# DRAFT Climate and Hydrology Datasets for Use in the River Management Joint Operating Committee (RMJOC) Agencies' Longer-Term Planning Studies

## Part IV – Summary

U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Regional Office
Boise, Idaho
Technical Service Center
Denver, Colorado

U.S. Army Corps of Engineers
Northwestern Division
Portland District
Portland, Oregon

Bonneville Power Administration
Portland, Oregon

June 2011

*Photographs on front cover: American Falls Dam on the Snake River, Idaho, operated by the Bureau of Reclamation; The Dalles Dam on the Columbia River, Oregon, operated by the U.S. Corps of Engineers; and Bonneville Lock and Dam on the Columbia River, Oregon, operated by the U.S. Corps of Engineers.*

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- Bureau of Reclamation, Pacific Northwest Region: Patrick McGrane, Toni Turner, Chris Lynch, Ted Day, Jennifer Johnson, Sharon Parkinson, Bob Lounsbury, Carol Kjar, and Lori Postlethwait
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- Northwest Power and Conservation Council
- Columbia River Inter-Tribal Fish Commission
- BC-Hydro
- U.S. Fish & Wildlife Service
- National Oceanic and Atmospheric Administration, National Marine Fisheries Service
- University of Washington Climate Impacts Group
- Oregon Climate Change Research Institute
- Natural Resources Conservation Service

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# 1.0 INTRODUCTION

The Bureau of Reclamation (Reclamation), U.S. Army Corps of Engineers (USACE), and Bonneville Power Administration (BPA) pooled resources and collaborated on the adoption of an array of climate change and hydrology datasets and modeling efforts in support of their longer-term[1] planning activities in the Columbia River Basin. This collaboration also included input from the following stakeholder agencies so that their perspectives could be incorporated during the scoping and application of methods featured in this analysis:

- U.S. Fish and Wildlife Service
- National Oceanic and Atmospheric Administration, National Marine Fisheries Service
- Northwest Power and Conservation Council
- British Columbia-Hydro
- University of Washington Climate Impacts Group
- Oregon Climate Change Research Institute
- Oregon State University
- Natural Resources Conservation Service
- Columbia River Inter-Tribal Fish Commission

The RMJOC agencies hosted a series of technical workshops during the course of the study where the preliminary results and upcoming methodologies were discussed. Feedback was gathered from the stakeholders during those workshops and incorporated as part of the study.

This effort was led by the River Management Joint Operating Committee (RMJOC), a forum of water managers, hydrologists, and power schedulers from Reclamation, USACE, and BPA. The RMJOC meets regularly and evaluates operational and/or infrastructure actions that may impact Federal dam operations in the Pacific Northwest. Studying the benefits and effects of these actions requires making assumptions about future hydrology and water supplies, future water demands, and operational constraints that would affect system operations and management of water supplies.

Traditionally historical climate data has been used when evaluating proposed actions; however, there is growing evidence that the global and regional climate system is changing and is expected to continue changing (IPCC 2007). The RMJOC agencies' management of system facilities necessitates incorporating future climate change projection information into longer-term assessments.

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[1] "Longer-term" refers to 10 years or more in the future.

This study focuses on how climate change could impact hydrology and water supplies, and how supply-related impacts may affect the facility operations conducted by the three RMJOC agencies (Figure 1). Climate change effects on water demands and operating constraints are being assessed in ongoing research and potential follow-up collaboration.

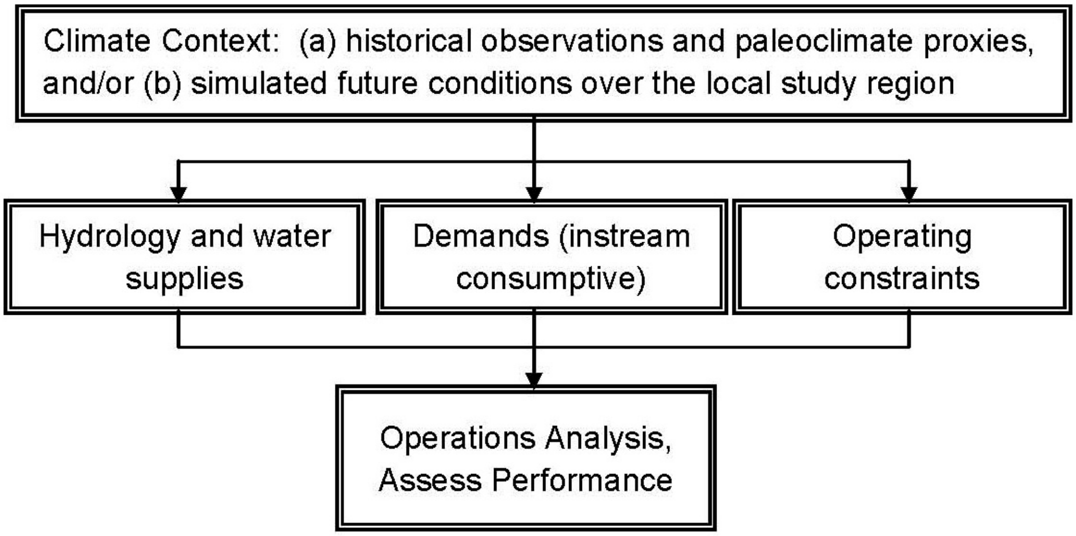

**Figure 1. Flow chart illustrating the role of climate in long-range operations assessments.**

This study, called *Climate and Hydrology Datasets for use in the RMJOC Agencies' Longer-Term Planning Studies* (Figure 2) has produced the following reports:

- Part I Report – Future Climate and Hydrology Datasets (completed December 2010)
- Part II Report – Reservoir Operations Assessment – Reclamation Tributary Basins (completed January 2011)
- Part III Report – Reservoir Operations Assessment – Columbia Basin Flood Control and Hydropower (completed June 2011)
- Part IV Report – Summary Report (this report)

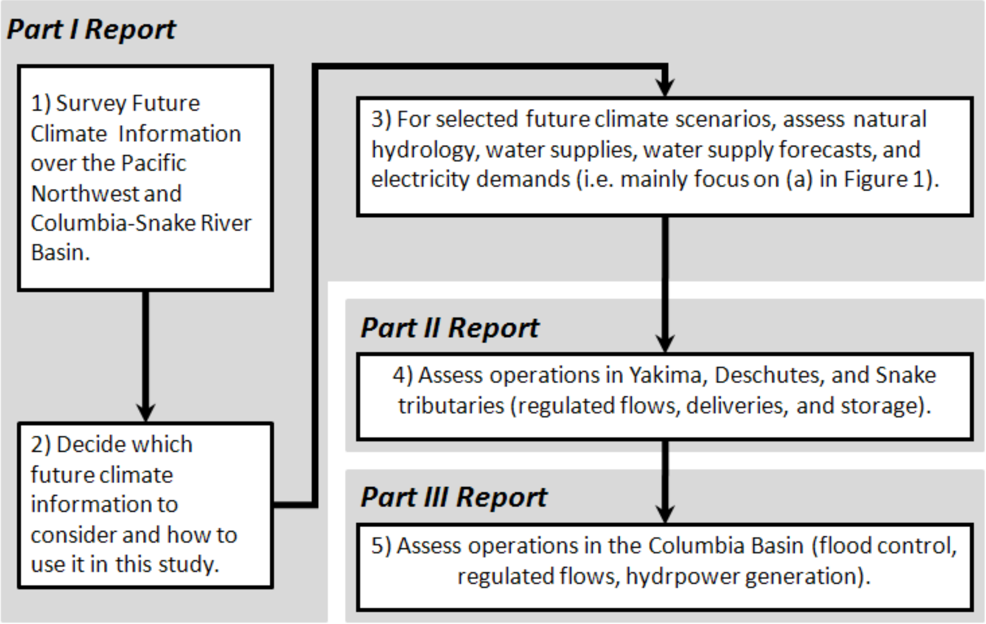

**Figure 2. Flow chart on how future climate and hydrology were defined for this assessment.**

The Part I Report focused on RMJOC's adoption of future climate and hydrology data from the University of Washington's Climate Impacts Group (CIG), the evaluation of those data, and the development of the associated water supply forecast series to reflect future hydrologic and climate conditions.[2] The Part II Report focused on Reclamation's simulation models of project operations in the Yakima, Deschutes, and Snake River subbasins (the subbasins in the study area with existing long-term functional reservoir models) and presented the results of the operational analyses conducted using the future climate and hydrology datasets described in the Part I Report. The Part III Report, which used output from the analyses completed for the Part II Report, took the existing flood control storage reservation diagrams in combination with projected future runoff and assessed the impacts of climate change on the Federal Columbia River Power System using BPA's power model. The Part I, II and III reports can be found in the appendix to this report. This Part IV Report summarizes the completed analyses and results from the more technical Parts I through III. The results are not meant to be construed as findings on future operational vulnerabilities that depend on stresses other than climate. Potential alternative future operations strategies that might offset such impacts were not considered for this study.

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[2] The term "Columbia-Snake River Basin" found in the Part I and Part II Reports was changed to "Columbia River Basin" in the Part III and Part IV Reports.

# 2.0 SUMMARY OF PART I: FUTURE CLIMATE AND HYDROLOGY DATASETS

The Part I report is the foundational document that contained a review of the recent studies focusing on past or future climate change over the Columbia River Basin and the implications for hydrology, water resources, and environmental resources. Historical climate trends over the Columbia River Basin were shown, indicating the presence and degree of climate change that appears to have occurred. Available future climate and hydrology data over the Columbia River Basin was surveyed for use in this RMJOC effort and an explanation of why this effort ultimately focused on using the University of Washington CIG House Bill 2860 (HB2860) information was given (see Section 2.1).

The University of Washington CIG HB2860 climate and hydrology data was further distilled, leading to the selection of a smaller subset of future climate and hydrology scenarios for use in RMJOC long-range assessments. The RMJOC future climate and hydrology scenarios represent a reasonable range of future conditions throughout the Columbia River Basin and reflect corrections for hydrology model biases (or error tendencies). A methodology was developed for estimating future water supply forecasts in the context of future climate and hydrology conditions, followed by application of this scheme in scenario development.

The Part I Report focused on the major subbasins in the Columbia River Basin (Figure 3). A review of this information at a basin-average scale shows that temperatures and precipitation have increased throughout the Columbia River Basin (Figure 4).

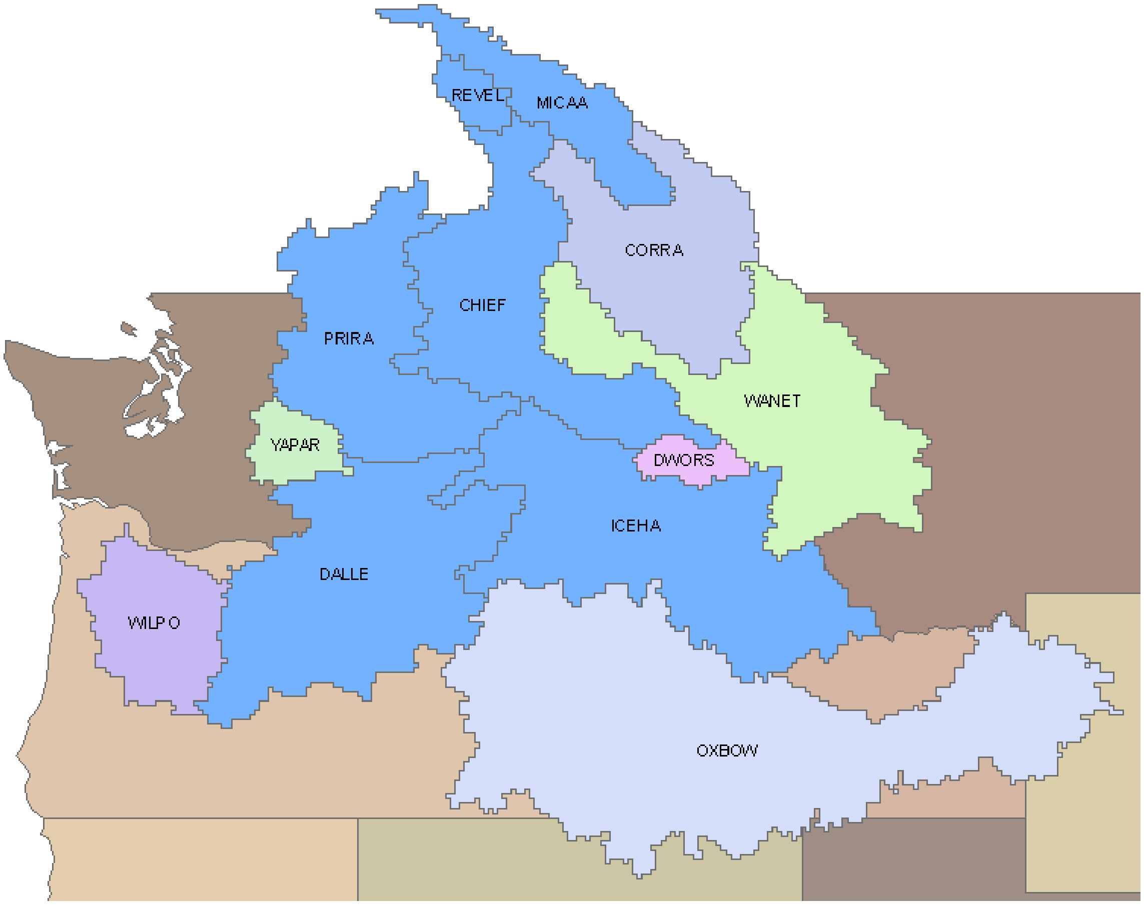

**Figure 3. River subbasins included in this study: Columbia River at Chief Joseph Dam (CHIEF), Kootenay River (CORRA), The Dalles (DALLE), North Fork Clearwater River (DWORS), Ice Harbor (ICEHA), Columbia River at Mica Dam (MICAA), Snake River (OXBOW), Columbia River at Priest Rapids Dam (PRIRIE), Revelstoke (REVEL), Flathead River (WANET), Willamette River (WILPO), and Yakima River (YAPAR).**

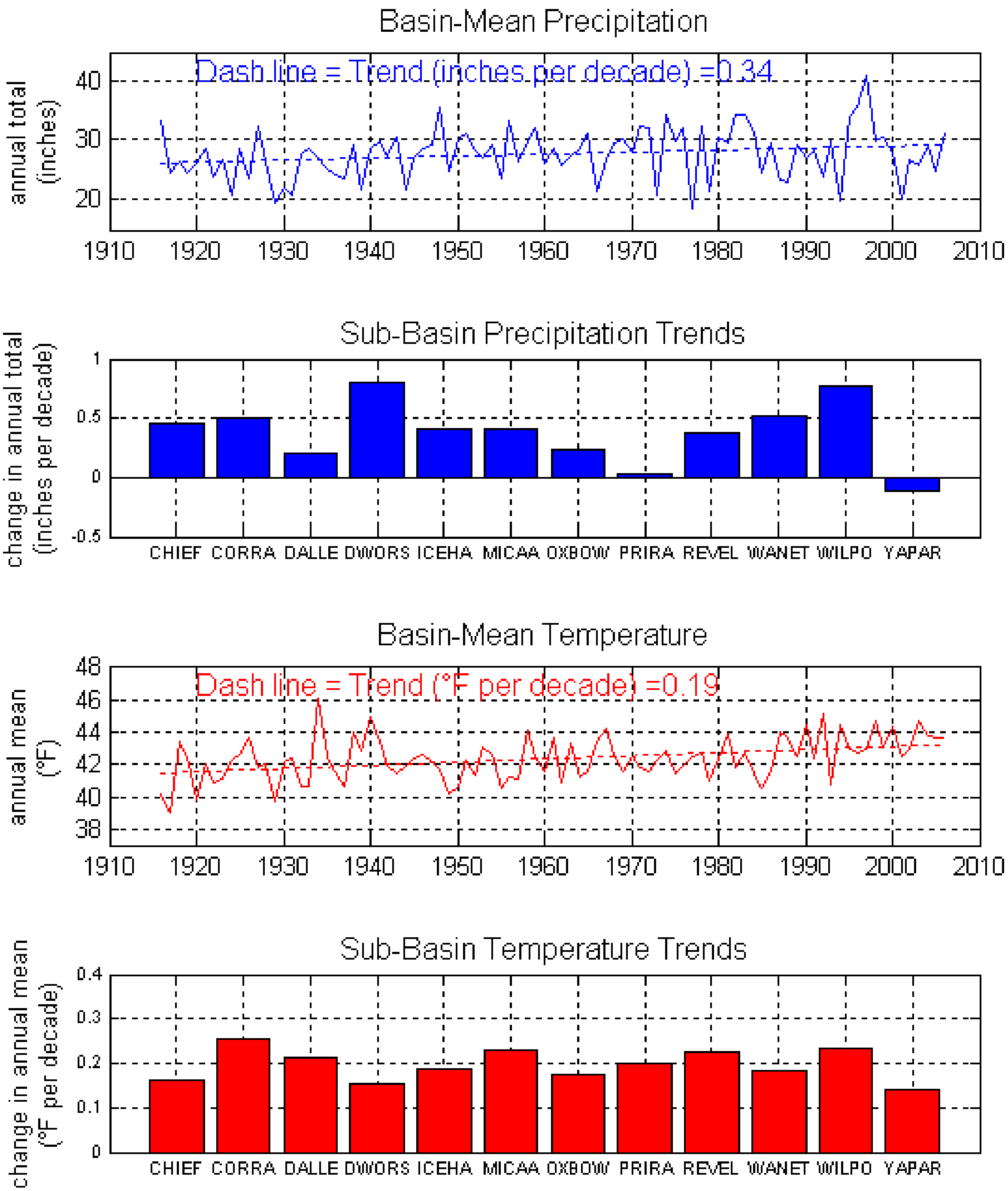

**Figure 4. Observed historical climate over the Columbia River Basin for Water Years 1916-2006: Columbia River at Chief Joseph Dam (CHIEF), Kootenay River (CORRA), The Dalles (DALLE), North Fork Clearwater River (DWORS), Ice Harbor (ICEHA), Columbia River at Mica Dam (MICAA), Snake River (OXBOW), Columbia River at Priest Rapids Dam (PRIRIE), Revelstoke (REVEL), Flathead River (WANET), Willamette River (WILPO), and Yakima River (YAPAR).**

Assessments on climate change science and summaries of contemporary climate projections have been conducted by international, national, State, and private organizations. In general, the results show that many components of the historical climate system are now changing, including the temperatures of the atmosphere, land, and oceans; the extent of sea ice and mountain glaciers; sea levels; the distribution of precipitation; and the length of seasons. Numerous studies have been conducted on the potential consequences of climate change for water resources in the Columbia River Basin. In general, these studies found that between 1970 and 1998, temperatures in the western United States increased (Cayan et al. 2001) and snowpack and snowfall ratios decreased from 1948 to 2001 (Knowles et al. 2007). Almost all climate change studies have indicated that, in general, temperatures are expected to continue to increase above historical levels.

Future trends in precipitation are less conclusive than future temperature trends in the Pacific Northwest. Projected changes in the mean annual precipitation averaged over all models are small, but some models projected an enhanced seasonal precipitation cycle with changes toward wetter autumns and winters and drier summers. These climate changes will impact hydrology, particularly regional snowpacks and runoff seasonality (Elsner et al. 2010), which in turn will influence water resources management. Peak flows will occur earlier in the year, possibly necessitating earlier drawdowns[3] of the reservoirs. Balancing the changes in the peak flow timing with water needs during the summer months when there are warmer temperatures and reduced flows may require changes in the operational procedures of the projects.

## 2.1 Future Climate Change Scenarios Selection

The RMJOC considered several general circulation models (GCMs)[4] and emission forcings[5] to generate climate change projections for use in this study (see the Part I Report for details).

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[3] 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.

[4] General Circulation Models are mathematical models of the atmosphere around our rotating planet. These complex computer programs account for the fluid motions, thermodynamics, chemistry, ocean current influences, water vapor, and other physical components that determine the earth's climates.

[5] Forcings are changes in the earth's atmosphere caused by natural or anthropogenic events that alter the amount of solar energy reaching the planet's surface. Changes in the atmosphere caused by greenhouse gases cause the lower atmosphere and surface of the earth to heat up. Estimates are then made by scientists about the level of emissions anticipated in the future based on natural and anthropogenic behavior and ranges are developed for use in the General Circulation Models.

Climate projections were spatially downscaled[6] for the Pacific Northwest region. Such downscaled climate projections served as the foundation for the future climate and hydrologic scenarios obtained from the University of Washington CIG. In 2006, the Washington State Legislature passed HB2860 authorizing the development of a Columbia River Water Supply Inventory that must be updated every 5 years. Washington Department of Ecology and the University of Washington CIG worked together to downscale climate projections for the development of climate and hydrologic modeling programs specific to the Columbia River Basin.

The RMJOC technical team conducted watershed simulation modeling analyses to translate the University of Washington CIG HB2860 downscaled climate projections into Columbia River Basin hydrologic runoff at select locations. To manage the amount of future climate and hydrology information for long-range assessments, RMJOC selected a small subset of the University of Washington CIG HB2860 scenarios that reflected a range of climate change estimates over the Columbia River Basin during the early 21st century (2019-2039 or “2020s”) and the middle 21st century (2030-2059 or “2040s”), as well as time-evolving estimates that reflected the possible future period 1950 through 2099. These scenarios featured the most spatially downscaled future climate characterized over the Columbia River Basin while representing a broad range of climate change projections. More significantly, the scenarios contained simulated Columbia River Basin hydrology under these future climate conditions.

A range of scenarios[7] framing the central estimate (the 50th percentile estimate) for both future periods (2020s and 2040s) was also selected, for example:

- Scenarios concerning greenhouse gas emissions that influence future global and Pacific Northwest climate
- Scenarios of future Pacific Northwest climate that influence Columbia River Basin hydrologic analyses
- Scenarios of future Columbia River Basin natural runoff that influence future RMJOC operations

For future climate and hydrology scenarios over the Pacific Northwest, the University of Washington CIG developed several types of scenario information, two of which were considered in this effort: Hybrid Delta scenarios and Transient scenarios. For the Hybrid-Delta assessment of the impacts on operations, a 30-year simulated historical climate change

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[6] Spatial downscaling is the process of taking global climate model output and translating it to a smaller spatial scale that is more meaningful for analyzing local and regional climate conditions.

[7] The term scenario refers to an assumption about future conditions. The combinations of climate change scenario influences and the simulated climate responses to them are called climate projections.

was used to compare to two projected future climate conditions. For the Transient scenario, a time-evolving period from 1950 to 2099 was used. This study focused only on supply-related changes. No changes to metrics such as demands or flood control curves[8] were made. As a result, a future assessment on how changing these and other metrics due to climate change should be considered in the future.

### 2.1.1 Hybrid-Delta Scenarios

The Hybrid-Delta (HD) scenarios reflect changes in climate from a simulated historical period to a projected future period. To keep the amount of future climate and hydrology information manageable for RMJOC long-range assessments, a small subset of HB2860 scenarios was selected for use. The subset was chosen so that it reflected central climate change estimates (50 percentile) over the Columbia River Basin during the early 21st century (2010-2039, or "2020s") and middle 21st century (2030-2059, or "2040s") as well as a range of climate change possibilities framing the central estimate for both future periods (e.g., the 10 and 90 percentiles in addition to the 50 percentile). This type of scenario is useful in exploring how reservoir operations would respond to climate changes because the frequency information from the reference climate remains closely tied to the historical weather and hydrology conditions (i.e., reoccurrence of relatively wet or dry, or warm or cool, conditions).

Selection of the HD scenarios for the 2020s and 2040s was made by defining the following parameters based on perspectives gathered from RMJOC agencies and the stakeholders:

- Climate change metrics: the 30-year metrics of average annual temperature and precipitation
- Climate change location: the spatially averaged change over the entire Columbia River Basin (rather than changes by individual subbasin)
- Climate range of change represented: the span included the central (or 50th percentile) and the 10th to 90th percentile changes among the HB2860 climate and hydrology data at the Columbia River Basin scale

This selection approach was applied independently to the separate HB2860 pools of 2020s and 2040s scenarios, which led to five scenarios selected for RMJOC purposes which were qualitatively named:

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[8] Flood control curves define the maximum reservoir pool surface elevations to maintain the balance between flood control and water supply objectives for each storage reservoir.

- Central (C)
- More warming and wetter (MW/W)
- Less warming and wetter (LW/W)
- More warming and drier (MW/D)
- Less warming and drier (LW/D)

A sixth scenario was included in the set to reflect minimal change (MC), roughly targeting less warming and central precipitation change over the Columbia River Basin. Annual change information for each of these scenarios and the other HB2860 candidate scenarios is given in the Part I Report in the appendix.

### 2.1.2 Transient Scenarios

The Transient scenarios reflect time-evolving climate conditions through historical and future periods. The twelve HD scenarios described above (six for the 2020s and six for the 2040s) were built from nine global projections and six of the nine projections were subjected to Transient analysis. The Transient scenarios are useful for adaptation planning for the timing and onset of the climate change impacts.

Assessment of the impacts of these scenarios was analyzed by using an ensemble of all six Transient projections and tracking the ensemble change through time. The Transient scenarios group represented what the climate and hydrologic possibilities might be during the projection at any point in time from the past to the future (i.e., 1950 through 2099). Assessing the Transient scenarios ensemble was meant to portray a range of climatic possibilities through time and the median of the group suggested a central tendency of a given climatic condition. The ranges in the group suggested the changes in climate variability and prediction uncertainty through time. More information for about each of these Transient scenarios is given in the Part I Report in the appendix.

## 2.2 Projected Future Climate Conditions

While the six scenarios were qualitatively labeled as C, MW/W, LW/W, MW/D, LW/D, and MC, there were complex differences in how the scenarios were actually represented in the Columbia River Basin that varied geographically and monthly. To illustrate these differences, temperature and precipitation changes in the future relative to historical conditions are described in the following section. An inventory of the datasets used in this effort may be found in the Part I Report.

### 2.2.1 Temperature and Precipitation

Historical mean annual daily maximum temperature is shown in Figure 5 and changes relative to that historical temperature are shown in Figure 6. While warming has consistently occurred in the Columbia River Basin, some areas have experienced more change than others. When comparing future mean annual daily maximum temperature changes to historical conditions for both the 2020s and 2040s, scenario-specific maps show that increments of warming vary spatially over the basin.

Mean annual daily minimum temperatures changes reflect similar geographic complexities as observed in the mean annual maximum temperature. The comparison of those changes and the month-to-month variability in future temperatures (both minimum and maximum) when compared to historical conditions are not shown here, but are presented in Part I.

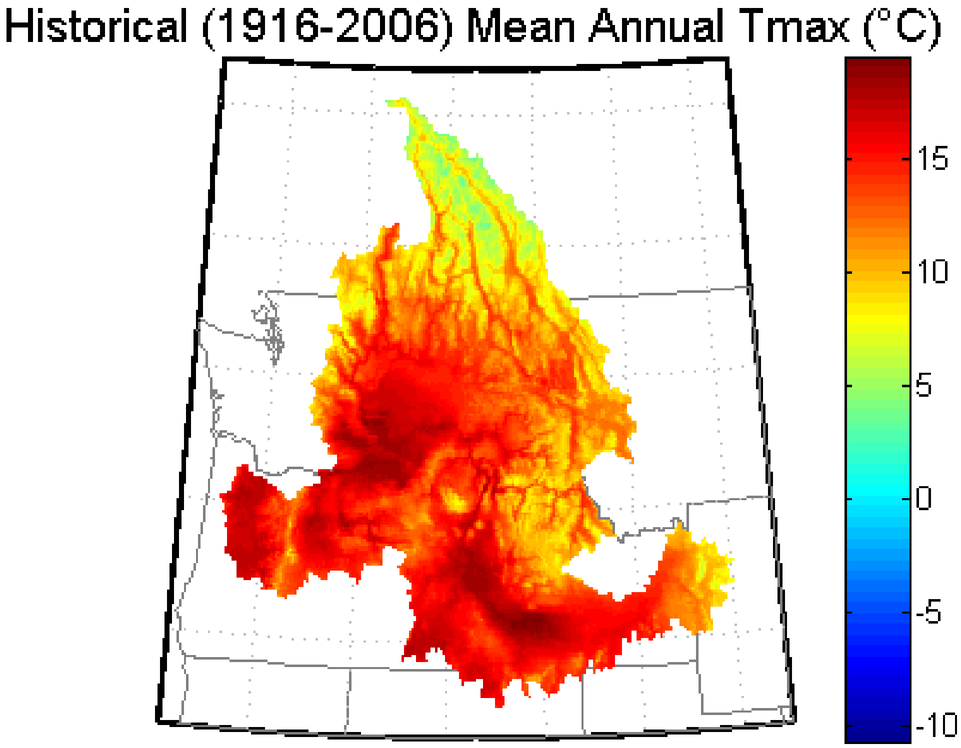

**Figure 5. Observed mean-annual daily maximum temperature in the Columbia River Basin, 1916-2006.**

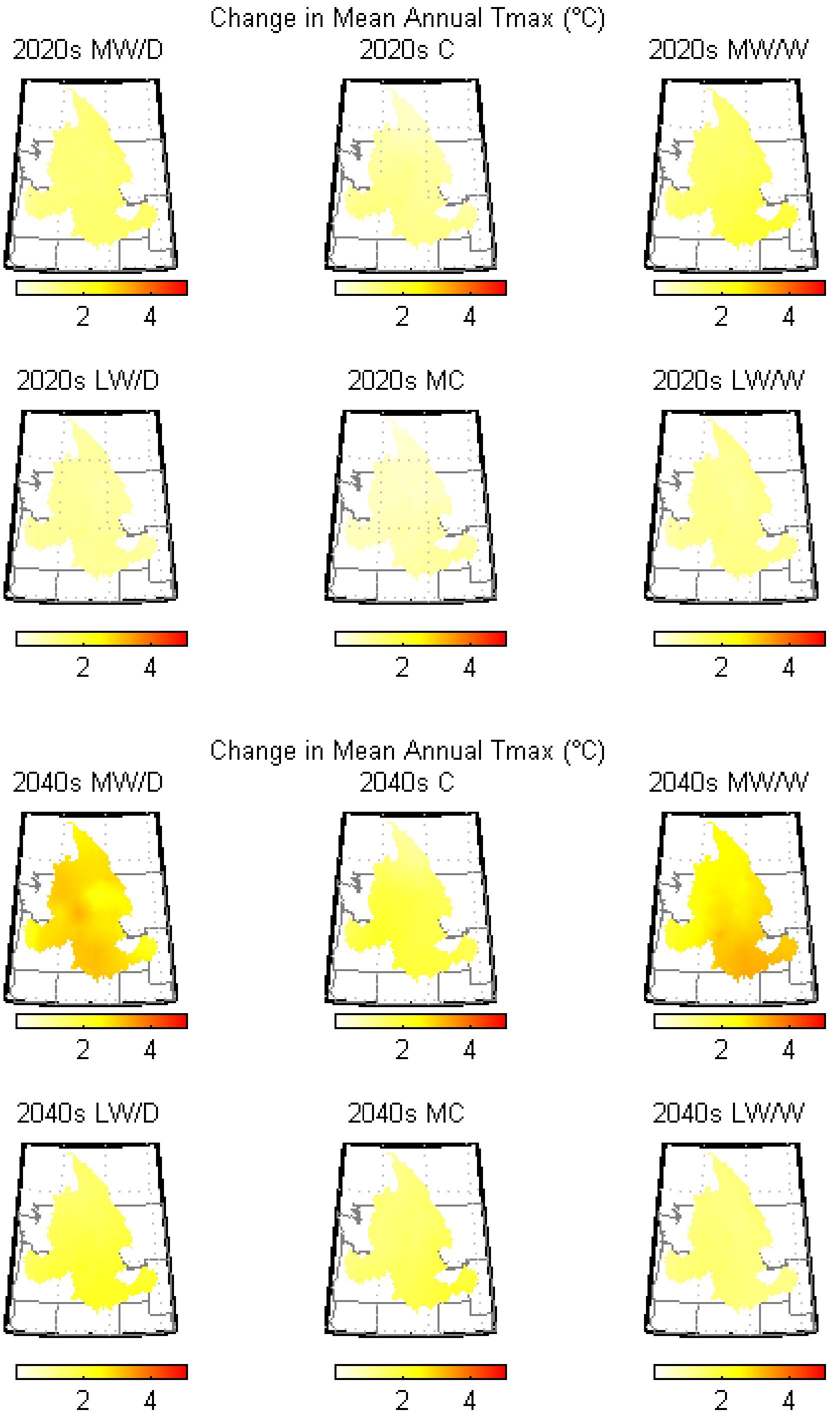

**Figure 6. Changes in average annual daily maximum temperature across the Columbia River Basin for HD 2020s and 2040s scenarios relative to the observed historical conditions. The scale of increased temperature change ranges from 0°C to 5°C (white to red, respectively).**

Figure 7 shows the historical mean annual precipitation from 1916 to 2006 and Figure 8 shows the changes in mean annual precipitation relative to that historical precipitation. While observed precipitation has increased across the Columbia River Basin, areas along the Cascade Mountains in Oregon and in southern Canada have experienced the largest increase. When compared to future conditions, the Snake River subbasin (OXBOW in Figure 3) is shown to have an increase in precipitation regardless of climate change scenario with the exception of the 2020 MW/D and 2040 LW/D scenarios. So while the range of climate scenarios met the criteria at the Columbia River Basin scale, when viewed at a smaller geographic scale (such as the Snake River subbasin), the intended patterns of climate variability were not necessarily met. Additional information about the changes in month-to-month mean annual precipitation is provided in the Part I Report in the appendix.

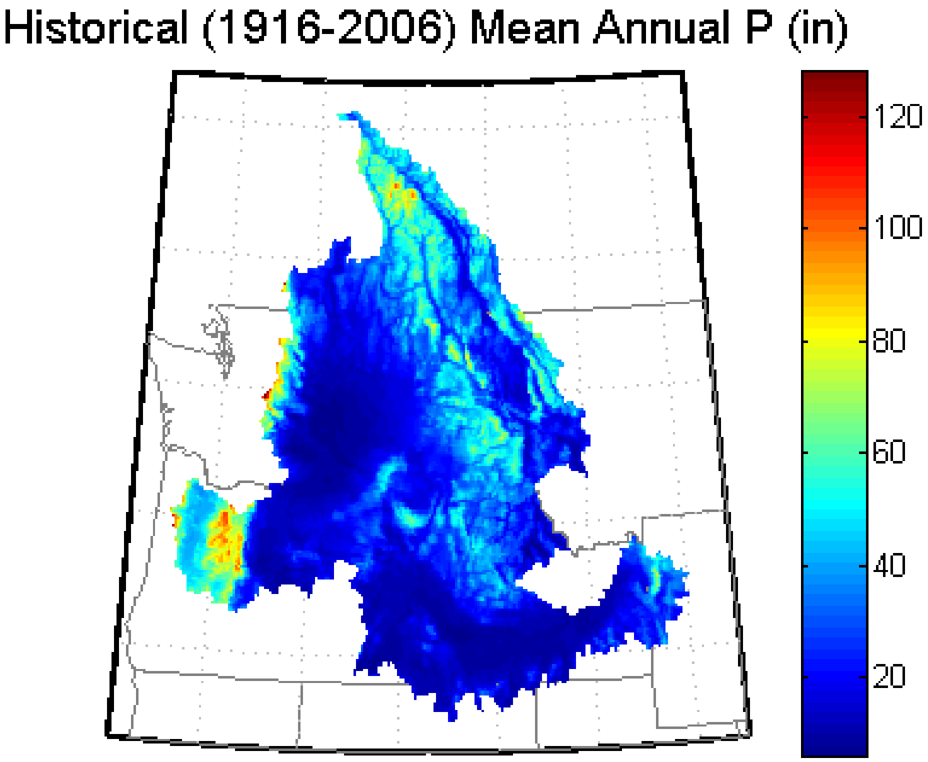

**Figure 7. Observed mean-annual precipitation in the Columbia River Basin, 1916-2006.**

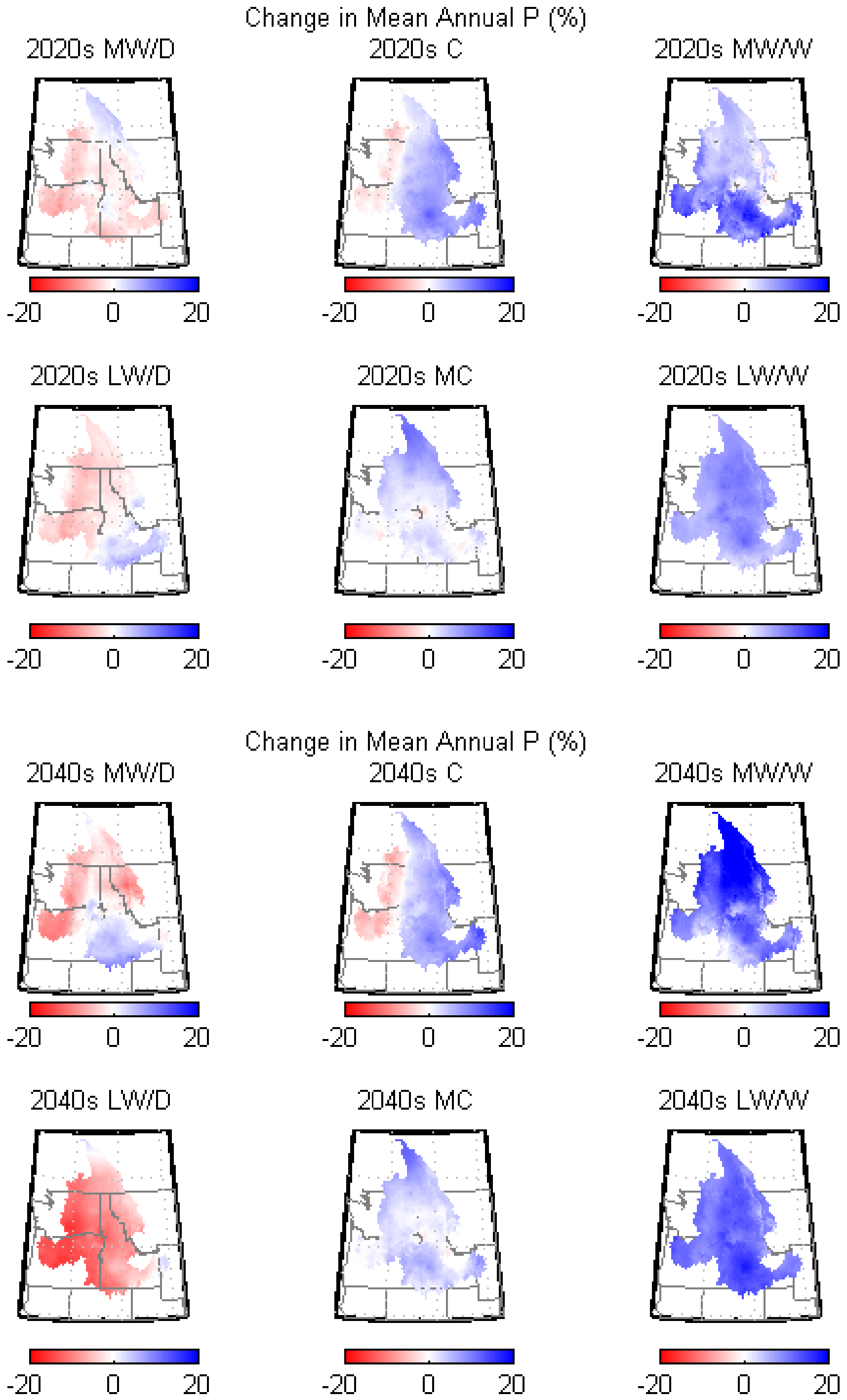

**Figure 8. Changes in average annual precipitation (%) across the Columbia River Basin for HD 2020s and 2040s scenarios relative to the observed historical conditions. The scale of change ranges from a 20 percent decrease to no change to a 20 percent increase (red to white to blue, respectively).**

The group of Transient climate scenarios tells a collective story though time. The temperature conditions generated by these scenarios suggest that the median of the mean daily maximum and minimum temperatures in the Columbia River Basin should continue to gradually increase throughout the 21st century (solid black lines in the left and center graphs of Figure 9). In contrast, the median of precipitation conditions (solid black line in right graph of Figure 9) appears to trend slightly toward wetter conditions, but with the trend being less pronounced relative to the range of possibilities through time. The range of variation is much greater in the precipitation plot (the blue lines in the right graph of Figure 9) than in the temperature plots (green and red lines in the left and center graphs of Figure 9).

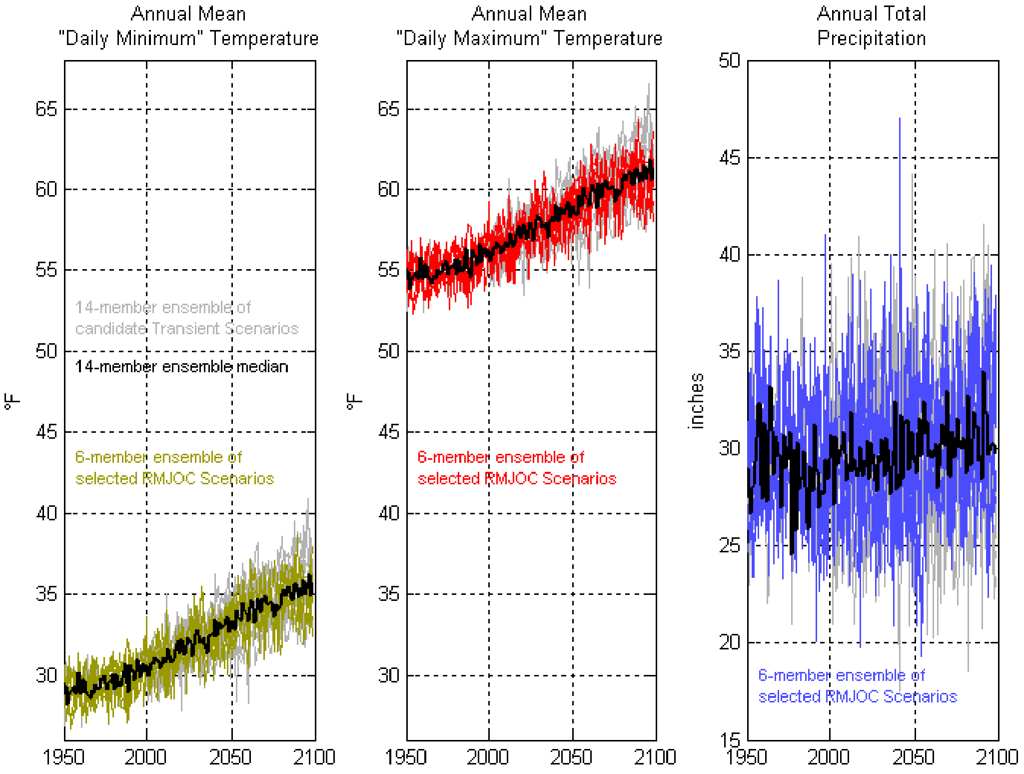

**Figure 9. Selected University of Washington CIG HB2860 Transient climate scenarios describing Columbia River Basin average climate conditions.**

# 2.3 Runoff under Future Climate Scenarios

## 2.3.1 Hydrologic Modeling and Bias Correction

The hydrologic conditions for the Columbia River Basin were simulated by the University of Washington CIG using the Variable Infiltration Capacity (VIC) hydrologic model. The VIC model simulates how watershed hydrologic processes (e.g., evaporation, snowpack, snowmelt, and runoff) will physically respond to changes in climate over the Columbia River Basin. The University of Washington CIG calibrated the Columbia River Basin VIC hydrologic model by the adjusting the model’s soil parameters to reproduce historical monthly and annual runoff from the major Columbia River subbasins shown in Figure 3.

For each scenario, a daily gridded time series of four weather variables were prepared and used to force VIC simulations: precipitation, minimum temperature, maximum temperature, and wind speed. VIC outputs include various conditions relevant to the surface water balance: potential evapotranspiration, actual evapotranspiration, soil moisture, snow water equivalent, and runoff.

The Columbia River Basin VIC hydrologic model had varying degrees of success in reproducing historical runoff under historical weather conditions, depending on the location in the Columbia River Basin (see the Part I Report for a full description of the VIC model and its limitations). More success was seen at calibration locations; less success was seen at many other runoff locations that are relevant to the RMJOC operations analyses (e.g., inflow locations to specific system reservoirs). A procedure was used to account for the VIC simulated runoff error tendencies, or biases, so that the simulated runoff variability under the historical climate scenario was consistent with system inflow variability in the RMJOC agencies’ historical operations assessments. These same adjustments were applied to the VIC simulated runoff under future climates scenarios. Application of these adjustments to each HD and Transient VIC scenario yielded datasets of bias-corrected natural runoff at the major system inflow locations used in RMJOC operations analyses (Part II and III reports).

### 2.3.2 Annual Runoff under HD Climate Change Scenarios

For subbasins in the Columbia River Basin, the trend from historical to future average annual runoff was found to generally follow the same trend as the average annual precipitation (Figure 8). Monthly runoff patterns are expected to change in the future relative to historical conditions, with warming leading to increased winter-spring runoff and reduced summer runoff. These seasonality changes are due to increased winter rainfall and reduced snowpack, which reduce the snowmelt volume through the summer. Scenario precipitation trends varied geographically within the Columbia River Basin; however, absent any precipitation change, warmer conditions led to increases in evapotranspiration and a reduction in runoff in these scenarios (Figure 6).

### 2.3.3 Monthly Runoff under HD Climate Change Scenarios

For most of the locations assessed, projected future monthly runoff patterns differed from the historical patterns with increased runoff during winter to early spring and reduced runoff during late spring to summer, stemming primarily from warming that increased winter rainfall instead of snowfall and increased snowmelt rates. Increased winter rainfall led to more winter runoff, less winter snowpack accumulation, and subsequently reduced snowmelt to support the spring-summer runoff in some locations. The degree to which this phenomenon occurred varied by the historical temperature conditions and by the amount of future warming. This generally means that such a transition in runoff seasonality occurs earlier in the 21st century for the western subbasins (e.g., Yakima River subbasin and the Cascade Mountains) when compared to the eastern and northern subbasins (e.g., upper Snake and upper Columbia River subbasins). Given that warming increases as the 21st century progresses, these effects may become more pronounced with time.

### 2.3.4 Annual Runoff under Transient Climate scenarios

The six Transient runoff scenarios suggested that for most subbasins, any trend in annual runoff through time was subtle when compared to the range of runoff possibilities in any given year. This subtlety was emphasized when the scenarios were viewed in a selected 10- or 30-year timeframe.

Using the Transient information was beneficial because it was used to understand decadal to multi-decadal variability within climate projections. Because the HD scenarios were developed from 30-year periods selected out of the climate projections, the decadal to multi-decadal climate variability occurring in the 30-year timeframes affected the interpretation of the Transient scenarios. The HD scenarios were intended to be interpreted as “climate change” possibilities and not multi-decadal variability. It is possible that some of the HD scenarios were selected in part because of the time periods chosen (2020s or 2040s) and the climatic departure from the trend happening within the climate projections during these periods.

For example, Figure 10 shows the Yakima Transient scenario smoothed through time using the 10-year moving mean. The 30-year period centered on the 2040s HD scenario was from 2030 to 2059. The 2040s LW/D HD scenario in Figure 10 was sampled from the same climate projection that underlies the Transient scenario labeled “echo-g” (see legend and caption on Figure 10). The “echo g” projection shows that during the decade around the 2050s, the runoff had a large dip relating to relatively dry conditions during this period in this climate projection. Thus it is fair to question whether the LW/D 2040s HD scenario is truly climate change or the result of sampling of decadal climate variability from the “echo g” projection during this period. This question is explored further in Report II on Operations Portrayal under Transient climate scenarios. In most cases, the LW/D 2040s HD scenario reflected the driest conditions.

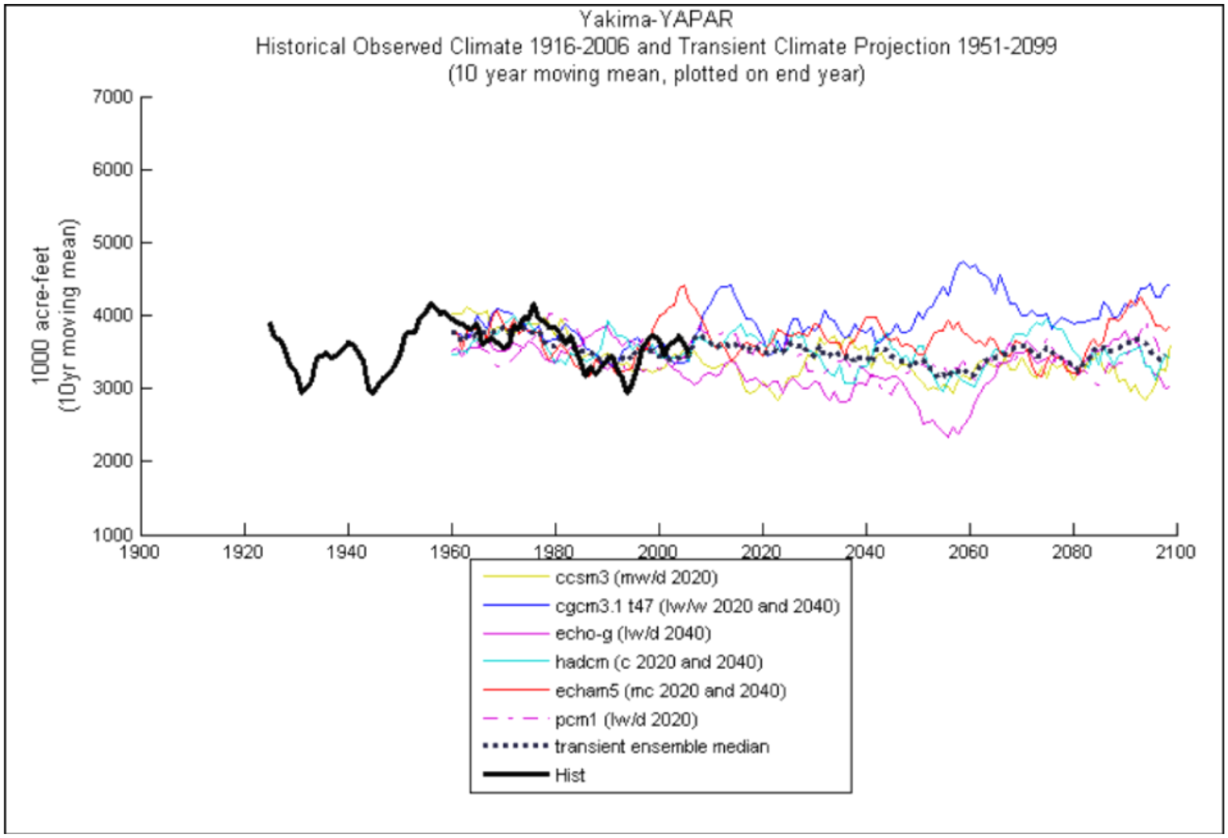

**Figure 10. Yakima River basin runoff under historical and transient climate scenarios: running 10-year mean-annual. The graph represents the different GCMs that were used in the modeling activities (color lines), the Transient ensemble median (dotted black line), and the historical conditions (solid black line). The Part I Report contains details on these modeling results.**

## 2.4 Water Supply Forecasts under Future Climate Scenarios

Traditional seasonal water supply forecasting is imperfect and based on snowpack monitoring. Seasonal warming diminishes the snowpack over time which gradually diminishes the value of using snowpack to predict seasonal water supply. Potentially losing snowpack as a water supply predictor is important because long-range operations simulations use snowpack in water supply forecasts. However, it was not certain whether characterizing future climate impacts on water supply forecasts was critical for simulating future operations, relative to characterizing changes in natural runoff and system inflows. To get a clearer understanding, the operations analyses were conducted using two types of water supply forecasts: “perfect” which is simply a look-ahead sum of inflows in future months and “imperfect” resembling real-world use of prior season precipitation and snow at the time of forecasting to predict seasonal runoff volumes during coming months. This dual type of water supply forecasting was conducted only for the historical and HD climate scenarios. For the Transient scenarios, only the perfect forecast was used. For imperfect forecasts, a process was applied on a scenario-specific basis (historical or HD) and for a large menu of forecast situations[9] collectively featured in the RMJOC agencies' long-range operations models. For each forecast situation, a water supply forecast model was developed within the context of each climate scenario (historical or HD) and designed to be similar to real-world forecast models in that it related seasonal precipitation to date (October to current date) and snowpack near the time of the forecast to seasonal runoff volume during a subsequent forecast period.

The water supply forecast models developed under historical climate scenarios generally reflected historical conditions, although they were not as accurate as the models that are currently used by various forecast providers in the Columbia River Basin (e.g., Natural Resources Conservation Service, National Weather Service Northwest River Forecast Center, BC-Hydro, Reclamation Pacific Northwest Region). Nevertheless, the resultant models provided reasonable projections under the historical climate scenarios for the operations assessments (Report Parts II and III).

Comparisons of the water supply forecasts estimated under historical and future HD climates broadly suggested that forecast skill, or the ability of the forecast to accurately predict future water supplies, should diminish for most locations as warming causes the snowpack to diminish. For the 2020s and 2040s HD time frames, decreased forecast skills seem primarily confined to early and late forecasts (e.g., January and February forecasts of spring-summer runoff or June and July forecasts of remainder-of-summer runoff). Forecast skill reductions varied by location, with some basins experiencing very little reduction (e.g., Columbia River at Keenleyside Dam, Columbia River at Mica Dam, and Snake River near Heise) and others experiencing more significant reduction (e.g., Deschutes River above Crescent Lake, North Fork Clearwater at Dworshak Dam, and Yakima River at Parker).

Any conclusions drawn from these results are limited given that this study did not exhaustively explore alternative predictors that might be used in the future to replace the predictive value currently offered by snowpack monitoring and there were no explorations of new snowpack monitoring sites at higher elevations. Nevertheless, like the historical forecast series previously mentioned, the future forecast series were viewed to be reasonable depictions of potentially impacted water supply forecasting under future hydrology and climate conditions. As such, they were viewed to be suitable for use in the operations assessments that followed.

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[9] A forecast situation is defined by its subbasin, the timing of the forecast (e.g., January 1), and the forecast period (e.g., April to July).

# 3.0 SUMMARY OF PART II REPORT: RECLAMATION OPERATIONS IN THE YAKIMA, DESCHUTES, AND SNAKE RIVER BASINS

The Part II report included a summary of the framework in which future hydrology scenarios were incorporated into Reclamation's long-range operations assessments within the Yakima, Deschutes, and Snake River subbasins. Also, a description of the reservoir system models used to simulate operations in these basins and the subsequent detailed results can be found in Part II. An assessment of modeled simulated operations under historical, HD, and Transient climate scenarios was conducted to characterize the general climate change implications for future operations, to understand how the implications vary across the HD climate scenarios of a given future period, and to determine how the implications vary (if at all) when assessed under HD or Transient conditions.

Reclamation operates projects in a number of tributary subbasins in the Columbia River Basin (Figure 11). Future RMJOC climate and hydrology scenarios were developed to study how climate change may affect project operations in the Yakima, Deschutes, and Snake River subbasins. These three subbasins already had fully functioning operations models that were available for immediate use in the analysis of climate change impacts.

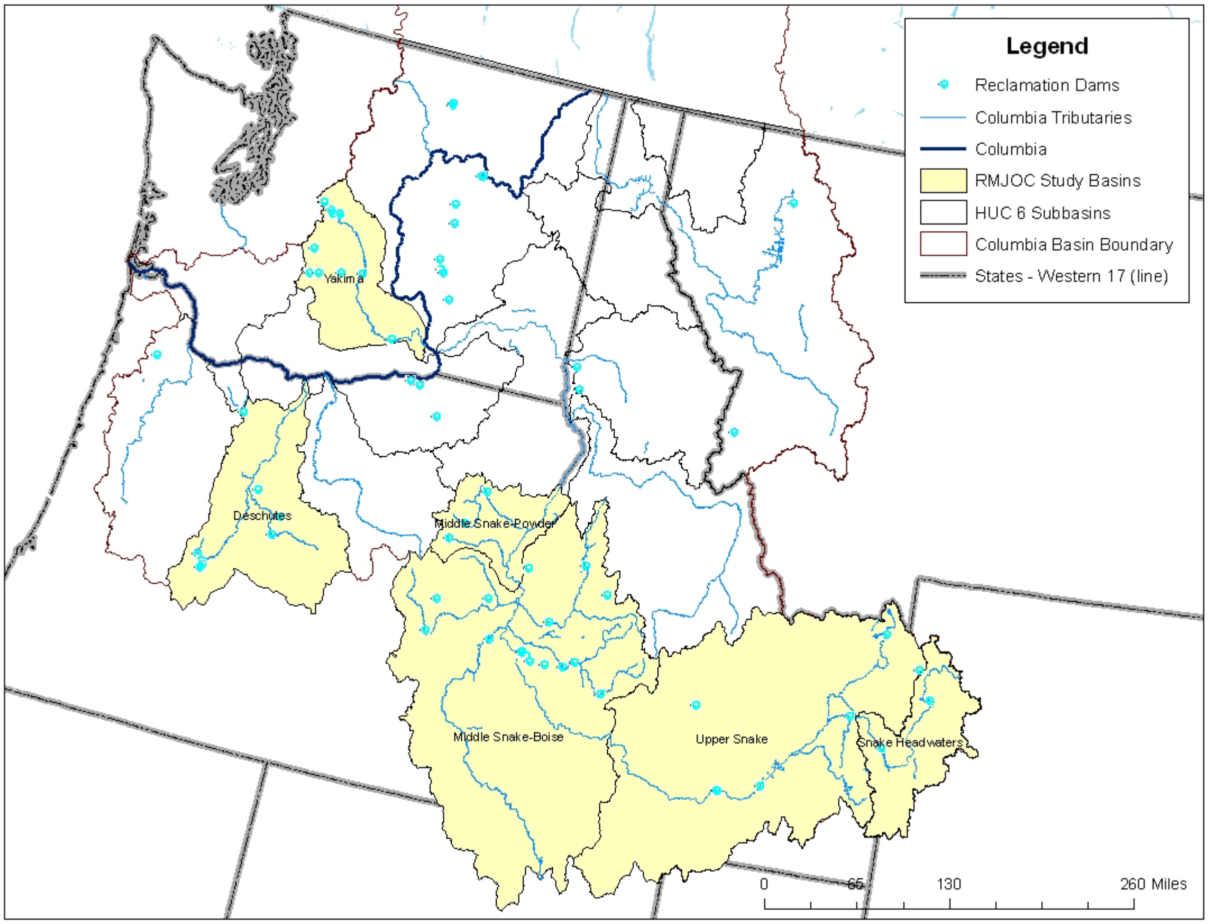

**Figure 11. Locations of Reclamation projects and major subbasins in the Pacific Northwest that were the focus of this study.**

In the following subsections, a brief summary of the metrics evaluated in each subbasin is provided with example graphics depicting the general results. These results are described in detail in the Part II Report which can be found in the Appendix.

## 3.1 Approach

The Yakima River Subbasin Planning Model simulated system operations on a daily basis whereas the Deschutes and Snake River Subbasin Planning Models featured simulations of monthly system operations. For each subbasin, a common menu of 32 simulations was conducted:

- (1-13) historical, HD 2020s, and HD 2040s climates under perfect water supply forecasts

- (14-26) historical, HD 2020s, and HD 2040s climates under imperfect water supply forecasts

- (27-32) transient climates under perfect water supply forecasts

Operations analysis in each subbasin was conducted using the 2010 level water demands and operating criteria. Additional modeling was completed on the Snake and Deschutes River subbasins using only naturalized flows[10] and results reported. Results were presented in several areas, including reservoir system inflows; instream flow at specific gages; ESA flow targets and other environmental objectives; surface water deliveries; flow augmentation on the Snake River; and end-of-month reservoir storage. A brief summary of some of these metrics in each subbasin follows.

## 3.2 Yakima River Basin

The Yakima River flows southeasterly for about 215 miles from its headwaters in the Cascades east of Seattle, Washington to its confluence with the Columbia River near Richland, Washington. The Yakima River system (Figure 11) includes the following storage reservoirs owned and operated by Reclamation: Keechelus, Kachess, and Cle Elum dams and reservoirs on the upper Yakima River and Bumping and Rimrock dams and reservoirs on the Naches River. These projects provide most of the physical operations capabilities needed to store and release water to meet irrigation demands, flood control needs, and instream fish flow requirements. The irrigable lands eligible for service under the Reclamation's Yakima Project total about 465,000 acres.

For the Yakima River subbasin, the operations impacts assessment focused on potential changes in water supply and system inflows occurring in the future climate scenarios. Across all of the scenarios, the modeling results generally showed a season-specific impact on water supply, with increased cool-season (November through March) inflow and decreased warm-season (April through September) inflow. The degree of the impact varied with the climate change scenario. Season-specific changes in system inflows affected the assessment of the total water supply available during the months of March through September and generally led toward a reduction of the total water supply available as warm-season inflows decreased. This change in the total water supply available affected the operating decisions related to river

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[10] Naturalized flows are defined as the flow volume if there were no demands (e.g., irrigation diversions) and no regulation of flows (e.g., reservoirs) in the river. Modified flows are defined for Reclamation subbasins as the flow volume with demands and flows regulated by reservoirs.

flow targets, water demand prorationing, and storage targets, resulting in a reduction of water supply available for delivery to junior water users in the system.

Although the variability in operations was similar between scenarios, the operation protocols were shifted according to the type of climate change (e.g., a shift towards reduced storage conditions for scenarios that involve drier conditions). For scenarios involving drier conditions, not only would typical delivery and storage conditions be reduced, but delivery and storage conditions during drought years would also be reduced relative to historical climate conditions.

Differences between the forecasting methods (i.e., perfect versus imperfect) were also evaluated. While it was expected that a future decline of snowpack due to increased temperatures would occur (thus reducing the effectiveness of snowpack as a predictor of inflow), the differences in the results between the two methods were negligible.

Based on the comparison of HD and Transient operations results, the portrayal of typical operational conditions was similar under both operations types when the Transient results were viewed from a median perspective and assessed during periods associated with HD climates. The Transient results differed from the HD climates in that they also characterized the trend in operating conditions in a time-evolving fashion through the years that occur before and after a given HD scenario.

### 3.2.1 Inflow

Water supply conditions were found to have season-specific impacts under the HD climates, generally featuring increased cool-season inflow (during November through March) and decreased warm season inflow (during April through September) (Figure 12). Season-specific changes in the system inflow affected the assessment of total water supply available during the months of March through September, which affected operating decisions related to river flow targets, water demand prorationing, and storage targets. For example, results show that the reductions in the total water supply available from March through September led to reduced flow targets on the Yakima River at Parker, particularly during the months of April and May. Reductions in regulated flow targets and reductions in system inflows (above upstream reservoirs and from local tributaries) led to corresponding changes in regulated flows.

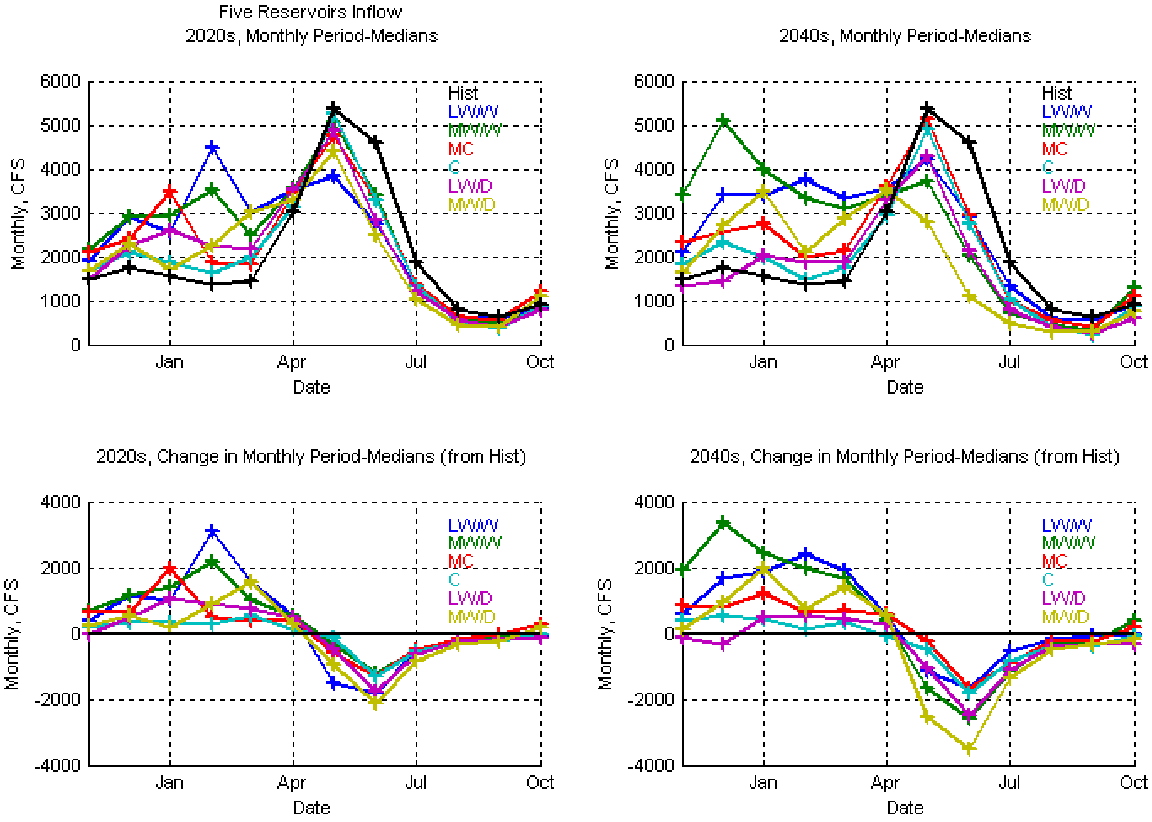

**Figure 12. Yakima River subbasin – median monthly system inflow, historical and HD climates.**

## 3.2.2 End-of-Month Storage

The increase in cool-season system inflow and reductions in the total water supply available from March through September led to an increase in typical cool-season storage, a decrease in storage during the warm-season, and a decline in end-of-season storage, an indication of less manageable water in the subbasin. Figure 13 depicts storage volume changes in five major reservoirs on the Yakima River. For scenarios involving drier conditions, not only would typical end-of-month storage volume be reduced, but drought year storage conditions would also be reduced relative to historical climate volume.

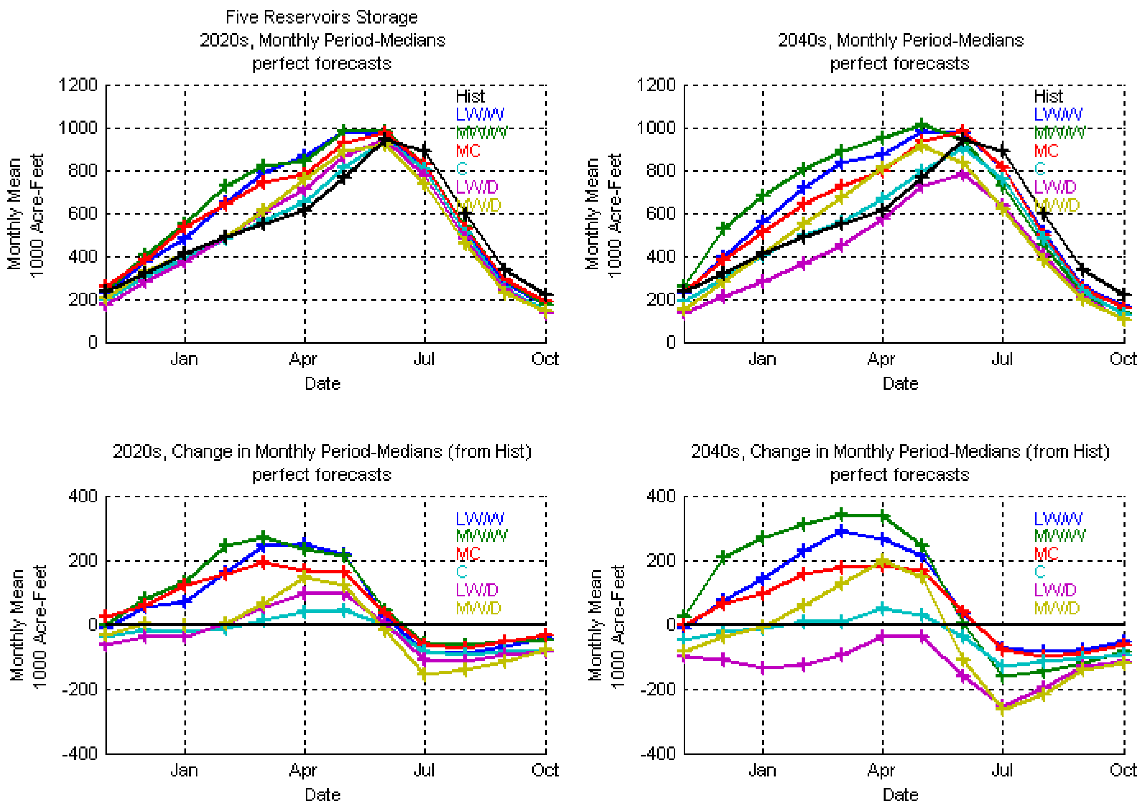

Figure 13. Yakima River subbasin – median monthly system storage, historical and HD climates.

## 3.2.3 Flow and Surface Water Delivered

Concerning flows and surface water deliveries, the study results varied considerably across the HD climates during both periods (2020s and 2040s), where the degree of change generally depended on the type of HD climate change (e.g., less warm-season flow or delivery reduction for the wetter HD climates, and more delivery reduction for the drier climates). For scenarios involving drier conditions, the typical delivery conditions would be reduced, but drought year delivery conditions would also be reduced relative to historical climate conditions. Surface water deliveries above the Parker gauge reflect these conditions (Figure 14).

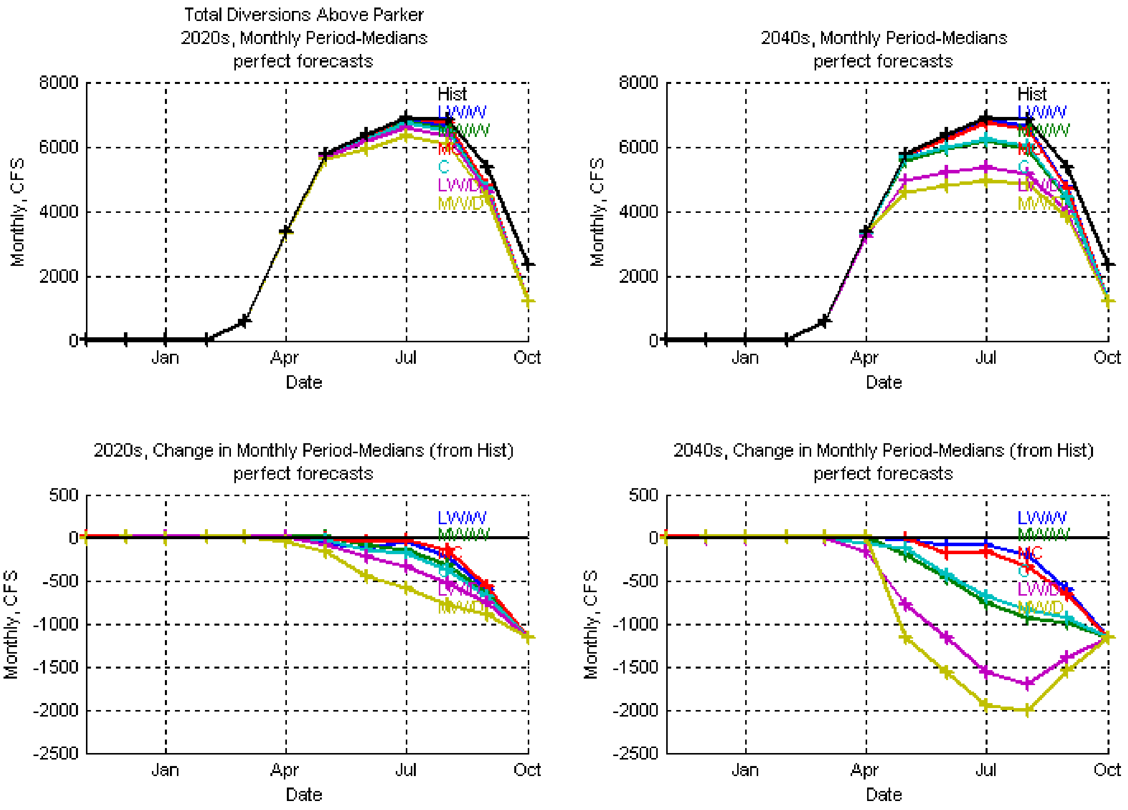

**Figure 14. Yakima River subbasin – median monthly total diversions above Parker, historical and HD climates.**

### 3.2.4 Forecasting

It appeared that Yakima River operations portrayal under the HD climates was not very sensitive to the use of *perfect* or *imperfect* forecasts in the operations simulations (Figure 15). The degree of climate change featured in the HD 2020s and HD 2040s climates may not have been substantial enough to diminish snowpack to the point of causing enough impact on the Yakima subbasin seasonal-runoff volume forecasting, total water supply available, and dependent operational decisions (at least during the period of March through May when the forecasts quality under HD 2020s and 2040s climates remains similar to historical). The Yakima River subbasin features simulated operational targets and decisions that can vary through time with varying forecasts as time goes on. This gives the system a built-in incremental ability to adjust as cumulative inflow and remainder-of-year forecast inflow conditions update through a given water year. As a result, it did not appear to be critical that the use of RMJOC climate/hydrology scenarios for Yakima River subbasin operations studies also include the use of the *imperfect* water supply forecasts developed for these scenarios.

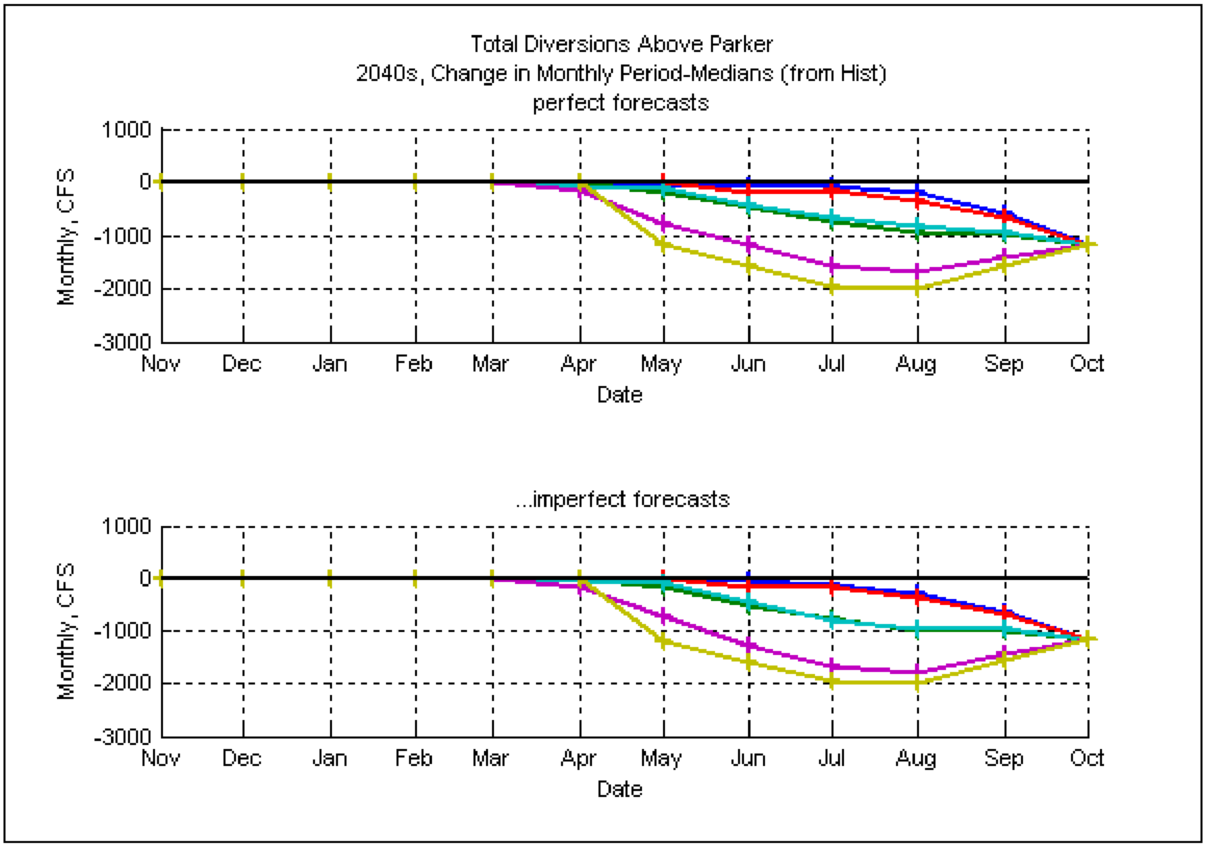

**Figure 15. Yakima River subbasin – change in median monthly total diversions above Parker, HD 2040s climates relative to historical, simulated using perfect and imperfect water supply forecasts.**

## 3.3 Deschutes River Subbasin

The Deschutes River subbasin is comprised of two smaller subbasins: the upper Deschutes River and the Crooked River (Figure 11). The upper Deschutes River subbasin includes the federally-owned Deschutes Project, located near Bend, Oregon, which includes Wickiup, Crane Prairie, Haystack dams and reservoirs, the North Unit Main Canal and lateral system, and the Crooked River Pumping Plant. The project furnishes a full supply of irrigation water to about 50,000 acres and supplemental water for more than 48,000 acres. The privately-owned Crescent Lake Dam Project on the Deschutes River provides irrigation for about 8,000 acres and is a recreational site. The Crooked River subbasin includes the Federally-owned Crooked River Project which includes the Arthur R. Bowman Dam on the Crooked River, Ochoco Dam on Ochoco Creek, a diversion canal and headworks on the Crooked River, Lytle Creek Diversion Dam and Wasteway, two major pumping plants, nine small pumping plants, and Ochoco Main and distribution canals which provide irrigation water to 20,000 acres. In addition to irrigation benefits, the project is operated to satisfy objectives related to environmental management, river and reservoir recreation, and flood control.

In the Deschutes River Basin, the six HD 2020 scenarios, the six HD 2040 scenarios, and the historical conditions were simulated using the modified flow models. The naturalized flow model was used to compare simulated historical conditions developed by the VIC model to Reclamation's naturalized flows. The overall pattern for the Deschutes River subbasin was earlier and higher runoff volumes than historical conditions, although these results were less dramatic in the HD 2020s scenarios than in the HD 2040s scenarios. In the dry climate projections, decreases in inflow, end-of-month storage, and flow in the channel at specific gage locations which would result in surface delivery reductions were predicted for the Crooked River in the HD 2040 scenario. In regard to flows, end-of-month storage, inflow to reservoirs, surface water delivered, and Endangered Species Act (ESA) objectives, the Crooked River system was projected to have greater variances from historical conditions than the variations projected for the upper Deschutes River subbasin. The change in available water supply occurred because of the shift to an earlier timing of peak flow runoff and a decrease in late summer instream flows. Reservoirs would release water earlier and be relied upon more heavily in the summer and late fall. These projected changes would create greater water supply concerns for irrigators with natural flow water rights than those with storage water rights.

Because the reservoir model is based on monthly input as opposed to daily input, the ESA objectives were analyzed using a surrogate monthly approach rather than the daily objectives as outlined in the 2010 Supplemental Federal Columbia River Power System Biological Opinion (Biological Opinion) (NOAA Fisheries Service 2010). In general, minimum flows are required at certain locations on the Crooked River and on the Deschutes River; if those flows are not met, outflows from Prineville Reservoir on the Crooked River are required to meet minimum flows. Based on this surrogate approach, occurrences of not meeting the average flow requirements for October (the only month evaluated) increased in dry projections and decreased in the wetter projections as expected. However, in the extremely dry conditions of the HD 2040 scenarios, there were two projected occurrences when the Prineville Reservoir did not have a sufficient water volume to supplement the Crooked River flow. Because these values were developed using monthly averages, they do not relate directly to the 7-day moving average requirement in the Biological Opinion, but may be indicative of trends that could occur in extremely dry or drought periods in the Deschutes River subbasin.

While the HD scenarios predicted larger variations in the metrics evaluated, the Transient scenarios indicated that over time, most of those metrics would have relatively low rates of change when viewed through the 150-year time window. The differences between the forecast method chosen (i.e., perfect vs. imperfect) were negligible.

### 3.3.1 Inflow

Inflow to Crane Prairie, Wickiup, and Crescent reservoirs (cumulative inflow for all three reservoirs), to Prineville and Ochoco reservoirs (cumulative), and in the entire Deschutes River subbasin at Lake Billy Chinook was evaluated (Figure 16 depicts the total system inflow changes). In the HD climates, total inflow (monthly median) into Lake Billy Chinook and into the three reservoirs on the upper Deschutes River increased above historical conditions. In addition, the peak of the total inflow (monthly median) magnitude shifted at least 1 month earlier in the year when compared to historical inflow. A slight increase in inflow was predicted to the Crooked River reservoirs, but no shift in peak inflow timing was observed. Inflows tended to be higher in magnitude earlier in the year and lower during the summer and fall when compared to the historical conditions overall. In the HD 2040 climates, these results were more exaggerated due to the large variation in temperature and precipitation in the climate models used as described above.

In the Transient scenario, the ensemble median reservoir inflow of all six climate change projections decreased slightly over time and then stabilized into the 22nd century.

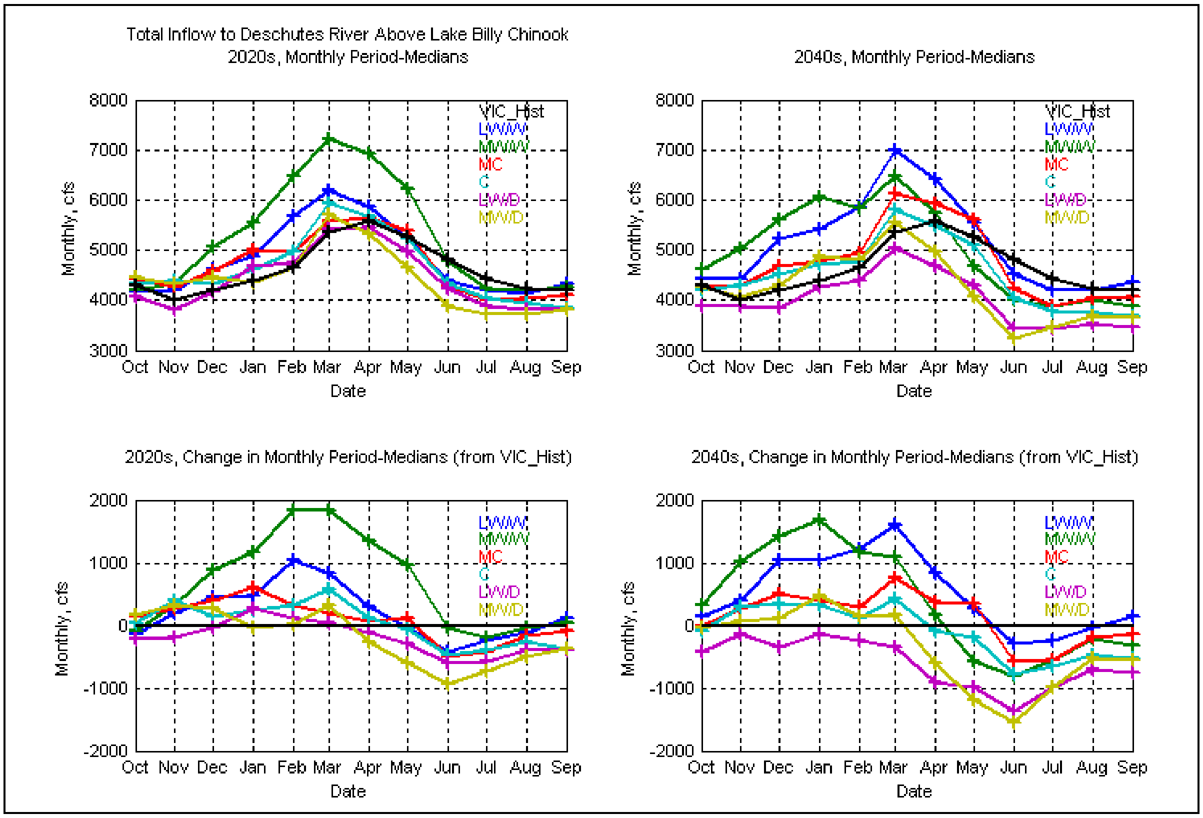

**Figure 16. Monthly median (top plates) and change in monthly median inflow from VIC simulated inflow (bottom plates) for the HD 2020 and HD 2040 climate change projections above Lake Billy Chinook on the Deschutes River.**

## 3.3.2 End-of-Month Storage at Major Reservoirs

End-of-month storage was evaluated for the Prineville and Ochoco reservoirs on the Crooked River, for Wickiup, Crescent, and Crane Prairie reservoirs on the upper Deschutes River, and in total at Lake Billy Chinook on the Deschutes River was evaluated (Figure 17 depicts the total system changes). The ability to refill the reservoirs each year in both HD scenarios was higher than historical refill levels from October through March or April because future winter precipitation comes in the form of rain, but reservoirs draft deeper during the summer months to meet demands. In extremely dry climates, the drafts that were required during the summer and fall were so significant that refill the following year was not possible. In the Transient climates, a decreasing trend in storage was predicted overall.

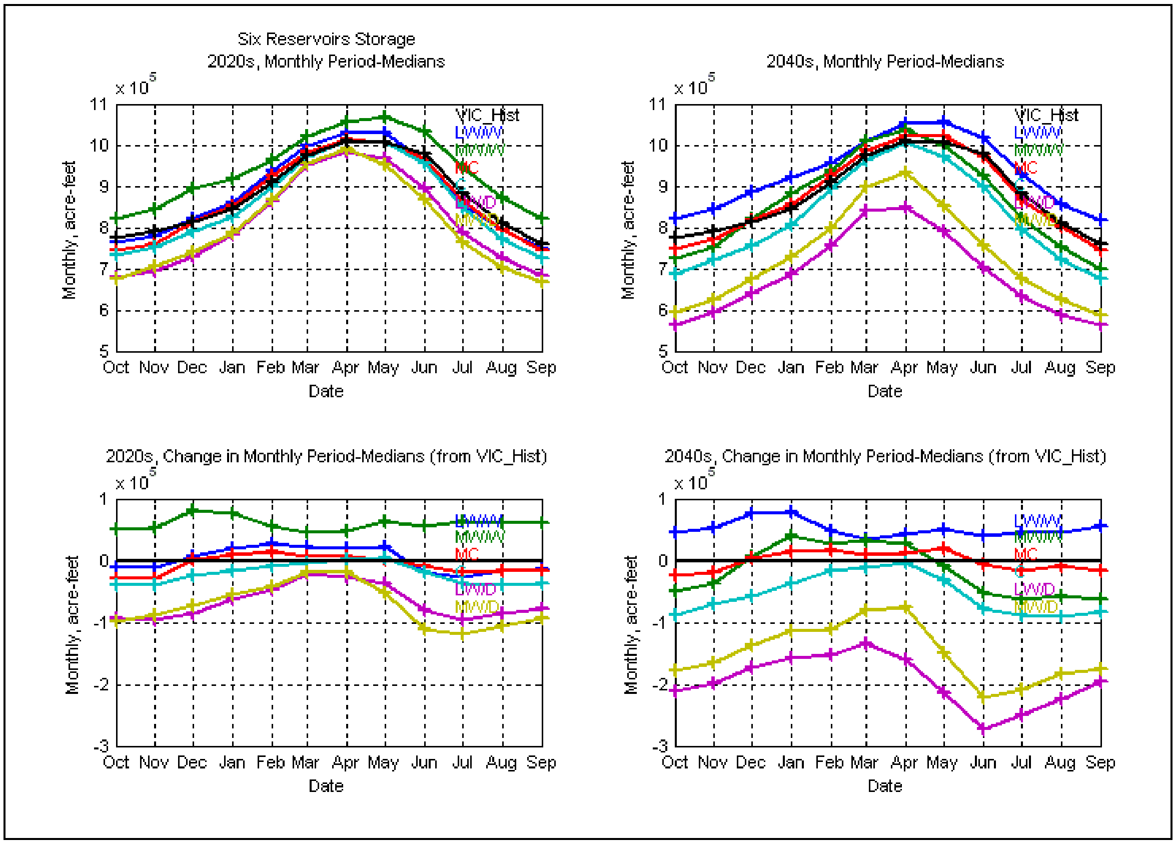

**Figure 17. Change in monthly period-median storage for the HD 2040 projections for all reservoirs storage on the Deschutes River.**

## 3.3.3 Flow

River flow was evaluated at two locations: on the Crooked River upstream of its confluence with the Deschutes River and upstream of Lake Billy Chinook on the Deschutes River (Figure 18). Generally, flow on the Crooked River upstream of its confluence increased in the wetter climates and decreased in the neutral or dry climates. The driest climates had the most severe decrease in flow in April each year in both HD scenarios. On the Deschutes River, this pattern was not observed. Generally, the Deschutes River upstream of Lake Billy Chinook was shown to have an increase in flow above historical in all of the climates for almost the entire year. Because of the influence of ground water in the Deschutes River subbasin, it likely contributed to flow volumes reported.

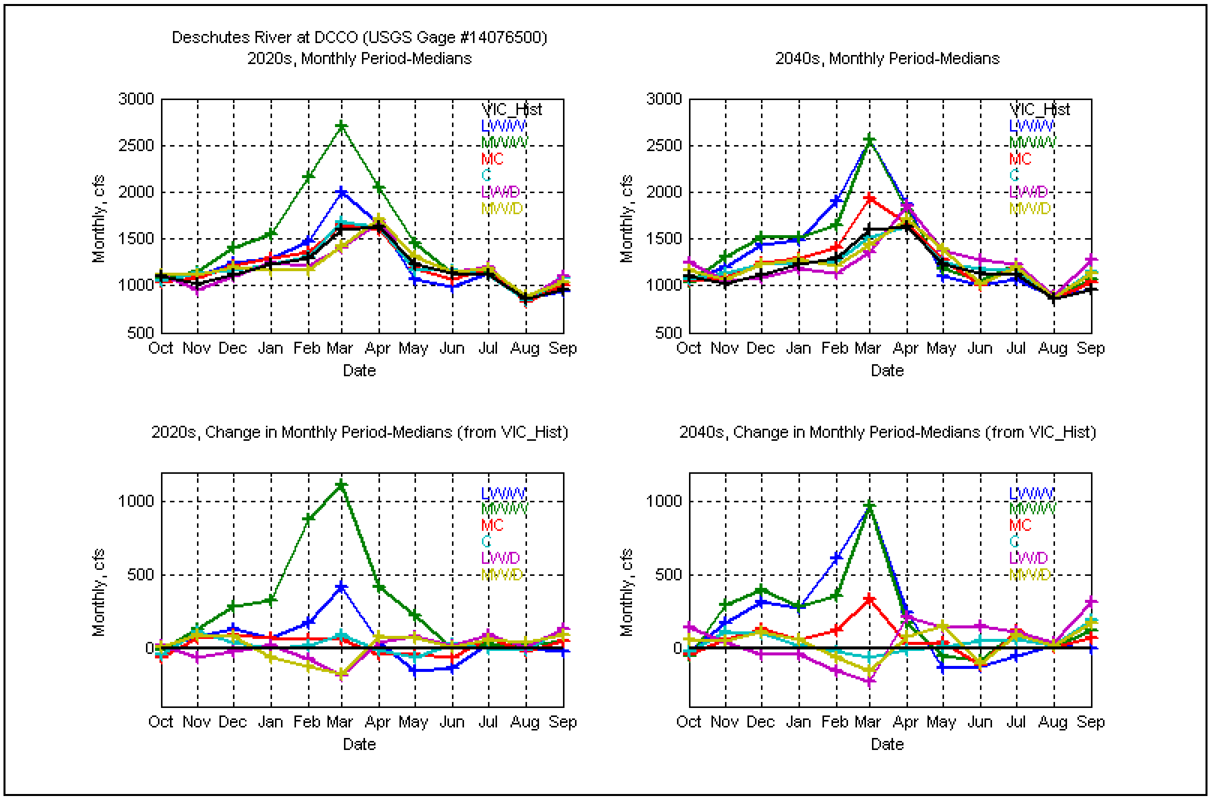

**Figure 18. Flow in total and change in total (from VIC historical) monthly period-medians at USGS Gage 14076500 (DCCO) on the Deschutes River.**

## 3.3.4 Surface Water Delivered

Surface water delivered was summed for all demands on the Crooked River, the upper Deschutes River and in the total system (Figure 19 depicts the total system changes). In the HD 2020 climates, the most significant decreases in delivery were in only the driest climates in May and June, but by the end of the summer, deliveries had generally rebounded to historical levels. In the HD 2040s, the surface water delivered was less than historical deliveries for the entire irrigation season. The change in supply occurred because of the shift to an earlier timing of peak flow runoff and a decrease in late summer instream flows.

Reservoirs began drafting[11] earlier and were relied upon more heavily in the summer and late fall. Predicted changes appeared to create greater water supply concerns for those with natural flow water rights when compared to those with storage water rights because of the availability of stored reservoir water for those with storage water rights.

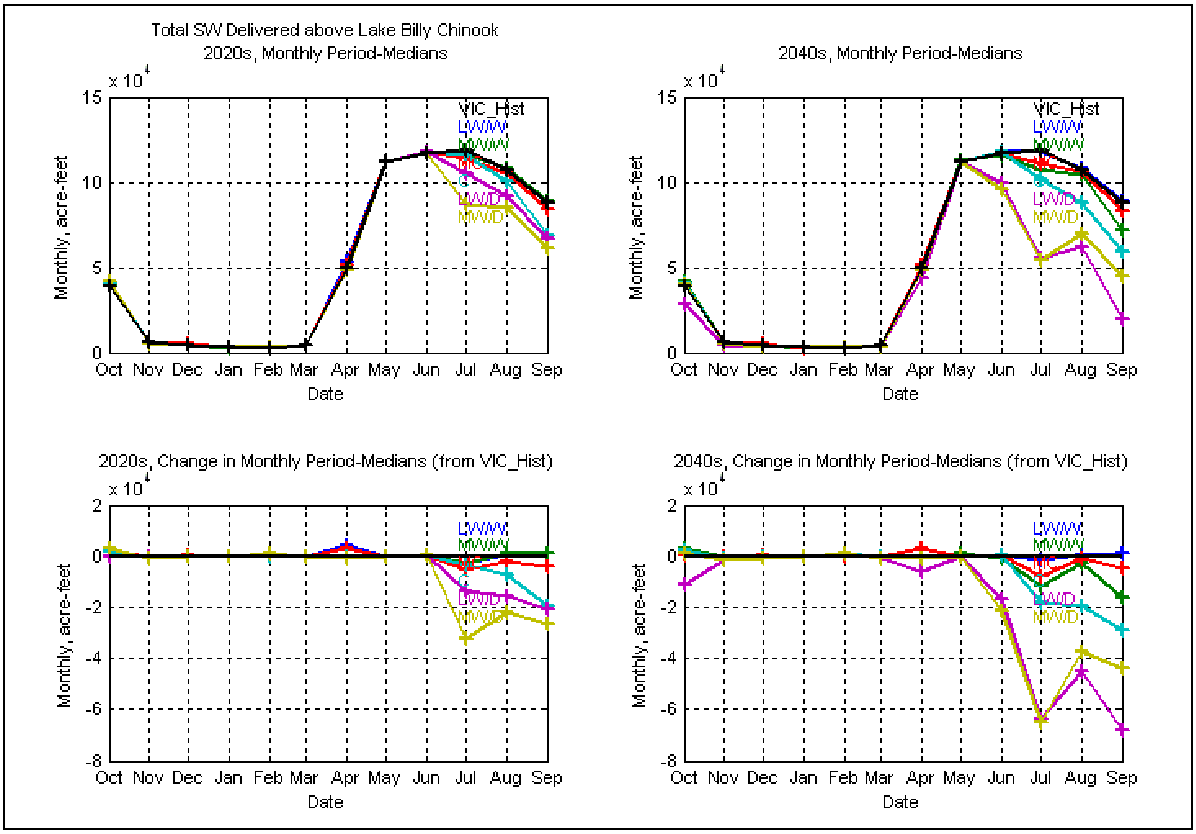

**Figure 19. Total and change in monthly-period medians (from VIC historical) of surface water delivered above Lake Billy Chinook.**

## 3.3.5 ESA for Resident Species and Other Environmental Objectives

In the Deschutes River subbasin, there are three ESA objectives (detailed in the 2005 Biological Opinion). Each requires certain flow volumes to be met on a 7-day moving average basis from October through mid-November of each year. Because the Deschutes Planning Model operates on a monthly time-step,[12] a surrogate approach was developed to evaluate the potential impacts of climate change on these daily requirements. This approach

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[11] Drafts are defined as the water that is removed or the act of removing water from a reservoir by releasing water to lower the water surface level (elevation) of the reservoir. For the purpose of flood control, drafting of the reservoir makes space available in the reservoir to capture winter rain events or spring snowmelt.

[12] A time step is the amount of time that conditions are assumed to be constant.

evaluated the monthly equivalent of the ESA requirements for the month of October only (as opposed to October and part of November). Based on this surrogate approach, occurrences of not meeting monthly average flow requirements increased in dry projections and decreased in the wetter projections as could be expected. However, in the extremely dry conditions in the HD 2040 scenario, there were two occurrences when no water was available in the reservoir to supplement channel flow. This surrogate approach may be indicative of trends that may occur in extremely dry or drought periods in the Deschutes River subbasin.

### 3.3.6 Forecasting

As warming continues, snowpack will diminish. It was believed that a decrease in snowpack would result in decreased accuracy in predicting runoff and that in turn would result in a change in the quality of water management decisions. This cause-and-effect relationship was not observed in this study because model output was relatively insensitive to whether a *perfect* or *imperfect* forecast mode was used. As reported in the Part II Report, forecasting quality done as part of the Deschutes River subbasin analysis was poor, but was consistent with real-time reservoir operations. Because very few reservoir operating decisions are made based on forecasts alone, it was not surprising that the model output was not significantly different between either forecasting modes.

## 3.4 Snake River Subbasin

The Snake River subbasin above Brownlee Reservoir has numerous Reclamation projects, both large and small, including Minidoka, Palisades, Ririe, Boise, and Payette. The Minidoka Project furnishes irrigation water from five reservoirs that have a combined active storage capacity of more than 3 million acre-feet. The project consists of Minidoka Dam and Powerplant and Lake Walcott, Jackson Lake Dam and Jackson Lake, American Falls Dam and Reservoir, Island Park Dam and Reservoir, Grassy Lake Dam and Grassy Lake, two diversion dams, canals, laterals, drains, and 177 water supply wells. In addition to irrigation benefits, the project is also operated to satisfy objectives related to environmental management, recreation, hydroelectric power generation, and flood control. Reclamation's projects in the upper Snake River are generally operated as a unified storage system.

The Palisades project principally features Palisades Dam Reservoir and Powerplant on the South Fork of the Snake River that has an active capacity of 1.2 million acre-feet. The project provides a supplemental water supply to about 650,000 acres of irrigated land and the 176,600-kilowatt hydroelectric powerplant furnishes energy needed in the upper valley to serve irrigation pumping units, municipalities, rural cooperatives, and other power users. In addition to providing needed holdover storage, the project is operated for flood control and hydropower generation.

The Boise Project includes the Boise and Payette rivers, both major tributaries to the Snake River. The system of reservoirs is operated primarily for irrigation, flood control, recreation, and Endangered Species Act (ESA) issues. Reclamation's reservoirs in the Boise River subbasin are operated as unified storage systems as are those in the Payette River subbasin. The Boise Project features five storage dams impounding about 1.8 million acre-feet of water, two diversion dams, three powerplants, seven pumping plants, canals, laterals, and drains and furnishes a full irrigation water supply to about 224,000 acres and a supplemental supply to about 173,000 acres in southwestern Idaho and eastern Oregon. In addition to irrigation benefits, the project is also operated to satisfy objectives related to environmental management, recreation, hydroelectric power generation and flood control. The Payette Division includes the Deadwood and Cascade dams and reservoirs. From these projects, 60,000 acres receive a full water supply and 61,000 acres receive a supplemental supply.

In the Snake River subbasin, the six HD 2020 scenarios, the six HD 2040 scenarios, and the historical conditions were simulated using the modified flow models. As with the Deschutes, the naturalized flow model was used to compare simulated historical natural flows generated by the VIC model and those naturalized flows generated by Reclamation. Future climate projections used in this study were selected at a Columbia River system scale to represent the 10, 50, and 90 percentile changes relative to historical conditions. However, this approach inadvertently resulted in primarily wetter climate change projections at a Snake River subbasin scale when compared to historical temperatures and precipitation amounts. As a result, most of the climate projections indicated increased inflow to major reservoirs in the late spring/early summer, higher reservoir elevations in spring, and increases in spring flows. In the late summer/early fall, most drier climate projections indicated lower reservoir elevations and a decrease in irrigation season flows with impacts on surface water deliveries. A wider range of potential climate change projections should be considered in future work at the subbasin level.

### 3.4.1 Inflow

Inflow volumes to major reservoirs were summed in the upper Snake River above Brownlee Reservoir included Jackson, Palisades, Island Park, Grassy Lake, Ririe, American Falls, and Minidoka reservoirs. Major reservoirs on the Boise River include Anderson, Arrowrock, and Lucky Peak and on the Payette River reservoirs included Payette Lake, Cascade, and Deadwood.

Inflow hydrology experienced a shift in either peak flow timing, volume, or both in all of the major reservoir groups. In flow volume to the reservoirs above Brownlee Reservoir increased in all of the climate scenarios from January to April or May and decreased in the summer to fall seasons (Figure 20). A shift of one month in the timing of the peak inflow of the wettest climate simulations was observed in the inflow to reservoirs on the upper Snake River above

Brownlee Reservoir. A similar change in the pattern of inflow volume was observed in the Boise River, but no shift in the timing of peak of the inflow occurred in any of the climates. The Payette River reservoirs had moderate increases in inflow early in the calendar year and the lowest inflow volume occurred in June in all climates. No shift in the timing of the peak inflow was evident in the Payette River subbasin.

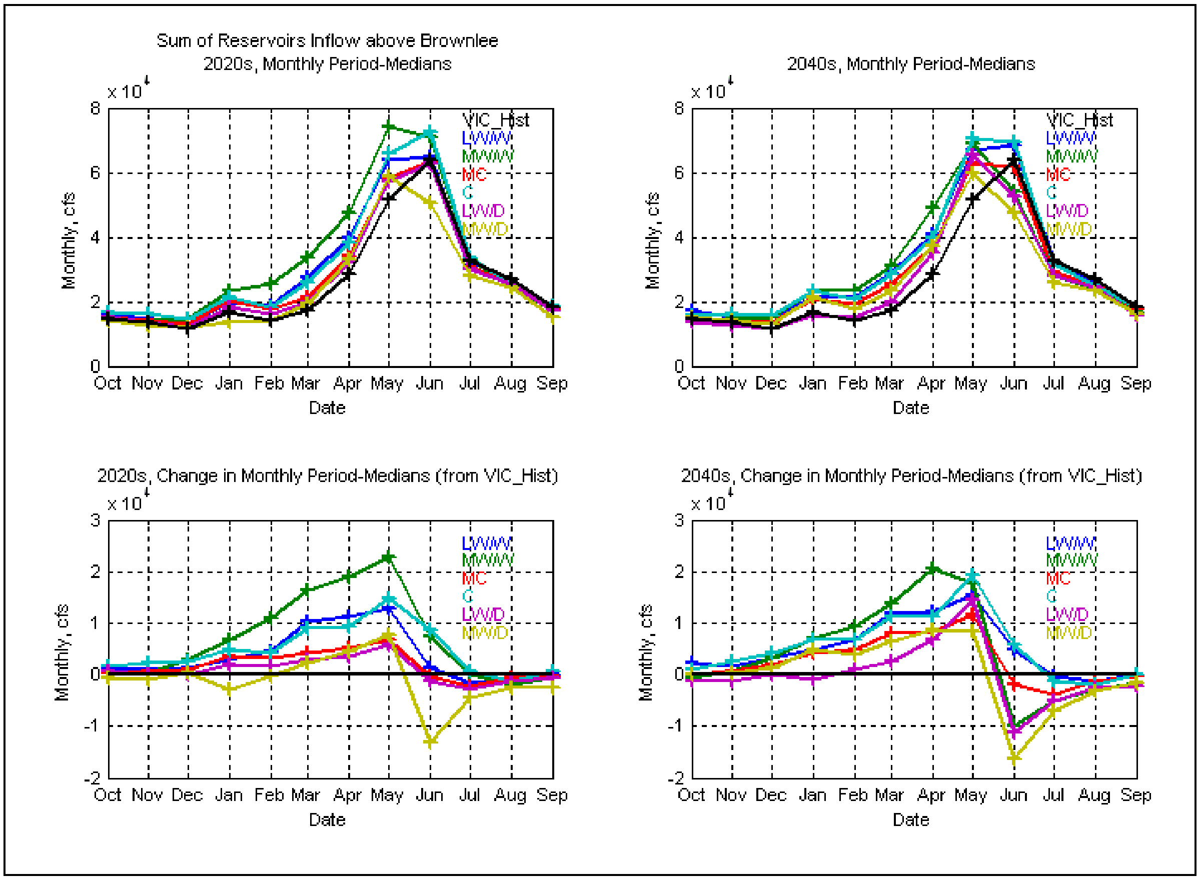

**Figure 20. Total (top panel) and change in period-median monthly inflows (bottom panel) from VIC simulated historical above Brownlee Reservoir in the upper Snake River subbasin.**

## 3.4.2 End-of-Month Storage

End-of-month storage[13] values are presented as a cumulative reservoir volume above the reporting point (i.e., Boise River, Payette River, Snake River above Minidoka, Snake River above Milner, and Snake River above Brownlee). The resultant value is a cumulative amount of total storage volume of the reservoirs in that system, not an individual reservoir.

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[13] End-of-month storage is the remaining volume of water in each reservoir or system of reservoirs after water releases have been made based on inflow, irrigation demands, flood control, and current operational constraints.

The increase in inflow volume that was observed in 2020 and 2040 HD scenarios for most of the 12 climate change projections resulted in a shift in the timing of the peak end-of-month storage to earlier in the year at most reporting points in the Snake River subbasin. End-of-month storage in reservoirs above Brownlee Reservoir reflected an increase in storage through May or June and then a decrease in end-of-month storage during the irrigation season through September when compared to historical storage (Figure 21). In the driest climate in either the HD 2020s or HD 2040s, end-of month storage volume was less than historical storage at the end of the water year and did not fully reach refill until January or February of the following year. This pattern was indicative of a greater need for stored water during the high demand summer season.

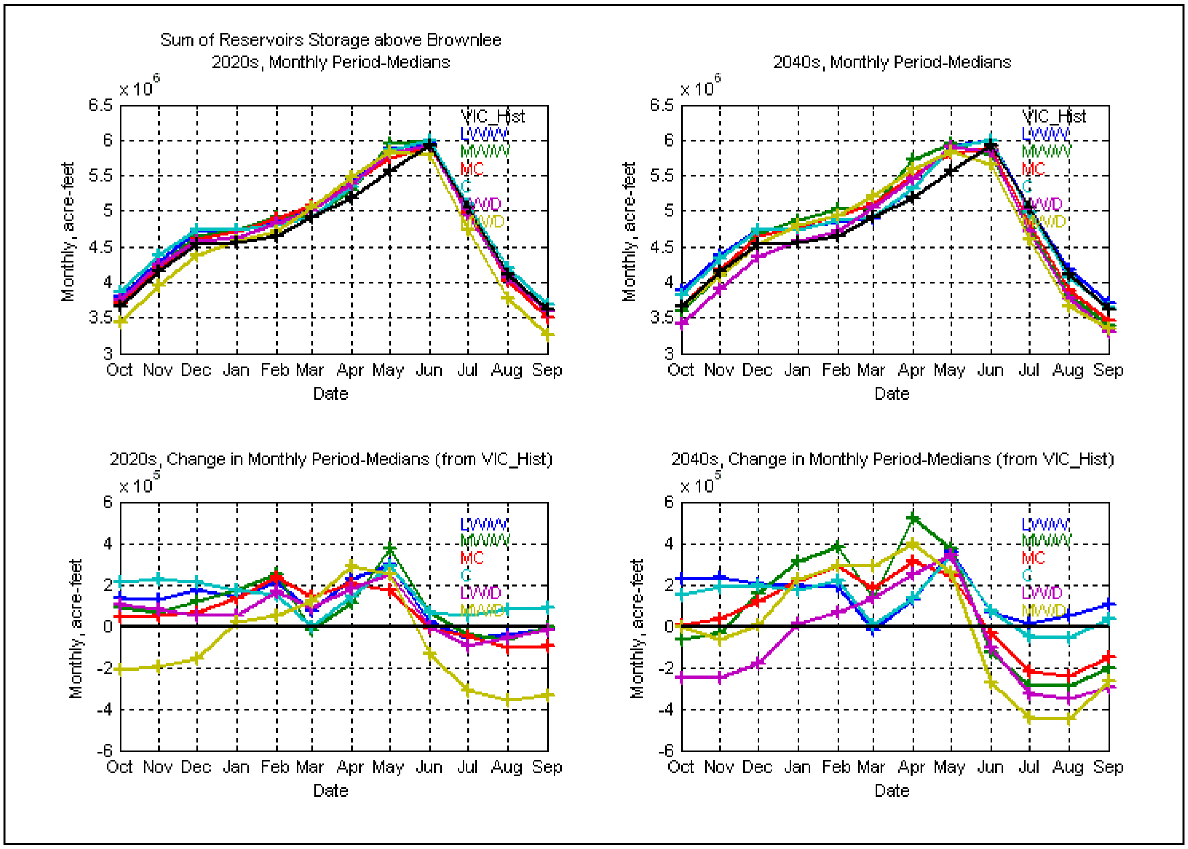

**Figure 21. Total and change in monthly period-median (from VIC simulated historical) end-of-month storage above Brownlee Reservoir in the Snake River subbasin.**

On the Boise River (not shown), the end-of month storage volumes followed similar patterns as on the upper Snake River. During dry years, a 10 to 15 percent decrease in volume was observed for late summer and fall. The drafts required to meet demands during irrigation season made refill the following year a challenge in the driest projections. The timing of the monthly peak did not appear to shift to earlier in the year, but it should be noted that with a monthly time-step model, a shift in timing by days or weeks would not be evident. While the peak flow timing does not significantly change on the Boise, the increased magnitude of the winter and spring flow volumes result in higher reservoir elevations earlier in the year when compared to the VIC historical scenario. The modeled hydrology from lesser tributaries to the Snake (e.g., Owyhee River) was not presented in the Part II Report, but the data suggested that runoff from these lower elevation subbasins will generally peak in March. The shift in timing of peak inflow seen at Brownlee Reservoir was a culmination of a shift in Snake River flows at Minidoka coupled with increased earlier run-off volumes in the Owyhee and eastern Oregon subbasins that ultimately demonstrated the shift seen in the model output.

The timing of flow on the upper Snake River at Heise (not shown) did not appear to significantly shift to earlier in the year. By the time the flow reached Minidoka, the peak appeared to shift to roughly a month earlier. This location includes flow from other watersheds such as the Henry's Fork River, Blackfoot River, and Willow Creek. The Snake River between Minidoka and King Hill is heavily influenced by aquifer spring flow. The modeled hydrology illustrated that the influence of this spring flow coupled with the change in flows in the climate change scenarios created a peak flow during the month of March. Similarly, the modeled hydrology on the Owyhee also peaked in March and when combined, inflow peak to Brownlee occurred earlier from April to March when compared to historical conditions.

Because the Snake River reservoirs filled consistently in all but the driest scenarios, it suggested that drafting the reservoirs to the current flood control rule curves would not appear to appreciably prevent reservoir fill. In the model, the flood control draft of Reclamation's reservoirs is guided by dynamic flood control rule curves that use the forecasted volumes from January through June and tracks the water that has already passed the forecast location. For example, in early January, a volume is projected from January through June. In the February forecast, the forecast volume is updated by subtracting the amount of runoff in January. If this forecast runoff occurs a month or two earlier as a result of climate change, the flood control storage requirement adjusts the reservoir target elevations to accommodate changes in runoff timing without negatively affecting reservoir fill capabilities.

### 3.4.3 Flow

Several flow locations were chosen for evaluation because they are used in operational decisions or are considered important in other studies on the Snake River. These sites included Heise and Minidoka on the Snake River, at the confluence of the Snake and Boise rivers on the Boise River, and at the confluence of the Snake and Payette rivers on the Payette River.

The Snake River above Brownlee Reservoir annual flow volumes increased above VIC simulated historical flow during the winter and spring in the HD scenarios (Figure 22). On the Snake River at Heise flow location, which is further upstream in the watershed, flow was shown to increase during winter and spring in all but the driest projections in both HD 2020 and HD 2040 (except MW/D). Only the MW/W climate projection in the HD 2040 scenario peak flow timing was observed to shift to earlier in the year by one month. Flow on the Snake River at Minidoka Reservoir also had larger volumes of flow in the winter and spring with a shift in the timing of that peak flow. Current spring return patterns peak in March, influencing the Snake River flow at King Hill. The Boise River at the confluence with the Snake River was shown to have increased flows in winter and spring, but no change in the timing of the peak. Peak flow on the Payette River at the confluence with the Snake River, was generally shown to both shift in timing and increase in volume in both HD scenarios and most climate change projections.

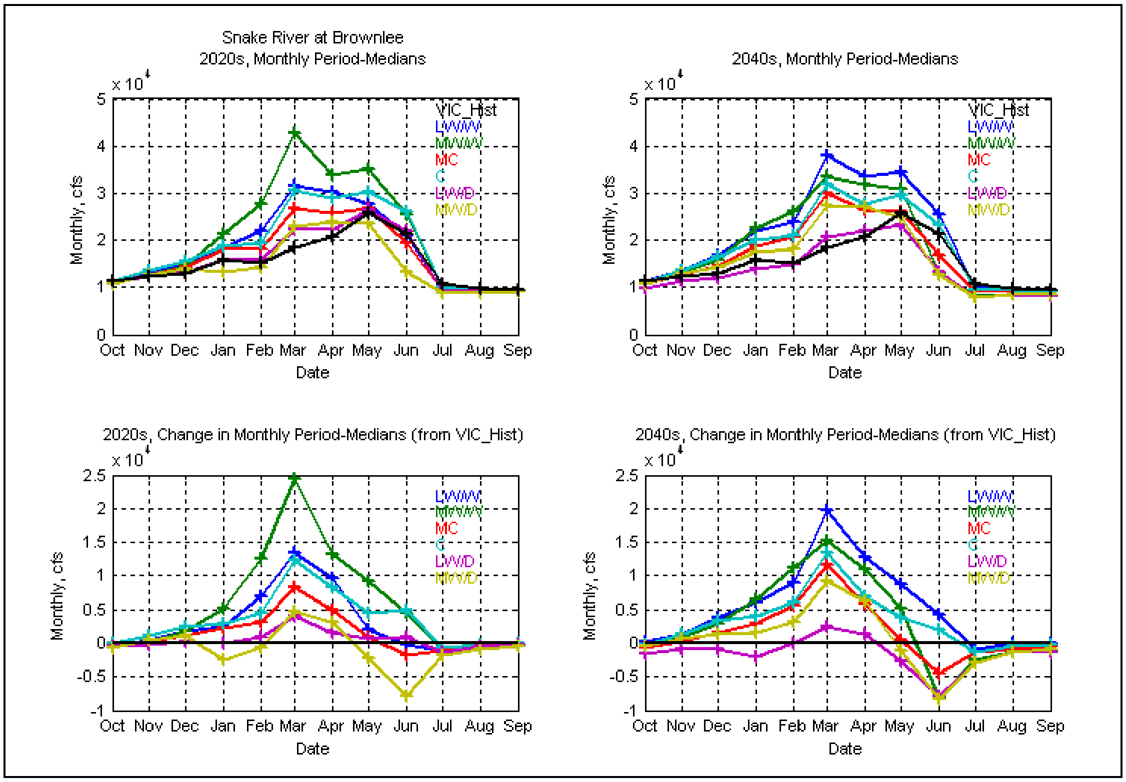

**Figure 22. Total and change in total (compared to VIC simulated historical) monthly period-medians flow in at Brownlee Reservoir on the Snake River.**

### 3.4.4 Surface Water Delivered

Surface water delivered (natural flow and storage water) was cumulatively summed as was done in the end-of-month storage metric. The amount of surface water delivered above Brownlee Reservoir decreased slightly (Figure 22). A decrease in surface water delivery occurred in the latter part of the irrigation season above Brownlee Reservoir on the upper Snake River, most of which occurred above Milner. On the Payette and Boise rivers, deliveries were generally unaffected in most climates except the driest in the HD 2040 scenario.

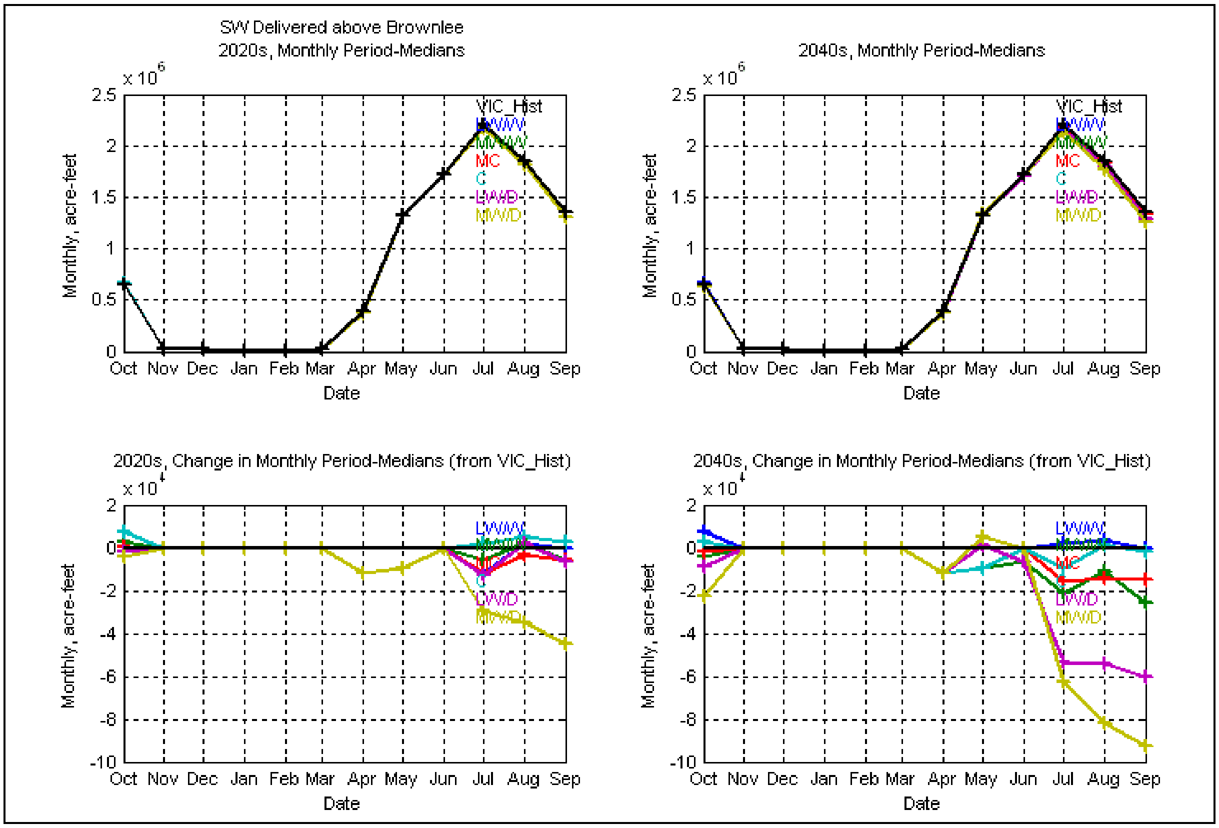

**Figure 23. Total and change in surface water delivered above Brownlee Reservoir in the HD 2020 and HD 2040 scenarios.**

The most significant decrease in surface water delivered was observed in the driest climates in both HD scenarios on all river systems presented. For irrigators, this study suggests that there will be a shift in use of irrigation water from natural flow to storage water to meet demands under the drier future conditions. While winter flow increases and is stored, the lower summer flows causes more reliance on that stored water in August and September. This apparent shift has benefits and downsides to various facets of managing the Snake River subbasin for all the needs and constraints imposed under the current level of development. Implications to the ground water aquifers and river interaction were not analyzed and addressed in this analysis.

It should also be noted that the driest climate used in this analysis was minimally dry when compared to historical conditions. Additional GCMs that indicate larger decreases in precipitation in the Snake River subbasin should be evaluated to fully understand the range of potential impacts due to climate change.

### 3.4.5 ESA for Resident Species and Other Environmental Objectives

A shift in the likelihood of delivering flow augmentation water for ESA-listed salmonids was observed occurs in both HD scenarios when compared to the VIC simulated historical deliveries. While achieving the full 487,000 acre-feet of flow augmentation may become more difficult, particularly under the HD 2040 scenario, the likelihood of providing at least 427,000 acre-feet was predicted to improve. This analysis was completed using the current augmentation assumptions with regard to access to rental pool water in storage reservoirs. Changes to these assumptions were not analyzed in this study.

Other environmental objectives such as water quality pools, minimum flows for resident fish, and meeting ESA objectives for ESA-listed snails and bull trout are a high priority for Reclamation. This was reflected in the modeling constraints. The release of storage water from an upstream reservoir may be necessary to satisfy bull trout or snail objectives. The frequency of meeting environmental objections and subsequent impact to other parts of the river system were evaluated. Palisades Reservoir’s minimum flows of 900 cfs were met between October and March for all of the climate change projections. The early fall appeared to be drier in most instances, resulting in a longer duration of lower flows; however, the wetter winter months maintain higher flows than VIC simulated historical conditions. This study suggests that it will be more difficult to meet minimum pools at Cascade, Arrowrock, and American Falls dams in the driest future climate projections.

Transient scenarios were presented for all metrics except ESA flow augmentation and ESA requirements for resident species. Despite annual runoff holding relatively steady through the year 2100, surface water deliveries on the Snake River and both major tributaries decreased over the 150-year time frame studied. This decrease was because many irrigators depend on natural flows. The timing of runoff in the future allows for more water to run off during the winter and spring and there is a finite amount of storage space. This would result in less water available for natural flow diversion by late summer and fall.

### 3.4.6 Forecasting

As warming continues, snowpack will diminish. It was believed that a decrease in snowpack would result in decreased accuracy in predicting runoff and that in turn would result in a change in the quality of water management decisions. This cause-and-effect relationship was not observed in this study because model output was relatively insensitive to whether a *perfect* or *imperfect* forecast mode was used. As reported in the Part II Report, forecasting quality done as part of the Snake River subbasin analysis was considered good; however, the modeling output remained insensitive to the forecast mode used.

# 4.0 SUMMARY OF PART III REPORT: USACE COLUMBIA BASIN FLOOD CONTROL AND BPA HYDROPOWER OPERATIONS

## 4.1 Approach

The Part III Report presented the assessment of the projected climate change impacts on hydroregulation studies using the current reservoir operating criteria which includes current flood control storage reservation diagrams, hydropower operating rules, and ESA objectives. Flood control curves were determined by the USACE and provided to BPA for use in the hydroregulation model, HYDSIM. The HYDSIM Model output consisted of 14 periods (one for each month, with April and August split into the first and second half of each month) of average flows, end-of-period reservoir elevations, and hydropower generation.

Flood control curves[14] influenced by climate change were developed for use in BPA's power model which assessed the impacts of climate change on the Federal Columbia River Power System. The flood control[15] analysis addressed the twelve Hybrid scenarios in forecast mode (six 2020s and six 2040s), the 2000 Level scenario[16] in forecast mode, and the six Transient scenarios which were only available in the observed mode. The forecast mode assumed an imperfect forecast of runoff volumes and the observed mode flood control datasets assumed a perfect forecast of runoff volumes. The flood control curves for the 2000 Level scenario were compared to the climate change scenarios. The reservoir modeling period was for the 70-year period of 1929 through 1998. While Transient climate projections were made for the years 1950 through 2099, the 70-years of data that the flood control curves were prepared for were based on the Transient 70-year period 1999 through 2068.

The flood control analysis for this study determined the flood control curves during January through April, given seasonal volumes and estimated the flood control curves during the refill

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[14] Flood control curves define the maximum reservoir pool surface elevations for each day of the year to maintain the balance between flood control and water supply objectives for each dam.

[15] Recently, the Corps has adopted the term "Flood Risk Management" to reflect new Corps guidance to include risk-based analyses in future flood studies; however, for purposes of this report, the Corps will use the term "flood control" to reflect common terminology used historically in flood damage reduction studies.

[16] The 2000 Level scenario used the 70-year set of streamflow data for 2000, with the irrigation depletions for 2000 applied to all years. As noted in Section 3, Reclamation analyses were conducted using 2010 Level flows.

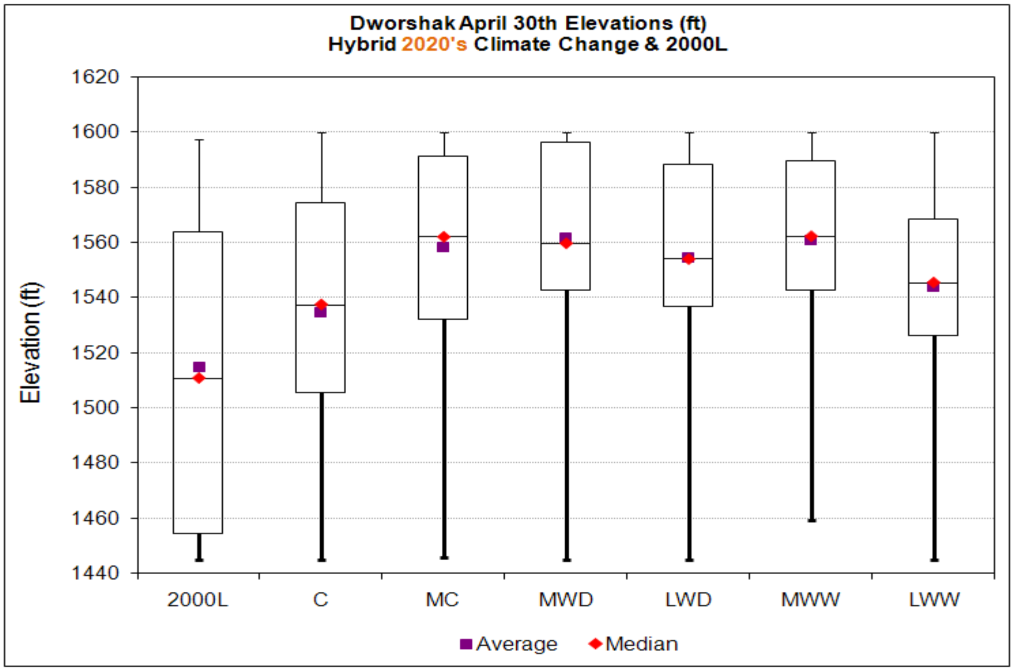
period of May through July. Flood control analyses usually require daily streamflow data for system flood control modeling (regulations) to determine flood control refill operations that meet ESA objectives at The Dalles, but due to time limitations, daily modeling was not performed. From a probabilistic or risk perspective, analyses were not developed of how existing procedures meet system flood flow objectives with climate change hydrology; however, the drawdown curves developed from this study are a good representation of climate change impacts during drawdown given the current flood control procedures.

The reservoir operations assessment was performed by first establishing two Base Case scenarios, one for comparison with the HD scenarios and one for comparison with the Transient scenarios, assuming current level operations and fishery constraints. The HD Base Case assumed forecasted volumes in developing the flood control curves and the Transient Base Case assumed observed volumes (perfect foresight) in the determination of the flood control curves. A total of eighteen climate change scenarios (six HD 2020s scenarios, six HD 2040s scenarios, and six Transient scenarios) with their respective climate changes in water supply were modeled and compared to the two Base Case scenarios. The model results identified the climate change impacts to reservoir elevations, outflows, spill outflows, and Federal and regional hydropower generation. The comparisons of the climate change scenarios to the Base Case scenarios showing the impacts of climate change on the power system can be found in the Part III Report in the appendix.

## 4.2 Key Findings

### 4.2.1 Flood Control

In general, while climate change projections indicate increased annual average runoff volumes in the Columbia River Basin, higher winter flows and earlier spring snowmelt also indicate slightly less runoff from April through August. The impact to flood control curves, the highest reservoir elevations at which the projects may operate, is dependent upon the subbasin’s climate response, where the project is located in the subbasin, and the climate change scenario. For example, in nearly all of the HD scenarios, the May through September volume of runoff at Hungry Horse Reservoir and the April through July runoff at Dworshak Reservoir are significantly less with climate change scenarios than under historical conditions, resulting in average higher flood control upper curves for each month January through April. To demonstrate this concept, Figure 24 shows the April 30 average and median upper curve elevations for Dworshak Reservoir for each HD 2020 scenario. The top and bottom of the boxes are the 25 percent and 75 percent exceedances, respectively. The dashes at the top and bottom of the vertical lines are the maximum and minimum elevations for that scenario. For other projects such as Libby and Brownlee reservoirs, about half the HD scenarios resulted in average higher curves and half resulted in average lower curves as shown in Figure 25.



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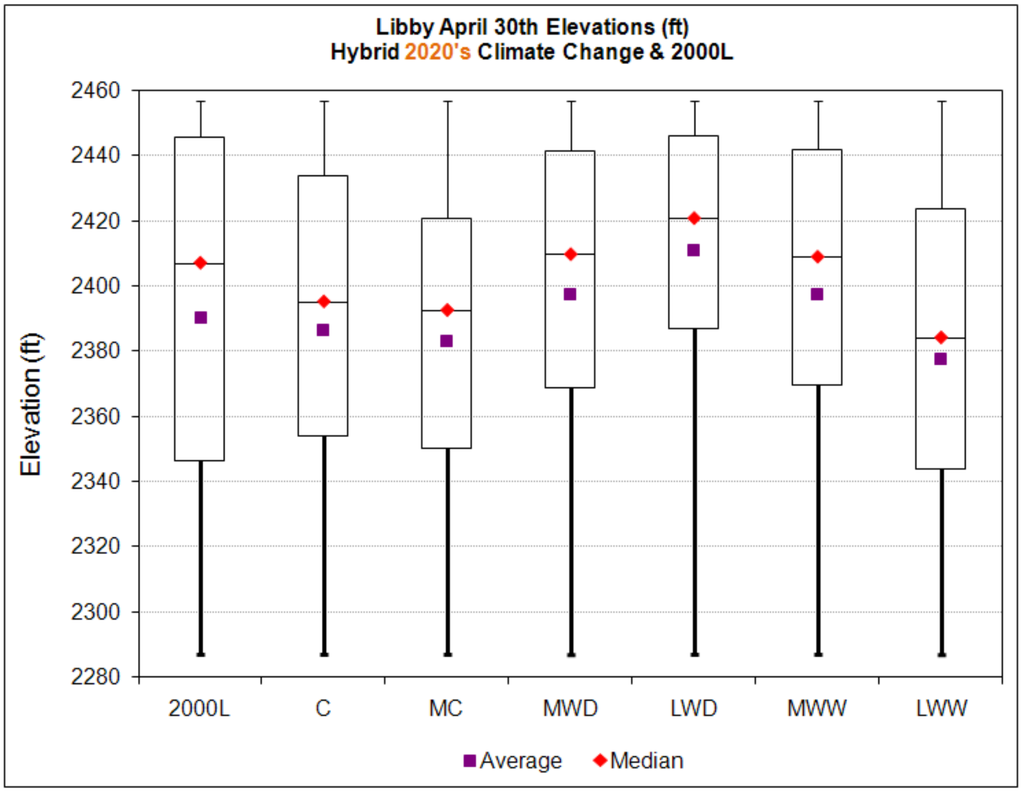
906 **Figure 24. April 30 flood control elevations for Dworshak Dam in the HD 2020s and 2000 Level scenarios**
907 **(the higher the elevation, the less space is required to capture floods).**



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909 **Figure 25. April 30 flood control elevations for Libby Dam in the HD 2020s and 2000 Level scenarios.**

The current flood control procedures may need to change in response to climate changes. For system flood control, the timing of the average monthly peak flow will shift from June to May, the runoff period will shift from an April through August runoff period to a March through July runoff period and the runoff volume will increase. Earlier maximum reservoir drafts at flood control projects may be needed to create space in order to capture the earlier runoff. Winter flood control procedures may need to change to accommodate an increase in the number of rain-driven events and rain-on-snow events for both system flood control as measured at The Dalles and local flood control downstream of projects on the headwaters of tributaries. For example, for local flood control at Dworshak Dam, winter inflows were projected to be larger and may occur earlier so the reservoir may need to draft deeper and earlier to contain these winter events. In addition, climate changes can impact local runoff characteristics, potentially requiring new forecast procedures. Also conflicts can arise in between releasing water for drafting the reservoirs for capturing spring snowmelt versus storing water for managing winter time flood events. Finally, earlier draft and refill of the projects could have late spring and summer impacts, such as lower river flows for fisheries objectives.

Transient climate change scenario trends show that spring runoff volumes decreased, resulting in higher flood control curves (i.e., lower space requirements) for all projects.

### 4.2.2 Columbia River Reservoir Assessment

The change in the runoff volume is the single characteristic of all the climate change scenarios that most impacts the projects on the Columbia River and its tributaries. Section 2.3.2 describes the seasonal shifting of the natural streamflow runoff in the HD climate change scenarios. These climate scenarios reflect higher streamflows during the January through April timeframe and lower streamflows during the summer months of June through August, relative to the Base Case 70-year 2000 Level Modified Flow dataset. As an example, Figure 26 illustrates various seasonal volumes for the HD 2040 scenarios at The Dalles Dam as compared to the Base Case. The runoff volumes during the January through April timeframe in the climate change scenarios vary from 120 percent to 185 percent (excluding the dry LW/D scenario) relative to the Base Case. The summer volume runoff varies from 65 percent to 95 percent relative to the Base Case.

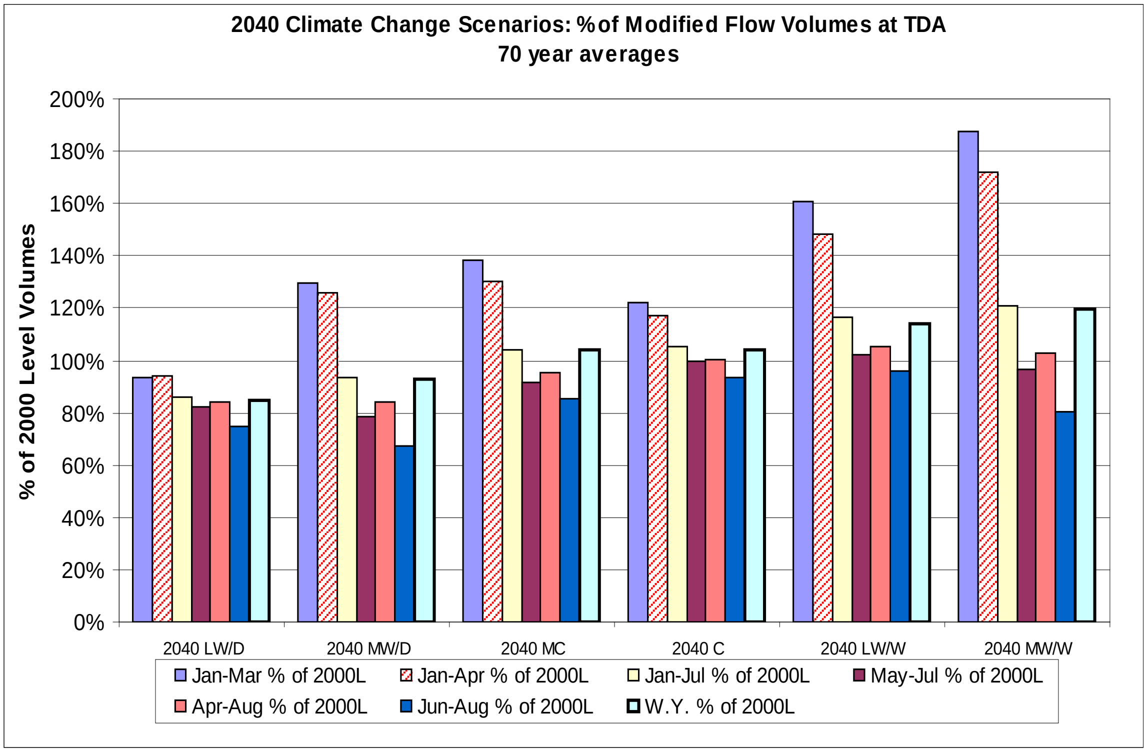

**Figure 26. Six HD 2040 scenarios flow volumes over various periods at The Dalles Dam (TDA) as percentages of the Base Case 70-year 2000 Level Modified Flow volume over the same periods.**

This change of runoff patterns with higher winter flows and lower summer flows results in a change in the regulated outflows from the projects. The increase in the January through April outflows results in higher hydropower generation during this period and an increase in the frequency of forced spills at most of the projects. Figure 27 shows the change in average outflows at McNary Dam relative to the Base Case for the HD 2040s scenarios. The reduced outflows during July and August are particularly problematic from both a flow and power perspective. The change in runoff patterns at McNary Dam could also impact the ability to meet Biological Opinion objectives during the summer. The ability to meet the fishery objectives could be reduced due to the lower average discharge available (as shown in Figure 26). However, based on the uncertainties in climate change forecasts, the full extent of potential impacts would require further review and assessment. Hydropower production is also reduced at the same time as increased temperatures caused by climate change trigger the demand for greater summer power loads.

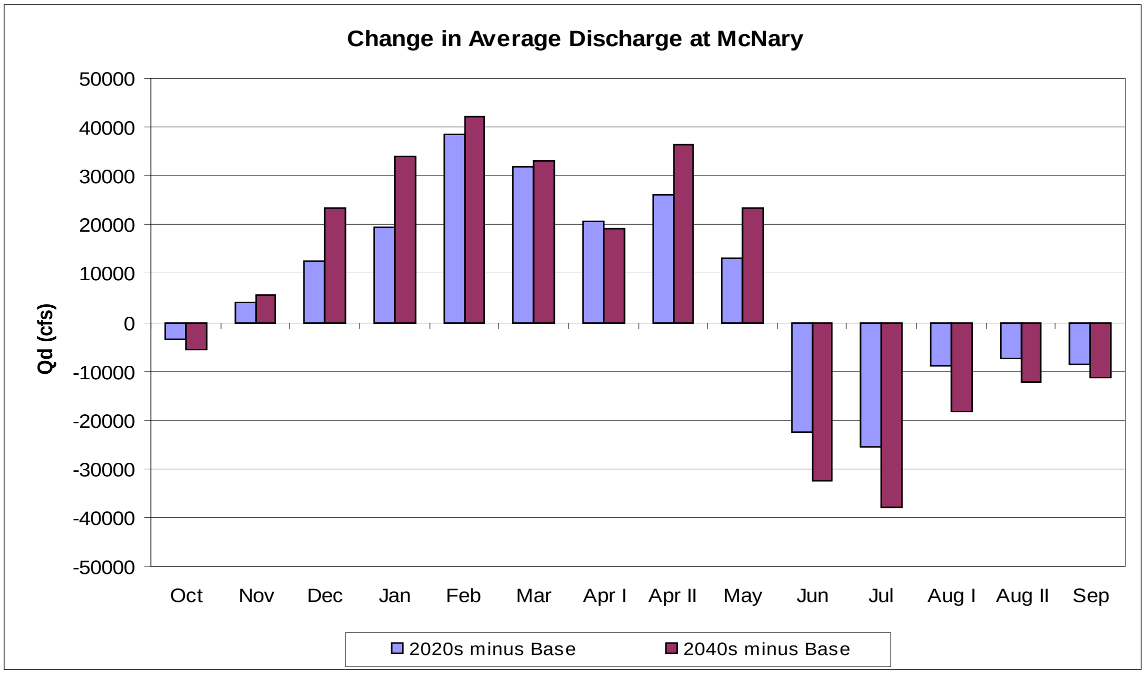

**Figure 27. McNary Dam average monthly discharge change for Base Case and HD climate change scenarios.**

Some of the projects, such as Hungry Horse Dam and Libby Dam, had challenges in maintaining flood control objectives during the wetter climate change scenarios. When comparing the Base Case to some scenarios, the increase in winter runoff as a result of more precipitation falling as rain rather than snow resulted in the 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 during the peak runoff periods in the modeling simulations, and different refill procedures and changes to the storage reservation diagrams maybe required.

Comparisons of hydropower generation values among three climate change scenarios (C, MW/W, and LW/W) and the Base Case are shown in Figure 28 for the Federal Columbia River Power System. The trend is similar to the project outflows, namely higher generation during the winter and early spring months, but reduced generation during the late summer period. This trend increases in the 2040s relative to the 2020s. The generation impacts during the month of June, and to some extent May, due to climate change were not as significant as the rest of the year because the peak of the natural runoff occurs during this 2-month period. In most scenarios, the natural flows are high enough to operate the projects at or near maximum turbine capacity. The additional flows are manifested in generally higher spill amounts during this 2-month period.

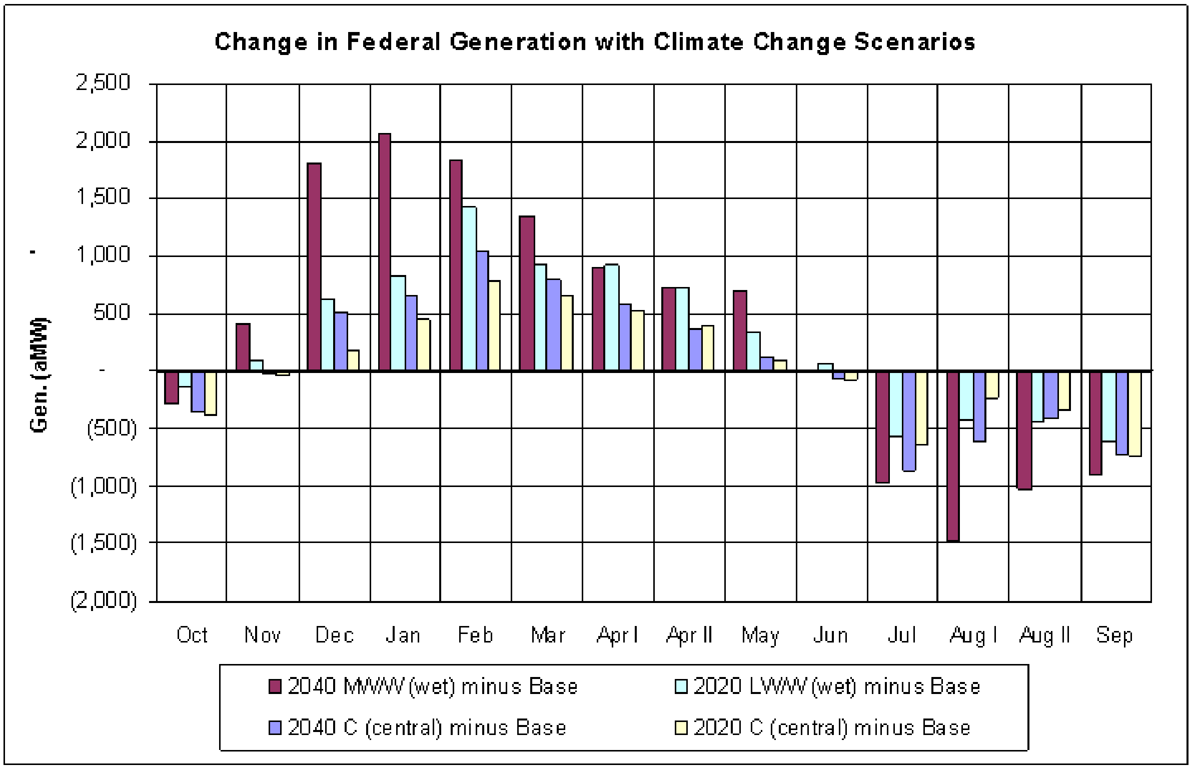

**Figure 28. Federal hydropower generation impacts with to climate change scenarios.**

Climate change might impact the ability to meet some Biological Opinion objectives. Because of the uncertainties associated with climate change analysis, the full extent of potential impacts would require further review. It appears that some objectives would benefit and some would not in a changing climate.

# 5.0 UNCERTAINTIES

The selection of future climate and hydrology scenarios for RMJOC long-range assessments reflect the best available datasets and data development methodologies; however, there were a number of analytical uncertainties associated with developing such scenarios, including those in the following areas:

- Global climate forcings: Although the study considered climate projections representing a range of future greenhouse gas emission paths, the uncertainties associated with these pathways were not explored in this analysis. Considerable uncertainty also remains associated with natural forcings, with the cooling influence of aerosols being regarded as the most uncertain on a global scale (IPCC 2007).

- Global climate simulation: There are still uncertainties in our understanding of the physical processes that affect climate, how to simulate those processes in climate models (e.g., atmospheric circulation, clouds, ocean circulation, deep ocean heat uptake, ice sheet dynamics, sea levels, land cover effects from water cycles, and vegetative and other biological changes), and how to do so in a mathematically efficient manner given computational limitations.

- Climate projection bias-correction: This study is framed by the University of Washington CIG efforts recognizing that the General Circulation Models may simulate climate in a way that is biased toward being too wet, too dry, too warm, or too cool. The University of Washington CIG identified and accounted for these tendencies, issuing bias-corrected climate projections data prior to their use in defining the HD and Transient climate and hydrology scenarios that framed this study. Bias-correction of climate projections data introduces uncertainty in characterizing future climate and associated responses in runoff, water supply, and operations.

- Climate projection spatial downscaling: This study used projections that were empirically downscaled, using spatial disaggregation on a monthly timeframe. Although this technique has been used to support numerous water resources impacts studies (e.g., Payne et al. 2004, Maurer and Duffy 2005, Maurer 2007, Anderson et al. 2008, LCRA/SAWS 2008, Reclamation 2008, Reclamation 2009), uncertainties remain about the limitations of empirical downscaling methodologies.

- Generating weather sequences consistent with climate projections: This study uses two different techniques to generate weather sequences for hydrologic modeling that reflect observed historical climate variability blended with projections about changes in monthly conditions. The choice of a weather generation technique depends on the aspects of climate change that are being targeted in a given study. Preference among available techniques remains to be established.

- Generation of natural runoff data: This study utilized several different reference data to generate the final bias-corrected hydrologic data used in the hydroregulation models. Naturalized runoff data used in Reclamation subbasins at monthly intervals was combined with 2000 Level Modified Flow data at 14-period intervals for the rest of the Columbia River Basin. Though the differences maybe minor when considering flood and reservoir regulation impacts, they may be more significant for different study objectives that consider ecosystem function.

- Natural runoff response: This study analyzed natural runoff response to changes in precipitation and temperature while the other watershed features such as vegetation and evapotranspiration remained constant. The models used in this study represented the relationship between weather and runoff as affected by historical land cover. If climate changes alter vegetation patterns, the runoff models would need to be recalibrated to reflect the changed conditions.

- Generating water supply forecasts under future climate and runoff conditions: This study focused on relationships between seasonal precipitation prior to the forecast, snow water equivalent at the time of the forecast, seasonal runoff volume after the time of the forecast, and how these relationships are impacted by climate change. Soil moisture is of interest heading into each water year since it indicates the degree to which the soil moisture deficit and infiltration volume may affect snowmelt runoff during spring and summer. Autumn streamflow is sometimes referenced as a proxy for autumn soil moisture conditions in forecasting. Also of interest are atmospheric and/or ocean conditions that correlate with subsequent seasonal basin weather conditions.

- Under a warming climate, snowpack is expected to diminish and thereby offer diminishing predictive information for forecasting spring-summer runoff volume. Uncertainties in the forecast seasonal volumes and the timing of the runoff in late spring and early summer are the major factors in being able to control flood flows at the desired levels. With less predictability in volume runoff and rain events, projects may need to operate more conservatively to account for this uncertainty.

- The limitation of this effort with respect to flood control is that, from a probabilistic or risk perspective, there is uncertainty of how adequate existing procedures that determine the flood control curves during the reservoir draft period of January through April and during refill in May through July would be at meeting system flood flow objectives with climate change hydrology. To analyze how existing flood control procedures perform using climate change hydrology, flood regulation studies using daily streamflows are required. With the tools currently available, regulation studies are performed one year at a time, results are examined, and the regulation is adjusted as needed to meet the flood flow objective at The Dalles Dam. A new tool is being developed to automate this process and is planned to be used in future climate change studies.

# 6.0 POTENTIAL NEXT STEPS

The scope of this study is complete and the information will be used in future analyses of the individual RMJOC agencies. BPA and the USACE plan to build on this information for the Columbia River Treaty 2014/2024 review. Reclamation will use this information in its West-Wide Climate Risk Assessments and other studies.

This study represents the first Federal agency coordinated study using the current level of climate change information and data. The next steps generally fall under three categories: monitoring, evaluation, and additional studies. For monitoring, historical records and present conditions will be reassessed to see if the transition towards future climate change scenario characteristics is underway. This will help establish a timeline for applying the evaluations and reviewing our current water and river management procedures.

For evaluation, agencies would seek to understand what the climate change data signifies and its limitations. Climate change scenarios other than those selected for this study should be evaluated and assessed. Methods for downscaling General Circulation Modeling, which is based on monthly data, to produce daily streamflow data are being investigated and may be improved. Bias-correction methods to account for hydrologic model biases are being analyzed and may be improved as well. Information about Canadian glacial snowmelt was not available at the onset of this study, but may be included in future studies.

In addition, agencies may explore alternative processes to achieve objectives for water supply, aquatic species, power, and flood control under a new set of climate change rules. The evaluation phase will also incorporate newer climate change information as it becomes available and develop the data and tools to better facilitate climate change data development and updates. It is expected that the evolution of technology and science of climate change, particularly in the Pacific Northwest region, will result in more confidence in the results and in planning processes that are more consistent with the nature of climate change as it is projected to unfold in the Columbia River Basin.

## 6.1 Additional Studies

This study examined the potential impacts of water supply changes due to climate change on existing operations of the projects under the jurisdiction of the three participating RMJOC agencies. Because of this initial work, additional studies or areas for further examination have been identified for future assessments. This list is not exhaustive, but is representative of future efforts that should be considered:

- Water demands: As flow timing, frequency, and duration patterns change, changes to current flood operations, diversion practices, carryover volumes, reservoir outflows, and other factors may need to be reconsidered. Because this study was conducted to understand how changes in water supply may affect operations, additional work should be completed to understand changes in water demands, flood control operations, and other variables.

- Magnitude and duration of the impacts of climate change (e.g., prorationing, flow augmentation, and ESA objectives)

- Frequency of spillway use

- Operational changes (flood control curves, operating rule curves): In some locations, Reclamation uses dynamic flood control curves; however, in those locations where fixed flood control curves are present in models, the modeling should be updated to allow for additional analyses of dynamic flood control curves.

- Results from this study should be compared to those done previously by other entities and comparisons reported, including other types of General Circulation Models used in the studies to achieve a comprehensive understanding of the similarities and differences.

- Flow data from these studies should be combined with General Circulation Model temperature data to conduct water quality studies and the effect of a changing climate on aquatic ecosystems. In the Secure Water Act, ecosystem resiliency is a major parameter to be evaluated and monitored and as such, should be given attention in future work.

- The Crooked River subbasin should be studied in greater detail. Only one VIC location was used to develop flows on this tributary to the Deschutes River so adding more VIC inflow location nodes in the model to improve calibration would be helpful. Also, conducting the climate flow development process with a more appropriate hydrologic model than the VIC model for capturing groundwater-dominated systems, or coupling groundwater/surface water models, could improve flow results. Groundwater influence below Opal Springs should be addressed.

- The upper Deschutes River and the middle Snake River have a significant influence from groundwater and the groundwater/surface water interaction should be studied.

- In the calibration process, University of Washington CIG uses bias-correction techniques to adjust hydrologic model output to better reflect historical naturalized flows. It is unknown how bias correction affects future simulations results. Model runs characterized by excellent calibration should be compared to those that are heavily dependent on bias correction.

- Future efforts could focus on climate change impacts on fisheries and environmental conditions, which could translate into impacts on environmental water demands found in reservoir systems management.

- With respect to flood control, tools and procedures to enable daily data modeling should be developed to identify areas of concern to guide future paths. Flood control modeling could be performed to determine peak regulated flows with existing procedures. A comparison of the regulated flow frequency curves with the historical flows could assess the effectiveness of current procedures with climate change flows. Daily modeling can help assess if earlier spring peak flows are problematic with the current methods. The resulting peak flows during the winter events should also be analyzed. If it is determined that climate change has an undesired effect on the regulated exceedance frequency of peak flows (i.e., the exceedance frequency of flows at levels that cause flood damages), flood operations may need to be changed to reduce undesired impacts. However, this assessment is dependent on the development of regionally accepted methods and processes that create climate change daily flows and forecasts for input to reservoir models.

- The datasets produced under this study will be used to provide climate change scenario analysis for longer-term hydropower studies and fishery related studies, including future Biological Opinion studies, ESA and fisheries related studies, and hydropower system asset planning studies.

- As new climate change data becomes available and new technology evolves, it is anticipated that the processes and insights gained in this study will be repeated with new data to better understand climate change impacts and risks to the hydropower system.

# 7.0 ONGOING STUDIES WITH CLIMATE CHANGE CONSIDERATIONS

## 7.1 West-Wide Climate Risk Assessment

In 2009, Public Law 111-11, named the Secure Water Act, was passed by Congress requiring several Federal agencies to determine risks to water supplies (e.g., groundwater, snowpack, flow) due to climate change and to understand what the impacts of those supply changes would be on matters such as ecosystems, operations, demands, and other water concerns. Section 9503 required Reclamation to complete this work within 2 years from the date the law was enacted and to implement this effort, the West Wide Climate Risk Assessment team was formed. In compliance with Section 9503, Reclamation submitted its first comprehensive assessment report in March 2011, quantifying supply changes in the future and qualitatively documenting what those changes may mean to the major areas identified in the law. This series of assessment reports is the first required, with subsequent updates due every 5 years.

In addition to Section 9503, Section 9505 of the Secure Water Act calls for the Federal Power Marketing Administrations (PMAs) to assess the effects of climate change on water supplies required for hydropower generation at Federal water projects. This Hydroelectric Power Assessment will include an assessment by the four PMAs: Bonneville Power Administration, Southeastern Power Administration, Southwestern Power Administration, and Western Area Power Administration. This assessment is expected to be completed in the fall 2011.

## 7.2 Columbia River Treaty 2014/2024 Review Program

The Columbia River Treaty (Treaty) was signed by the United States and Canada in 1961 and implemented in 1964. The Treaty doubled water storage capacity on the Columbia River system with the construction of three large storage projects in Canada (Duncan, Keenleyside, and Mica) and Libby Dam in the United States. Through a coordinated operation, these Treaty projects have provided billions of dollars (U.S.) of flood damage reduction and power benefits shared equally in both Canada and the United States.

Although the Treaty has no expiration date, beginning in 2024 and thereafter, either country has the option to terminate most of the provisions of the Treaty with 10 years written advance notice. In addition, the Canadian-assured storage provisions for flood control purchased in

1964 expire in 2024, resulting in potentially significant changes in the management of flood risk in the Columbia River Basin. After 2024, the Treaty calls for a shift to an operation under which the United States calls upon Canada for assistance. Due to this change in the Treaty, the USACE and BPA are taking the necessary steps to address the impacts of this change and determine the future of the Treaty or possible Treaty negotiations. Given the importance of these issues, the U.S. Entity[17] has embarked on a multi-year effort to understand the implications of these issues. The U.S. Entity will make a recommendation to the U.S. Department of State about the future of the Treaty by September 2013.

To arrive at an informed recommendation for the future of the Treaty, the U.S. Entity (supported by the USACE and BPA), the sovereign review team (comprised of States, Tribes, and agencies directly affected by the Columbia River Basin), and stakeholders are undertaking a series of studies to collect critical information to support this recommendation. Collectively, this effort is called the "Columbia River Treaty 2014/2024 Review" (CRT Review). Since these important issues pertain to the year 2024 and beyond, climate change is very germane to this effort and therefore, an important element of this work. The data and lessons learned from this RMJOC study will be utilized in the CRT Review to evaluate the Treaty issues and decisions as they pertain to flood risk management, hydropower production, ecosystem functions, and other river uses.

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[17] The U.S. Entity, composed of the Administrator of the Bonneville Power Administration and the Division Engineer of the Northwestern Division of the U.S. Army Corps of Engineers, is charged with implementing the Columbia River Treaty in the United States.

# 8.0 LESSONS LEARNED

## 8.1 Models

Models are used in various stages of climate change analysis work. Global Circulation Models generate temperature and precipitation data (among other parameters) that are used as input to hydrologic models that ultimately generate flows in rivers at specific locations. The flow data is then used to understand hydraulic changes, impacts on reservoir operations, or the ability to divert water at specific times of the year. The locations of points used to calibrate flows need to be considered carefully. Location selection can affect the way models work and the ease of maintaining mass balance, calibrating efforts, checking results, and other parameters. More VIC inflow locations in each subbasin, selected at locations that help to improve mass balancing, would have been very helpful in this analysis.

VIC historical time series data does not necessarily match Reclamation historical time series data or patterns, particularly in the smaller, upstream subbasins. Bias correction (Part I Report) can cause large swings in adjacent time increments, causing model instability. This requires additional work to ensure that sites in the upper watersheds of each subbasin for closer analyses before that data can be used for additional work.

## 8.2 Resources

Funding to complete studies of this type could be extensive. Staffing levels require a wide range of expertise including experts in hydrology and other sciences, computer programming, computer modeling (all types), automation, engineering, and other scientific fields. High-speed computers are needed to manage data and complete model simulations.

The selection of climate projections should be considered at a subbasin scale (e.g., Snake, Deschutes, and Yakima rivers) in addition to a larger basin scale (e.g., Columbia River Basin scale in this case).

It may be best to use all of the available GCMs and emission scenarios as input to a hydrologic model as opposed to selecting a subset in the future. If automation of the entire process continues to improve, use of more modeling may provide a better suite of results.

The current operating criteria that use specific months to define forecast periods for the different reservoirs should be considered for adjustment. Maintaining sets of rules based on the same seasonal periods (as present is no longer realistic when streamflow timing shifts are predicted to occur.

# 9.0 LITERATURE CITED

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# Appendix

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