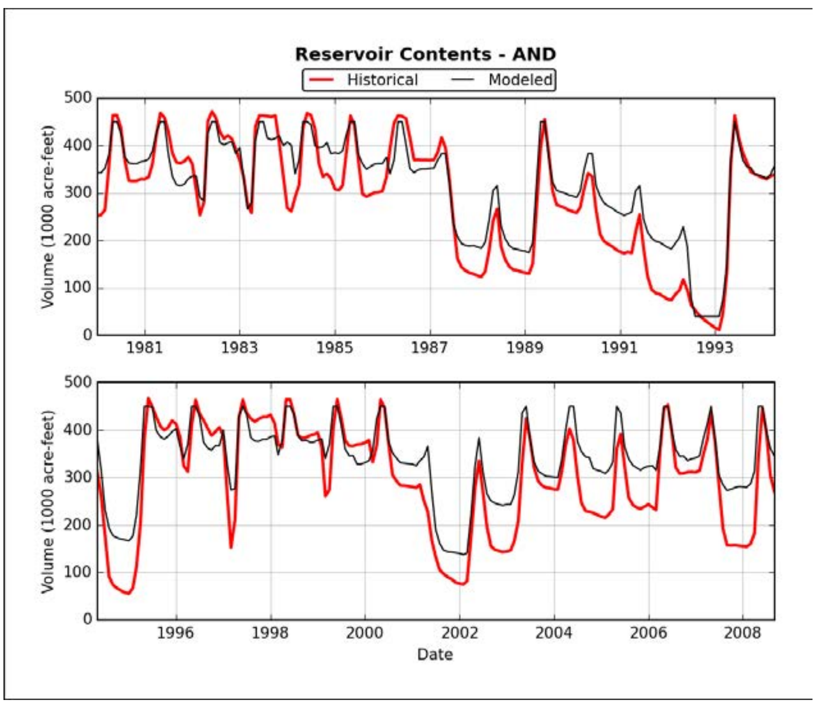


Figure 9: Historical and modeled reservoir contents at Anderson Dam (AND).

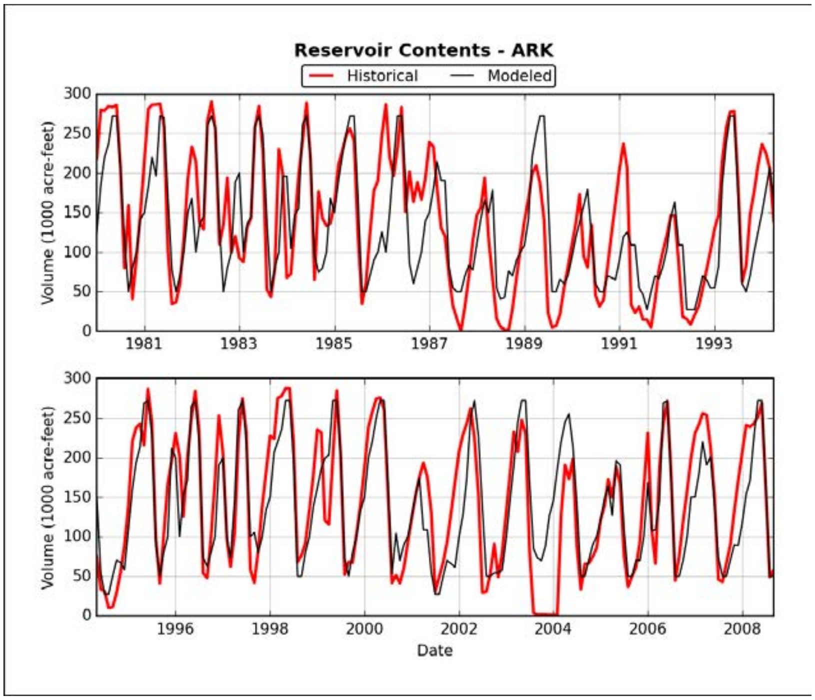


Figure 10: Historical and modeled reservoir contents at Arrowrock Dam (ARK).

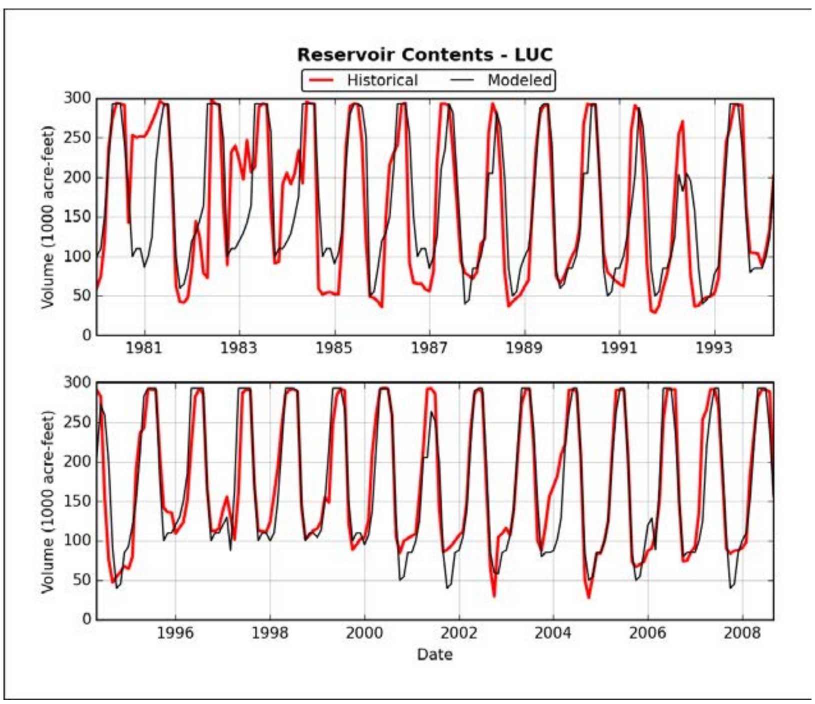


Figure 11: Historical and modeled reservoir contents at Lucky Peak Dam (LUC).

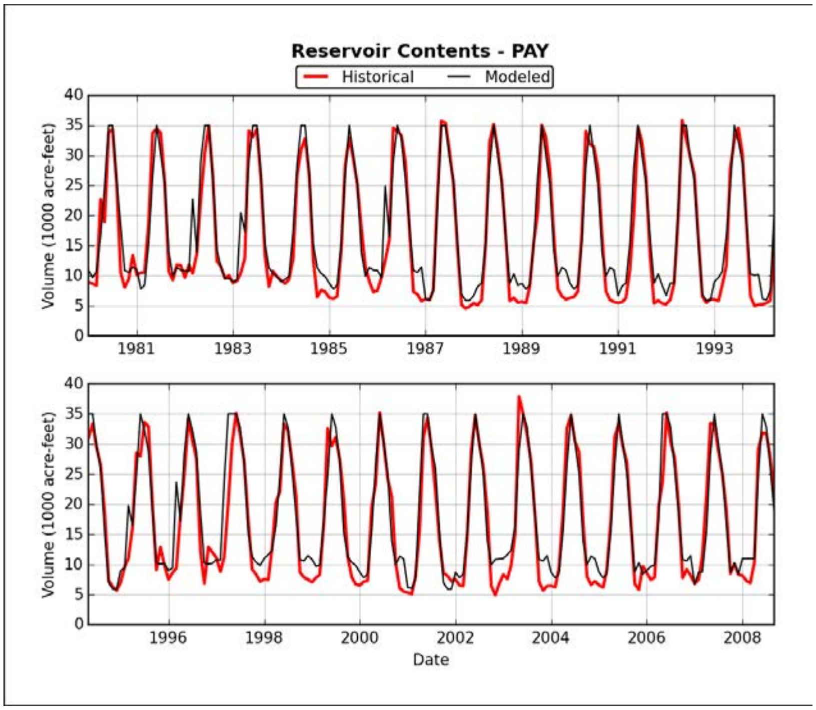


Figure 12: Historical and modeled reservoir contents at Payette Lake (PAY).

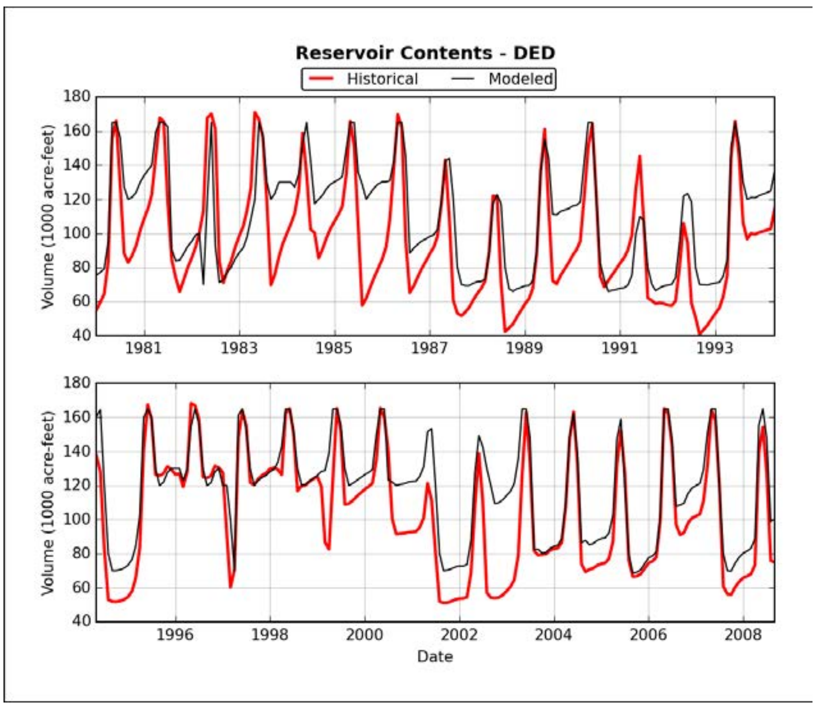


Figure 13: Historical and modeled reservoir contents at Deadwood Reservoir (DED).

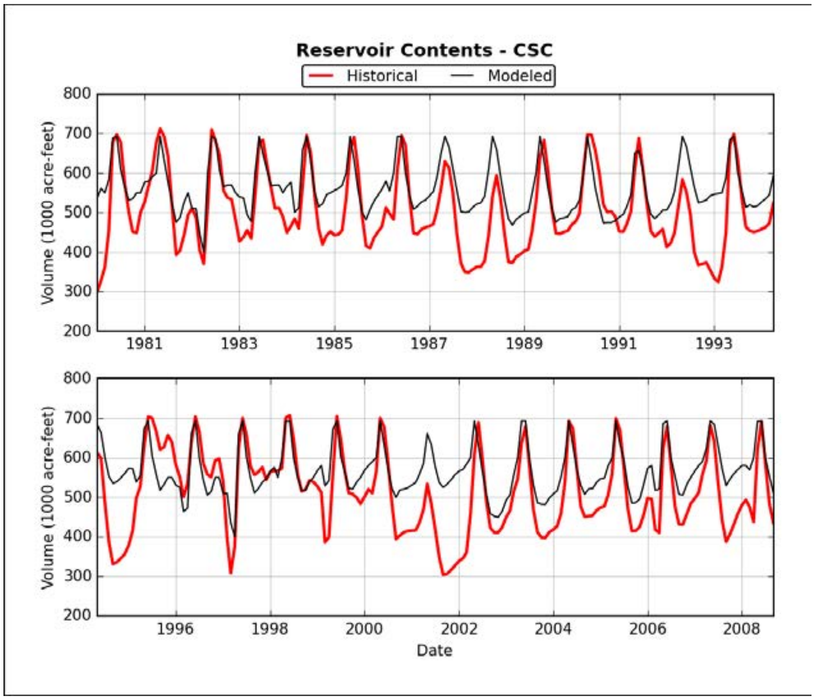


Figure 14: Historical and modeled reservoir contents at Cascade Lake (CSC).

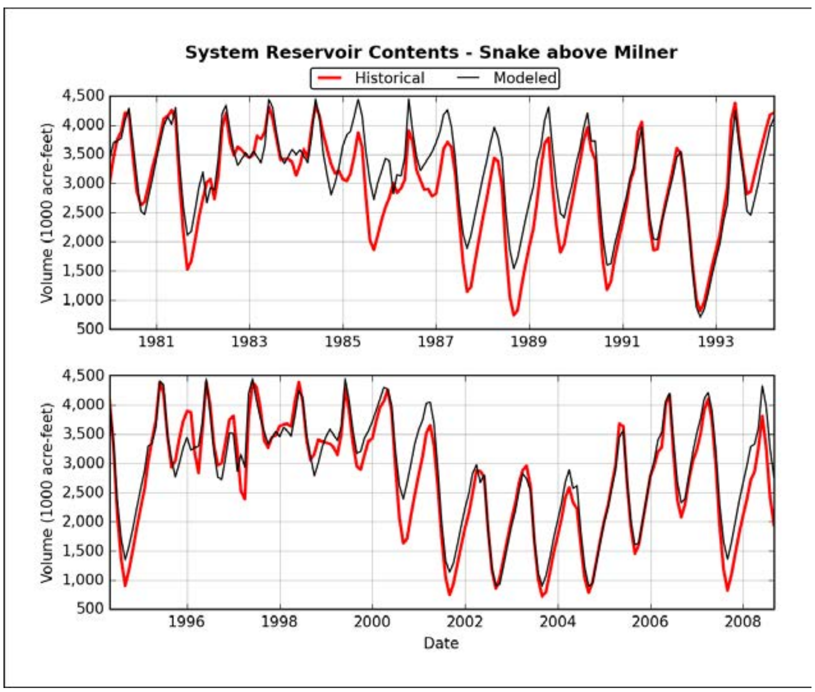


Figure 15: Historical and modeled system reservoir contents in the upper Snake River Basin above Milner.

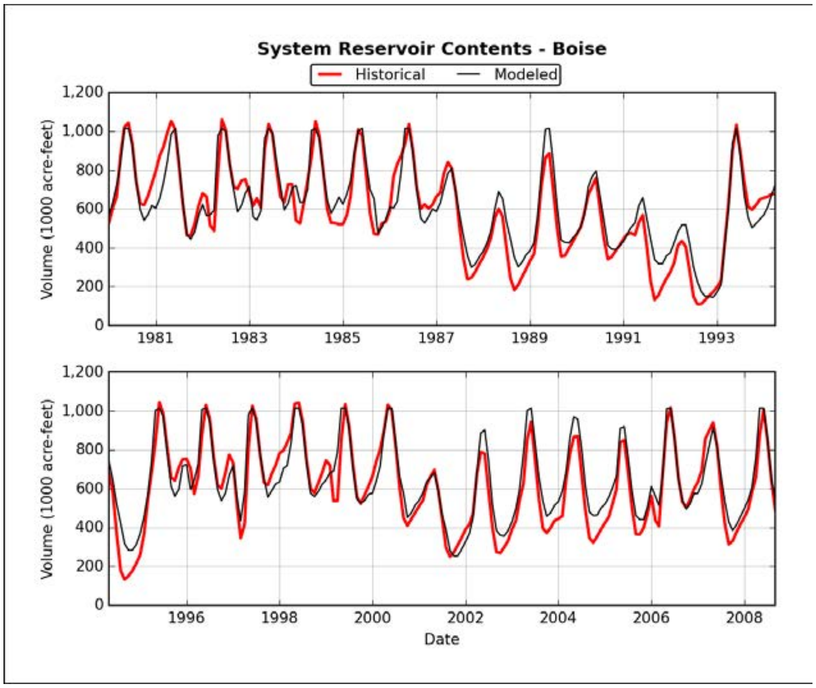


Figure 16: Historical and modeled system reservoir contents in the Boise River Basin.

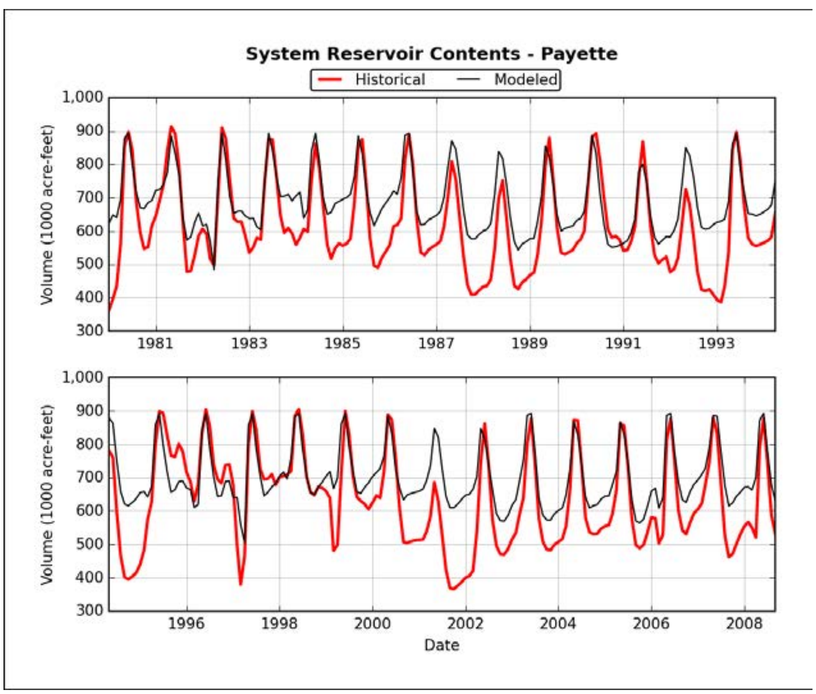


Figure 17: Historical and modeled system reservoir contents in the Payette River Basin.

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RECLAMATION
Managing Water in the West

APPENDIX C

West-Wide Climate Risk Assessment

Columbia River Basin

Climate Impact Assessment

Technical Memorandum: Determining Agricultural Diversions for Use in Water Resources Models

U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Regional Office

March 2016

Mission Statements

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.

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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1 INTRODUCTION

The Bureau of Reclamation (Reclamation) is taking a leading role in assessing the risks and impacts of climate change to Western U.S. water resources, and in working with stakeholders to identify climate adaptation strategies. Adequate and safe water supplies are fundamental to the health of citizens, strength of the economy, and protection of the environment and ecology in the Western U.S. Global climate change poses a significant challenge to the protection of these resources.

Section 9503 of the SECURE Water Act, Subtitle F of Title IX of P.L. 111-11 (2009) (SWA), authorizes Reclamation to evaluate the risks and impacts of climate change in western river basins and to work with stakeholders to identify climate adaptation strategies. The Columbia River Basin was one of the major Reclamation river basins identified for evaluation in the SWA. The purpose of the Columbia River Basin Impact Assessment (Assessment) (under the WaterSMART Basin Study Program West-Wide Climate Risk Assessments) is to generate reconnaissance-level hydrologic data and analysis on the potential effects of climate change in the basin, and how those effects relate to water supply and demand.

Agricultural consumptive use is a large subset of water use in the Columbia River Basin and is a necessary set of information when modeling water resources. Water resources models are used to simulate the physical and human controlled processes that determine the movement of water through a regulated river system. They can be used to project how regulated river systems may respond to changes in water supply, system management, or physical system structure, and, in this case, they are useful in determining potential system impacts due to projected future climate change water supplies.

This technical memorandum describes a process to develop projected future diversion data for water resource models using projected future net irrigation requirement data that were produced by Reclamation and Desert Research Institute for the West-Wide Climate Risk Assessments (WWCRA) Irrigation Demand and Reservoir Evaporation Projections Study (Reclamation 2015) (henceforth called the WWCRA Demand Study).

1.1 Project Background

Water resources models use diversion data to represent water that is removed from a river for various uses including agriculture, municipal, and industrial. In the Columbia River Basin, just over 40 percent of surface water diversions are used for irrigated agriculture (USGS 2014). For historical analysis, historical diversions can be quantified using actual diversion rates that are typically measured by various entities including irrigation districts and state water management agencies. Quantifying diversions for future analysis can be difficult because one must account for the changing crop needs due to changes in temperature and precipitation along with system loss.

The diversion values used in water resources models represent all of the water that is diverted from the river, which includes the water that is required by the crop for evapotranspiration and the additional water required to deliver the water to the field (Figure 1). In a perfectly efficient system, irrigation diversions would be made up only of the water that is needed by the crops that are being irrigated over and above what is provided by precipitation (also called net irrigation requirement – NIWR). However, in most irrigation systems, there are losses that occur during delivery and application such as canal seepage and on-farm losses.

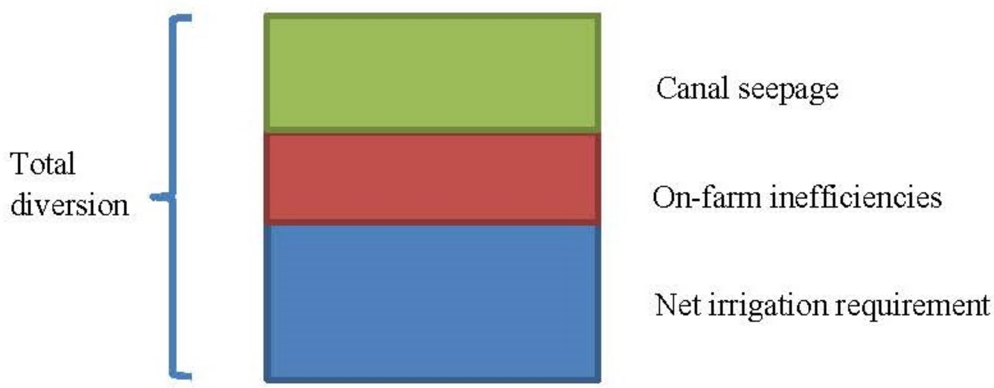


Figure 1: Illustration of the categories of water that make up a diversion.

The 2015 WWCRA Demand Study produced bias-corrected and downscaled projections of evapotranspiration (ET) and NIWR using crop types and quantities from the year 2010 at the Hydrologic Unit Code eight digit (HUC8) level drainage area scale. The ET and NIWR estimates were calculated for three future periods 2020s (2010 through 2039), 2050s (2040 through 2069), and 2080s (2070 through 2099). For each future period, five climate scenarios were developed using the CMIP3 (Coupled Model Intercomparison Project Phase 3) (Meehl at al. 2007) datasets to represent less warming-dry (LW/D), less warming-wet (LW/D), more warming-dry (MW/D), more warming-wet (MW/W), and central (median – M) tendency conditions.

The data developed for the WWCRA Demand Study cannot be directly used in water resources models for the following reasons. First, the water resources models require an estimate of total diversion and the data developed for the Reclamation study is only the NIWR portion of the total diversion without any adjustment for system loss. Second, the data was developed for the crop quantities and types for available Met stations (i.e. weather stations) and HUC8 drainage areas, and do not perfectly spatially correspond to lands that are served by a diversion.

Another consideration when using data generated in the WWCRA Demand Study for water resources modeling is the climate projection selection. Ideally, the climate projections selected to generate surface water flows used in water resources modeling would be the same projections that were used to develop the demand data. However, this is not always possible given that existing datasets may be used for a study, and the existing datasets may have been generated using different future periods or scenarios. At a minimum, the study should acknowledge the future periods and scenarios that were used to generate both the flow and diversion data and make some attempt to understand the possible disparities between the two datasets.

1.2 Goal of Study

The goal of this technical memo is to describe a process that can be used to develop future diversion data for use in water resource models using projected future NIWR data that were produced for the WWCRA Demand Study (Reclamation 2015). This technical memo describes two methods that can be used to prepare the projected future NIWR data for use in water resource models.

2 Estimating Future Irrigation Demands

This section describes a process for developing projected future diversions that can be used in water resources models. The future diversions are informed by the results of the WWCRA Demand Study (Reclamation 2015).

For this analysis, two methods were explored that could be used to develop projected future diversion estimates. The first method, called the Total Irrigated Acres method, calculated future diversion estimates by quantifying the amount of irrigated acres for each model diversion location and multiplying the acres by the projected NIWR estimates with consideration of system losses (i.e. canal seepage and on-farm inefficiencies). The second method, called the Linear Regression method, calculated future diversion estimates based on the empirical relationship between historical diversion data and historical NIWR.

A water resources model (MODSIM; http://modsim.engr.colostate.edu/) of the Upper Snake River Basin simulates water storage and delivery throughout the basin (Reclamation 2010). Figure 2 shows the lands irrigated by water diverted from the Snake River and its tributaries.

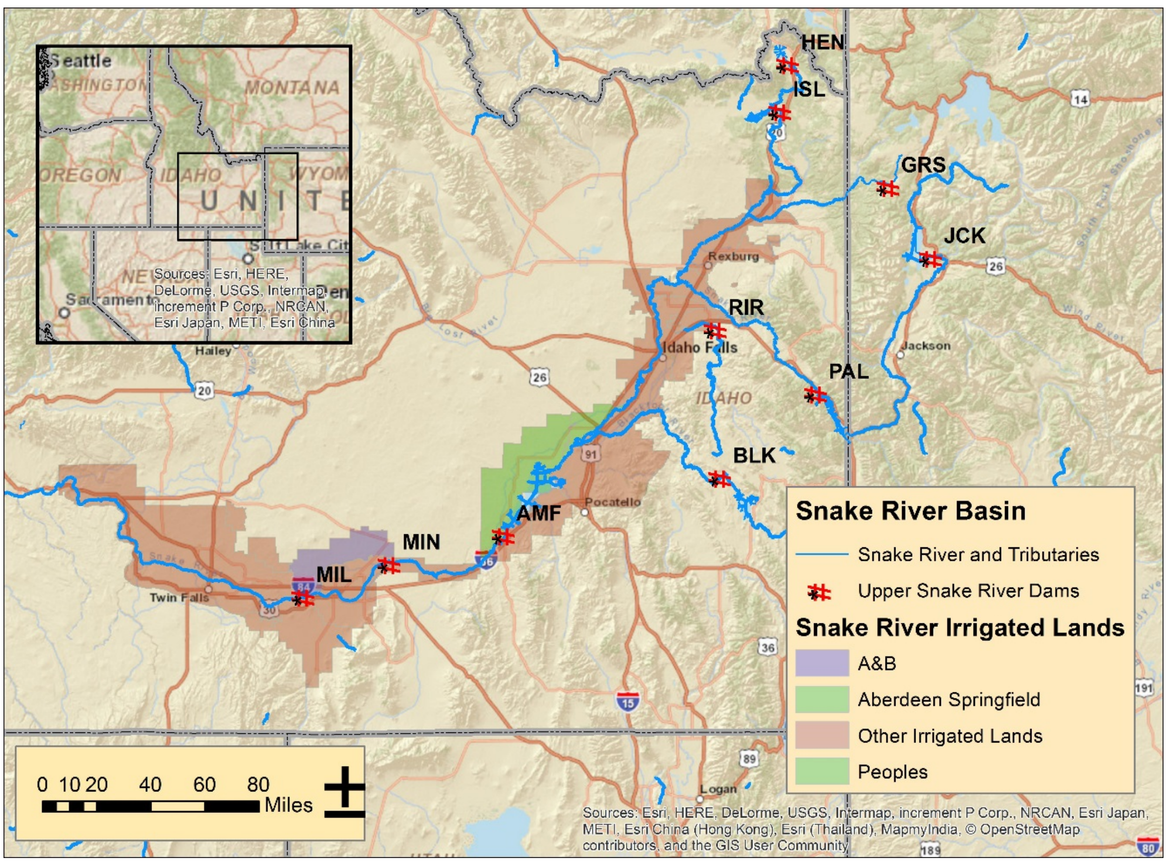


Figure 2: Surface water irrigated lands in the Snake River Basin.

The two methods developed in this analysis were tested using two diversion locations that are represented in the MODSIM model using Demand nodes: A_BPump and PeopAber. The lands irrigated by the water diverted in the A_BPump node are in the A&B Irrigated district (shaded purple in Figure 2) and the lands irrigated by the water diverted from the PeopAber node are in the Aberdeen Springfield and Peoples Irrigation districts (shaded green in Figure 2).

As mentioned previously, the lands irrigated by water diverted from specific surface water resources model nodes do not correspond to the HUC8 lands that were used to generate the WWCRA Demand dataset. Figure 3 shows an example of the difference between the lands that are served by a diversion and the HUC8 drainage areas that are nearby. Note that the A&B lands span two HUC8 drainage areas, but cover only a small portion of the areas. The PeopAber Lands are mostly contained within one HUC8 drainage area, but again only cover a portion of the area. These differences prevent the data from the WWCRA Demand Study from being used in the MODSIM model without spatial interpretation analysis or adjustments.

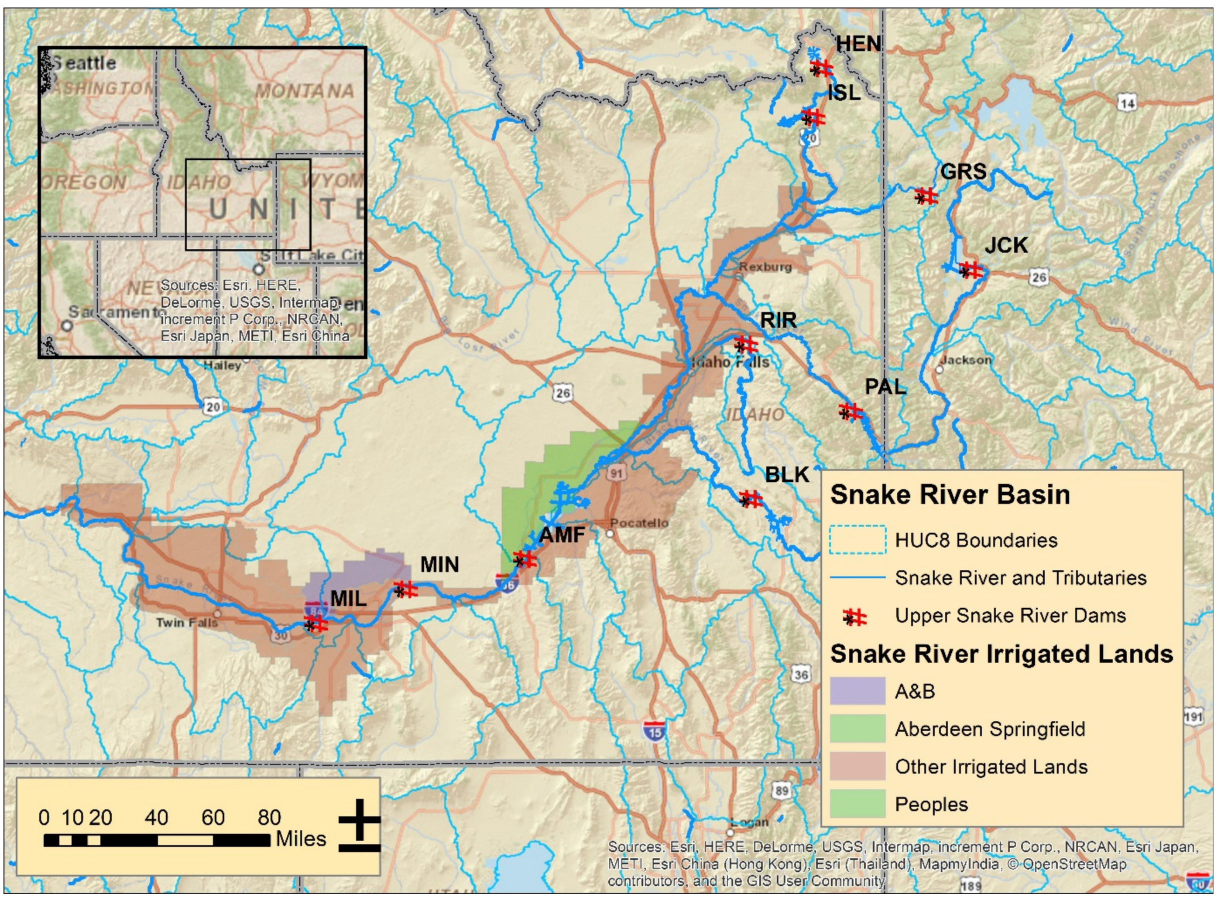


Figure 3: Map of A&B irrigation district lands served by the water resource model diversion and the nearby HUC8 drainage areas.

2.1 Total Irrigated Acres Method

The Total Irrigated Acres Method uses an estimate of irrigated acres to calculate the volume of irrigation water required for the current crop mix associated with the water resources demand node. The average NIWR time series values that were generated for the Met station nearest the node are multiplied by the acres to calculate the volume of water necessary for the crops served by the demand node. The volume of water is then adjusted for system losses (i.e. canal seepage, inefficiencies, return flows) that are not accounted for in the NIWR estimate.

The estimate of irrigated acres associated with a demand node can come from multiple sources, and is dependent on the configuration of the water resources model. For the two demand nodes evaluated in this analysis, estimates of irrigated acres were available from the Idaho Department of Water Resources (IDWR), generated during the Eastern Snake Plane Aquifer Modeling Study (IDWR 2015). Table 1 shows the average irrigated acres for each demand node as determined by IDWR.

Table 1: Irrigated acres estimates for the two water resource model nodes.

MODSIM Demand Node	IDWR Entity	Irrigated Acres
A_BPump	SW001 A&B	**12,223**
PeopAber	SW002 AbSpring + SW034 Peoples	23,476 + 20,173 = **43,649**

Using the time series of historical NIWR estimates for the nearest Met station, a time series of the volume of water needed to irrigate the crop mix can be calculated for each node. Figures 4 and 5 show the historical average monthly diversion volume along with the calculated average monthly NIWR volume for each node. The difference between the two values can be interpreted as the system losses. Note that for these two nodes, system losses are substantial and are due to a combination of partial flood irrigation and canal seepage (IWRRI 2010a; IWRRI 2010b).

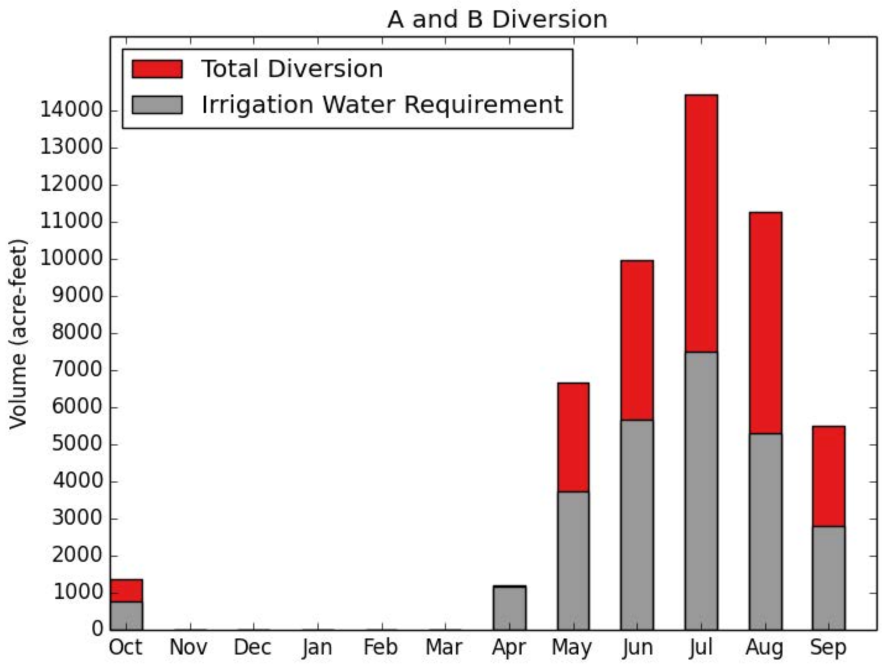


Figure 4: The average monthly historical diversion and calculated NIWR volume for the A_BPump node.

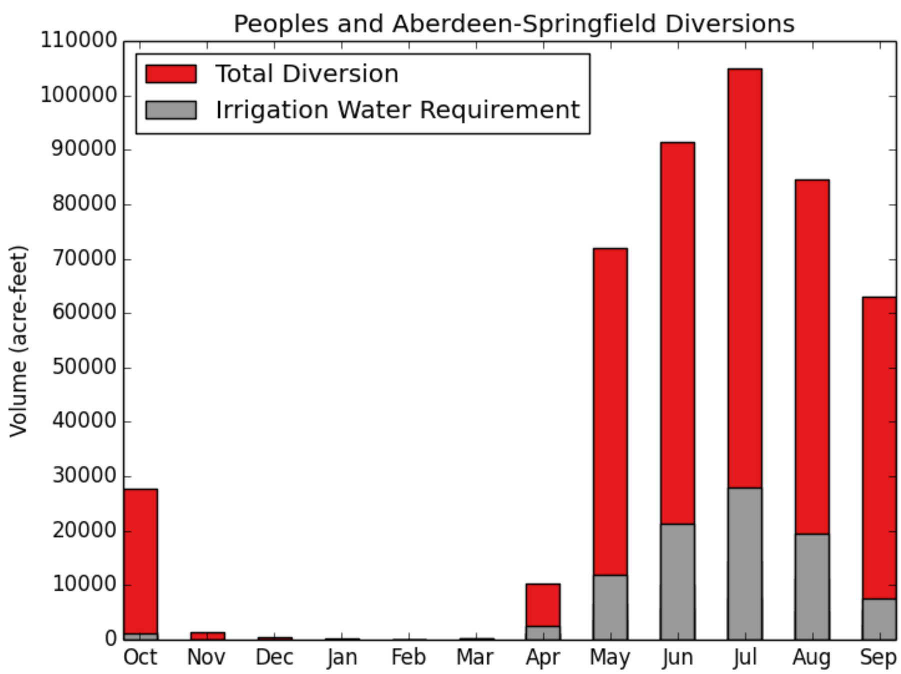


Figure 5: The average monthly historical diversion and calculated NIWR volume for the PeopAber node.

System losses associated with the future NIWR estimates can be handled in different ways depending on the goal of the analysis. For example, it may be assumed that irrigation districts will increase system efficiencies (i.e. lining canals or converting from flood to sprinkler irrigation) under future conditions, so system losses could be assumed to be a fraction of the historical losses. For this analysis, it was assumed that system losses would remain similar to those in the past.

A monthly fraction of system loss was calculated for each node based on the difference between the historical average monthly diversion volume and the calculated NIWR volume. The monthly values for each node are shown in Table 2. These calculated values are slightly less than the estimated values for the Eastern Snake Plane modeling study where A_BPump had an average loss fraction of 0.51 and PeopAber had an average loss fraction of 0.83 (calculated using the steady-state modeled diversion and crop irrigation requirement).

Table 2: Calculated monthly average loss factions for A_BPump and PeopAber.

Month	A_BPump Loss Fraction	PeopAber Loss Fraction
Oct	0.45	0.96
Nov	0.00	0.00
Dec	0.00	0.00
Jan	0.00	0.00
Feb	0.00	0.00
Mar	0.00	0.00
Apr	0.004	0.76
May	0.44	0.83
Jun	0.43	0.77
Jul	0.48	0.73
Aug	0.53	0.77
Sep	0.49	0.88
Average (without zeros)	**0.40**	**0.74**

Using the future NIWR timeseries, the estimate of irrigated acres, and the estimate of system losses, future demand timeseries were calculated for each demand. Figures 6 and 7 show the average difference between the estimated demands that were calculated and the baseline for the two water resource model nodes.

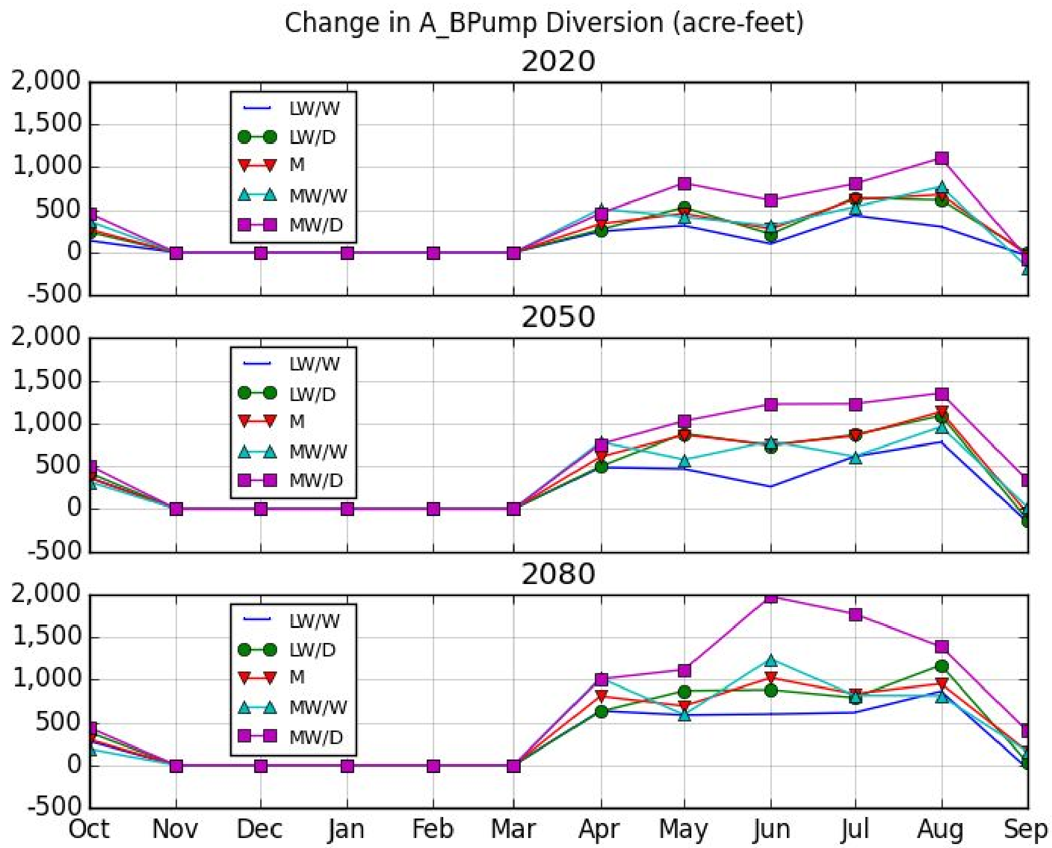


Figure 6: Average difference between the calculated future diversion and the baseline for the A_BPump water resources node for scenarios of Less Warming/Dry (LW/D), Less Warming/Wet (LW/W), More Warming/Dry (MW/D), More Warming/Wet (MW/W), and Median (M) tendency conditions.

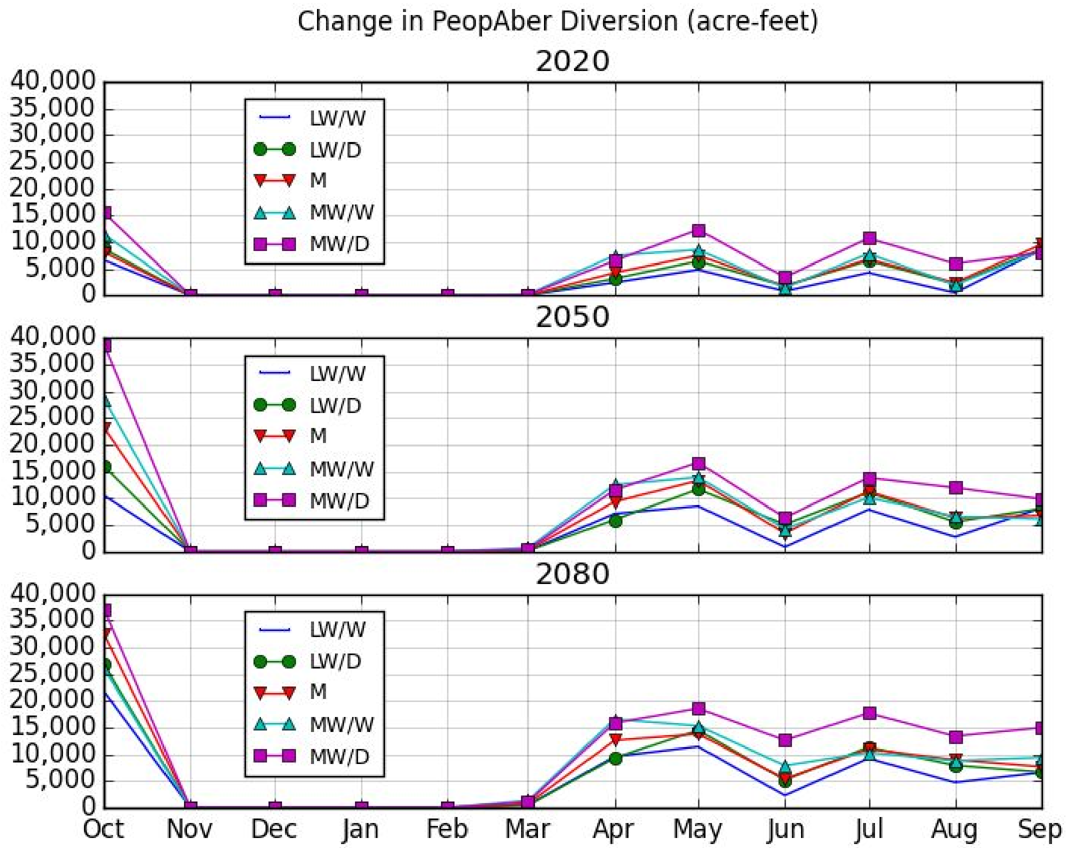


Figure 7: Average difference between calculated future diversion and baseline for the PeopAber water resources model node for scenarios of Less Warming/Dry (LW/D), Less Warming/Wet (LW/W), More Warming/Dry (MW/D), More Warming/Wet (MW/W), and Median (M) tendency conditions.

The change in demand for both nodes was greatest in the summer months for the MW/D scenario. This is consistent with the idea that crops would require more irrigation water in dryer and more warming conditions. The changes are smallest for the LW/W scenario, which is also consistent with the idea that crops would require less irrigation water in less-warm and wetter conditions.

2.2 Linear Regression Method

The Linear Regression Method was explored for situations where an estimate of irrigated acres is not available. In general, a linear regression equation is developed using the historical demand time series and the historical NIWR time series. The equation is then applied to the future NIWR values to calculate future demands. The system losses are embedded into the linear regression equation since diversion data is used to develop the regression, but are scalable with the change in NIWR versus remaining a constant fraction as described in the previous section.

Figure 8 shows the scatter plots of the historical demand and NWIR for the A_BPump water resource model node. The linear regression equation for this node is:

Future Diversion = 246 + ***Future_NIWR*** * 1894,

and it is fit with an r-squared value of 0.92.

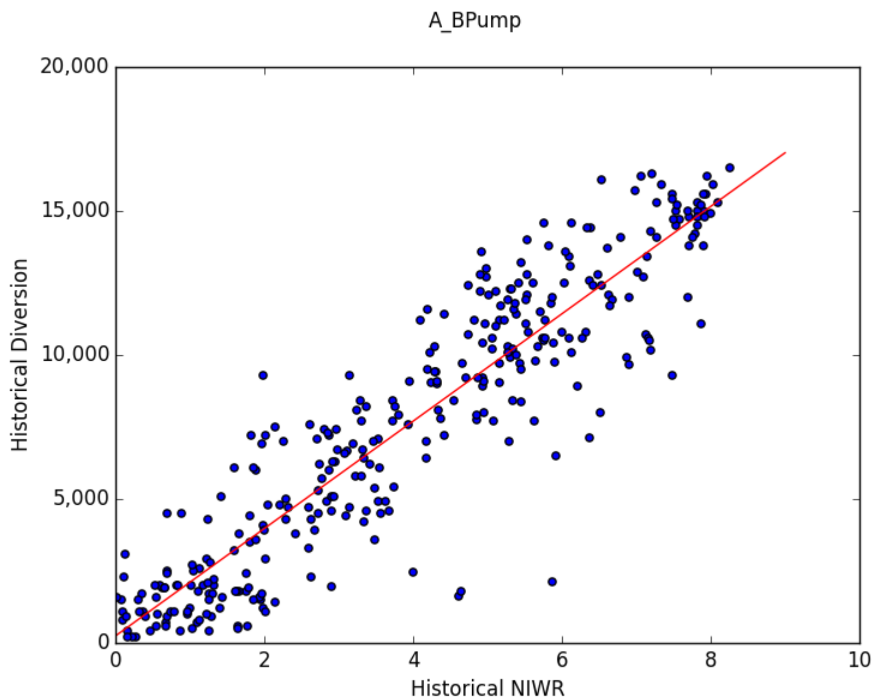


Figure 8: Scatter plot of historical diversion and historical NIWR for the A_BPump node.

Figure 9 shows the scatter plot for the PeopAber water resources model node. The linear regression equation for this node is:

$$\boldsymbol{Future\_Diversion} = 21{,}168 + \boldsymbol{Future\_NWIR} * 11{,}673,$$

and it is fit with an r-squared value of 0.86.

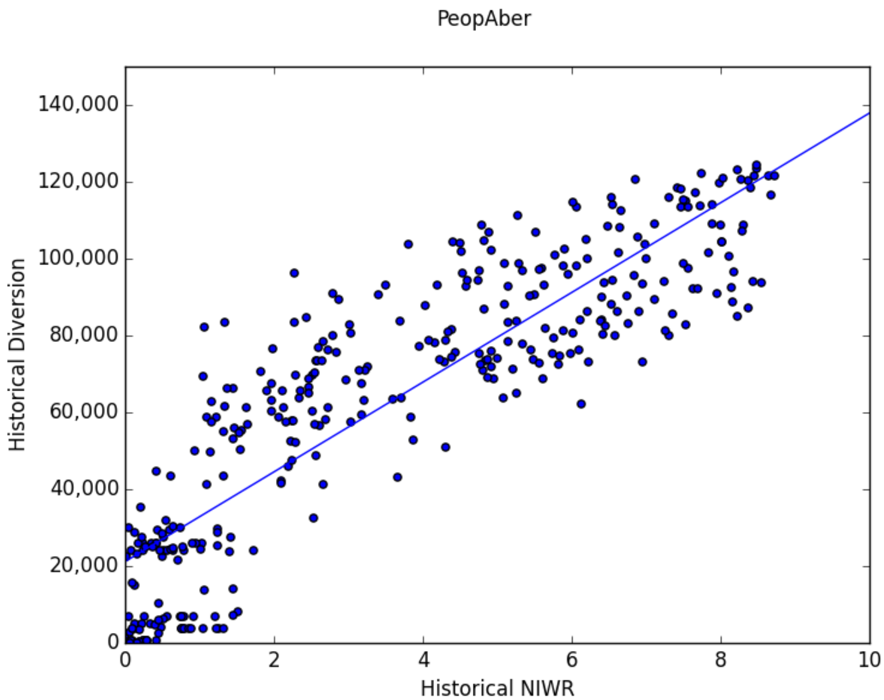


Figure 9: Scatter plot of historical diversion and historical NIWR for the PeopAber node.

Figures 10 and 11 show the change in future irrigation diversion as predicted by the linear regression equations shown above. As in the Total Irrigated Acres method, the greatest change in future projected diversion is in the MW/D scenario and the smallest change is in the LW/W scenario.

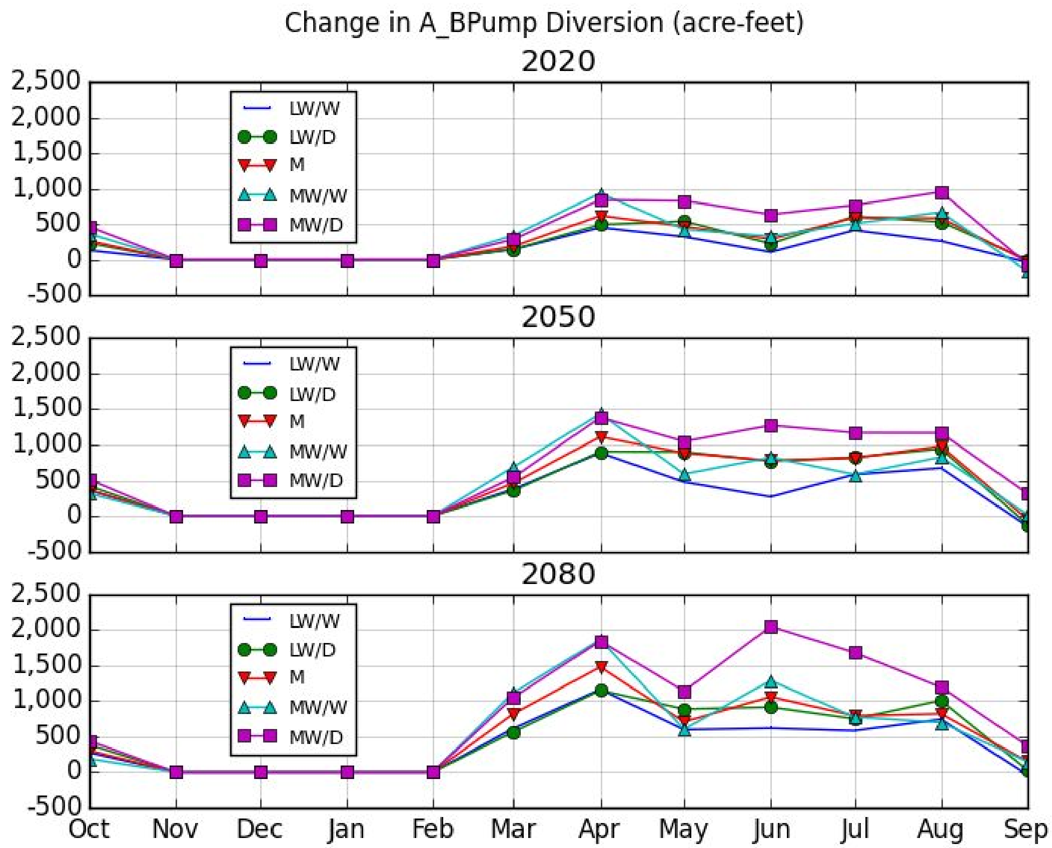


Figure 10: Average difference between the calculated future diversion and the baseline for the A_BPump water resources node for scenarios of Less Warming/Dry (LW/D), Less Warming/Wet (LW/W), More Warming/Dry (MW/D), More Warming/Wet (MW/W), and Median (M) tendency conditions.

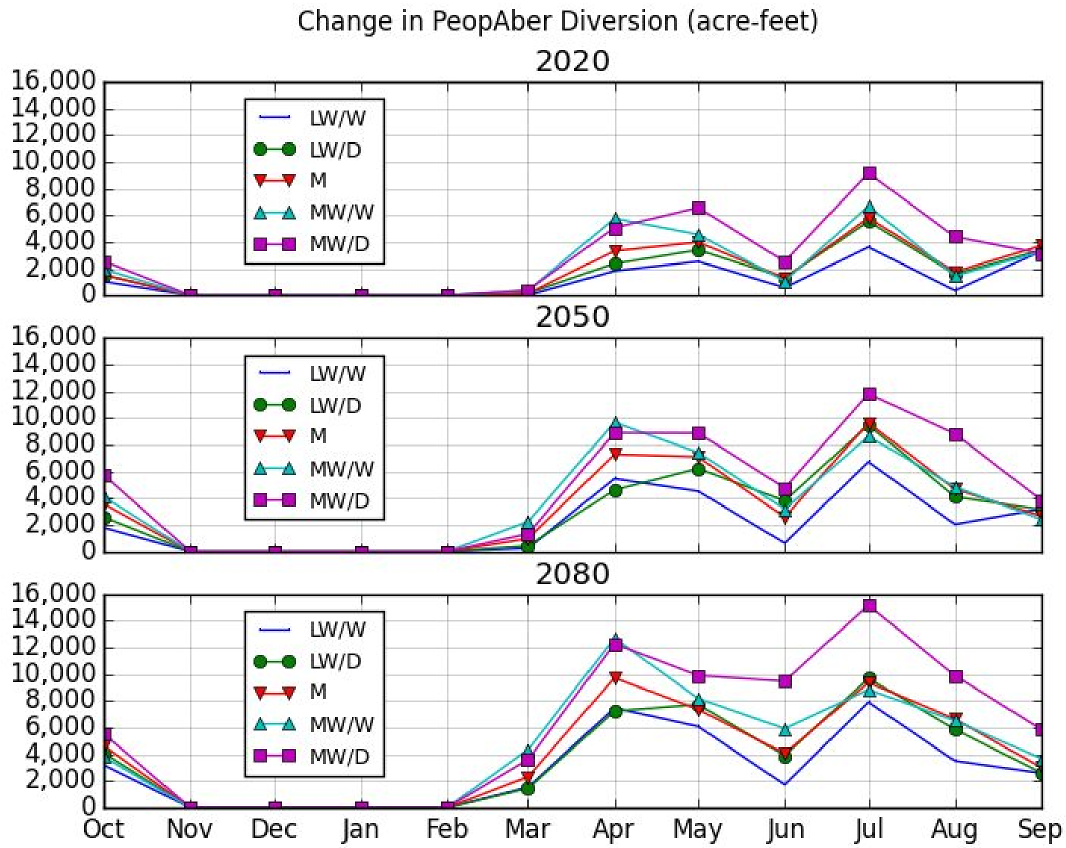


Figure 11: Average difference between the calculated future diversion and the baseline for the PeopAber water resources node for scenarios of Less Warming/Dry (LW/D), Less Warming/Wet (LW/W), More Warming/Dry (MW/D), More Warming/Wet (MW/W), and Median (M) tendency conditions.

3 DISCUSSION

Since two methods were presented as possible ways to determine future irrigation diversions for water resources models, a question may arise as to which one should be used. The Total Irrigated Acres method requires that the total number of irrigated acres is known for each water resources model diversion location. Historical water resources models are typically developed using historical diversion data, so the number of acres that are irrigated with that diversion quantity may or may not be known. If the number of acres is known, this method will provide an estimate of delivery losses, which may become important in studies of possible future conditions. With this method, losses could be adjusted to evaluate changes in delivery and irrigation efficiencies.

The Linear Regression method is a simpler method, only requiring the historical diversion information and the output from the WWCRA Demand Study. This method does not make any estimation of delivery loss since the loss is embedded in the linear regression equation.

Both methods produced similar projected future irrigation diversions for the water resources model nodes. Table 3 shows the root mean square error (RMSE) of the predicted and historical diversion data for the historical period for both water resource model nodes. It can be seen from this table that the RMSE values are similar. The ratio of the prediction of the historical diversion data of the Total Irrigated Acres method to the Linear Regression method (TIA/LR) is just over 0.9 for both nodes indicating that the Total Irrigated Acres method produces values that are slightly lower than the Linear Regression method. From these statistics developed for the two MODSIM nodes, it would appear that both methods produce results that are relatively similar. The linear regression method requires less information to developed the data (i.e. the irrigated acres are not needed for the calculation), and may be the preferred method for that reason.

Table 3: Root mean square error, r-squared, and ratio of predicted values for both methods.

Method	Node	RMSE (acre-feet)	R-squared	TIA/LR
Total Irrigated Acres	A_BPump	1,313	0.97	0.91
	PeopAber	16,513	0.93	0.92
Linear Regression	A_BPump	1,466	0.96	
	PeopAber	14,622	0.94	

The system loss portion of the irrigation diversion for these two water resources model nodes is substantial and is characteristic of Columbia River Basin irrigation delivery systems. In addition to the impacts to irrigation demand that may result from increased NIWR for crop production due to changes in temperature and precipitation under climate change, changes to the systems that increase delivery efficiency may also impact diversions and may need to be accounted for in water resource modeling efforts. This analysis assumes that the proportion of system loss remains constant while NIWR changes due to future projected climate conditions.

4 CONCLUSIONS

This technical memorandum described two possible methods for developing future irrigation diversion inputs for water resources models using projected future crop needs—the Total Irrigated Acres method and the Linear Regression method. Both methods produced similar projected future irrigation diversions. Since the Linear Regression method requires less input data, it may be considered the preferred method.

Both methods assume that current crop distribution, irrigated acres, and system losses will remain the same under future conditions. A number of tasks could be completed in the future to futher understand potential future water diversions. First, a west-wide analysis on system losses could be used to determine which systems may be more or less sensitive to changes in NIWR. Second, collection and aggregration of current irrigated lands spatial data could be collected and associated with diversion points in water resources models. This would provide more information for use in the Total Irrigated Acres Method or other more sophisticated methods for determining future agricultural water diversions. Third, methods could be developed that could be used to predict changes to crop distribution, irrigation practices, and land use that may result from future climate conditions.

5 LITERATURE CITED

Parenthetical Reference	Bibliographic Citation
Bureau of Reclamation. See Reclamation.	
IDWR 2015	Idaho Department of Water Resources. 2015. Excel spreadsheet containing irrigated acres for Eastern Snake Plain Modflow Model. https://www.idwr.idaho.gov/Browse/WaterInfo/ESPAM/model_files/Version_2.1_Current/Development_Data/Diversions/Diversions/ESPAM2_DIVS_WORK_FILE_20120116.xls (last accessed January 30, 2016).
IWRRI 2010a	Idaho Water Resources Research Institute. 2010. Irrigated Land Sprinkler Fractions for the Eastern Snake Plain Aquifer Model Version 2, As Built. IWRRI Technical Report 201008.
IWRRI 2010b	Idaho Water Resources Research Institute. 2010. Representation of Recharge from Canal Leakage for Calibration of Eastern Snake Plain Aquifer Model Version 2, As Built, Revision 1. IWRRI Technical Report 200907.
Meehl et al. 2007	Meehl, G.A., C. Covey, T. Delworth, M. Latif, B. Mcavaney, J.F.B. Mitchell, R.J. Stouffer, and K.E. Taylor. 2007. "THE WCRP CMIP3 MULTIMODEL DATASET – A New Era in Climate Change Research," Bulletin of the American Meteorological Society, 88(9), 1383–1394.
Reclamation 2010	Bureau of Reclamation. 2010. Modified and Naturalized Flows of the Snake River Basin above Brownlee Reservoir. Prepared by the U.S. Department of the Interior, Bureau of Reclamation, Pacific Northwest Regional Office, Boise, Idaho. May 2010.

Parenthetical Reference	**Bibliographic Citation**
Reclamation 2015	Bureau of Reclamation. 2015. *West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Irrigation Demand and Reservoir Evaporation Projections.* Technical Memorandum No. 86-68210-2014-01. Prepared by U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Water Resources Planning and Operations Support Group, Denver, Colorado and Desert Research Institute, Division of Hydrologic Sciences, Reno, Nevada. February 2015.
USGS 2014	U.S Geological Survey. 2014. Estimated Use of Water in the United States in 2010. U.S Geological Survey Circular 1405.

RECLAMATION
Managing Water in the West

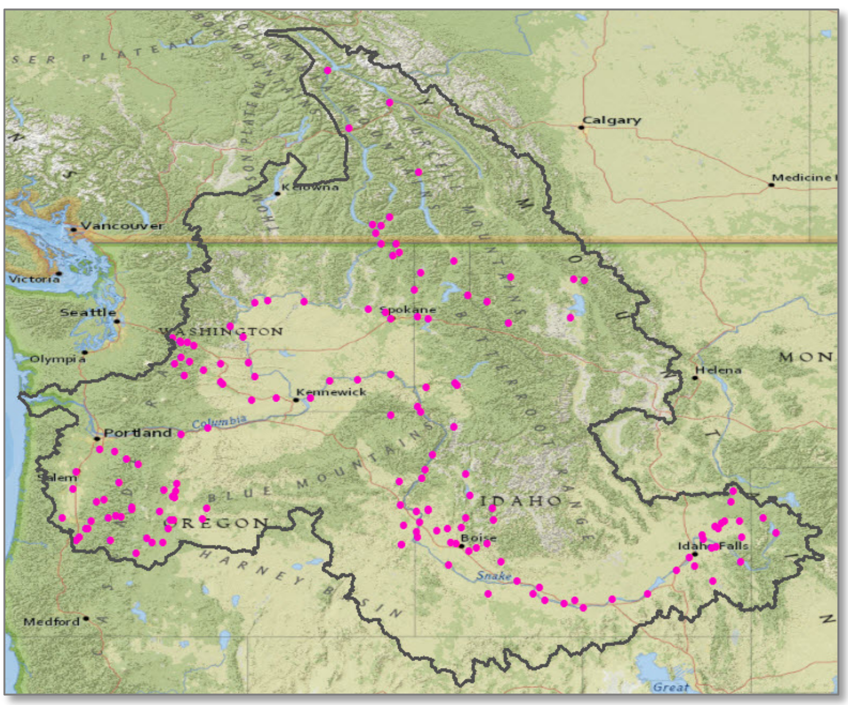
APPENDIX D

West-Wide Climate Risk Assessment

Columbia River Basin

Climate Impact Assessment

Technical Memorandum: GIS Coordination and Data Management



U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Regional Office

March 2016

Mission Statements

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.

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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1 EXECUTIVE SUMMARY

The Columbia River Basin Impact Assessment (Assessment) (under the WaterSMART Basin Study Program West-Wide Climate Risk Assessments) was initiated to establish baseline risks to water supplies and demands in Reclamation river basins and to establish a foundation for more in-depth analyses and the development of adaptation strategies. The Assessment will result in a better understanding of the potential impacts of climate change in the Columbia River Basin. This Technical Memorandum (TM) describes the development of a file-based data management strategy to organize and support sharing of climate model work. This TM also describes how the modeling outputs are managed using GIS to facilitate discovery and delivery of climate-adjusted projected streamflow data to interested parties. Projected streamflow data is available for 157 locations in the Columbia River Basin.

Internet mapping technology and web services, provided by Reclamation's Enterprise GIS, will assist interested parties in discovering and obtaining climate-adjusted projected streamflow data that is generated for the Columbia River Basin by the Variable Infiltration Capacity (VIC) model. It is notable that the file-based data management strategy, the Dublin Core metadata procedure, and delivery of data with web mapping technology can all be replicated by other Reclamation offices to conduct basin studies or similar climate impact assessments.

2 INTRODUCTION

2.1 Project Background

Reclamation is taking a leading role in assessing the risks and impacts of climate change to Western U.S. water resources, and in working with stakeholders to identify climate adaptation strategies. Adequate and safe water supplies are fundamental to the health of citizens, strength of the economy, and protection of the environment and ecology in the Western U.S. Global climate change poses a significant challenge to the protection of these resources.

Section 9503 of the SECURE Water Act, Subtitle F of Title IX of P.L. 111-11 (2009) (SWA), authorizes Reclamation to evaluate the risks and impacts of climate change in western river basins and to work with stakeholders to identify climate adaptation strategies. The Columbia River Basin was one of the major Reclamation river basins identified for evaluation in the SWA. The purpose of this Assessment is to generate reconnaissance-level hydrologic data and analysis on the potential effects of climate change in the basin, and how those effects relate to water supply and demand.

2.2 Purpose and Scope

The purpose of this TM is to document the GIS Coordination and Assistance effort included in the Assessment Scope of Work. This task was to develop a file-based data management strategy for climate modeling efforts conducted in support of the Assessment. Although much of the work involved did not fall into the traditional GIS realm, the underlying data management principles and strategies used in managing geospatial data can be applied to climate data, which is inherently geographic.

A primary task was to develop a standard file structure for climate model run files (input files, parameter files, output files, documents, etc.). A model run package contains all the component pieces required to reproduce the results or output of the model, including but not limited to: input data, model code, model parameters, intermediate or temporary files, output data, and documentation.

The file structure design is hierarchical and is organized around a combination of the following:

- Major hydrologic units – basin, subbasin, watershed

- Model category – surface hydrology, ground water, water quality, etc.

The scope included conducting a pilot project using the standardized file structure. This required coordinating with hydrologic modelers to explore reasonable approaches for restructuring existing data into the standardized file structure. Due to the modelers' time and priority constraints, this element of the scope was not completed.

The input data for the hydrologic modeling conducted in the Assessment was generated using data analysis and processing tools in the Climate Analysis Toolkit (Reclamation 2013), which was being developed concurrently in a Reclamation Science and Technology Program research project.

Another aspect of this GIS effort was to develop a basic metadata template for documenting key information about a model run and its data. In essence, the effort documented the who, what, when, where, why, and how of the data. Metadata was designed based on the international metadata standard known as Dublin Core (Dublin Core 2014). It is important to note that the products of this task can be extended to basin study projections and other climate impact assessments.

3 CLIMATE DATA MANAGEMENT

3.1 Overview

For the Assessment, climate data management centered largely on the acquisition, organization, and logical storage of thousands of digital files. A well understood data organization and file structure were important for data access and discovery, as well as to ensure data integrity. An often overlooked aspect of a standardized file structure is the inherent information provided by the structure itself.

The approach to data management used for the Assessment was designed to support replication in other Reclamation office locations, and by other climate impact assessment projects.

3.2 Source Data Acquisition and Management

Global coupled ocean-atmosphere general circulation models, or GCMs, are the key data source for all climate change analyses. Reclamation participates in partnerships with other Federal, State, and local agencies to process, store, and deliver GCM data to scientists, researchers, and interested parties. Reclamation referenced an online repository hosted by the Lawrence Livermore National Laboratory (LLNL) as the principal data resource for GCM used in the Assessment.

Reclamation and its partners provide access to this repository to all interested parties via a website. The repository contains global climate and hydrology projections from the Coupled Model Intercomparison Project Phase 3 (CMIP3) of the World Climate Research Programme. Global climate and hydrology projections from CMIP5 were added from 2010 to 2014.

Specifically, the repository contains the following:

- 112 bias-corrected, spatially downscaled (BCSD) CMIP3 projections
- 134 bias-corrected, constructed analogs (BCCA) CMIP3 projections
- 234 BCSD CMIP5 projections
- 134 BCCA (version 2) CMIP5 projections
- Routed streamflow projections for 97 sites

Visitors to the website will find a web interface designed to allow them to select and build a data package based on the following choices, as shown in Figure 1:

- Time period ranging from 1950 to 2099
- Geographic extent
- Products, variables, and projections
- Analysis, such as statistics spatial mean, and spatial standard deviation
- Download format in NetCDF or comma-delimited text files

The site can be found at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/#Welcome

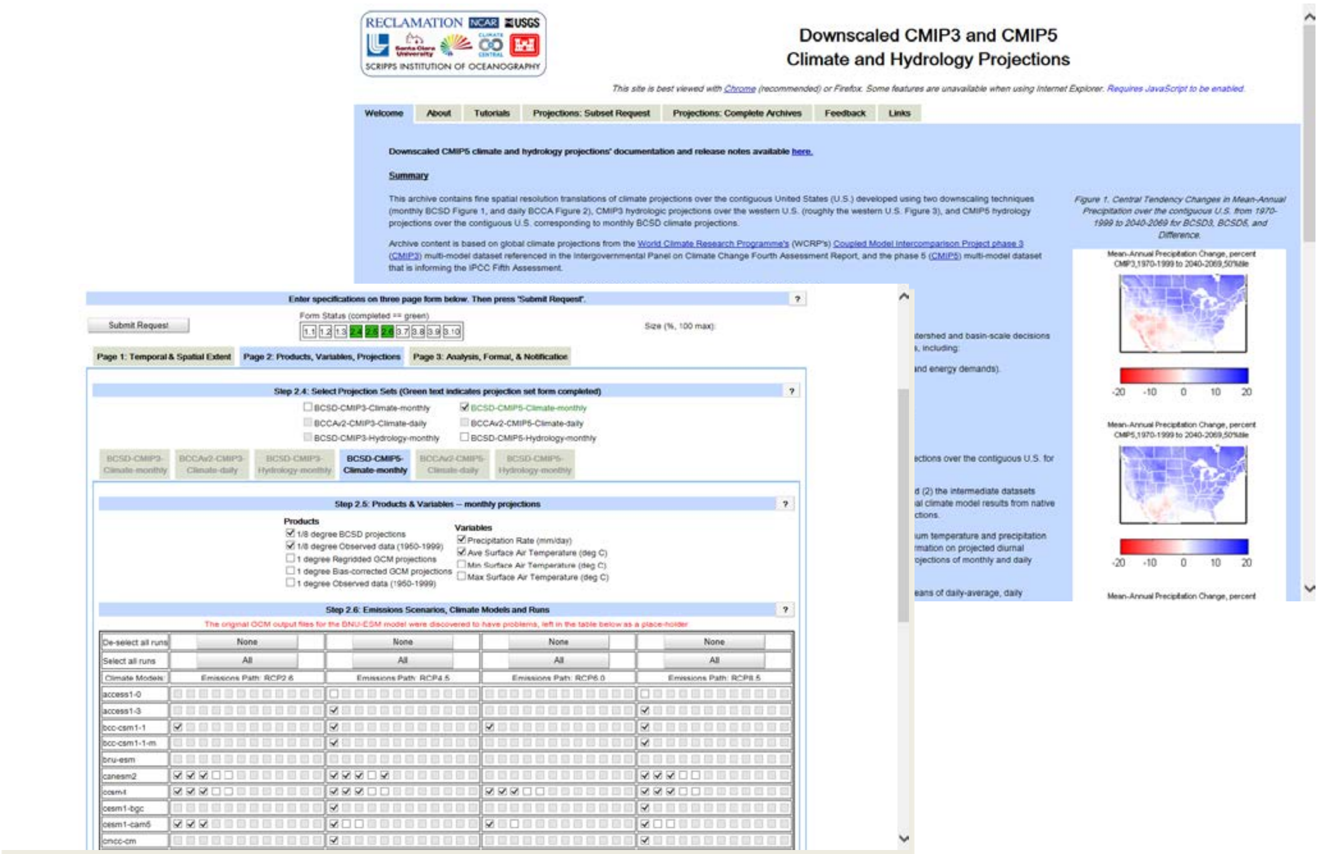

Figure 1: Lawrence Livermore National Laboratory Website Showing Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections.

3.3 File-Based Data Management Strategy

One of the challenges facing hydrologic and hydraulic modelers is managing the complex and voluminous array of digital files associated with configuring and running a model. Modelers mostly manage their files to suit their own needs, which may or may not be comprehensible by another modeler. This approach is generally considered adequate because typically only the output products of modeling are shared with others. However, the Assessment presented a need to share models in their entirety with others in Reclamation, and potentially partners and other interested parties. To meet this requirement, a standardized file organization and structure with naming conventions was developed for the Assessment.

GIS staff collaborated with modelers to explore existing file management approaches to determine common practices or conventions that should be incorporated into a standardized file-based data management strategy. The first step was to determine the most logical, or most easily understood, top tier for the structure. Models have a number of high-level characteristics that could serve in this capacity, including:

- Geographic extent
- Type of model – hydrologic, climate (VIC, DHSVM), ground water, etc.
- Associated office or organizational unit
- Model run date

The top tiers of the file structure were identified through a series of meetings with modelers. The top-level is the major organization context, in this case, the Pacific Northwest Region. This tier is necessary to support consolidation of data at the Bureau level, if needed. The next two tiers describe the general type of modeling and the general geographic extent. The subsequent level in the structure is the top of a model run. For the model run, the structure then breaks down into a standard, but flexible folder structure as shown in Figure 2.

Model Packages

A convention for naming the folder containing a model run and all its associated files makes it possible to create model packages for easy sharing with interested parties. This is accomplished by using a file compression utility, like WinZip, to create a single file containing the complete content of a model run.

The name of the zip file uses the names of the top three folder tiers along with the model folder as shown in the example below:

PNRegion_ClimateModel_ColumbiaRiverBasin_VIC224_20130413.zip

Although the zip file can be somewhat large, it contains the complete file structure and all the files necessary for another person to evaluate and run the model.

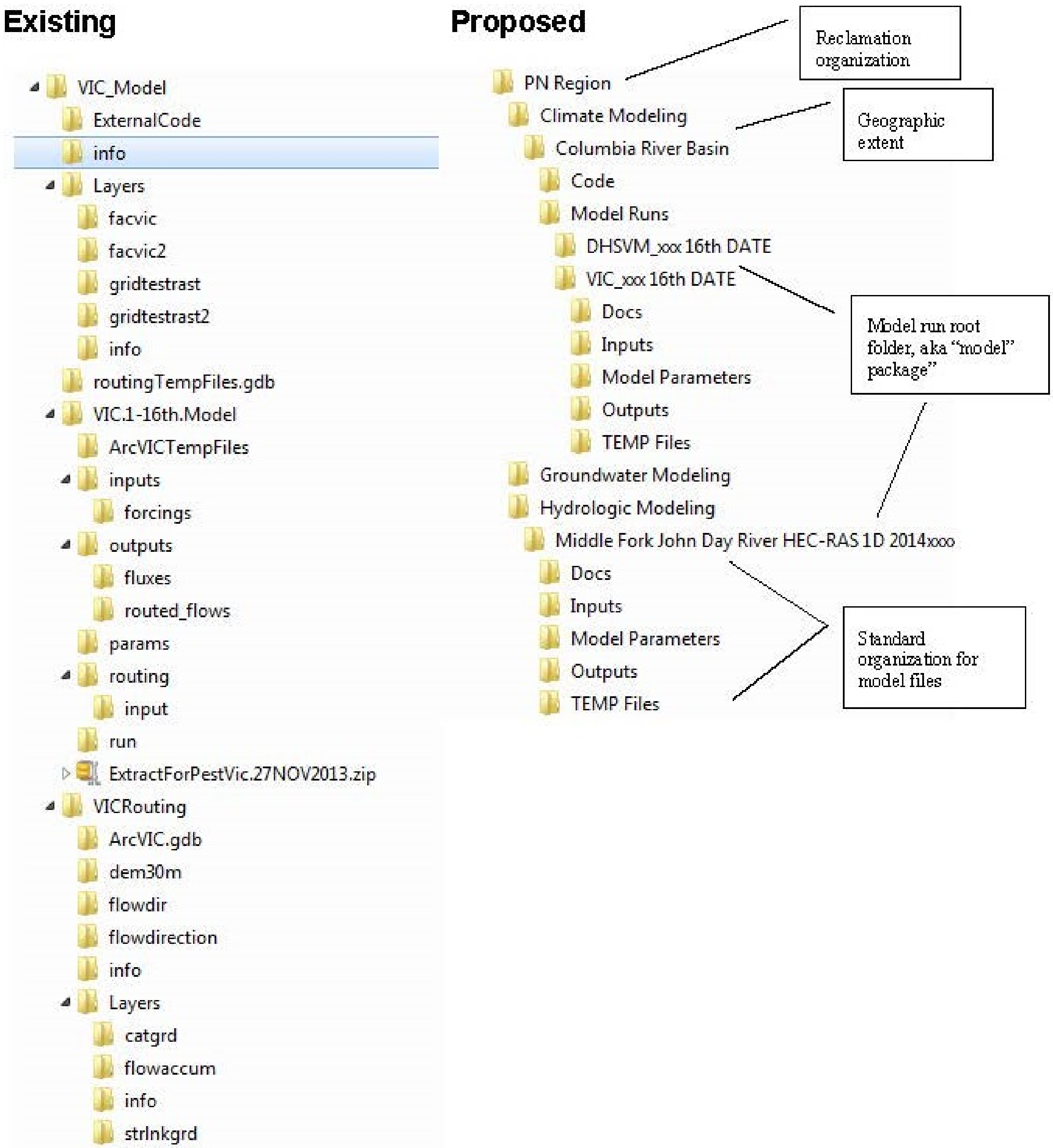

Figure 2. Climate and Hydrologic Model Data Storage Structure

A set of best practices were developed for implementing the standardized file structure and to provide guideance for naming. These include the following:

1. Use additional subfolders as needed under main folders to organize.

   Example: \Output
   \Model output
   \Derived products

2. Use descriptive *geographic name* + *model name* + *yyyymmdd* for model run folders and file package names.

3. Copy metadata files for resources used by the model to the \Input folder, if input is used by multiple models. Note that resource metadata files need to indicate data storage location.

4. To transfer a model package, use file compression utility (e.g., WinZip) to zip the model run folder, and use the top tier folder names and the folder's name as the zip filename. Delete the zip file after it is copied to portable media.

3.4 Metadata for Hydrologic Models

Metadata for model products are not typically created because modelers generally do not need to share final model data products. Model output is usually summarized in a report in the form of charts, graphs, and tables, and then the metadata are provided in the report. However, for the Assessment, models needed to be shared in their entirety. In this case, metadata were needed to accompany the model and its numerous files.

It is not feasible to repair individual metadata records for all the files typically associated with a single model run and even creating metadata for output data products is onerous. Therefore, a solution was devised in collaboration with the modelers that made the task of creating metadata manageable. The solution was to leverage an international metadata standard known as Dublin Core. This international metadata standard was chosen because of its flexibility and simplicity. The main requirement for metadata for climate models and their numerous associated files is to provide users with sufficient information to determine if the data meets their needs along with links to access additional information. The complexity and many required elements not relevant to climate modeling made metadata standards, like the Content Standard for Digital Geospatial Metadata or ISO 19115:2003 Geographic Information, infeasible for use in the Assessment. The Dublin Core standard also has the advantage of being widely used and is supported by online resources.

The relative simplicity and availability of an online metadata creation tool made Dublin Core the best candidate for the Assessment. A standard procedure was developed to assist modelers in using the online tool to create metadata records to accompany model output, as well as other important model files that may be shared. The procedure document describes each metadata element and provides examples for documenting information about model and version, grid cell size, selected ensembles and/or projections, data/time of run, contact information for the modeler, data storage location, links to more detailed technical documents, and related information.

The metadata elements and procedure for creating standard metadata for climate and hydrologic models is provided in Appendix 1.

3.5 Climate Analysis Toolkit and HydroDesktop

The selection and pre-processing of GCM data in preparation for climate modeling work conducted for the Assessment was accomplished using a combination of GIS and statistical analysis tools. The GIS task of the Assessment leveraged the Climate Analysis Toolkit, which was being developed under a concurrent Reclamation Science and Technology Program research project (Reclamation 2013). Statistical data processing scripts developed by climate modelers in the PN Region were incorporated into the Climate Analysis Toolkit. This software is built as an extension to the open source GIS software named HydroDesktop (CUAHSI 2010). With input from PN Region modelers, a set of software tools were developed to analyze GCMs into clusters of projections, or ensembles, to characterize precipitation and temperature change into major tendencies to enhance the signal in the data, as shown in Figure 3.

The ensembles represent the following five scenarios:

- Less Warming Wetter (LW/W) – a cluster of 10 future projections around the 20^{th} percentile of temperature and 80^{th} percentile of precipitation;
- Less Warming Drier (LW/D) – a cluster of 10 future projections around the 20^{th} percentile of temperature and 20^{th} percentile of precipitation;

- Median (M) – a cluster of 10 future projections around the 50th percentile of temperature and 50th percentile of precipitation;
- More Warming Wetter (MW/W) – a cluster of 10 future projections around the 80th percentile of temperature and 80th percentile of precipitation; and,
- More Warming Drier (MW/D) – a cluster of 10 future projections around the 80th percentile of temperature and 20th percentile of precipitation.

For each ensemble, the Climate Analysis Toolkit was then used to generate forcing files for each of five scenarios of future temperature and precipitation conditions to characterize the future climate in each the following 30-year periods:

- 2010 through 2039
- 2030 through 2059
- 2050 through 2079
- 2070 through 2099

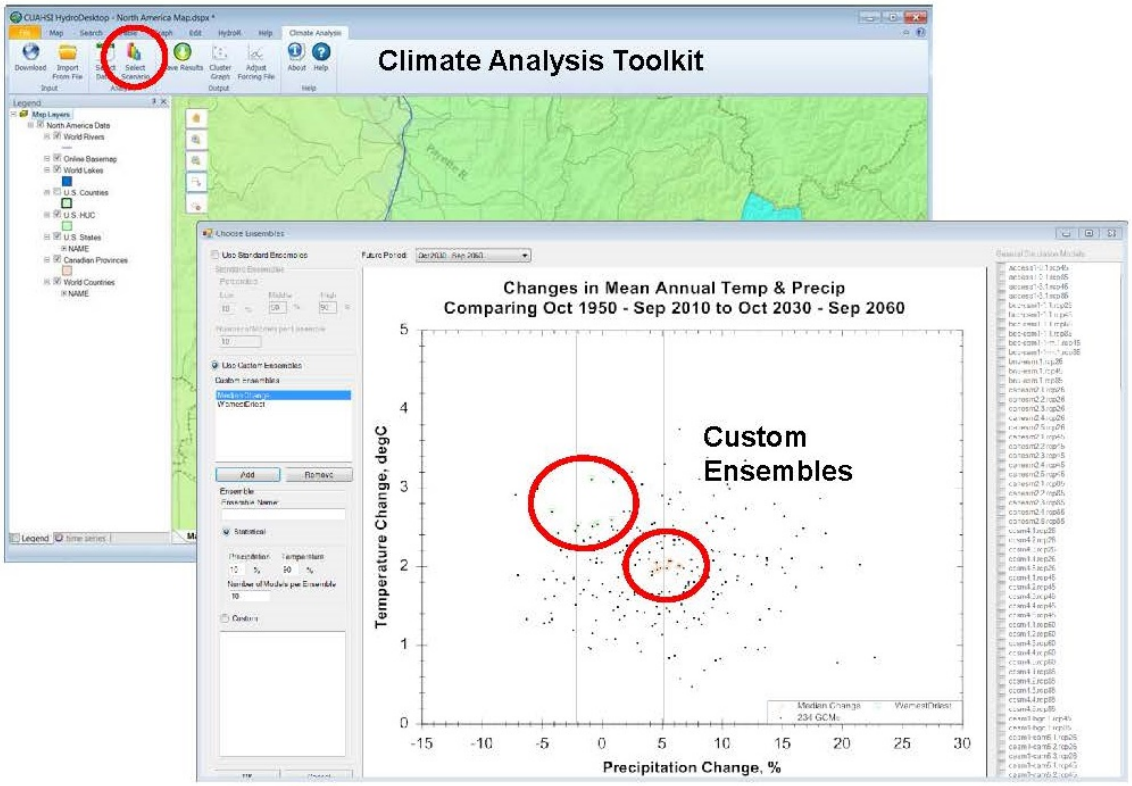

Figure 3: Processing Ensembles of GCMs

The cluster graph (Figure 3) displays all of the GCMs based on the relative change in precipitation and temperature that each represents for the selected period. The ensembles are defined based on the values provided in the user interface. For the Assessment, the previously described five ensembles of 10 projections were selected and processed.

The Climate Analysis Toolkit was then used to create a set of output files of the ensembles based on the selections made in the Create Files dialog shown in Figure 4. For the Assessment, the Hybrid Delta Ensembles were selected. Output files consist of:
1) Ensemble, the data files; 2) Projection Summary, a summary list of the GCMs in each ensemble; and 3) the Cluster Graph. The Ensemble files are generated according to each method selected. The Projection Summary and Cluster Graph files are useful for documenting the selection of GCMs for use in hydrologic models.

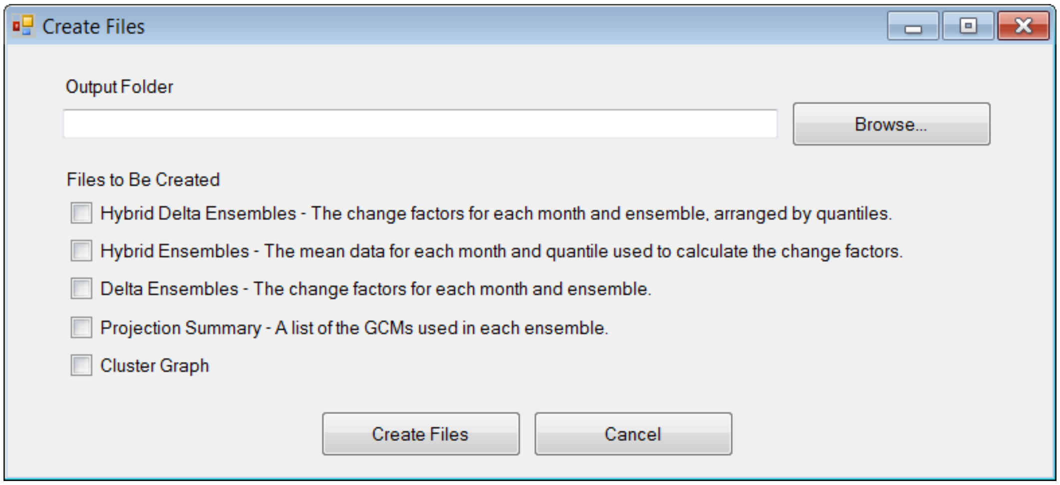

Figure 4: Generating Output Files

The Hybrid Delta Ensemble files were then processed into input files according to the selected hydrologic model as shown in Figure 5. For the Assessment, the selected model was the VIC model. This tool generates the forcing files in a model-compatible format to be used as input in a model run.

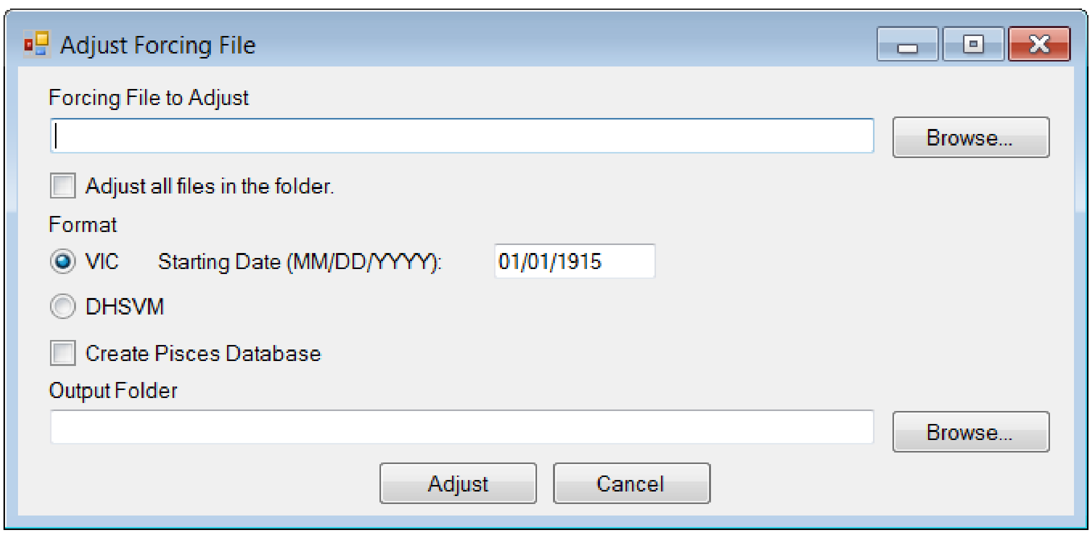

Figure 5: Creating Forcing Files

The forcing files generated for the selected model and ensembles were copied into the appropriate location in the model folder structure and ready for use in the model run. The results of the VIC models are climate-adjusted streamflow projection files, which are described in the next section.

4 STREAMFLOW PROJECTIONS DATA

One of the major data products of the Assessment is the climate-adjusted streamflow projections generated from the VIC model run for the Columbia River Basin. The model run generated streamflow projection data for 157 locations across the region shown in the figure on the cover page of this Technical Memorandum. For each location, there are modeled streamflow projections data for the five ensembles for each of the four future periods previously described.

The streamflow projection data are made available to Reclamation staff and other interested parties through a web mapping application titled *Streamflow Projections for the Western United States* (http://gis.usbr.gov/Streamflow_Projections). The web mapping application provides online access to climate-adjusted streamflow projection data in zipped files organized by the four future periods. The web mapping application also provides online access to streamflow projection data processed using CMIP3 climate models for 300+ sites in the western U.S. completed in 2012.

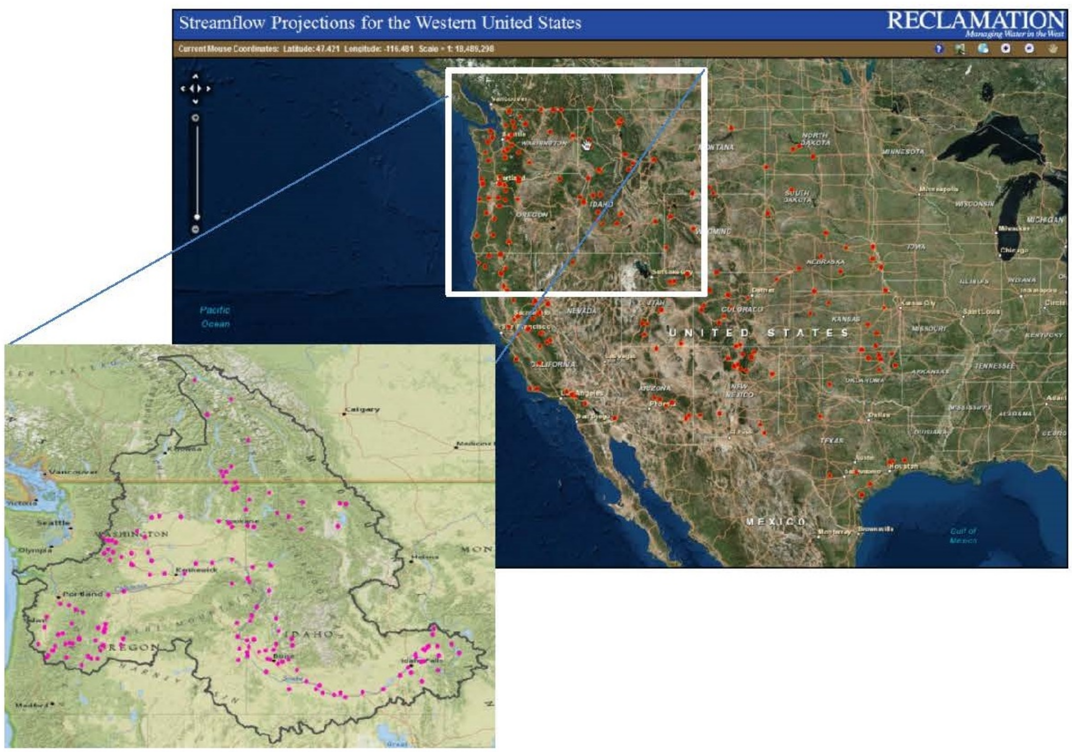

Figure 6: Streamflow Projection Data for the Assessment

The streamflow projection data files are accessed by clicking on the site locations on the map. A popup window appears that displays the files available for download. Files are downloaded by double-clicking on the file name.

5 LITERATURE CITED

Parenthetical Reference	**Bibliographic Citation**
Bureau of Reclamation.	See Reclamation.
Dublin Core 2014	Dublin Core Metadata Initiative. 2014. http://dublincore.org (last accessed November 5, 2015).
Reclamation 2013	Bureau of Reclamation. 2013. Science & Technology Program, Project x9449, *Design and Development of a Prototype Tool for Integrated Climate Downscaling and Streamflow Prediction Using Open Source GIS Software*. R13AS10009.
CUAHSI 2010	HydroDesktop. 2010. Consortium of Universities for the Advancement of Hydrologic Science Inc. http://his.cuahsi.org/hydrodesktop.html (last accessed November 5, 2015).

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6 APPENDIX

Procedure and Guide for Creating Standard Metadata for Climate and Hydrologic Modeling Projects

1. Use Dublin Core metadata elements as reference:

   http://dublincore.org/documents/usageguide/elements.shtml

2. Use Dublin Core Generator online metadata application to create records:

   http://www.dublincoregenerator.com/generator.html

3. Save the metadata record as a XML file in the modeling folder structure

Dublin Core metadata elements

Title

Title + Model (version) + Run + Date

For example: Columbia River Basin VIC 4.1.1 Run 1 20141029

Creator

Name and contact information of person who setup and ran the model

For example: John Doe
Bureau of Reclamation, Pacific Northwest Region
Boise, ID

Subject (one or more instances)

Type of model, name and version

For example:
Hydrologic model
VIC 4.1.2

Description

Describe in reasonable detail the key characteristics of the model project. In particular, cite the input data and how they were processed, and summarize key configuration decisions and parameters choices, any assumptions made, etc. In brief, describe all the things one would want to know about the model.

For example:

VIC model run for Columbia River Basin Impact Assessment. The model used bias-corrected, spatially downscaled CMIP5 climate models obtained from the Lawrence Livermore National Laboratory online repository. The model also used calibrated soils data. Initial conditions were established by running the model from 1950-1979 using historical and climate change adjusted forcing files for 1980-2009. The model generated routed streamflow projections for the periods 2010-2039, 2030-2059, 2050-2079, and 2070-2099. Refer to README!.pptx files in the project files.

Publisher

Bureau + Region

For example: Bureau of Reclamation, Pacific Northwest Region

Contributor (one or more instances)

Entity Name (any organization that contributed)

For example: Lawrence Livermore National Laboratory

Date

Date of model run

For example: 10/29/2014

Type (one or more instances)

Describe the type of content. For modeling projects this is typically multiple.

For example:

Collection (indicates that there are multiple pieces like the many output files)

Dataset (indicates there are data)

Software (indicates software is included as part of the project)

Format (one or more instances)

Describe the format(s) type of content.

For example: ASCII text files, XML parameters

Identifier

A unique resource reference typically managed by a content or data management system. Reclamation does not have anything that would generate an identifier. This can be treated as a placeholder.

Coverage (one or more instances)

Describe the geographic extent of the model.

Descriptive geography

For example: Columbia River Basin

Bounding rectangle (decimal degrees)

For example: 41.10, -126.25, 49.75, -109.55

Source (one or more instances)

List the main sources of input data.

For example:

BCSD CMIP5 climate projections, Lawrence Livermore National Laboratory

Language (one or more instances)

List the language(s) of the content. [Just part of the standard]

For example: English

Relation (one or more instances)

Describe the relationship of this content to other content. [At this point, this element is a placeholder in the event that the components of a model project are separated. At that point, the separated content (e.g., output files) should have its own metadata record indicating it "is part of" this record.]