RECLAMATION

Managing Water in the West

Climate and Hydrology Datasets for Use in the RMJOC Agencies' Longer-Term Planning Studies:

Part II – Reservoir Operations Assessment for Reclamation Tributary Basins

U.S. Department of the Interior

Bureau of Reclamation
Pacific Northwest Region
Boise, Idaho

January 2011

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The mission of the Department of the Interior is
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and related resources in an environmentally and economically sound manner
in the interest of the American public.

Photographs on front cover from left to right: Arrowrock Reservoir, Boise River, Idaho; Payette River, Idaho; Yakima Valley, Washington.

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Regional Resource & Technical Services
River & Reservoir Operations

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U.S. Department of the Interior

Bureau of Reclamation
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Boise, Idaho

January 2011

Acknowledgements:

RMJOC Sponsors:

- Patrick McGrane, Bureau of Reclamation, Pacific Northwest Region
- Rick Pendergrass, Bonneville Power Administration
- Jim Barton, U.S. Army Corps of Engineers, Northwestern Division

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- Bureau of Reclamation, Pacific Northwest Region: Patrick McGrane, Chris Lynch, Jennifer Johnson, Sharon Parkinson, Bob Lounsbury, Ted Day, Carol Kjar, and Lori Postlethwait
- Bonneville Power Administration: Rick Pendergrass, Brian Kuepper, Nancy Stephan
- U.S. Army Corps of Engineers: Jim Barton, Seshagirir Vaddey, Peter Brooks, Malar Annamalai, Keith Duffy, Joel Fenolio, Patricia Low, Kristian Mickelson, John McCoskery, William Proctor, and Randal Wortman

Additional Comments and Contributions from:

- Northwest Power and Conservation Council
- Columbia River Inter Tribal Fish Commission
- BC-Hydro
- U.S. Fish & Wildlife Service
- NOAA Fisheries Service
- University of Washington Climate Impacts Group
- Oregon Climate Change Research Institute

Abbreviations and Acronyms

BC	Bias-corrected
BCSD	Bias-Correction Spatial Disaggregation
BiOp	Biological opinion
BPA	Bonneville Power Administration
C	Central change scenario
C°	degrees Celsius
cfs	cubic feet per second
CROO	Reclamation Hydromet site for the Crooked River below Opal Springs near Culver, Oregon
CSRO	USGS gage location on the Crooked River below Opal Springs near Culver, Oregon
CULO	Reclamation Hydromet site for the Deschutes River near CROO near Culver, Oregon
DCCO	USGS gage location on the Deschutes River above Lake Billy Chinook at near Culver, Oregon
DPL	Daily proration level
DPM	Deschutes Planning Model
ENSO	El Nino Southern Oscillation
ESA	Endangered Species Act
F°	degrees Fahrenheit
GCM	General Circulation Model
HB 2860	Washington State House Bill No. 2860
HD	Hybrid-Delta
KAF	Thousand acre-feet
LW/D	Less warming and drier
LW/W	Less warming and wetter
LW/W	Less warming and wetter
MAF	Million acre-feet
MC	Minimal change
MW/D	More warming and drier

MW/W	More warming and wetter
NOAA Fisheries Service	National Oceanic and Atmospheric Administration Fisheries Service
NRNI	No regulation, no irrigation
O&M	Operation and maintenance
PARW	Reclamation Hydromet site identification of the Yakima River near Parker
PRVO	The average Bowman Dam release
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
RMJOC	Reservoir Management Joint Operating Committee
SPM	Snake Planning Model
SWE	Snow water equivalent
TWSA	Total water supply available
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
UW CIG	University of Washington Climate Impacts Group
VIC	Variable Infiltration Capacity model
VIC BC	Variable Infiltration Capacity model, bias-corrected
WY	Water year
YAPAR	NRNI site identification for the Yakima River near Parker
YPM	Yakima Planning Model

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EXECUTIVE SUMMARY

The Bonneville Power Administration (BPA), U.S. Army Corps of Engineers (USACE), and the Bureau of Reclamation (Reclamation) collaborated to adopt climate change and hydrology datasets for their longer-term planning activities in the Columbia-Snake River Basin. This was coordinated through the River Management Joint Operating Committee (RMJOC), a subcommittee of the Joint Operating Committee that was established through direct funding Memorandum of Agreements between BPA, Reclamation, and the USACE. The RMJOC is specifically dedicated to reviewing the practices, procedures, and processes of each agency to identify changes that could improve the overall efficiency of the operation and management of the FCRPS projects.

In addition to creating these datasets, the RMJOC agencies worked together to adopt a set of methods for incorporating these data into those longer-term planning activities. Several goals framed this effort:

1. Arrive at consensus agreement on which available climate projection information should provide a range of future climate and hydrologic scenarios for use in RMJOC agencies' long-term planning, where the approach is flexible and can accommodate updates in climate projection information

2. Demonstrate capability in using selected future climate and hydrology scenarios in the context of reservoir systems analyses typically conducted by RMJOC agencies.

3. Promote efficient use of each agency’s limited resources in satisfying the first two objectives, avoiding redundancy where possible

4. Collaborate with other stakeholders in the region to gain their support for this analysis and data

Throughout this process, RMJOC agencies gathered input from several stakeholder groups, including BC-Hydro, Columbia River Inter-Tribal Fish Commission, NOAA Fisheries Service, Northwest Power and Conservation Council, Oregon Climate Change Research Institute, U.S. Fish and Wildlife Service, and the University of Washington Climate Impacts Group.

Report Part II serves as the second of four documents to be produced in this effort entitled, *Climate and Hydrology Datasets for use in the RMJOC Agencies’ Longer-Term Planning Studies*.

- *Report - Part I: Future Climate and Hydrology Datasets* (completed December 2010) Part I focused on the RMJOC adoption of future climate and hydrologic data from the University of Washington's Climate Impacts Group (UW CIG) HB2860 effort, evaluation of those data, and development of associated water supply forecast series to reflect future hydroclimate conditions. The overarching motivation for this collaborative effort and key scoping considerations were also discussed in the Part I Introduction.

- *Report - Part II: Reservoir Operations Assessment – Reclamation Tributary Basins* (this document)

- *Report - Part III: Reservoir Operations Assessment – Columbia Basin Flood Control and Hydropower* (expected Spring 2011).

- *Summary Report* (expected Spring 2011)

Part II focuses on Reclamation's simulation models of reservoir operations in the Yakima, Deschutes, and Snake River subbasins, which are the three subbasins in the Columbia-Snake River Basin that have long-term functional models constructed. This Part II presents results of the operational analyses conducted using the future climate and hydrology datasets described in Part I. In this assessment, future climate change impacts on operations might be interpreted from study results; however, these results are not meant to be construed as findings on future operational vulnerability, which depends on stresses other than climate. Likewise, this effort was not scoped to consider potential alternative future operations strategies that might offset such impacts.

The remainder of this executive summary offers chapter capsules describing the contents of this report:

Chapter 1 – Introduction: This chapter summarizes the framework in which climate change projection information was related to longer-term operations planning, selection and brief description of the climate and hydrology scenarios (see Part I for detailed discussion), and introduces the operations analyses performed in Part II. The RMJOC selected Hybrid-Delta (HD) and Transient scenarios for use in this study. The HD scenarios reflect an adjusted historical 30-year window of climate change in the future relative to a reference historical period. Transient scenarios reflect time-evolving climate over a 150-year continuous timeframe taken directly from the global climate models (GCMs) rather than from any observation. A total of 19 future climate and hydrology scenarios were selected from the UW CIG HB2860 for use in this study: 13 HD scenarios (12 future climates plus the historical condition) in which 6 climates were centered on the 2020s; 6 scenarios which centered on the 2040s; and 6 Transient climate projections.

Chapter 2 – Description of Current Reservoir Operations by Subbasin: This chapter summarizes the basic information about each of the three subbasins this report focused on, the current operations in each, and any special operational aspects relevant to that subbasin (Figure 1).

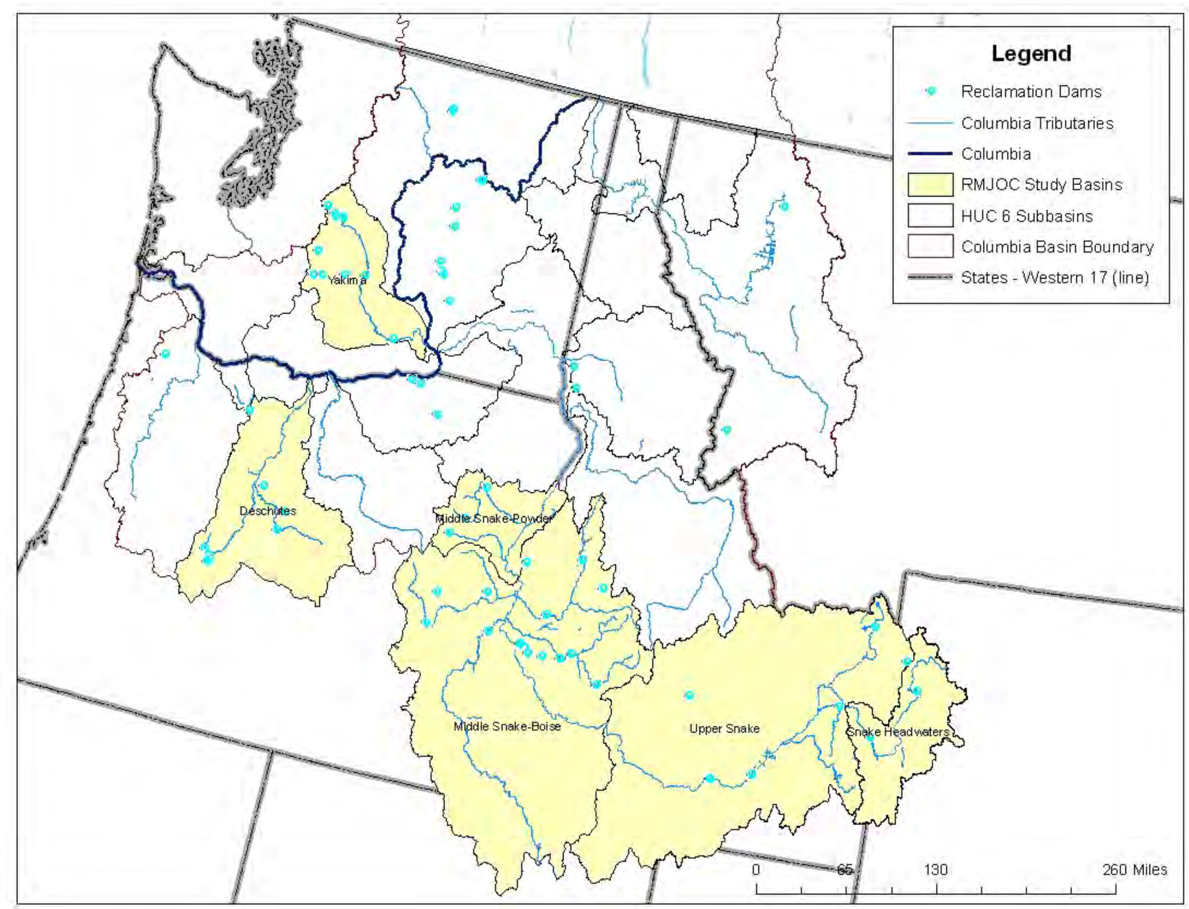

Figure 1. Locations of Reclamation systems and major subbasins of study focus in the Pacific Northwest.

Chapter 3 – Description of Operations Simulation Modeling and Inputs Adjusted for RMJOC Climate and Hydrology Scenarios: This chapter reviews the reservoir model type and approach used to evaluate climate change projections in each subbasin and discusses the climate change inflow hydrology datasets. In each subbasin, the 19 HD and Transient scenarios were bias-corrected and spatially downscaled (BCSD) to produce inflow hydrology and water supply forecasts at specific locations in each subbasin.

Yakima River subbasin: The RiverWare application (a daily time step) was used to simulate Yakima Project operations consistent with real-world operations. Bias-corrected (BC) monthly and daily supply information was provided to the model at 11 specific locations.

Deschutes River subbasin: The monthly time step MODSIM river management decision model was used to evaluate the climate change projections in the Yakima River subbasin. A total of 12 flow input locations were used in both naturalized (no demands or reservoirs operations) and modified (2010 level demands, full reservoir operations) flow models to evaluate mass balance and operational impacts due to a change in supply, respectively.

Snake River subbasin: A monthly time step MODSIM model was used as well, but with 28 flow input locations used to input climate change hydrology into both naturalized (no demands or reservoirs operations) and modified (2010 level demands, full reservoir operations) flow models to evaluate mass balance and operational impacts due to a change in supply, respectively.

Chapter 4 – Results of Operations Modeling on the Yakima, Deschutes, and Snake River Subbasins: Chapter 4 is the heart of the study in which the technical details of the results of the climate change analysis are presented by subbasin. Both *perfect* and *imperfect* forecasting modes were evaluated in the HD scenarios, but none of the subbasin operations was very sensitive to either mode in the operational simulations.

Yakima River subbasin: Water supply conditions were found to have season-specific impacts under the future HD scenarios, generally featuring increased cool-season inflow (during November through March) and decreased warm season inflow (during April through September). Season-specific changes in system inflow affect the assessment of total water supply available (TWSA) during the months of March through September, which affects operating decisions related to river flow targets, water demand prorationing, and storage targets.

Another consequence of March-September TWSA reductions is a reduction of water supply available for delivery to junior water users in the system. For both flow and delivery metrics, results vary considerably across future HD scenarios during a given period (2020s or 2040s), where more degree of change generally trends with the type of HD climate change (e.g., less warm-season flow or delivery reduction for the wetter HD climates, and more reduction for the drier climates). Lastly, the increase in cool-season system inflow and reduction in March-September TWSA leads to an increase in typical cool-season storage and a decrease during the warm-season and a decline in end of season storage, an indication of less manageable water in the subbasin.

The qualitative range of variability of operations is similar; however, depending on the quality of the climate change (i.e., more or less warming, wetter or drier), the envelopes are shifted accordingly (e.g., shift towards reduced storage conditions for scenarios that involve drier conditions). This has implications for extremes, such as high-inflow months or droughts. For scenarios involving drier conditions, not only would typical delivery and storage conditions be reduced, but drought-year delivery and storage conditions would also be reduced relative to historical climate conditions.

Based on comparison of Transient and HD operations results, the portrayal of typical operational conditions is similar under both operations types when the Transient results are viewed from an ensemble-median perspective and assessed during periods associated with HD climates. The Transient results differ from HD climates in that they also characterize the trend in operating conditions in a time-evolving fashion through periods that extend before and after a given HD scenario.

Deschutes River subbasin: The 2020 and 2040 HD scenarios were simulated using both naturalized and modified flow models in the Deschutes River subbasin. In the naturalized model, VIC simulated flow volumes were found to be almost 3.5 percent higher in total water volume for the entire period of record when compared to the Reclamation naturalized flows. On an average monthly basis (e.g., all of the January values averaged for the period of record, all of the February values for the period of record, etc.), variations between the two datasets were generally between 1 and 4 percent and on an annual average basis, variations were as high as 30 percent in some years. Because of this variation, it is possible that the wetter climates overestimate flow volumes and the drier climates underestimate the extent of the dry volumes and subsequently the impact of those climates. As discussed in Part I, the VIC model is a shallow subsurface hydrology model that does not simulate flows in ground water dominated areas, such as the Deschutes River subbasin, well. Modeling these types of systems with a more appropriate model other than VIC and improving the calibration to Reclamation naturalized flow data would likely narrow these differences.

The overall pattern for the subbasin as a whole and in the upper Deschutes River was earlier and higher runoff volume. These results were less dramatic in the HD 2020s than in the HD 2040s climate projections. Decreases in inflow, end-of-month storage in the latter part of the irrigation season, flow in the channel at specific gage locations during the summer months, and subsequent surface delivery reductions in the dry climate projections is possible on the Crooked River.

Anticipated changes will create greater water supply concerns for those with natural flow water rights when compared to those with storage water rights. The change in supply occurs because of the shift to an earlier timing of the peak flow runoff and a decrease in late summer in-stream flows. Reservoirs start drafting earlier and are relied upon more heavily in the summer and late fall than historically.

Because a monthly time step model was used for this work, the ESA objectives were analyzed using a surrogate monthly approach as opposed to the 7-day moving average objectives outlined in the Biological Opinion (BiOp). Based on this surrogate approach, occurrences of not meeting the average flow requirements for the month of October (the only month evaluated) 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 insufficient water volume was available in the Prineville Reservoir to supplement Crooked River flow. This surrogate approach does not allow direct comparison to the 7-day moving average objective in the BiOp, but it may be indicative of trends that could occur in extremely dry or drought periods in the Deschutes River subbasin.

The Transient scenarios indicated that while HD scenarios showed larger variations in the metrics, over time most of those metrics appeared to have relatively low rates of change when viewed through the longer, 150-year time window.

Snake River subbasin: All of the HD scenarios were simulated using both naturalized and modified flow models. In the naturalized model, VIC simulated flows volumes were found to be almost 0.2 percent higher in total water volume for the period of record when compared to the Reclamation naturalized flows. On an average monthly basis, most variations between the two datasets were slightly less than 0.5 percent. These results are significantly better than those from the Deschutes River subbasin. However, as with the Deschutes River results, on an annual average basis, variations were as high as 30 percent or more in some years.

One major difference in the climate change models selected for the Snake River subbasin is that they tended to be wetter than historical conditions. Future climates were selected at a Columbia River System scale, which unintentionally resulted in the primarily wetter climate change projections when compared to historical temperature and precipitation at the smaller Snake River subbasin scale. As a result, most of the climate projections resulted in increases in inflow to major reservoirs in the late spring/early summer, higher reservoir elevations in spring, and increases in spring flow. However, in the late summer/early fall, most climate projections continued to show lower reservoir elevations in fall and a decrease in irrigation season flows with impacts on surface water deliveries.

Inflow hydrology and end-of-month storage experience a shift in either peak flow timing or volume or both in most locations evaluated. Inflow volume to major reservoirs is likely to increase in all but the driest climates, but peak flow timing does not appear to shift on the Boise River (note that with the monthly time-step used in this modeling, a shift in timing of the peak flow by days or weeks is not evident). For the upper Snake River above Brownlee Reservoir, almost all of the climate change projections are shown to shift by at least one month to earlier in the year and in some cases, by as much as two months (from May to April or March).

An increase in volume is observed in most climate change projections in both HD scenarios and timing of the peak end-of-month storage also shifts to earlier in the year on the system scale as well as in Payette River. On the Boise River, a small decrease in peak storage volume is shown to occur during dry years making refill the following year less likely in some of projections, particularly in the HD 2040 scenario, which had one of the driest projections, but the timing of the monthly flow peak does not shift.

Annual flow volumes at the Snake River above Brownlee Reservoir increase above VIC simulated historical flow during the winter and spring in the HD scenarios. At the Snake River at Heise flow location, which is further upstream in the watershed from Brownlee Reservoir, flow also increases during winter and spring in most projections except the driest ones in both HD scenarios. The Snake River at Minidoka Reservoir location shows increased volumes of flow in the winter and spring and a shift in the timing of peak flow. The Boise River at the confluence with the Snake River has increased flows in winter and spring, but at a monthly time step, no change in the timing of the peak was detectable; however, peak flow on the Payette River at the confluence with the Snake River is expected to both shift in timing and increase in volume in both HD scenarios and most climate change projections.

Because the Snake River reservoirs refill consistently in all but the driest scenarios, it suggests that drafting the reservoirs to the current flood control rule curves does not significantly prevent refill. The flood control drafting of Reclamation’s reservoirs is guided by dynamic flood control rule curves. These drafts are determined based on the forecast from January through June and then subtracts the water that has already runoff.

A decrease in surface water delivery occurs in the latter part of the irrigation season. For irrigators with supplemental storage water, this study suggests that there will be a shift from using natural flow to using storage water to meet demands under the drier future conditions. 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 have not been analyzed nor addressed in this analysis.

A shift in the likelihood of delivering flow augmentation water for ESA-listed salmonids was observed when compared to the VIC simulated historical deliveries occurs in both HD scenarios. While achieving the full 487 KAF of flow augmentation may become more difficult, particularly in the climate change projections in the HD 2040 scenario, the likelihood of providing at least 427 KAF is predicted to improve.

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. 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 was evaluated. Palisades Reservoir’s minimum flows of 900 cfs are met between October and March for all of the climate change projections. The early fall appears 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 does suggest that it will be more difficult to meet minimum pools at Cascade, American Falls, and Arrowrock reservoirs in the driest future climate projections.

Transient scenario results are presented for all metrics except ESA flow augmentation for anadromous species and ESA objectives for resident species. Despite annual runoff holding relatively steady through the year 2100, surface water deliveries on the Snake River and both major tributaries (Boise and Payette rivers) decreased over the 150-year time frame studied. This decrease is 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.

Chapter 5 – Uncertainties and Limitations: The uncertainties and limitations of the modeling, the evaluation, and Part I are summarized in this section. One of the major limitations of this effort was the selection of predominately wetter climates for the Snake River subbasin. Future studies should consider drier projections so that the potential impacts of drier patterns in the Snake River subbasin may be better evaluated. Another limitation was the use of the VIC hydrologic model to generate flows in a ground-water-dominated system such as the Deschutes River subbasin. The model also had difficulty developing ground-water-dominated flows around the Eastern Snake River Plain Aquifer (Hoekema 2010). Another model or better calibration of the VIC model to Reclamation naturalized flows could have improved the mass balance evaluation results presented in this Part II.

Chapter 6 - Lessons Learned: Throughout the last year, many lessons were learned that were worth documenting in hopes of improving future studies related to climate change. Of primary importance are the funding and staffing resources as well as the need for higher end computer systems to manage large volumes of data.

Chapter 7 - Future Study Possibilities: Follow-on studies or additional work tangential to this effort are summarized here. Additional studies to consider as a result of changing climate may include demand adjustments, potential changes to operations, flood control rule curve impacts, and ground water and surface water interactions, among others.

1.0 INTRODUCTION

The Bonneville Power Administration (BPA), U.S. Army Corps of Engineers (USACE), and the Bureau of Reclamation (Reclamation) collaborated in the adoption of a climate change and hydrology dataset and the demonstration of how these data may be applied to support their long-term planning activities in the Columbia-Snake River Basin. In this demonstration, the agencies also collaborated to develop a shared understanding on an appropriate set of methods for incorporating these data into long-term planning activities. The data and methods will promote efficiency by pooling agency resources and provide consistent incorporation of regional climate projection information in the agencies' planning efforts.

This report serves as the second of four documents produced through this collaborative effort, respectively titled *Climate and Hydrology Datasets for use in the RMJOC Agencies' Longer-Term Planning Studies*:

- Part I Report – Future Climate and Hydrology Datasets (issued in December 2010)
- Part II Report – Reservoir Operations Assessment – Reclamation Tributary Basins (this document)
- Part III Report – Reservoir Operations Assessment – Columbia Basin Flood Control and Hydropower (expected Spring 2011)
- Summary Report (expected Spring 2011)

This report follows Part I,[1] which focused on River Management Joint Operating Committee (RMJOC) adoption of future climate and hydrologic data from the University of Washington's Climate Impacts Group (UW CIG) HB2860 effort,[2] evaluation of those data, and development of associated water supply forecast series to reflect future hydroclimate conditions (i.e., Elements 1 and 2 from Figure 2 and most aspects of Element 3 pertaining to analyzing watershed hydrologic response). The overarching motivation for this collaborative effort and key scoping considerations are also discussed in the Part I Report Introduction. The Part II Report picks up where the first report ends, transitioning focus to Reclamation's long-term simulation models of reservoir operations in the Yakima, Deschutes, and Snake river subbasins, which have operational models already constructed and available for immediate use.

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[1] Reference to Part I report– Future Climate and Hydrology Datasets issued in December 2010.

[2] http://www.hydro.washington.edu/2860/

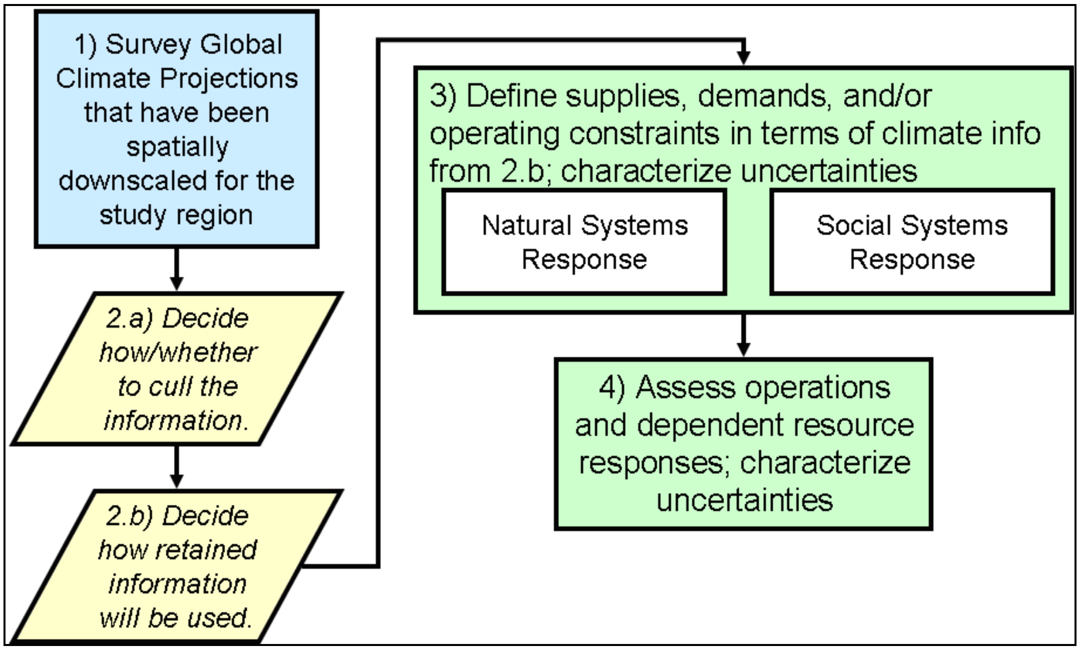

Figure 2. Framework for relating climate projection information to longer-term operations planning.

As the Part I Introduction indicated, this effort considered the use of two types of HB2860 climate and hydrology scenarios within RMJOC agencies' long-term operations analyses: Hybrid-Delta and Transient. These two scenario types were introduced in Section 3.2.2 and discussed further in 4.2.1 and 4.2.2 of the Part I report. Generally speaking:

- Hybrid-Delta scenarios reflect "adjusted historical" envelopes of climate variability. They are useful for defining a climate condition for a particular future period and relative to a reference historical period. The same sequence of relative historical climate variability is retained for each Hybrid-Delta scenario, but is adjusted to reflect changes in the period-monthly distribution of conditions (i.e., expansion or compression of the envelope of variability). Hybrid-Delta scenarios are useful for many types of long-term water resources planning studies where the focus is on system conditions during a given future period (e.g., general assessments, environmental compliance efforts) and where there are questions about how future study results might be sensitive to assumptions about future climate. Such studies might feature the default assumption that future climate variability is defined by historical climate variability (i.e., the stationarity assumption [Milly et al. 2008]). This default assumption would then be complemented by one or more alternative "stationary" climate variability assumptions, where the alternative climate is essentially an "adjusted historical" condition defined using the Hybrid-Delta technique. To assess sensitivity of study results to future climate, results under the default climate assumption (historical variability) and alternative climate assumption(s) (adjusted historical variability) would be compared.

- Transient scenarios contrast sharply from Hybrid-Delta scenarios. They characterize time-evolving climate from a simulated past to a simulated future (also described as intervening years). This time-evolution is told in a climatic sequence taken directly from global climate models (GCMs) rather than from observations. So whereas the Hybrid-Delta scenarios reflect adjusted historical sequences, the Transient scenarios reflect "possible climate" from GCM-simulated historical to GCM-simulated future (albeit with the numerous caveats explained in Part I Sections 3.2.2 and 4.2.2). This time-evolving characterization can be useful for studies that do not have a fixed future period of interest, but rather are interested in system conditions during intervening years from present to future (or from past to future). An example of this type of view might be studies focused on system vulnerabilities, aiming to understand the timing when system conditions might cross a threshold and what that means for scheduling of system modification (infrastructure or otherwise) to avoid such threshold crossings.

In total, 19 future climate and hydrology scenarios were selected from the UW CIG HB2860 dataset: a 30-year historical scenario centered on the 1990s, six 30-year Hybrid-Delta scenarios centered on the 2020s, six 30-year Hybrid-Delta scenarios centered on the 2040s, and six 150-year time-evolving Transient scenarios from 1950 to 2099. Thus for each major tributary, an operations analysis is given in the following sections in which each scenario's hydrologic conditions from Part I are translated into model inflows and other hydrology-related inputs, effectively framing an operations impact analysis reflecting climate change effects on water supplies and runoff conditions.

The operations analyses involve completing long-term simulations of reservoir operations, river flows and water deliveries framed by input hydrology and existing or unchanged demands and operating constraints. *Perfect* and *imperfect* forecast (Part 1 Report, Section 5) input was used to adjust forecasting locations within each model. Using the new future climate hydrology and updated forecasting, seven simulations were completed using *perfect* forecasting on the Hybrid-Delta 2020s (historical and six future hydrology scenarios) and six for the Hybrid-Delta 2040s (using the same historical simulation from the Hybrid-Delta 2020s). Another 13 simulations were completed using *imperfect* forecasting values (including an additional historical simulation using *imperfect* forecasting). For the transient simulations, only observed or *perfect* forecasts were used in the simulations for a total of six for each tributary. A total of 32 simulations were conducted.

The scope of the operations analyses involved performing model simulations for each future hydrology scenario as described above. Future climate hydrology inputs had a significant impact on the model results more so than did forecasting. Little change, if any, was observed between forecasting approaches in any of the tributaries modeled.

2.0 DESCRIPTION OF RESERVOIR OPERATIONS BY RIVER SUBBASIN

Reclamation operates reservoir systems in various tributary subbasins of the Columbia River. Figure 3 illustrates the approximate location of these systems. In this effort, the focus is on how future RMJOC climate and hydrology scenarios affect operations in three tributary subbasins, which include the Yakima, Deschutes, and Snake River subbasins. This section provides a brief description of Reclamation water projects in these subbasins, along with operating objectives and key water features.

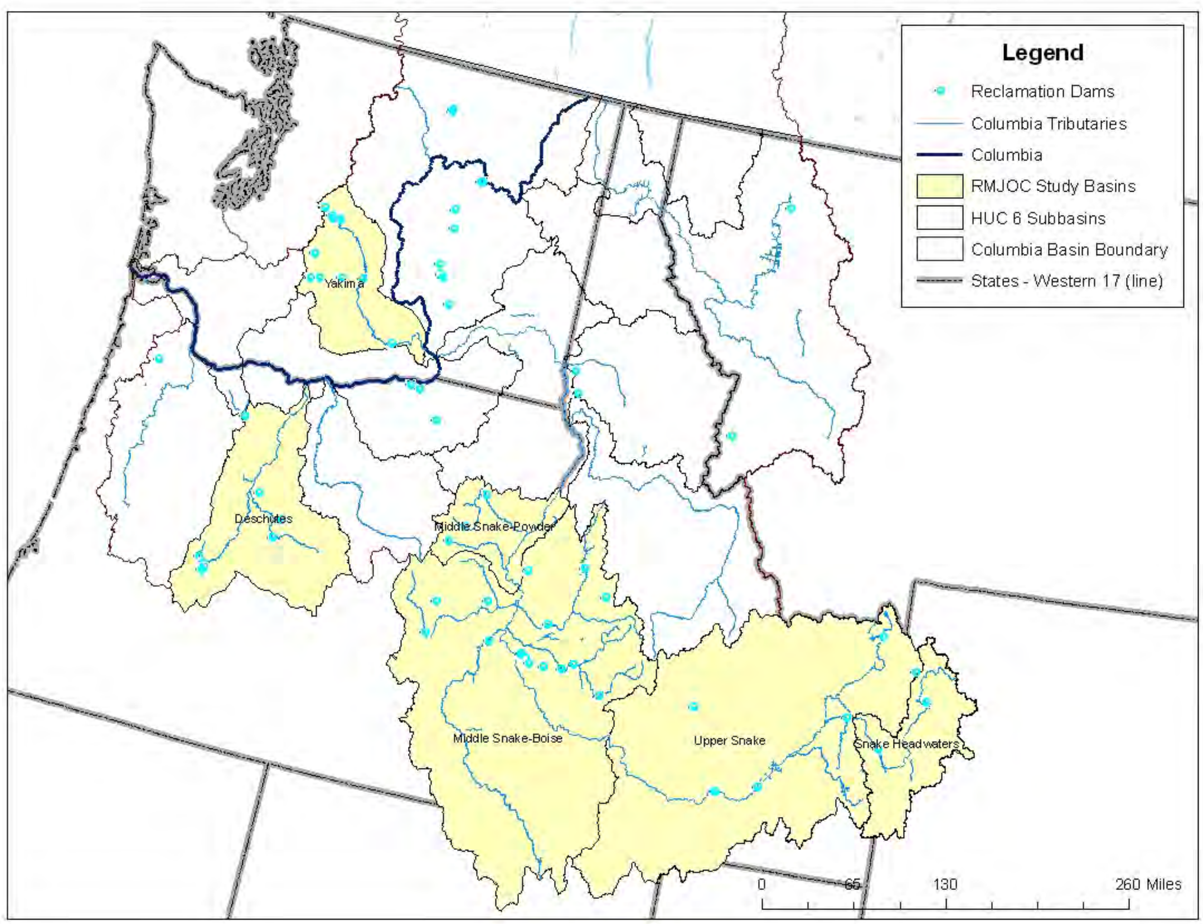

Figure 3. Locations of Reclamation systems and major subbasins of study focus in the Pacific Northwest.

2.1 Yakima River Subbasin

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. Altitudes in the subbasin range from 8184 feet above mean sea level in the Cascades to 340 feet at the confluence. The Naches River is the largest tributary of the Yakima River, entering the river at the city of Yakima. Major tributaries of the upper Yakima River (above the Naches confluence) include the Kachess, Cle Elum, and Teanaway rivers. Major tributaries of the Naches River are the Bumping River, Rattlesnake Creek, and the Tieton River. Toppenish and Satus Creeks, both originating on the Yakama Indian Reservation, are the major tributaries of the lower Yakima River below the Naches confluence. Numerous smaller tributaries contribute seasonal flows to the rivers.

The project provides irrigation water for a comparatively narrow strip of fertile land that extends for 175 miles on both sides of the Yakima River in south-central Washington (Figure 2). The irrigable lands, eligible for service under the Reclamation’s Yakima Project total about 465,000 acres. There are seven divisions in the project. Reservoir storage constitutes one division. In addition, there are six water delivery divisions: Kittitas (59,123 acres), Tieton (27,271 acres), Sunnyside (103,562 acres), Roza (72,511 acres), Kennewick (19,171 acres), and Wapato. The Wapato Division is operated by the Bureau of Indian Affairs, but receives most of its water supply from the project for irrigation of 136,000 acres of land. Over 45,000 acres not included in the seven divisions are irrigated under supplemental water supply contracts with Reclamation.

The Yakima River system (Figure 4) includes the following storage reservoirs owned and operated by Reclamation: Keechelus, Kachess, and Cle Elum reservoirs on the upper Yakima River and Bumping and Rimrock reservoirs on the Naches River. They provide most of the physical operations capabilities needed to store and release water to meet irrigation demands, flood control needs, and instream flow requirements. Other project features include 5 diversion dams, 420 miles of canals, 1,697 miles of laterals, 30 pumping plants, 144 miles of drains, 9 power plants (3 in private ownership), plus fish passage and protection facilities constructed throughout the project.

Reclamation operates the Yakima Project to meet specific purposes: irrigation water supply, instream flows for fish, and flood control. Project operations are defined in the Interim Comprehensive Basin Operating Plan for the Yakima Project (Reclamation 2002) with subsequent operational adjustments and modifications based on the Draft Biological Assessment of the Yakima River subbasin, and agreements made at River Operations meetings and System Operation Advisory meetings. A more detailed description can be found in the “Naturalized and Modified Flows of the Yakima River Basin, Columbia River Tributary, Washington” (Reclamation 2010a).

Irrigation operations and flood control management have been the historical priorities for reservoir operations. Instream flow and requirements of anadromous fish have been incorporated as part of the current routine operation of the system, and take primary status based on legislation or judicial orders at certain times of the water year. Hydroelectric power is produced incidental to other project purposes. Reservoir storage releases are not made to meet hydroelectric power demand and, at times, power subordination[3] is implemented in order to meet instream flow requirements. Legislation was passed in 1994[4] stating that an additional purpose of the Yakima Project "*shall be for fish, wildlife, and recreation. Also, the existing storage rights of the Yakima Project shall include storage for the purposes of fish, wildlife, and recreation. But, the above specified purposes shall not impair the operation of the Yakima Project to provide water for irrigation purposes nor impact existing contracts.*"

The average annual unregulated flow of the Yakima River subbasin near Parker (below Union Gap near Yakima) totals about 3.4 million acre-feet (MAF), ranging from a high of 5.6 MAF (1972) to a low of 1.5 MAF (1977). The average annual irrigation diversion by entities recognized in the 1945 Consent Decree (Decree) totals approximately 2.2 MAF (period of record, 1961-1990). This does not include the other requirements for water in the subbasin, including instream flow, hydroelectric generation, and municipal and industrial uses. The total demand is supplied through a combination of stored water releases, unregulated flow (natural flow), and return flow. Total storage in the subbasin is a little over 1 MAF. The remainder of the demands, both instream flow and irrigation demands, is supplied through unregulated tributary flow and bypassed reservoir inflow (reservoir inflow that is directly released rather than stored) and return flows. Demand cannot always be met in years of below average runoff. Shortages are reflected in rationed water supply to the prorated (junior) irrigation water rights and lower target flows.

The following are notes on seasonal operations aspects, discussed further in Reclamation (2010):

- *Winter operations*: Inflows to the reservoirs in excess of downstream requirements are stored. Flows are bypassed or storage is released to provide minimum flows for the incubation of spring Chinook salmon eggs, fry, and other fish demands. Release schedules also consider flood control requirements, for providing both a minimum amount of space for winter rain-on-snow floods, and a variable amount of space based on runoff forecast for spring snowmelt floods. The main objective during flood

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[3] A power subordination flow is a low flow target observed while water is or would be diverted for hydropower.

[4] Yakima River Basin Water Enhancement Program legislation Title XII, describing target flows located at Sunnyside (PARW, **Error! Reference source not found.**) and Prosser Diversion Dams (Yakima River near Prosser, YRPW, **Error! Reference source not found.**).

control operations is to provide maximum protection against flood damage in the Yakima River subbasin as a whole, without jeopardizing the irrigation water supply for the following year. Other issues or constraints at this time include migration flow and possible power subordination to insure minimum stream flows are met in the bypass reaches of the river system.

- *Spring and early summer operations*: Streamflow into the reservoirs in excess of downstream requirements is stored. Irrigation diversion demand is largely met from natural flow accruing below the reservoirs from unregulated tributaries. Some supplemental releases are made for instream flow maintenance for incubation and rearing where unregulated inflow downstream of the dams is inadequate. Other issues or constraints at this time include flood control; fish passage in the river and at the reservoirs; ramping rates; various minimum target flows; balanced refill and use of reservoirs; and power subordination, as well as migration flows.

- *Summer and fall operations*: Normally from sometime beginning in mid-June to early July (but ranging from April in very dry years to August in very wet years) through the end of the irrigation season (normally October 20). The system is on “storage control” when reservoir releases in excess of inflows are required to meet downstream demands, including the Title XII target flows. This results in a decline in total storage while the flow at Parker is controlled to near the minimum target flow. Other issues or constraints at this time include passage flows in the river and at the reservoirs, ramping rates, various minimum target flows, balanced use of reservoirs, and power subordination.

Reclamation (2010) provides additional description of Yakima operations to support fisheries objectives. These include “flip-flop” operations involving reservoir releases to encourage anadromous fish spawning at lower river stages in the upper Yakima River subbasin, “mini flip-flop” release operations at Keechelus and Kachess Lakes, Bumping releases for spawning support on the Bumping River, and winter incubation flow targets set during the fall months and adjusted after December 1 depending on the El Nino Southern Oscillation (ENSO) condition, the storage system carry-over on November 1, precipitation in November, and other prevailing conditions.

Reclamation manages the entire system’s water supply, but physically operates only the storage division. System water supply is measured by the metric total water supply available (TWSA), which is used to characterize water supply available during the Yakima River subbasin irrigation season. It was first defined in the 1945 Consent Decree which defined the water supply and how it would be distributed, particularly in a water short year. The TWSA is the sum of system reservoir contents, the seasonal unregulated flow volume passing the Yakima River near Parker (PARW), and seasonal irrigation return flow volume. It is computed each month from April through September as needed. It quantifies the supply volume in acre-feet from the first of the month it is computed to the end of September. The TWSA is used to define instream flow targets, shortages, evaluate water transfers, etc. In order to provide anticipation of TWSA, project operations make use of PARW seasonal runoff volume forecasts (i.e., water supply forecasts) that are initially issued in January for the upcoming irrigation season, and then updated monthly.

Prorationing is necessary when the TWSA is not adequate to meet all irrigation entitlements and required stream flow targets. Prorationing defines the shortfall in supply that must be born equally by the junior users whose water rights have a May 5, 1905, appropriation date. Senior users hold water rights with appropriation dates prior to May 5, 1905. Senior rights have not experienced a shortage since the 1945 Consent Decree implemented the TWSA method. Prorationing is calculated by taking the water left in the TWSA after subtracting the estimated carry-over system storage on September 30, the estimated seasonal flow past the Yakima River at Parker stream flow gage (includes minimum flow requirements as well as uncontrolled spring and summer snowmelt flows), and senior entitlements. In other words, once all other demands are met (including 100 percent of the senior entitlements), the junior users equally split the remaining available water. The prorationing level for junior users has ranged as low as 37 percent historically (1994 and 2001). Some amount of prorationing has occurred in ten out of the last 30 years, with significant prorationing (less than 70 percent) in five of those years.

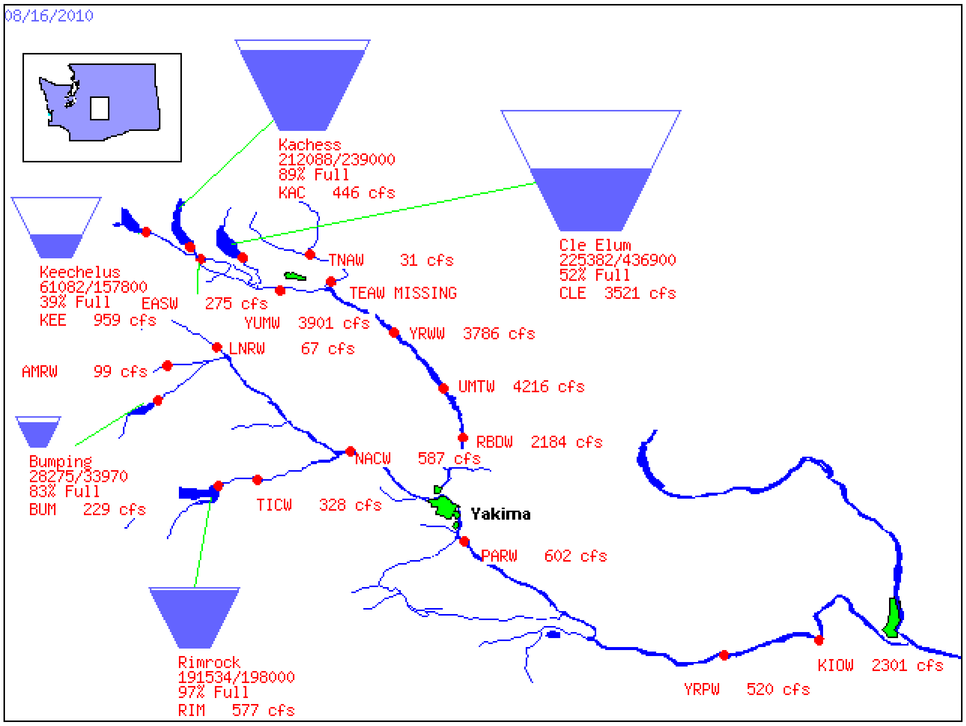

Figure 4. Major reservoir system features in the Yakima River subbasin.

2.2 Deschutes River Subbasin

This section provides summary descriptions of the Deschutes River subbasin and its two major subbasins, the upper Deschutes River and the Crooked River. The upper Deschutes River subbasin includes the federally-owned Deschutes Project and the privately-owned Crescent Lake Dam Project. The Crooked River subbasin includes the federally-owned Crooked River Project. More details about Reclamation projects and project features can be found in Reclamation's online Projects and Facilities database.[5]

The Deschutes Project is located near Bend, Oregon (Figure 5). Its principal features include Wickiup Dam and Reservoir, Crane Prairie Dam and Reservoir, Haystack Dam and Reservoir, 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 of land within the North Unit Irrigation District and a supplemental supply for more than 48,000 acres in the Central Oregon Irrigation District and Lone Pine Irrigation District (also known as Crook County Improvement District No.1). Storage for the North Unit Irrigation District is provided in Wickiup Reservoir on the main Deschutes River, about 35 miles southwest of Bend. Releases from the reservoir are diverted from the river at North Canal Dam. Water is carried to project lands by the North Unit Main Canal and distributed through a system of laterals. Water stored in Crane Prairie Reservoir is also diverted by the North Canal Dam into delivery and distribution systems privately built and operated by Central Oregon Irrigation District and Crook County Improvement District No. 1.

The private Crescent Lake Dam Project is composed of lands in the Tumalo Irrigation District on the west side of the Deschutes River near Bend, Oregon. The principle feature of the project is Crescent Lake Dam, which irrigates approximately 8,000 acres and provides recreational opportunities.

The Crooked River Project primarily lies north and west of Prineville, Oregon. The water resources of Ochoco Creek and Crooked River are used to furnish irrigation water for approximately 20,000 acres. Project features include 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 (not shown on Figure 5), two major pumping plants, nine small pumping plants, and Ochoco Main and distribution canals. In addition to irrigation benefits, the project is operated to satisfy objectives related to environmental management, river and reservoir recreation, and flood control.

More information on the operational aspects of the projects on the Deschutes River can be found in 2010 Modified Flow Report on the Deschutes Basin, Reclamation, 2009.

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[5] Database can be found at http://www.usbr.gov/projects/.

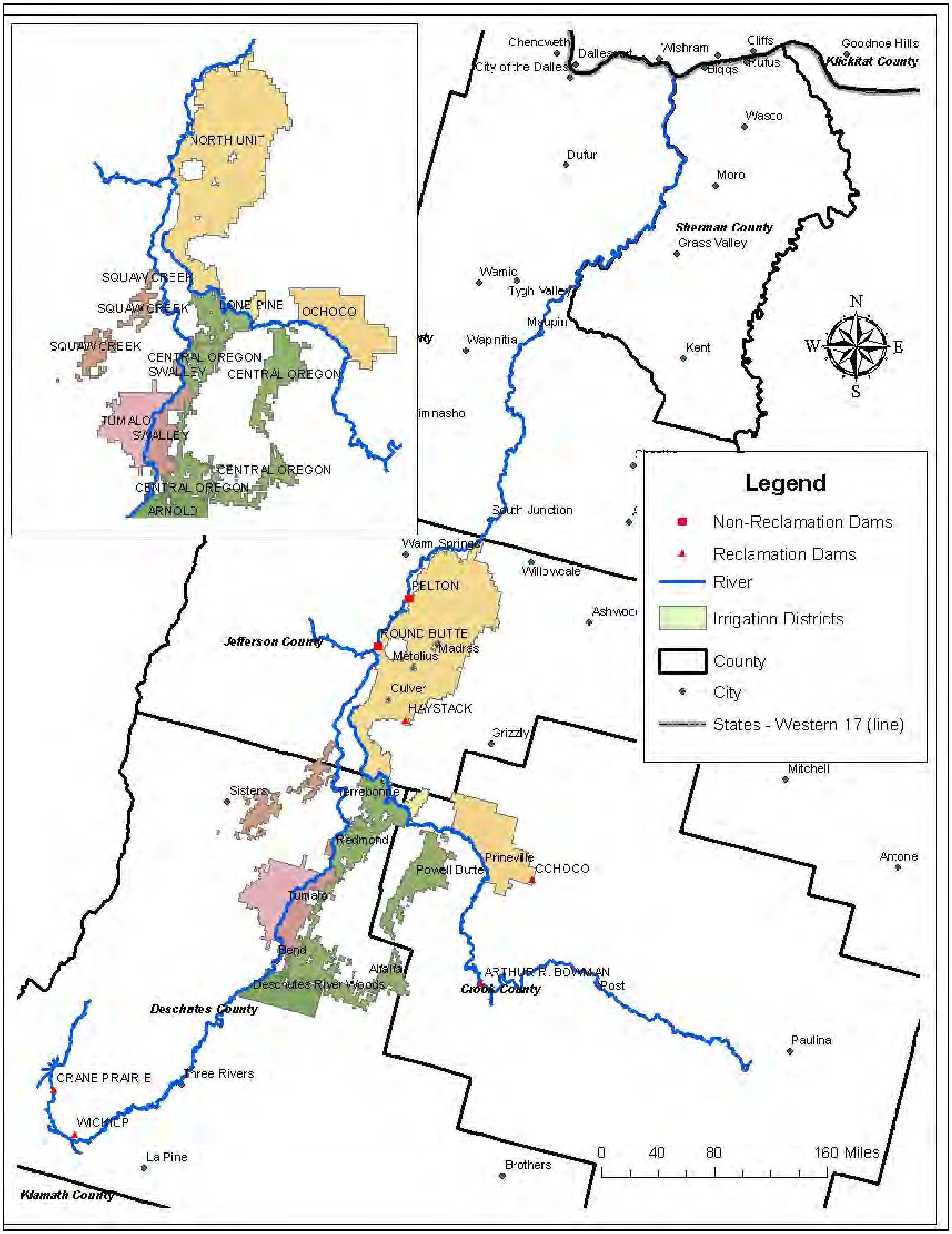

Figure 5. Major system features in the Deschutes River subbasin.

2.3 Snake River Subbasin above Brownlee Reservoir

This section describes the larger projects located in the Snake River subbasin above Brownlee Reservoir that were primary evaluation locations in this study and includes the upper Snake River subbasin (general area above Brownlee Reservoir) including the projects on the Boise and Payette river tributaries (Figure 6). Specific operational protocols are not described in this document, but this information may be found in the Biological Assessments for operation and maintenance of the projects (Reclamation 2004; Reclamation 2007).

2.3.1 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 (Figure 6). Descriptions for the other projects in this subbasin can be obtained from Reclamation's online Projects and Facilities database.[6]

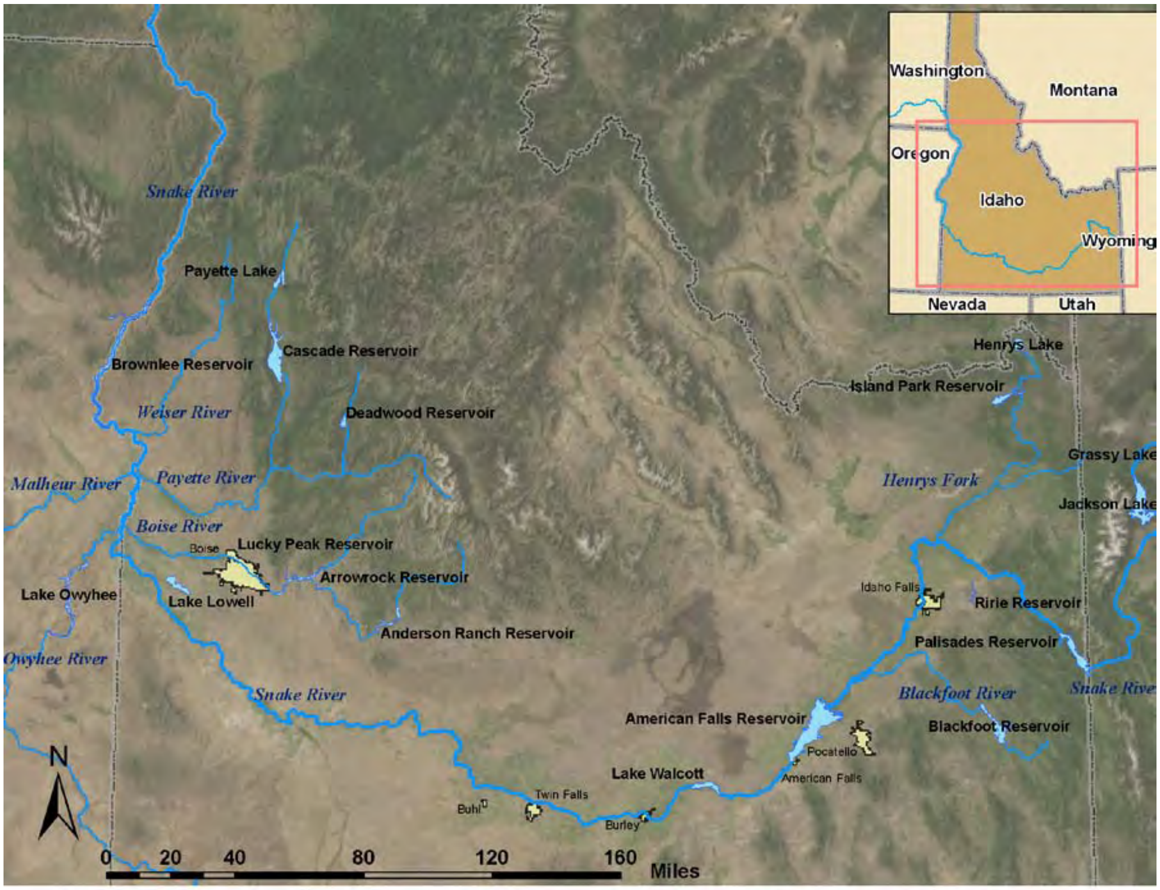

Figure 6. Location map of the upper Snake River subbasin.

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[6] Database can be found at http://www.usbr.gov/projects/.

The Minidoka Project lands extend discontinuously about 300 miles downstream starting from the town of Ashton in eastern Idaho to the town of Bliss in south-central Idaho. The project furnishes irrigation water from five reservoirs that have a combined active storage capacity of more than 3 MAF. 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. The project reservoirs are shown in Figure 6. 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. Palisades Dam is on the South Fork of the Snake River at Calamity Point in eastern Idaho about 11 miles west of the Idaho-Wyoming boundary, with an active capacity of 1.2 MAF. The project provides a supplemental water supply to about 650,000 acres of irrigated land in the Minidoka and Michaud Flats Projects. 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 to help control floods, and develop a substantial block of power. This water is stored to the credit of and delivered to the water users who made the savings possible.

2.3.2 Boise-Payette River Subbasin

The Boise Project includes both the Boise and Payette rivers (Figure 7). The system of reservoirs is operated primarily for irrigation and flood control; however, it has evolved into a multi-purpose operating system coordinated for 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 furnishes a full irrigation water supply to about 224,000 acres and a supplemental supply to some 173,000 acres under special and Warren Act contracts. The irrigable lands are 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.

Principal facilities include five storage dams (excluding Lucky Peak Dam constructed by the Corps of Engineers and Hubbard Dam, a re-regulatory facility) which form reservoirs with a total capacity of 1,793,600 acre-feet (active 1,663,200 acre-feet), two diversion dams, three powerplants with a combined capacity of 50,200 kilowatts, seven pumping plants, canals, laterals, and drains. To facilitate organization of the administrative and operating procedures, the irrigable project lands are divided into the Arrowrock and Payette Divisions. Some of the features serve only one division; other features serve both divisions as well as other nearby projects.

The Arrowrock Division provides a full irrigation water supply to some 164,000 irrigable acres, and supplemental water to an additional 112,000 acres. Water for the division is stored in Anderson Ranch Reservoir on the South Fork of the Boise River, in Arrowrock Reservoir on the Boise River, and in Lake Lowell, an off-stream reservoir impounded by three low dams in a natural depression (Figure 7). Lucky Peak Dam, built by the Corps of Engineers, is about 1 mile upstream of Boise River Diversion Dam and backs water up to Arrowrock Dam. Lucky Peak Reservoir has a total storage capacity of 293,100 acre-feet (active 264,400 acre-feet) and was built for flood control and irrigation purposes. By agreement among the Corps of Engineers, the Boise Project Board of Control, and Reclamation, the Anderson Ranch, Arrowrock, and Lucky Peak storage reservoirs on the Boise River are operated jointly for the benefit of irrigation, power, and flood control. Power operations are incidental. These three reservoirs have a total capacity of 1,058,500 acre-feet (active 959,800 acre-feet).

Lands in the Payette Division receive water from the Payette River and surplus drainage from the Arrowrock Division. There are 60,000 acres receiving a full water supply and 61,000 acres receiving a supplemental supply. Storage features are Deadwood Dam on Deadwood River, a tributary of the South Fork of the Payette River, and Cascade Dam on the North Fork of the Payette River (Figure 7). Water is diverted at Black Canyon Dam into canals on the south and north sides and then into the distribution system.

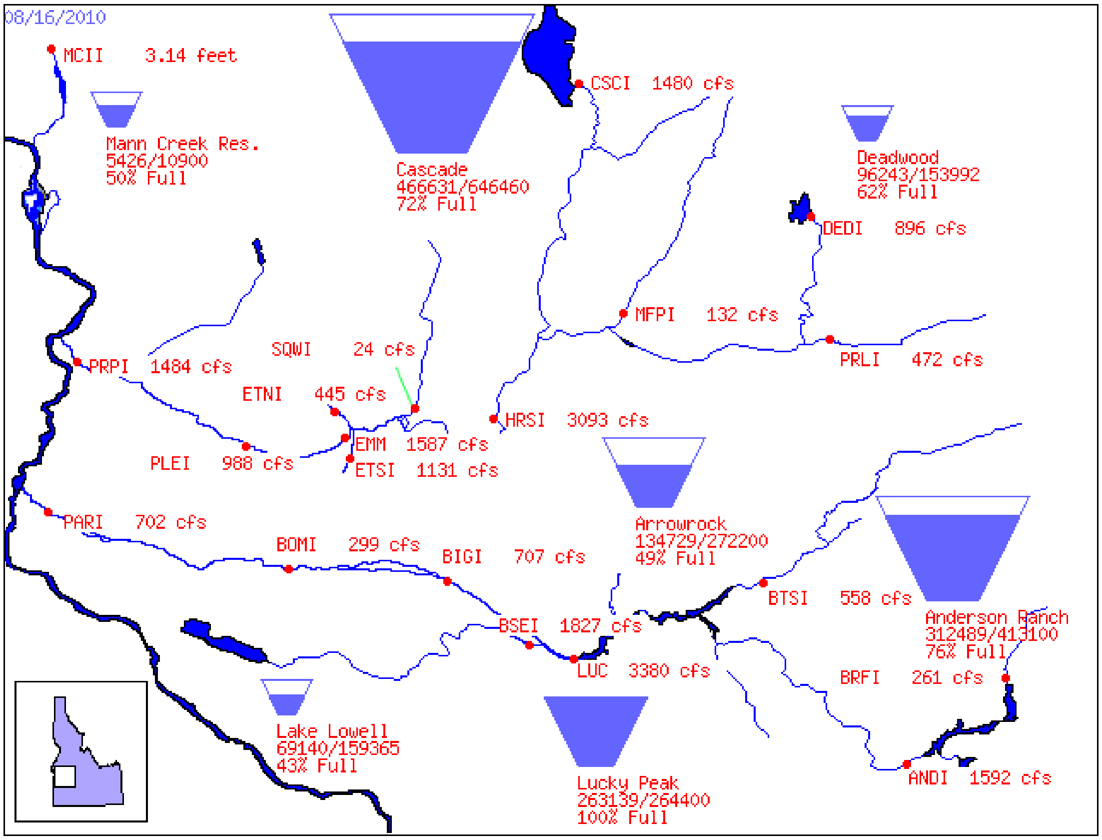

Figure 7. Major reservoir system features in the Boise and Payette rivers tributaries to the Middle Snake River subbasin.

2.3.3 Southeast Oregon

Several Reclamation projects lie west of the Snake River in southeastern Oregon including the Baker Project on the Powder River, the Burnt River Project on the Burnt River, the Vale Project on the Malheur River, and the Owyhee Project on the Owyhee River (Figure 8). The Owyhee Project, which is the largest of those in southeastern Oregon, is located in Malheur County, Oregon, and Owyhee County, Idaho. It furnishes a full irrigation water supply to over 105,000 acres of land, with about 72 percent of the lands in Oregon and 28 percent in Idaho along the west side of the Snake River. An additional 13,000 acres are furnished supplemental water. Irrigable lands are divided into the Mitchell Butte, Dead Ox Flat, and Succor Creek Divisions on the Owyhee. The key feature of the project is Owyhee Dam, on the Owyhee River about 11 miles southwest of Adrian, Oregon, which acts as both a storage and diversion structure. The project also includes canals, pipelines, tunnels, nine pumping plants, laterals and drains. The Vale, Baker, and Burnt River projects are not modeled in this study.

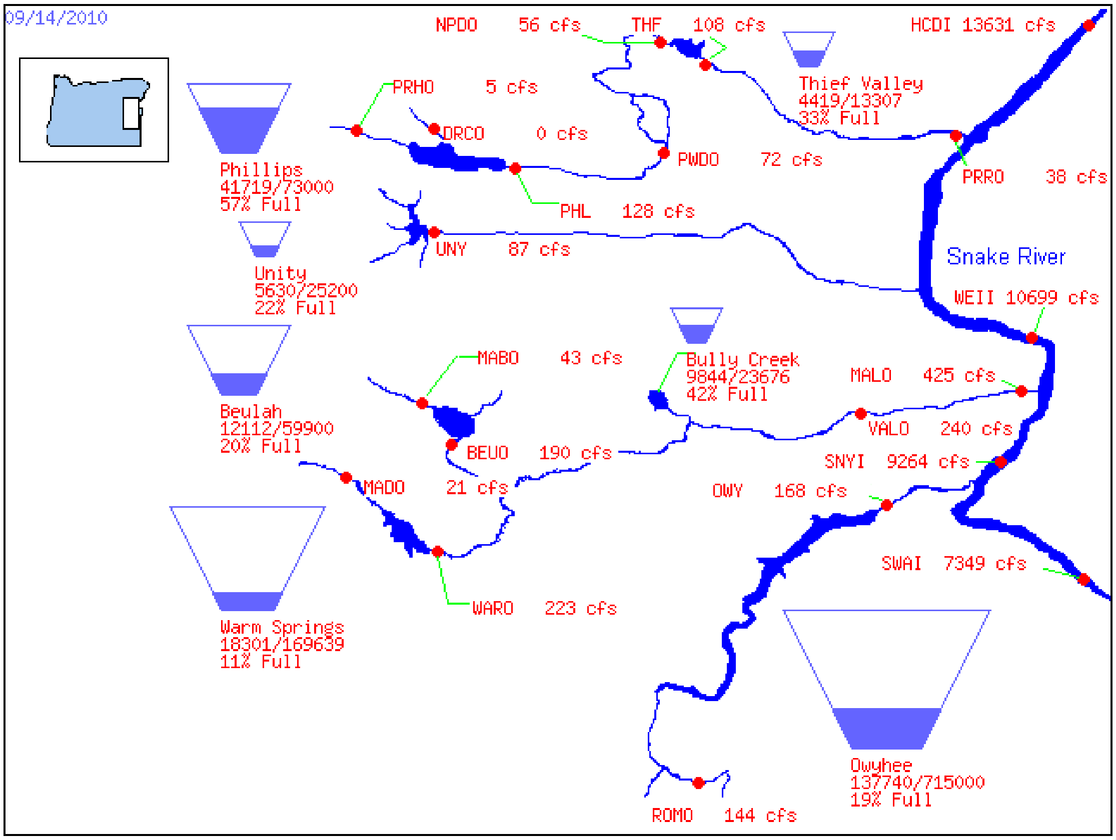

Figure 8. Major reservoir system features in southeastern Oregon tributaries to the Middle Snake River subbasin.

Additional information on operational aspects of the Snake River Basin Projects may be found in the Biological Assessments for operation and maintenance of the projects (Reclamation 2004; Reclamation 2007).

3.0 DESCRIPTION OF OPERATIONS SIMULATION MODELS AND INPUTS ADJUSTED FOR RMJOC CLIMATE AND HYDROLOGY SCENARIOS

3.1 Yakima River Subbasin

3.1.1 Yakima Planning Model (RiverWare Application)

As with the 2010 Modified Flow study (Reclamation 2010a), a RiverWare[7] reservoir and river simulation model of the Yakima River subbasin is used in this effort to characterize Yakima River subbasin river regulation given the scenarios of RMJOC climate/hydrology and current objectives and criteria for Yakima Project reservoir operations. This model, referred to as the Yakima Planning Model (YPM), has been developed over the last decade and is meant to simulate Yakima Project operations consistent with real-world operations described in Section 2.1.

By design, the YPM is a versatile model tool, capable of simulating project operations under a range of water supply, water demand, and operating constraint conditions. Specifically, three types of YPM inputs were specified for each RMJOC climate-specific simulation: inflow hydrology, water supply forecasts, and ENSO classification. Beyond these categories of inputs, the remaining RiverWare model assumptions and inputs in the RMJOC effort were the same as those used in the 2010 Modified Flows study (e.g., water demands, operating criteria). Methods of specifying water supply-related YPM inputs are summarized in the following sections, including key differences between YPM application for the 2010 Modified Flows study and this RMJOC study as related to water supply conditions.

3.1.2 Inflow Hydrology

In the 2010 Modified Flows study, results were meant to portray regulated river flows given the scenario of historical “no-regulation, no irrigation” (NRNI) streamflow being affected by reservoir operations, river regulation, and 2010-level water demands in the Yakima River subbasin. The 2010 level demands are based on data from 1991-2001 and are largely made up of irrigation demands. Instream flow targets that have been part of normal operations over the past 5 years also make up a set of demands on the system. In this RMJOC effort, the scenario of historical NRNI natural streamflow gets replaced by a scenario of climate-specific

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[7] For a software description, see: http://cadswes.colorado.edu/riverware/.

simulated natural streamflow obtained from the UW CIG HB2860 dataset. As described in the Part I report, 19 climate-specific scenarios are considered: historical climate, six Hybrid-Delta 2020s climates, six Hybrid-Delta 2040s climates and six Transient climates. Note that the simulated streamflows associated with historical climate are based on results from a watershed hydrology model that have been bias-corrected to be very similar to the NRNI flows in terms of variability envelope, but with some sequencing differences (Part I report).

In the 2010 Modified Flows study, the period of operations analysis corresponded to a period of hydrology variability during water years (WY) 1926 through 2009 (i.e., November 1, 1925 through October 31, 2009).[8] In this effort, the 19 climate-specific streamflow scenarios have the following periods: (a) simulated historical climate and each Hybrid-Delta climate feature 81 water-year hydrologic sequences, indexed as WY1926-2006; and (b) each simulated transient climate features a 148 water-year hydrologic sequence, indexed as WY1951-2098.

The YPM model proceeds on a daily time-step for the period of simulation. This means that the YPM simulates daily operational decisions given daily information on supplies and demands to the model. Daily supplies are characterized by inflows at various system locations, including those where NRNI flows were estimated and also locations labeled "local inflows" and representing subbasin runoff nested within NRNI estimates.

To utilize UW CIG HB2860 information, both bias-corrected monthly runoff and biased daily runoff results had to be utilized. These runoff results were reported at each of the NRNI locations (Table 1). The original HB2860 runoff information includes daily runoff as simulated by UW CIG's watershed hydrology model (i.e., the Variable Infiltration Capacity (VIC) model application for the Columbia-Snake River Basin, described in Part I Report, Section 4) and monthly runoff that is time-aggregated from the daily runoff. These daily and runoff values are biased in the sense that UW CIG's hydrology model has error tendencies when simulating runoff under observed historical weather conditions. Part I Report, Section 4 describes this issue, how these error tendencies were identified, and how they were removed on a monthly and annual basis in order to create bias-corrected monthly runoff used in the RMJOC effort.

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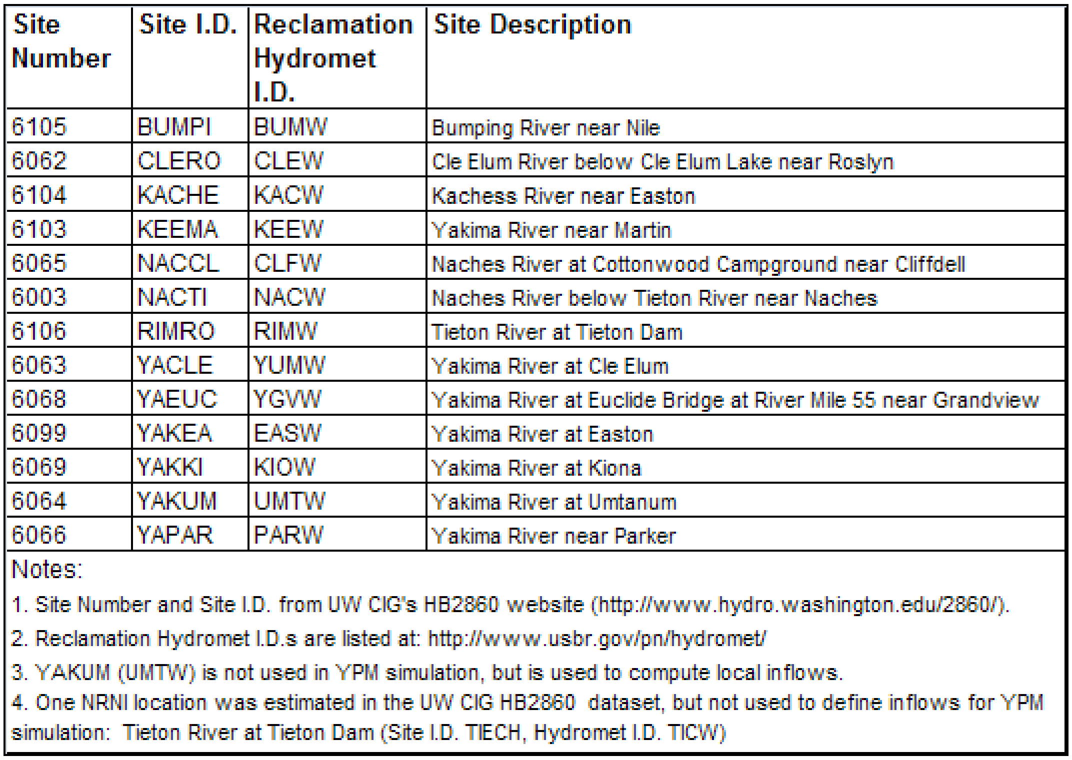
[8] WY for Yakima operations analysis is November 1 through October 31. WY for Deschutes and Snake operations analysis is October1 through September 30.

Table 1. NRNI locations used in computing YPM Daily Inflows.



Site Number	Site I.D.	Reclamation Hydromet I.D.	Site Description
6105	BUMPI	BUMW	Bumping River near Nile
6062	CLERO	CLEW	Cle Elum River below Cle Elum Lake near Roslyn
6104	KACHE	KACW	Kachess River near Easton
6103	KEEMA	KEEW	Yakima River near Martin
6065	NACCL	CLFW	Naches River at Cottonwood Campground near Cliffdell
6003	NACTI	NACW	Naches River below Tieton River near Naches
6106	RIMRO	RIMW	Tieton River at Tieton Dam
6063	YACLE	YUMW	Yakima River at Cle Elum
6068	YAEUC	YGVW	Yakima River at Euclide Bridge at River Mile 55 near Grandview
6099	YAKEA	EASW	Yakima River at Easton
6069	YAKKI	KIOW	Yakima River at Kiona
6064	YAKUM	UMTW	Yakima River at Umtanum
6066	YAPAR	PARW	Yakima River near Parker

Notes:

1. Site Number and Site I.D. from UW CIG's HB2860 website (http://www.hydro.washington.edu/2860/).
2. Reclamation Hydromet I.D.s are listed at: http://www.usbr.gov/pn/hydromet/
3. YAKUM (UMTW) is not used in YPM simulation, but is used to compute local inflows.
4. One NRNI location was estimated in the UW CIG HB2860 dataset, but not used to define inflows for YPM simulation: Tieton River at Tieton Dam (Site I.D. TIECH, Hydromet I.D. TICW)

Returning focus to adjusting YPM daily inflows, a two-step procedure was used to generate inflows, and relied on using both bias-corrected VIC monthly runoff and biased VIC daily runoff results. The first step occurs at the NRNI locations. Referencing VIC simulated flows at a given location, daily bias-corrected flows are computed as the daily biased flows scaled by the ratio of monthly bias-corrected to biased flows. In other words, Step 1 is a time-disaggregation of monthly bias-corrected flows to daily bias-corrected flows, preserving the relative sequencing from the daily biased flows. Step 1 is implemented on a climate, location, and month specific basis.

The second step is then to compute local inflows that force the YPM simulation. Some VIC simulated flows at NRNI locations correspond directly to YPM upstream inflow locations (i.e., BUMPI, RIMRO, NACCL, KEEMA, KACHE, and CLERO). Below these locations, NRNI flows had to be spatially disaggregated to specify local reach-specific inflows. These local inflows are computed primarily based on mass-balance constraints, but also using flow-similarity assumptions at some locations. In total, 11 local inflows had to be estimated from VIC simulation flows at NRNI locations. Calculation of local inflow by location is described below, with locations outlined generally from upstream to downstream, and referencing UW CIG HB2860 Site I.D.s for NRNI locations (Table 2):

Table 2. UW CIG HB2860 Site I.D.s for NRNI locations, upstream to downstream.

UW CIG HB2860 Site I.D.	NRNI Locations
amrw_qd	American near Nile Revised Gage is estimated as a function of BUMPI, preserving historical ratio of amrw_qd to BUMPI. The ratio is unique for each BUMPI quantile and based on historical amrw_qd and BUMPI flows in the 2010 Modified Flow study.
clfw_ql	Naches River at Cottonwood Campground Near Cliffdell = NACCI – BUMPI – Amrw_qd. Formula does not include Little Naches because model computes Little Naches as a function of CLFW and because Little Naches is not in NRNI nor a VIC node.
nacw_ql	Naches River at Naches = NACTI – RIMRO – NACCL.
easw_ql	Yakima River at Easton = YAKEA – KEEMA – KACHE.
yumw_ql	Yakima River at Cle Elum = YACLE – YAKEA – CLERO.
umtw_ql	Yakima River at Umtanum = YAKUM – YACLE.
augw_qd	Ahtanum Creek at Union Gap is estimated as a function of RIMRO, preserving the historical ratio of augw_qd to RIMRO. The ratio is unique for each RIMRO quantile and based on historical augw_qd and RIMRO flows in the 2010 Modified Flow study.
parw_ql	Yakima River near Parker = YAPAR – YAKUM – NACTI – augw_qd.
ygvw_ql	Yakima River at Euclid Bridge at River Mile 55 Near Grandview = YAEUC – YAPAR.
kiow_ql	Yakima River at Kiona = YAKKI – YAEUC.
yrpw_ql	Yakima River at Prosser is estimated as a function of kiow_ql, preserving the historical ratio of yrpw_ql to kiow_ql. The ratio is unique for each kiow_ql quantile and based on historical yrpw_qd and kiow_ql flows in the 2010 Modified Flow study.

3.1.3 Water Supply Forecasts

Water supply forecasts inform three aspects of YPM operations simulation: flood control operating decisions, storage management decisions unrelated to flood-control (e.g., how to fill or release storage), and the TWSA computation. The forecasts reflect anticipated PARW irrigation-season runoff volumes (or YAPAR irrigation-season runoff volumes following the UW CIG HB2860 I.D. for this location). Forecasts are issued initially during winter months and updated monthly into the irrigation period (i.e., January issue of April-through-September PARW runoff volume, February through April issues of the same, and then May through July issues of date-through-September PARW runoff volume).

In the 2010 Modified Flows study, these PARW seasonal runoff volumes were *perfect* forecasts, meaning they were simply summations of YPM input inflows during the upcoming season of interest. In this RMJOC effort, both *perfect* and *imperfect*[9] forecasts of PARW seasonal runoff volume forecasts are considered. Both were developed uniquely for this effort to be consistent with each climate-specific streamflow dataset (see Hydrology above), where *perfect* forecasts were considered for all 19 climates and *imperfect* forecasts were developed for the first 13 climates (a historical, six Hybrid-Delta 2020s, and six Hybrid-Delta 2040s) reflecting water supply predictability informed by relationships between seasonal runoff volume and antecedent precipitation and snow-water equivalent conditions (Part I Report, Section 5). This led to a total of 32 YPM simulations (discussed further in Section 4).

During simulation, the YPM must re-evaluate anticipated runoff from the date of simulation through the end of the forecast period (e.g., if the YPM simulation is on April 15, then the April 1 issue of April 1 through September 30 PARW runoff volume needs to be adjusted to reflect April 15 through September 30 volume). This step is done internally, with cumulative runoff-to-date subtracted from the most recent issue of forecast runoff volume.

3.1.4 ENSO Classifications

ENSO classification affects Cle Elum Reservoir operations in the YPM, as they relate to winter incubation flow targets that are set during fall months and adjusted after December 1 (Section 2.1). In the 2010 Modified Flows study, the RiverWare model included this logic, and was informed by historical ENSO classifications during the historical NRNI period. For the RMJOC study, a time series of ENSO classifications had to be developed based on (1) identifying a relationship between observed historical December-through-January PARW volume and ENSO classification, and (2) applying that relationship with a given climate-specific scenario of annual PARW volume in order to infer a corresponding ENSO classification.

Three ENSO states are defined in YPM: La Niña, Neutral, and El Niño. ENSO classification is related to hydrology using the historical linear relationship between ENSO classification and NRNI December-through-July PARW volume. Given that this historical relationship has uncertainty, estimates of ENSO events also include a random error term to reflect this uncertainty in the ENSO classification, resulting in a classification that is not computed solely based on the historical linear relationship.

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[9] The Part I Report, Section 5 describes *perfect* versus *imperfect* forecasts. Briefly, imperfect forecasts reflect the real-world situation where forecast-period runoff is anticipated at a time of forecast issue based on basin monitoring at time of issue (e.g., snow water equivalent information at various stations), and observations prior to the time of issue (e.g., precipitation during the water year to-date, and/or runoff conditions during the previous summer, potentially indicating soil moisture conditions going into the coming snowmelt season and affecting the melt partition to infiltration versus runoff). These real-world forecasts are imperfect, mainly due to uncertainty about the weather occurring between time of forecast issue and the end of the forecast period, and also due to uncertainties about hydrologic processes in the basin, both observed and otherwise.

3.2 Deschutes River Subbasin

3.2.1 Deschutes Planning Model (MODSIM Application)

The Deschutes Planning Model (DPM) network begins with the headwaters and extends to Lake Billy Chinook. Flow into Lake Billy Chinook was considered the location from which results would be quantified and reported to other partners in this study. To quantify inflows to Lake Billy Chinook on the Deschutes River under varying hydrologic conditions, the MODSIM Model, version 8.0 was used. MODSIM is a generic river subbasin management decision support system used to assess short-term and long-term planning strategies. It is a general-purpose river and reservoir operations computer simulation model that was constructed to replicate historical data and systems operations as well as future scenarios.

The DPM network of the Deschutes and Crooked rivers was developed cooperatively by Reclamation, the Oregon Water Resources Department (2001) and Natural Resources Consulting Engineers, Inc. to replicate the period of record. Two DPM networks were configured: one to represent a naturalized flow condition (no reservoirs or diversions are included in the model) and the other a modified flow condition (current year diversions and reservoir operations are modeled for the entire period) to quantify the depleted flows in the river. Both naturalized flow and modified flow DPMs were used to complete the climate change analyses in the Deschutes River subbasin.

For this study, runoff was the major input that changed between the VIC simulated historical and future climate change simulations. When these supply changes were placed in the modified flow DPM, other parameters in the model were automatically adjusted because of the algorithms within the MODSIM model. So although demand patterns were not manually adjusted, as future runoff changed, the modeled water deliveries automatically changed to reflect how water users have responded historically to different water supplies in the modified flow DPM. Flood control and other reservoir operations are also dependent on runoff and forecasted reservoir carryover. The same demand, flood control, and reservoir operations schemes were used for both the Hybrid-Delta (HD) and Transient climate change runs. No effort was made to update potential changes to demands, flood control, or reservoir operations due to climate change in this study.

In the HD projected simulations of the Deschutes River system, it was necessary to make minor adjustments to the Prineville and Ochoco storage target levels to accommodate changes in runoff timing. These limits tell the model how much volume in the reservoir is available for release when certain water levels within the reservoir are attained. Once these minor adjustments were made, releases from the reservoirs were more realistic.

The minor adjustments made to the Prineville and Ochoco storage target levels were retained for the six Transient climate change projections; however, any time series data in the model had to be extended to 2099 (e.g., ground water, reservoir evaporation) because the Transient scenarios had 150 years of data. To extend the ground water time series data, the Reclamation naturalized historical time series from 1928 to 2006 were copied into the future years such that the ground water pattern remained static (e.g., the trend line did not reflect an upward or downward slope in ground water). A similar approach was taken to update other time series data.

3.2.2 Inflow Hydrology

3.2.2.1 Naturalized Flow Hydrology

Naturalized flows are flows that would have occurred in the river without reservoir regulation or irrigation demands. The difference between naturalized and NRNI flows that were described in the Yakima River hydrology (Section 4.1.2) is that an attempt has been made to remove the lagged effects of past irrigation and ground water use on the ground water flow component in the naturalized flows (Reclamation 2009).

Ground water has a significant influence on the Deschutes River subbasin hydrology. Substantial ground water discharge occurs in the upper Deschutes River subbasin along the southern part of the subbasin near the Cascade Range, in the Metolius subbasin adjacent to the Cascade Range, and the area surrounding the confluence of the Deschutes, Crooked, and Metolius rivers (Gannet et al. 2001). The contributions from ground water to the upper Deschutes River are large compared to the contributions from snowmelt and changes the timing of flow that occurs in the river when compared to a snowmelt driven system. In the Crooked River subbasin, the headwaters are fed primarily by snowmelt. During the summer months, the Crooked River at Opal Springs is fed by ground water flow, which significantly increases the flows in the Crooked River just above its confluence with the Deschutes River. Most of the irrigation occurs above Opal Springs, so although flow can increase significantly at Opal Springs, the subbasin is considered to be snowmelt driven for irrigation and operational purposes.

When water is applied to irrigated lands, excess water can seep below the root zone and travel, via the aquifer, back to the river. The time it takes for that water to return to the river is described by a time dependant function known as a ground water response function. Response functions are also used to describe the lagged effect on the river due to pumping water from the aquifer. The response functions for the Deschutes model were calculated using a ground water model of the subbasin (Gannett and Lite 2004). In addition, the ground water model described where the water returns to the system and these locations were incorporated into the MODSIM model (Reclamation 2009).

Naturalized flows were calculated as the first set of input to a distribution model at various points along the river. Because inflows into Lake Billy Chinook are a combination of flows from different locations, the MODSIM model was used to calculate inflows to the lake that would result from naturalized flows elsewhere in the river. All reservoir regulation and irrigation demands, along with lagged ground water impacts that result from irrigation, were removed from the naturalized flow DPM run. Naturalized flows were created using the model for the years 1929 to 2005. They were not created for 2006 to 2008, but rather historical flows were used to compare to modeled flows for 2006 to 2008 to reflect current conditions because complete diversion records for that most recent period were not yet available (Reclamation 2009).

Reclamation naturalized flow data from 1929 to 2008 were provided to UW CIG for the locations shown in Table 3 and Figure 9. VIC flow output data generated by the UW CIG was then calibrated to Reclamation naturalized data using methods provided in the Part 1 Report, Section 4.4. This step was taken to ensure that runoff characteristics and mass balance at locations within a specific subbasin were retained. In addition, naturalized VIC flows were used as input to the Naturalized Flow DPM and compared to flows generated by Reclamation in the Naturalized Flow DPM. This additional step was taken on the Deschutes River (and Snake River as described in Section 4.2.2.1) to ensure the distribution of inflows between the VIC inflow locations (or nodes at a coarser scale) were disaggregated to the finer scale found in either DPM and retained mass balance.

Table 3. Description of CIG VIC and MODSIM naturalized flow input locations on the Deschutes River.

Description	MODSIM Link	VIC Name
unregulated discharge at Crane Prairie Reservoir Dam	gainCRA2_NonStorage19 Natural Flow Step Flow	CRANE
unregulated discharge at Wickiup Reservoir Dam	NonStorage4_NonStorage3 Natural Flow Step Flow	WICKI
unregulated discharge at Crescent Lake	gainCRE_NonStorage Natural Flow Step Flow	CRESC
unregulated discharge above Lake Billy Chinook	NonStorage48_Billy_in Natural Flow Step Flow	ABILL
Deschutes River at Moody, Near Biggs	Moody_ColumbiaRiver	REREG
Deschutes River at Pelton	MRSO	PELTO
Round Butte (Lake Billy Chinook near Metolius)	ConfluenceCR_blwConfluence	RNDBB
Deschutes River above Lake Billy Chinook	DCCO	DESCH
Crooked River below Opal Springs, Near Culver	blwOpal_ConfluenceCR	CROOK
White River Below Tygh Valley	14101500_Moody	WHITE
Warm Springs River Near Kahneeta Hot Springs	WarmSpringsR_NonStorage42	WARMS
Metolius River Near Grandview	Metolius	METOL

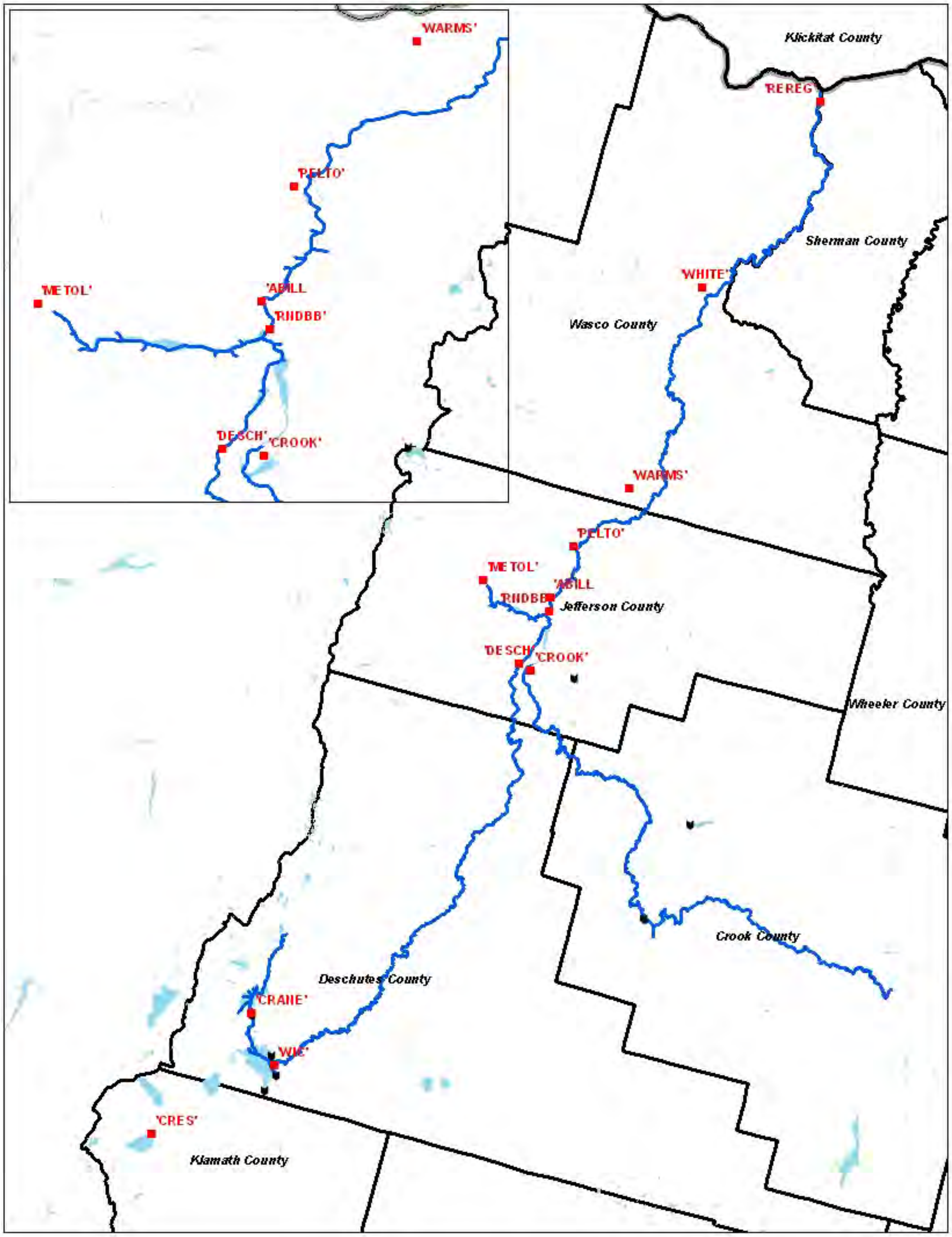

Figure 9. Location map of CIG VIC flow input locations on the Deschutes River (red squares on map).

3.2.2.2 Modified Flow Hydrology

Reclamation modified flows are flows that use 2010 level reservoir operations and irrigation demand levels throughout the period of record (1929 to 2008). The Modified Flows DPM was used to model the Reclamation Modified Flows dataset from 1929 to 2005. Actual inflows to Lake Billy Chinook provided by Portland General Electric were used to complete the dataset from 2006 to 2008.

The 2010 level demands were developed using data covering the period of 1993 to 2004. This period was used because it covered a wide range of conditions (wet, medium, and dry) for the subbasin, and because more current (2006 to 2008) diversion records were not yet available at the time of the 2010 Modified Flows Report. Because the diversions are largely made up of irrigation demands, increases in population were not assumed to have had a large impact between 1993 and 2008. Conservation and ground water mitigation efforts were also assumed to not have a detectable effect on the demand data (OWRD 2008).

3.2.2.2.1 Reclamation Modified Flow Model

The Modified Flow DPM was used to convey the new flow generated by UW CIG’s VIC model. VIC flow that represented the historical condition (1929 to 2006) was considered VIC simulated historical and those flows that represented any future climate were considered VIC simulated future. VIC simulated historical flow data was flow generated by the VIC model and used input to the Modified Flow DPM. These comparisons are provided in Section 5.0 of this report.

The reservoir operating rules used in the Modified Flows DPM simulation were equivalent to those expected in 2010, including ESA objectives for the Crooked River. Minor adjustments to the target storage levels, such as the percent of the available volume that was available for release at any given time step, were made in the HD Modified Flow DPM simulations to ensure output was more realistic.

In the Reclamation Modified Flows analysis that was completed in 2010, the model was corrected for ground water responses based on 2010 level demands. This was a challenge. In the Deschutes River subbasin, it can take up to 50 years for the system to equilibrate with respect to ground water responses. The model begins its calculation period in 1929. If equilibrium ground water responses were calculated based on current irrigation demands, the model would have to begin its calculation period in 1879. Because that was not feasible due to lack of available data for 1879 to 1929, it was necessary to calculate equilibrium ground water response hydrographs and input them directly into the Modified Flows DPM. In other words, the equilibrium ground water return flows were calculated separately and hardwired into the model.

These equilibrium responses were calculated in several steps. Because the model reaches an equilibrium condition in 1979, 50 years after the start of the DPM, the first step was to model the 1929 to 2005 period using current (1993 to 2005) irrigation demands.

The model reaches equilibrium conditions for the 1979 to 2005 period. This equilibrium 26-year dataset was then copied to create hydrographs from 1929 to 1978. The hydrographs were developed for each response location in the subbasin and input directly into the Modified Flows DPM (Reclamation 2009).

3.2.2.3 Methods and Adjustments

For the HD historical and future climate change simulations, Reclamation's Modified Flow DPM described above was edited to include additional nodes for input and distribution of VIC inflow. Other parameters as described above were generally unchanged.

Monthly VIC bias-corrected (VIC BC) runoff that was provided at the 12 locations in the Deschutes River subbasin (detailed in Table 3) was disaggregated into positive (supply) and negative (loss) gains within a VIC Reach (a reach between two locations at which VIC inflow was provided) to populate the finer scale nodes in either the Naturalized or Modified Flows DPM. To accomplish this, an Excel workbook was developed to perform ratio calculations that retained the spatial distribution patterns observed in the Reclamation dataset. The newly disaggregated VIC simulated historical and future climate change flows were then used as input to the DPM (both naturalized and modified models) and the simulations were performed. In some cases, the VIC reach was either too long or too short and had to be combined with other VIC reaches or separated into smaller VIC reaches for model stability. This general approach was used in both the HD and Transient scenarios.

3.2.2.3.1 Methods

The UW CIG VIC hydrology had to be adjusted to imitate Reclamation hydrology in the DPMs because there were hundreds of additional positive and negative gain nodes in the Reclamation DPMs and only 12 VIC inflow points. The UW CIG VIC hydrology input data (i.e., the 12 VIC flow points) were disaggregated such that all of the existing gain and negative gain nodes in either DPM could be populated with the VIC flow. This was accomplished by distributing the flow between two VIC inflow points in a manner that retained Reclamation's distribution pattern in the finer scale nodes that already existed in the DPM between those same two VIC points.

3.2.2.3.2 Adjustments

Once the VIC flow input data were disaggregated and spatially distributed, several adjustments had to be made to Reclamation's original Modified Flows DPM. For example, additional nodes were added to the DPM to manage large volume changes in adjacent time steps in the VIC flow or to manage VIC future flow if it was shown to be zero.

Transient scenarios predict supply through 2099. A relationship between Reclamation data and VIC future climate change data was developed so that the future climate flows could be distributed among all the DPM nodes using the same procedure described above. To develop this relationship, Reclamation flows and VIC simulated future projected flows were ranked and those ranked flows were matched at each time step. The disaggregation pattern at that Reclamation flow time step was then used to distribute the VIC projected flow among any gains (positive or negative) within a VIC reach.

3.2.3 Water Supply Forecasts

In real-time, Reclamation hydrologists forecast inflow to Prineville and Ochoco reservoirs only. For this study, volume runoff forecasting was completed at four locations in the Modified Flows DPM, including Crane Prairie and Wickiup; Crescent Lake (not shown); Prineville and Ochoco; and the sum of the three upstream forecast values taken at Lake Billy Chinook (near Pelton in Figure 5). The time period for each simulated forecast location is January through September.

Water supply forecasts are completed to support Reclamation operations and to describe the water supply conditions such as:

- Individual reservoir inflows: to guide decisions on reservoir releases during the refill season, which includes (in many cases) following the flood rule curves or refill curves that are based on forecasted volume (in reality, forecasts guide decisions at Ochoco and Prineville only).
- Water supply forecasts are issued during winter months, generally starting in January, and updated as conditions dictate, but no less than monthly (i.e., January water supply forecast volume is from January through June, February forecast is February through June).

In the 2010 Modified Flows study, these seasonal runoff volumes were *perfect* forecasts, which means that the forecasts were summations of monthly inflows at the forecast points. *Imperfect* forecasts, which reflect water supply predictability informed by relationships between seasonal runoff volume and antecedent precipitation and snow-water equivalent conditions (Part I Report, Section 5), were also evaluated in this study. Both were developed uniquely for this effort to be consistent with each climate-specific stream flow dataset (Section 3.2.2). *Perfect* forecasts were considered for all 19 climates (including Transient) and *imperfect* forecasts were developed for the first 13 climates (a historical, six Hybrid-Delta 2020s, and six Hybrid-Delta 2040s).

3.3 Snake River Subbasin above Brownlee Reservoir

3.3.1 Snake Planning Model (MODSIM Application)

The Snake River Basin planning model (SPB) was developed by Reclamation staff to replicate historical data and system operations from 1928 to 2008 historical water supply period of record. Two networks were configured for each subbasin to quantify the depleted flows in each river; one represented a naturalized flow condition where no reservoirs or diversions are included in the model) and the other a modified flow condition in which current year diversions and reservoir operations are modeled. These two SPMs were used to construct the climate change adjusted models for both naturalized and modified flow conditions.

The SPM surface water distribution model was structured with a monthly time-step. While the monthly time-step of the SPM output does not capture the variations of day-to-day circumstances and real-time operational decisions, it does provide a means to quantify changes and make relative comparisons between the different scenarios under different hydrologic conditions and system constraints.

Varying hydrologic conditions and numerous other factors influence the way reservoirs are managed. Daily reservoir operations and water deliveries are influenced by many factors, including recent precipitation, reservoir content at the beginning of the irrigation season, spatial water supply distribution, temperature, irrigation demand, special operating requests, or emergency situations. The Modified Flow SPM constraints reflect current operational protocol as a basis of comparison of the different hydrologic inputs. Additional information concerning the current operating protocols may be found in the Biological Opinions (USFWS 2005, NOAA Fisheries Service 2008).

The MODSIM model constraints define the irrigation demand pattern, minimum flows as a result of forecasted runoff volumes, and reservoir elevations to meet flood control, power, and environmental obligations. These patterns reflect the type of water year the system is experiencing (wet, average, or dry); therefore, any changes in the inflow will allow the model to satisfy various constraints without fundamentally changing the current operational protocols. This allows for a comparative analysis of the reservoir system response to the change in water availability.

3.3.2 Inflow Hydrology

3.3.2.1 Naturalized Flow Hydrology

The Naturalized Flow SPM can be described as a calibrated model network with the removal of surface water diversions, ground water pumping, and reservoir operations. SPM output represents the flows that would have occurred in the river without reservoir regulation or irrigation demands. The naturalized modeling effort is an attempt to remove the lagged effects of current and past surface and ground water irrigation practices in representing the natural hydrograph entering Brownlee Reservoir.

Reclamation naturalized flow data were provided to UW CIG at 28 locations. These 28 locations were used to generate VIC simulated naturalized flow data. Table 3 describes the 28 locations, the link in the SPM that was used to obtain the flow data, and the name of the VIC location. Figure 9 provides the geographical location of the 28 VIC flow input locations. VIC simulated flow output data was calibrated to Reclamation naturalized data using methods provided in the Part I Report, Section 4. In addition, naturalized VIC flows were used as input to the Reclamation Naturalized Flows SPM and compared to Reclamation's Naturalized Flow SPM output. This additional step was taken on the Snake River to compare the VIC simulated natural flows to the Reclamation's natural flows modeled using Naturalized Flows SPM.

Table 4. Description of CIG VIC and MODSIM naturalized flow input locations on the upper Snake River.

Description	MODSIM Link	VIC Name
Unregulated inflow to Jackson Lake Dam	JCKqu_abvJCK	JLAKE
Snake River above Heise	PALI_qm	PALIS
Snake River at Heise	HEII_qm	SNKHE
Unregulated inflow to Henry Lake	HENqu_abvHENI	HENRY
Henrys Fork near Ashton, ID	HFAI_qm	IPARK
Henrys Fork at Rexburg	REXI_qm	HFORK
Unregulated inflow to Ririe Dam	RIRqu	RIRDM
Snake River at Shelley	SHYI_qm	SNSHY
Unregulated inflow to Blackfoot Reservoir	BLKqu_abvBLK	BLADA
Snake River below American Falls Dam	AMFI_qm	AMERI
Snake River below Minidoka Dam	MINI_qm	MINAD
Snake River below Milner	MILI_qm	MILNE
Bruneau River inflow to Snake River	BruneauR	BRUNE
Snake River blw CJ Strike Dam Near Grandview, ID	CJSI_qm	CJSTR
Unregulated inflow to Owyhee Dam	NonStorage148_abvOWY	OWYHE
Malheur River inflow to Snake River	Malheur	MALHE
Unregulated inflow to Anderson Ranch Dam	gainAND	BOAND
Boise River abv Arrowrock Dam	ANDI_qm	BOTWI
Boise River abv Lucky Peak Dam	ARKI_qm	BOARK
Boise River abv Boise River Diversion Dam	LUC_qm	BOISE
Boise River at confluence with Snake River	PARI_qm	LBOIS
North Fork Payette River blw Cascade Dam	CSCI_qm	NPCSC
Unregulated inflow to Deadwood Dam	DEDqu_abvDED	DEADR
South Fork Payette River at Lowman	LOWI_SPGI	PAYLO
Payette River at confluence with Snake River	Payette_conf	PAYET
Burnt River inflow to Snake River	BurntR	BURNT
Powder River inflow to Snake River	PowderR	POWDE
Snake River abv Brownlee Dam	BRNim_qm	BROWN

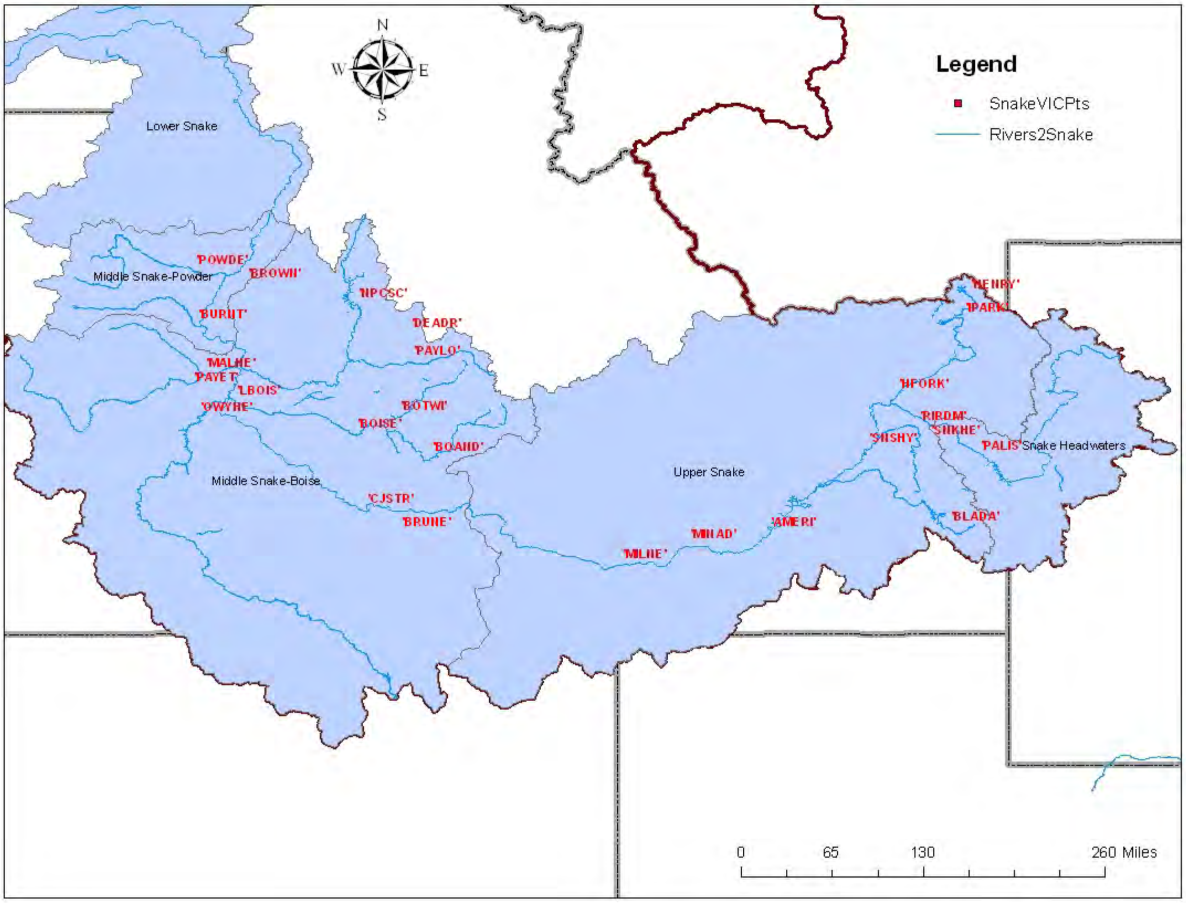

Figure 10. VIC input locations in the upper Snake River subbasin.

The original Reclamation Naturalized Flows SPM was used to develop the VIC naturalized model, but additional nodes were added to the VIC model to allow for input and distribution of the climate change flows (for more details on this process, see Section 3.2.2.3). Only flow input, disaggregated to gain and negative gain nodes as described earlier, have been changed in the VIC Naturalized Flows SPM. For information on the Reclamation Naturalized Flows SPM development, refer to the Snake River Modified Flow Report (Reclamation 2010b).

3.3.2.2 Modified Flow Hydrology

Reclamation's modified flow SPM network is the calibrated model network under 2010 surface water diversion development, 2010 level of ground water pumping, and 2010 reservoir operation protocols. Operation of the dams was defined in the SPM in accordance with the objectives of the Biological Opinions (USFWS 2005, NOAA Fisheries Service 2008). The Reclamation modified flow SPM was used to develop the VIC Modified Flow model for both the HD and Transient scenarios. Details about the Modified Flows SPM development can be found in the Snake River Modified Flow Report (Reclamation 2010b).

3.3.2.3 Methods and Adjustments

Monthly VIC BC runoff provided at the 28 locations in the Snake River subbasin was disaggregated and spatially distributed as described in Section 3.2.2.3. The new disaggregated climate change flows were then incorporated into to the Naturalized and Modified Flows SPMs and the simulations were performed.

With a few exceptions, input parameters other than flow were not changed. These other parameters include reservoir evaporation, ground water influences, start date of the irrigation system, cropping patterns and operational requirements for water delivery, flood control rule curves, and flow augmentation requirements.

3.3.3 Water Supply Forecasts

Snake River subbasin volume runoff forecasts are simulated at Heise on the Snake River (HEII), Lucky Peak on the Boise River (LUC in Figure 7), and Horseshoe Bend on the Payette River (HRSI in Figure 7). These are the same forecast points used in real-time reservoir operations. As described in the Part 1 report, forecasts were simplified to accommodate VIC weather variables specific to location and time period (forecast start and end months). At each of the three locations above, the simulated forecast period is January through June.

Forecasts are used to support Reclamation operations and to describe the water supply conditions including:

- Individual reservoir inflows: to guide decisions on reservoir releases during the refill season, which includes (in many cases) following flood rule curves or refill curves that are based on forecasted volume.
- Downstream flood control points: in multiple reservoir systems, flood control rule curves are usually based on capturing historical runoff to control flow at a downstream location (for example, Snake River near Heise, Payette River at Horseshoe Bend, Boise River at Boise [Lucky Peak natural flow]). Total system space is determined by the runoff forecast at the downstream control point, and the space distribution between the upstream reservoirs.
- ESA implications: The Heise forecast is used, in combination with November 1 system carryover volume, to determine how much flow augmentation water (described further in Sections 4.3.1.2.5 and 4.3.1.2.6) will be obligated from Water District 01 (upper Snake River) rental pool.
- Water supply forecasts are issued during winter months, generally starting in January, and updated as conditions dictate, but no less than monthly (i.e., January water supply forecast volume is from January through June, February forecast is February through June).

4.0 RESULTS

A total of 32 operations simulations were conducted for each of the Reclamation tributary subbasins. The simulations were divided into three groups:

- Group 1 (Simulations 1-13): Operations reflect Historical or HD climate and hydrologic scenarios and operating targets informed by *perfect* water supply forecasts.
    - Historical Climate
    - (2-7) six HD 2020s Climates[10]
    - (8-13) six HD 2040s Climates[10]
- Group 2 (Simulations 14-26): Operations reflect Historical or HD climate and hydrologic scenarios and operating targets informed by *imperfect* water supply forecasts.
    - (14-26) simulations order the same as Group 1 with respect to climates.
- Group 3 (Simulations 27-32): Operations reflect Transient climate and hydrologic scenarios and operating targets informed by *perfect* water supply forecasts.
    - (27-32) transient hydrologic sequences labeled to reflect the underlying climate simulation (see Part I Report, Table 2)

Results are evaluated in this section with consideration given toward several operations aspects, including water supply (system inflows), regulated river flows at various locations, water diversions, reservoir storage reported as end-of-month storage volume, and other subbasin-specific metrics relevant to operations in that particular tributary. Results are organized and discussed relative to three operations questions posed in this RMJOC study effort.

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[10] For sets of HD 2020s or HD 2040s climates, the scenarios are ordered by relative climate type within each set, and generally from better to worse climate conditions over the Columbia-Snake basin based on a runoff-abundance perspective: Referencing labels introduced in the Part I Report, climates in each set (HD 2020s or HD 2040s) are labeled qualitatively as: less warming and wetter (LW/W), more warming and wetter (MW/W), central (C), minimum change (MC), less warming and drier (LW/D), and more warming and drier (MW/D).

1. How do typical hydrologic conditions vary across RMJOC climate scenarios?
2. How does hydrologic variability differ for the various RMJOC climate scenarios? For example, how much do extreme hydrologic conditions under the future climate scenarios differ from the historical?
3. How does the portrayal of future operations depend on two analytical design choices:
    a. Type of water supply forecast (*perfect* versus *imperfect*)?
    b. Type of future climate scenario (Hybrid-Delta versus Transient)?

On the third question, the goal of the first part is to understand how portrayed operations impacts are sensitive to the assumption of *perfect* water supply forecasts rather than the less-convenient, but more "realistic" assumption of *imperfect* water supply forecasts. The goal of the second part is to understand how portrayed operating conditions (period-medians and period distributions) are sensitive to choice of future climate information type.[11]

The following evaluation approaches were used to address each question in the Yakima River subbasin:

- Question 1: Group 1 results were evaluated statistically, focusing on period-median annual and median monthly conditions for each climate. Evaluate change in period-medians for future climates relative to historical.
- Question 2: Group 1 results were evaluated using a distribution view, applying that view to annual or monthly conditions for each climate, and then comparing distributions across climates.
- Question 3:
    - First part: Group 2 results were compared to Group 1 to identify differences in both period-medians and period distributions.
    - Second part: Group 3 results were assessed initially using a time-series view, and then using a distribution view in order to compare against Group 1 results.

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[11] Hybrid-Delta climate and hydrology scenarios reflect use of climate simulations to indicate shifts in climate variability envelopes but not changes in climatic sequences (i.e., reoccurrence of climatic events). In contrast, Transient climate and hydrology scenarios reflect use of the same climate simulations to indicate both shifts in climate variability envelopes and climatic sequences, thereby portraying changing reoccurrence of climatic event possibilities (and only on monthly to longer time-scales based on design of Transient scenarios in the UW CIG HB2860 information set [Part I report]).

For the Deschutes River and Snake River subbasins, the same three questions were addressed, but by metrics specific to that subbasin. The evaluation approaches (e.g., statistics, distribution of data) were organized by metric (e.g., inflow, end-of-month storage) rather than by data statistics or distribution.

4.1 Yakima River Subbasin

This section describes Yakima River subbasin operations under the various future RMJOC climate scenarios, including operational changes relative to historical conditions. Generally speaking, each future RMJOC climate scenario involves a change in subbasin hydrology and associated water supply. These changes affect various aspects of system operation, including the ability to satisfy instream flow objectives, water demands of various customers, and storage targets linked to various system needs. Yakima River subbasin operations are characterized based on the following metrics, which are geographically located as shown on Figure 11.

- Water supply: (1) system inflow, which equals the sum of inflows to the five major Yakima Project reservoirs (Keechelus, Kachess, and Cle Elum reservoirs on the upper Yakima River and Bumping and Rimrock reservoirs on the Naches River), and (2) Total Water Supply Available which represents awareness of water supply at any time during simulation and is comprised of both current storage and anticipated PARW runoff volume during the upcoming irrigation season (April-September).

- Regulated river flows: (1) targeted river flow on the Yakima River at Parker, and (2) simulated river flows at four subbasin locations: Yakima River at Easton, Naches River at Naches, Yakima River at Umtanum, and Yakima River at Parker

- Water deliveries: (1) proration percentage experienced by proratable water customers (those who do not get a full supply in a year of shortage) in the Yakima Project, and (2) sum of all diversions in the Yakima River subbasin above Parker

- Storage: system storage which equals the sum of storage at the five major project reservoirs.

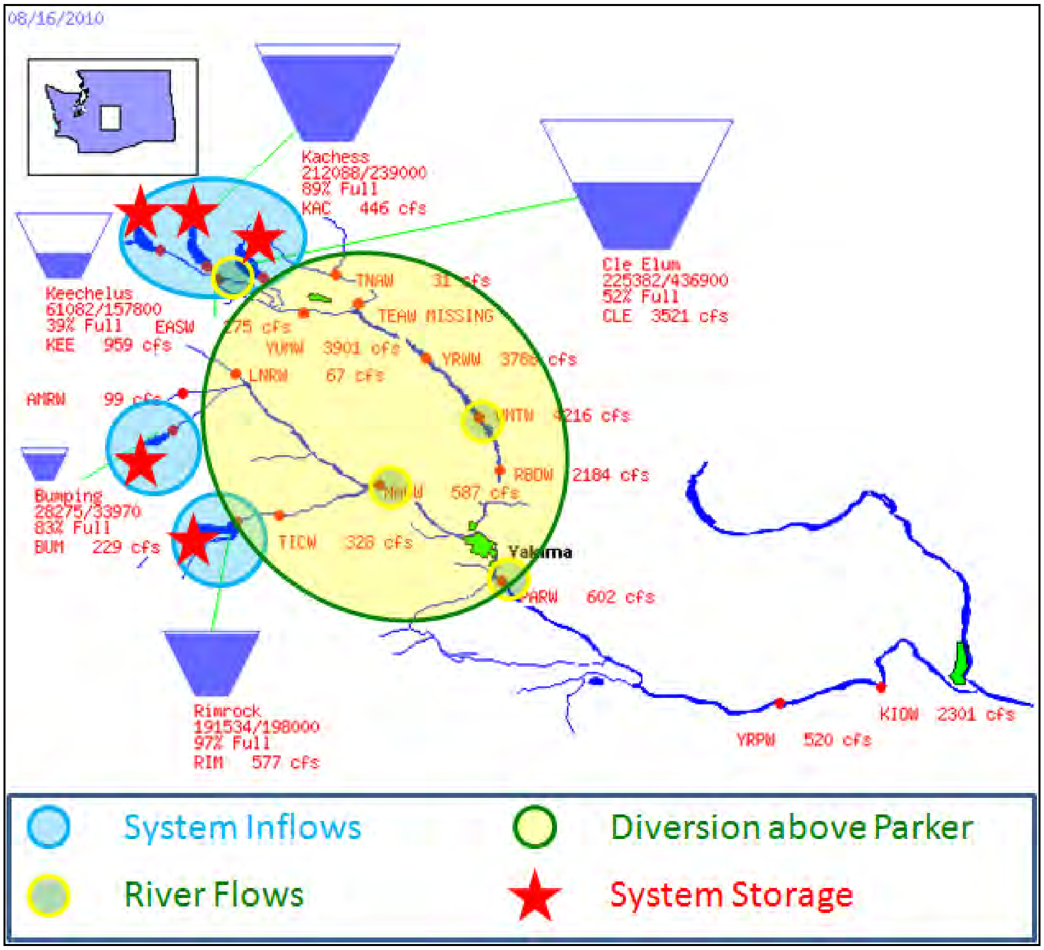

Figure 11. Location of assessment metrics in the Yakima River subbasin.

4.1.1 Typical Conditions under Hybrid-Delta Climates

This section addresses the first operations question asked in this RMJOC effort: how do typical operating conditions vary under various future RMJOC climates? To address this question, the evaluation focuses on results from operations simulations based on HD climates (not Transient) and use of *perfect* water supply forecasts. Subsequent sections address operations portrayal uncertainties introduced by using Transient climates or *imperfect* forecasts. The following discussion addresses typical conditions in the order of water supplies, regulated river flows, water diversions, and storage (Figure 12 through Figure 21). Note that each of these figures refer to Hybrid-Delta scenarios using qualitative labels introduced in the Part I Report, Section 3, generally describing greater to lesser water abundance over the Columbia-Snake River Basin: LW/W (less warming and wetter), MW/W (more warming and wetter), C (central), MC (minimal change), LW/D (less warming and drier), and MW/D (more warming and drier). The qualitative labels are specific to each future period (2020s and 2040s). Also, as described in the Part I Report, these labels apply to climate change over the entire Columbia-Snake River Basin, but may have relatively different qualities over subbasin tributaries such as the Yakima River subbasin. To review these tributary-specific qualities, see figures in the Part I Report, Section 3.

Water supply conditions were found to have season-specific impacts under the future RMJOC HD climates. Figure 12 shows the pattern of period-median monthly system inflows for historical and future HD climates, and also changes in period-median monthly system inflow for each future HD climate relative to historical. Results show that the RMJOC HD climates generally feature increased cool-season inflow (during November through March) and decreased warm season inflow (during April through September). These seasonal inflow changes appear to be related to cool-season warming, an increase in cool-season rainfall-runoff, reduction in corresponding snowpack development during cool-season, and reduction in warm-season inflow supported by snowmelt. The degree of cool-season inflow increase varies considerably among HD climates for a given future period (2020s or 2040s). The degree of increase generally corresponds to the type of mean-annual precipitation change associated with the given HD climate (e.g., wetter scenarios generally feature greater cool-season inflow increases and drier scenarios generally feature lesser cool-season inflow increases).

Season-specific changes in system inflow affect the assessment of the current and anticipated water supply conditions that drives operational decisions related to river flow targets, water demand prorationing, and storage targets. As discussed in Section 3, the YPM simulations reflect this continuing water supply assessment using the TWSA metric. Figure 13 shows period (WY1926-2006) median monthly TWSA conditions for historical and each HD climate. It also shows change in period monthly median conditions.[12] Focusing on simulated TWSA under the historical climate, TWSA is at a maximum during early winter, gradually diminishes leading into spring, and diminishes at a sharper rate through the summer as system supplies are used to satisfy various instream flow and water delivery objectives. TWSA reaches a minimum by end of September. This month-to-month pattern holds for each climate considered. The difference between historical and HD climates is that monthly median TWSA conditions are lower for all future HD climates relative to historical during the months of March through September. This means that operations targets dependent on assessed available water supply will more often be based on lower supply conditions. This foreshadows results to follow in this section, which concern reductions in instream flow targets, reduced volumes of water diversions, and reduced storage conditions. As with system

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[12] Figure 4 shows a step-change in TWSA from September to October months. Two comments: (1) YPM calculation of TWSA includes current system storage and anticipated April-through-September runoff volume at PARW, causing a step-change in TWSA when the simulation proceeds from September to October, and (2) YPM simulation ignores October TWSA values and instead uses an October-only calculation of water supply available that ignores the coming April-through-September runoff volume at PARW.

inflow, the degree of TWSA reduction during March through September generally trends with the type of precipitation change featured in a given HD climate relative to the others of the given future period; however, this is not a strict rule. For example, the March-September TWSA reductions for the 2040s MW/W climate were more severe than the reductions for the MC climate, suggesting the significance of greater warming in the MW/W scenario relative to the MC scenario such that a proportionately greater amount of the winter precipitation actually drained out of the system in January and February.

One consequence of March-September TWSA reductions is the increased frequency of instream flow targets to be set at levels corresponding to lower water supply conditions, leading to reduction in monthly median instream flow targets. For example, consider flow targets set for the Yakima River at Parker. Targets are actually updated daily during YPM simulation. For presentation purposes, these daily target values were aggregated to monthly average daily target, and then monthly medians were computed under historical and each future HD climate (Figure 14). Results show that TWSA reductions lead to median targets under future HD climates trend less than targets under the historical climate. Reductions in median target are more severe during the months of April and May.

Reductions in regulated flow targets and reductions in system inflows (both above upstream reservoirs and from local tributaries) lead to corresponding changes in regulated flows. Moving from upstream to downstream, and comparing period-median monthly conditions for historical and each future HD climate:

- Yakima River at Easton (Figure 15): Warming in the upper subbasin above Keechelus and Kachess Reservoirs appears to lead to greater cool-season reservoir inflow and releases to satisfy cool-season storage objectives (i.e., flood control reserves). As a result, there is typically greater regulated flow during winter (particularly December through February). Progressing toward the warm-season, warming also appears to lead to reduced cool-season snowpack development and snowmelt runoff during the warm season, leading to reduced reservoir releases to support regulated flow during late spring and early summer (April through June) because the reservoirs are using more of the inflows to fill and provide less spilled water. However, during the late warm-season, an interesting result is shown where regulated flow increases under future HD climates (July and August), reflecting increased upstream storage withdrawal. The cause for these withdrawal increases appears to be related to satisfying irrigation demands and flow objectives at Parker, when the natural unregulated inflows are less than they were historically which will be shown later in this section. Although these seasonal changes are broadly consistent across the future HD climates (for a given future period), there is still considerable variation in season-specific impact across HD climate, especially for cool-season Easton flow increases.

- Yakima River at Umtanum (Figure 16): Further downstream, the regulated river flow depends also on the operation of Cle Elum Reservoir. Compared to the Yakima River at Easton, the results at Umtanum show similar season-specific trends during winter (December through February) and the early part of the warm season (April through June). However, contrasting from Easton, the summer season Umtanum median flows are similar to historical during HD 2020s climates and slightly less than historical during HD 2040s climates. This suggests that the upstream releases from Keechelus and Kachess are offsetting reductions in Cle Elum release and local inflows below Easton in order to generally maintain regulated flows at Umtanum and meet demands downstream. As with Easton, there is considerable uncertainty about the season-specific changes in median Umtanum flows.

- Naches River at Naches (Figure 17): Regulated flow at this location is supported by upstream reservoir releases at Rimrock and Bumping Lake, as well as local inflow below these reservoirs. Season-specific results at this location show season-specific changes in median flows similar to those shown on the Yakima River at Umtanum: increase during winter, decrease during late spring and early summer, and generally minor decreases to no change during summer months.

- Yakima River at Parker (Figure 18): Regulated flows at this location reflect upstream operations and local inflows from both the Yakima and Naches River subbasins. Results show that period-median flows increase during the cool season for generally all future HD climates (particularly during January through March), and decrease during the first part of the warm season (April through June). From July through September, there is no change in simulated Parker flow under future HD climates relative to historical. This illustrates a high priority placed on meeting PARW flow objectives during July through September, and helps to explain the upstream July through August increases in Easton flow below Keechelus and Kachess reservoirs (Figure 15).

Switching attention to water deliveries, another consequence of March-September TWSA reductions is a reduction of water supply available for delivery to junior water users in the system. The percentage reduction in deliveries to junior water users is indicated by the simulated proration level. Figure 19 shows that as median TWSA decreases from historical to future climates during the March through September period, median monthly proration (percentage) also decreases during April through September.[13] As a result, this leads to a

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[13] October TWSA proration percentages are computed in YPM but do not affect simulated operations. The October TWSA (not to be confused with the October Water Supply Available [OWSA]) that you show in the graph is not used to determine anything in the model. It exists simply because RW computes TWSA all year beginning in October. So the value you are showing is for the subsequent WY. In real life we usually do not

corresponding reduction in median monthly water diversions above Parker during future HD climates relative to historical (Figure 20). For both delivery metrics, results vary considerably across future HD climates for a given period (2020s or 2040s), where more severe decreases are generally observed for the drier HD climates.

Lastly, the increase in cool-season system inflow and reduction in March-September TWSA leads to season-specific impacts for system storage (Figure 21). Results show that median monthly system storage during cool season is increased under future HD climates relative to historical, as more upstream runoff must be passed through project reservoirs. This condition persists into spring (April through May). During summer, system inflows and below-reservoir local inflows diminish under future HD climates, leading to generally greater storage withdrawals being required during summer in order to provide support for downstream river flow and water delivery objectives. This leads to summer storage conditions trending lower under future HD climates relative to historical, and also a trend toward lower carryover storage conditions from one water year to the next.

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start to compute TWSA until March, although sometimes, like in a short water year, we will estimate it in January. The OWSA is calculated specifically for October to determine water distribution in October.

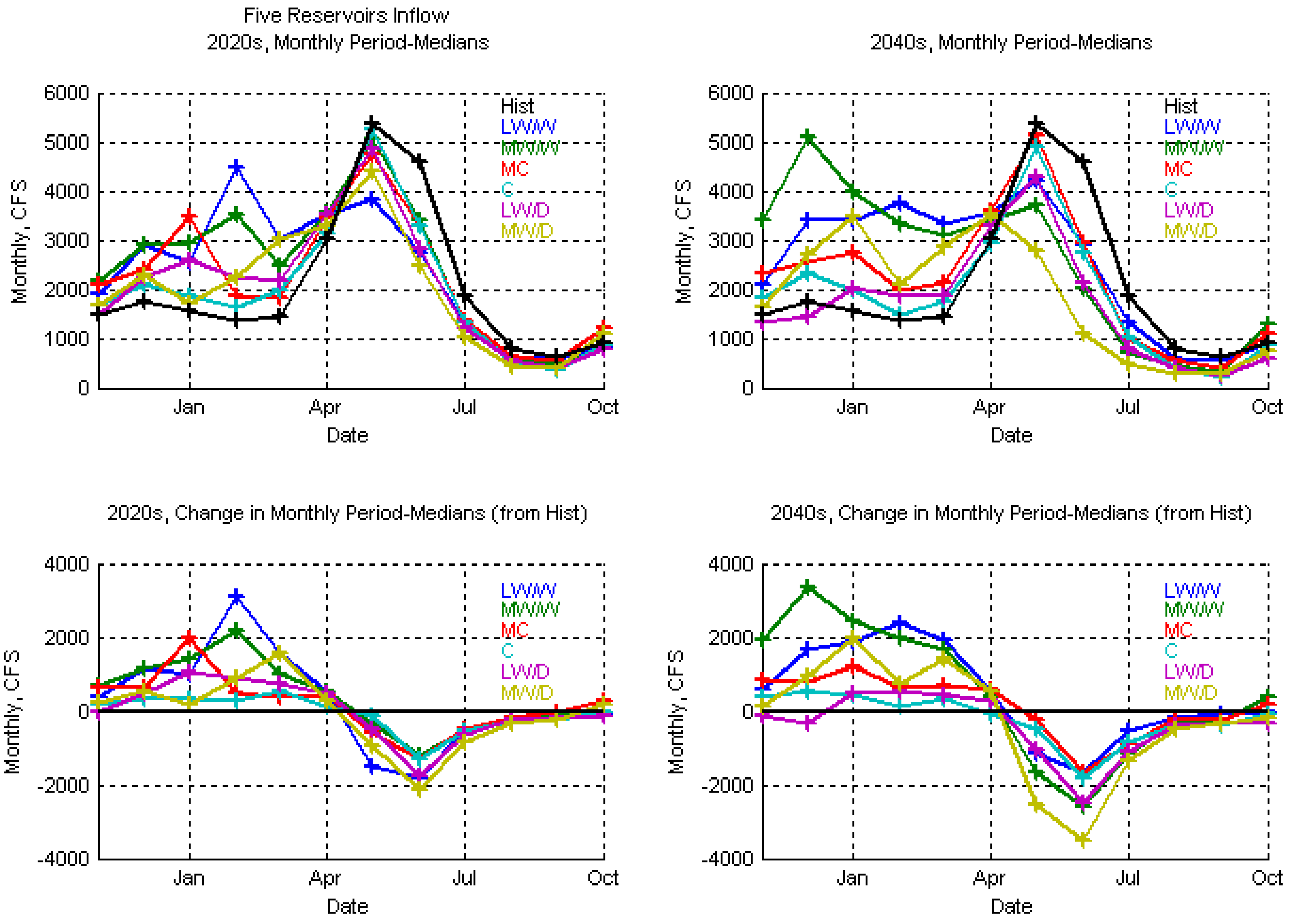


Figure 12. Yakima River subbasin –median monthly system inflow, Historical and HD climates.

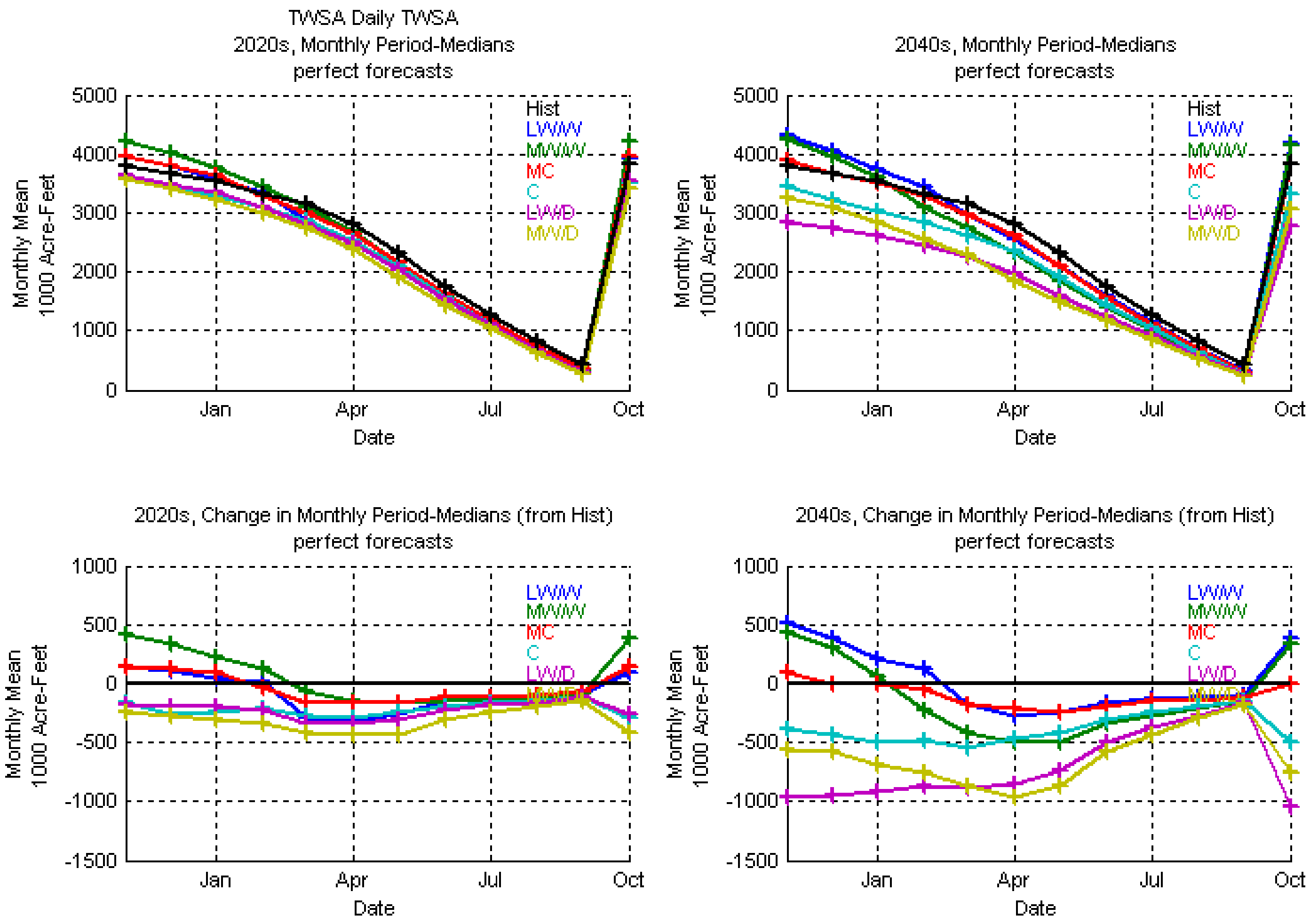


Figure 13. Yakima River subbasin – median monthly total water supply available (TWSA), Historical and HD climates.

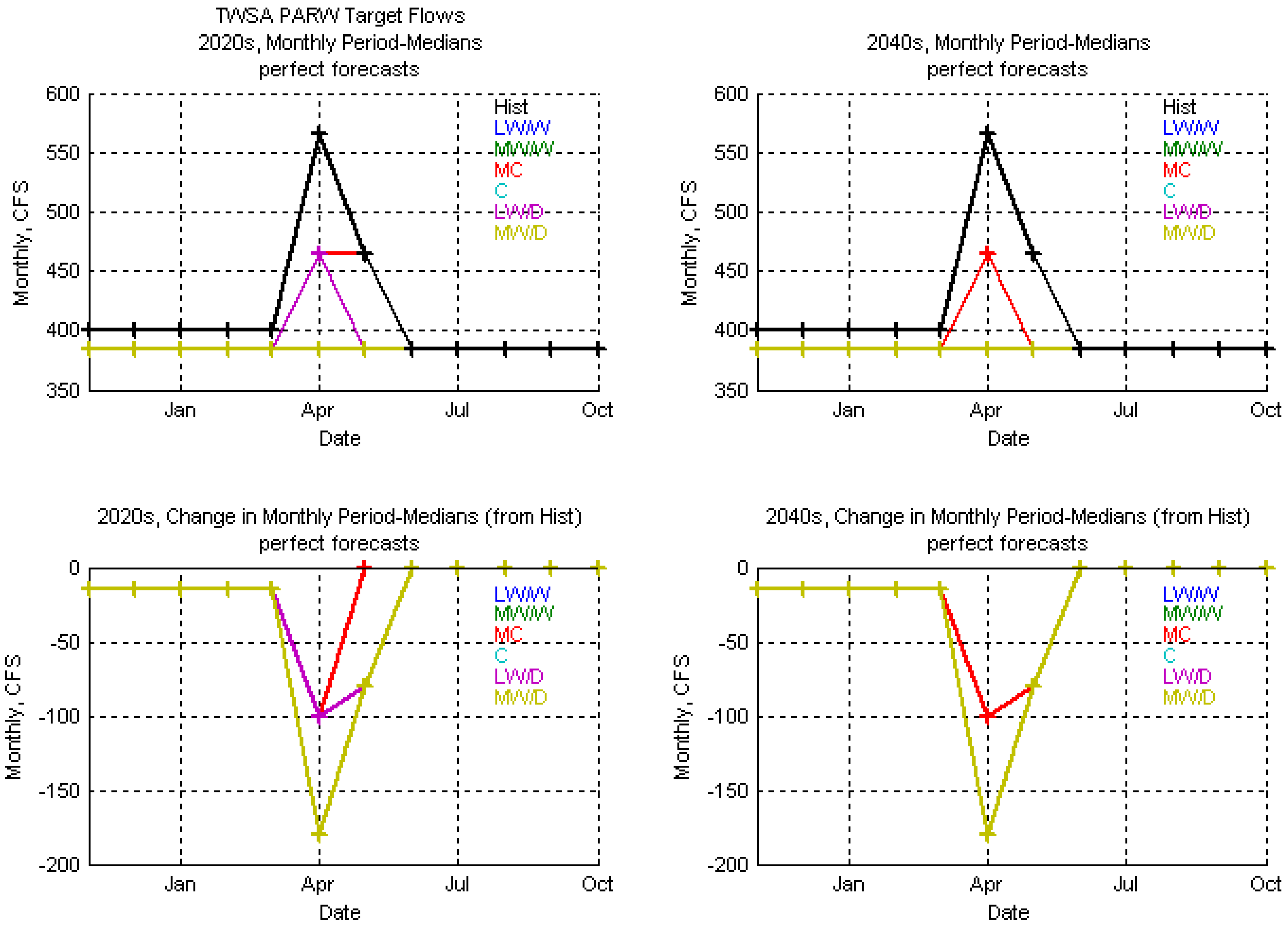
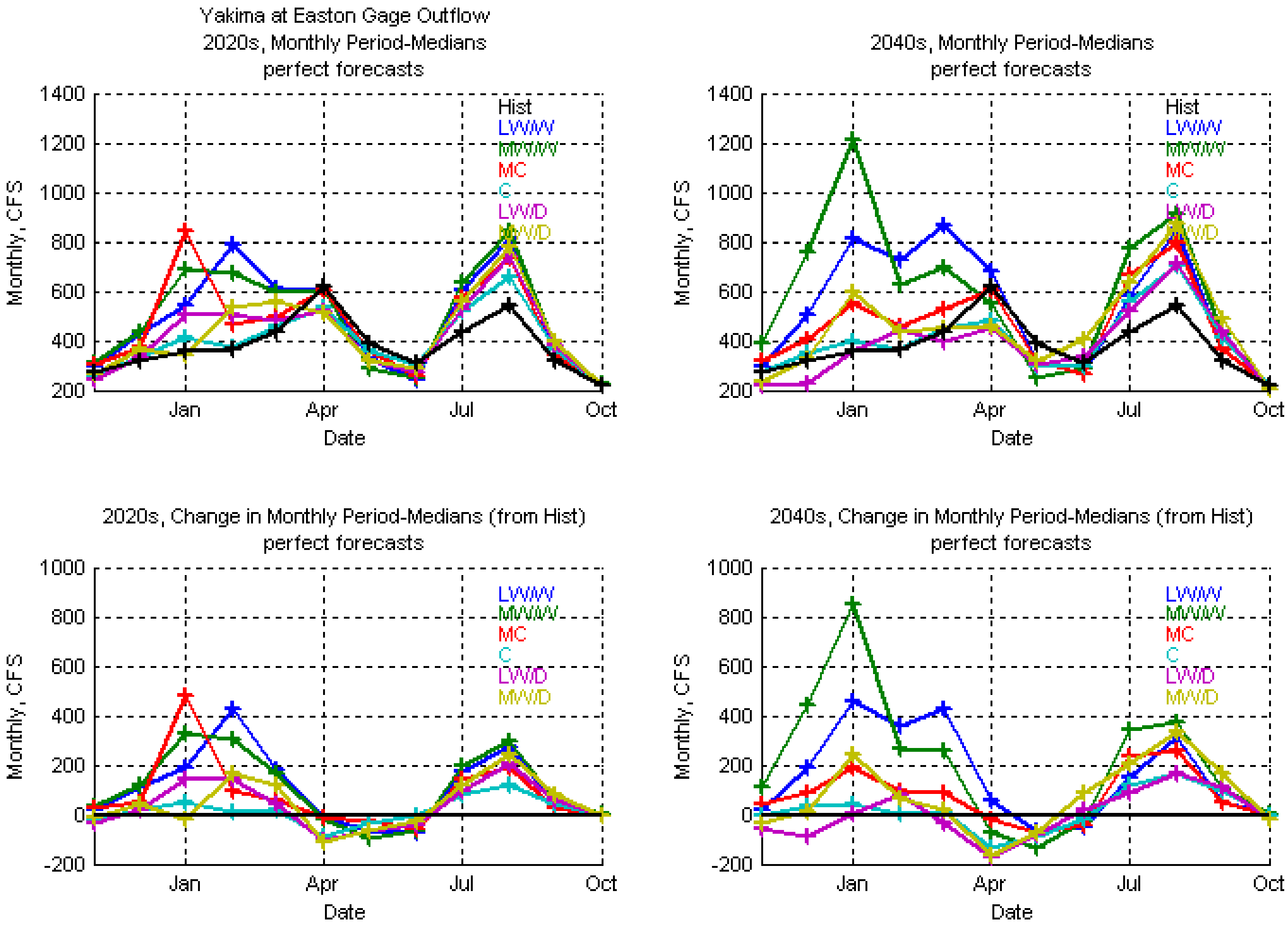


Figure 14. Yakima River subbasin – median monthly average daily flow target for Yakima River at Parker, Historical and HD climates.



Yakima at Easton Gage Outflow
2020s, Monthly Period-Medians
perfect forecasts

2040s, Monthly Period-Medians
perfect forecasts

2020s, Change in Monthly Period-Medians (from Hist)
perfect forecasts

2040s, Change in Monthly Period-Medians (from Hist)
perfect forecasts

Figure 15. Yakima River subbasin – median monthly Yakima River flow at Easton, Historical and HD climates.

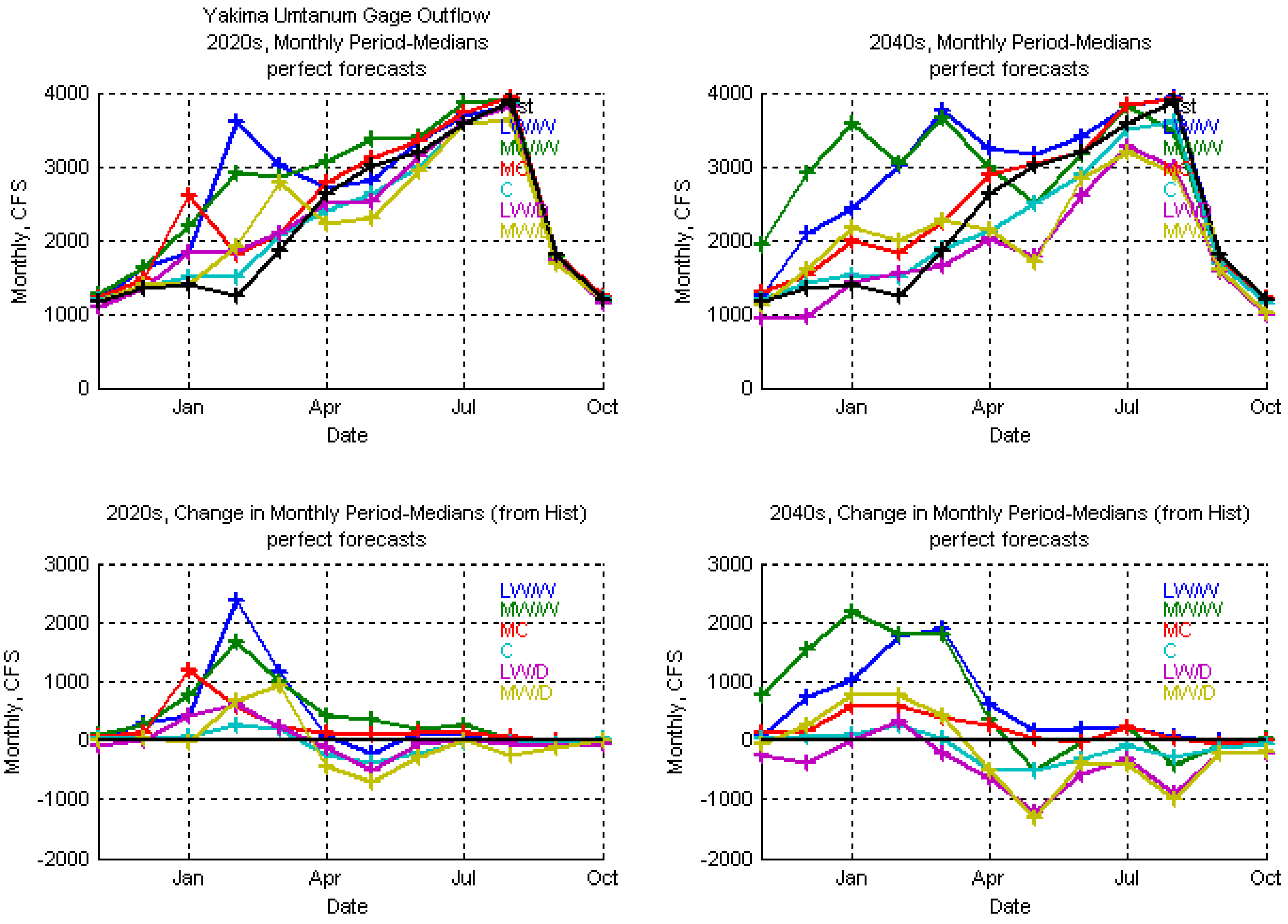


Figure 16. Yakima River subbasin – median monthly Yakima River flow at Umtanum, Historical and HD climates.

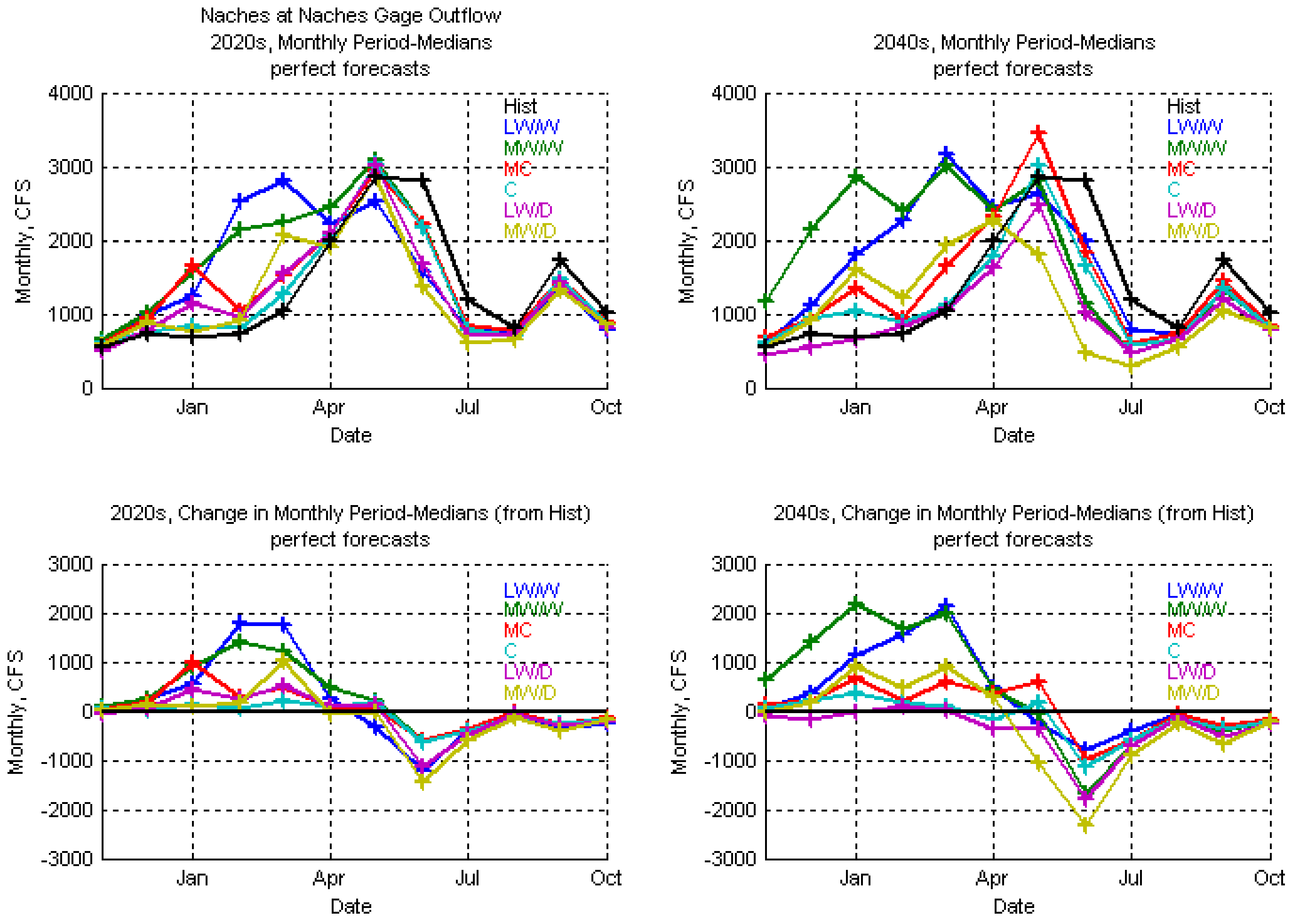


Figure 17. Yakima River subbasin – median monthly Naches River flow at Naches, Historical and HD climates.

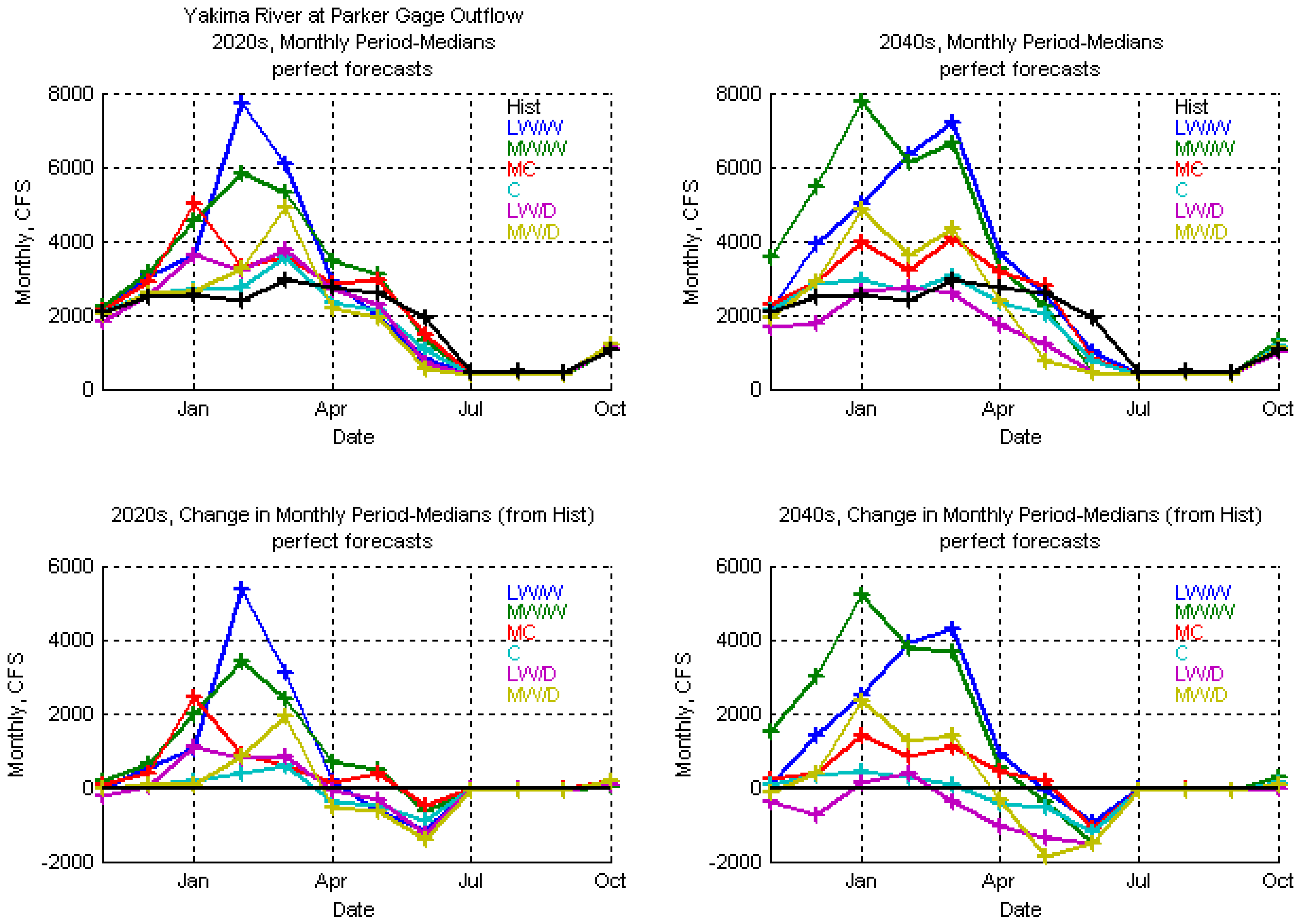


Figure 18. Yakima River subbasin – median monthly Yakima River flow at Parker, Historical and HD climates.

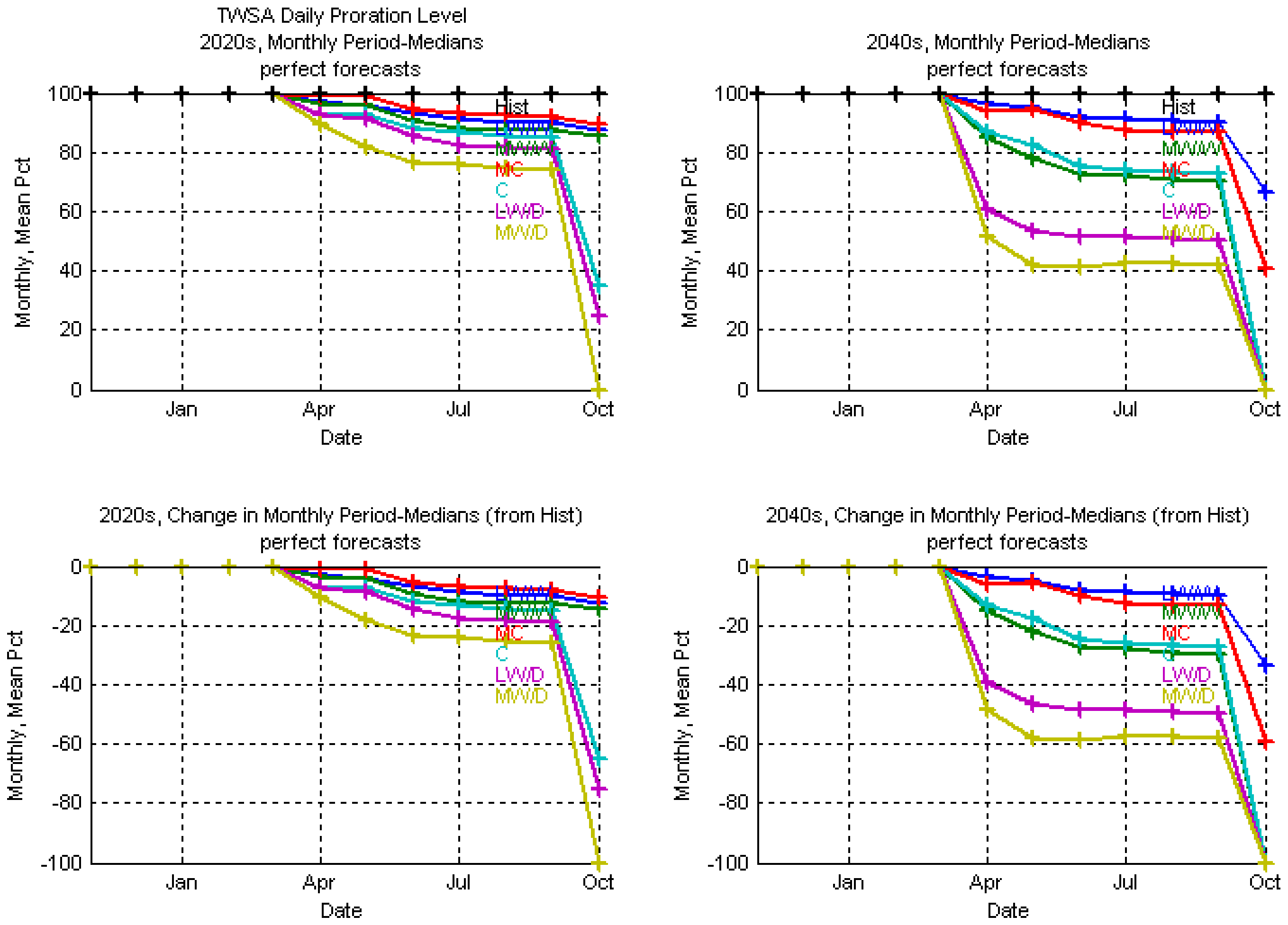


Figure 19. Yakima River subbasin – median monthly average daily proration level (%), Historical and HD climates.

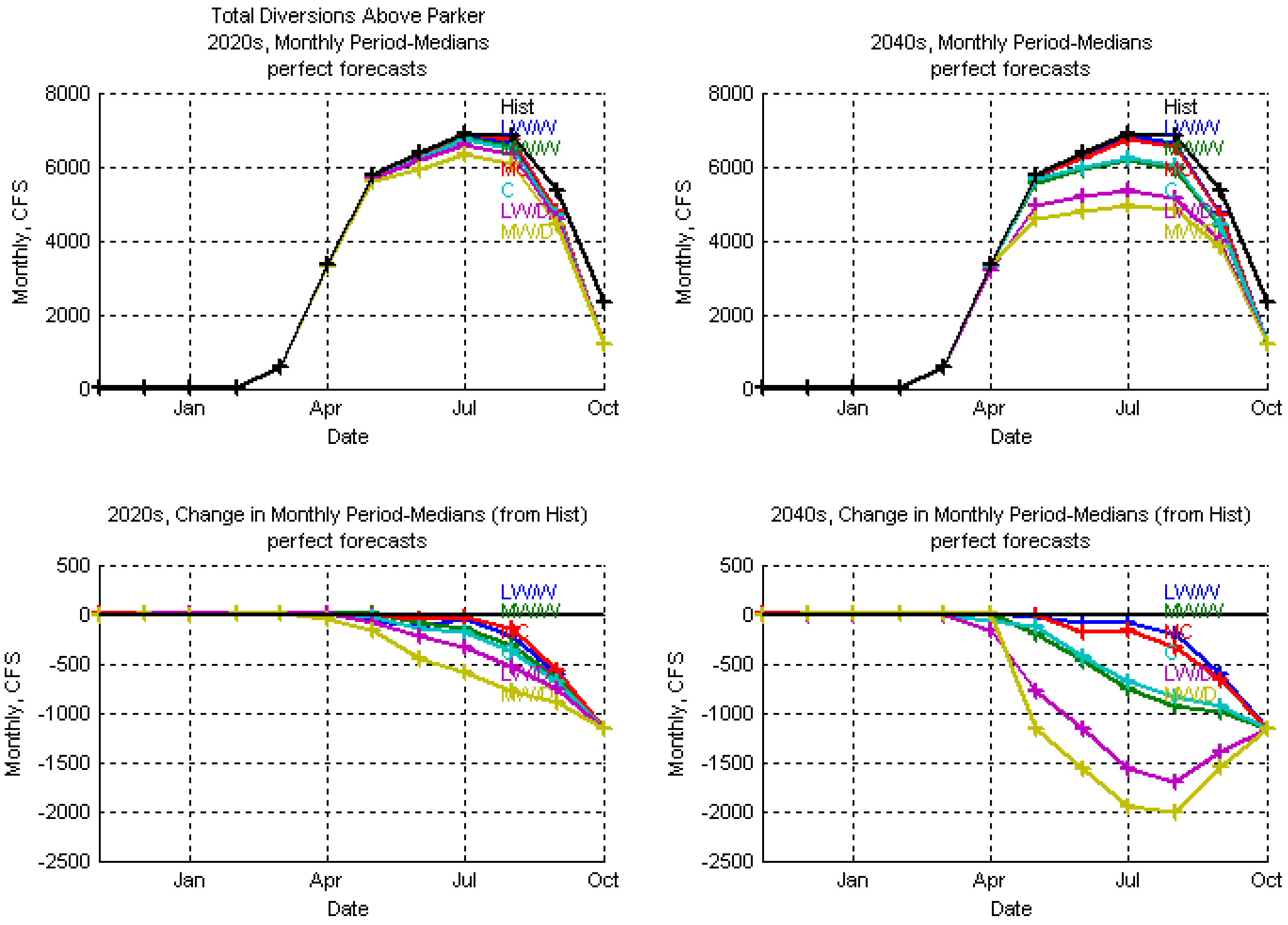


Figure 20. Yakima River subbasin – median monthly total diversions above Parker, Historical and HD climates.

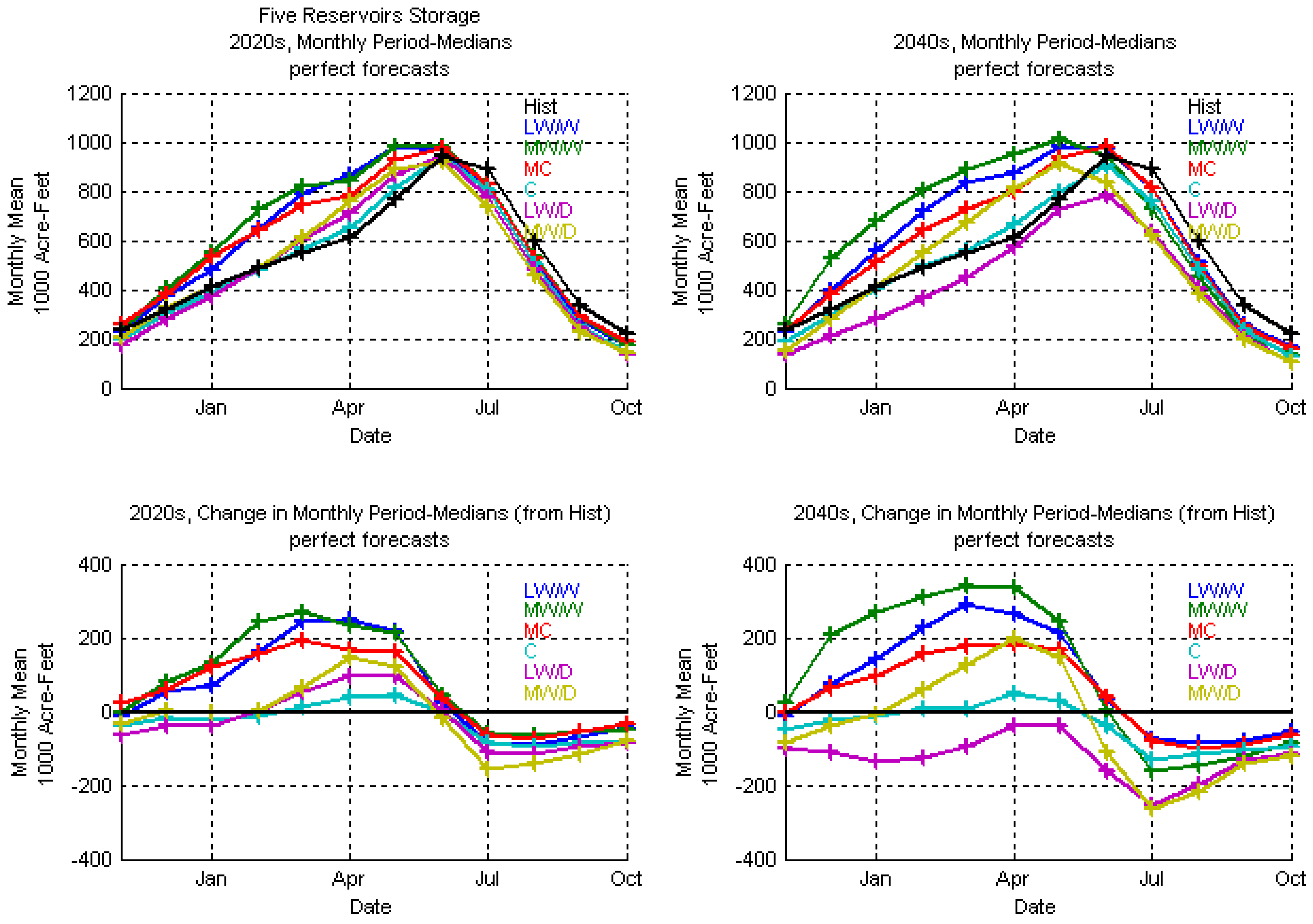


Figure 21. Yakima River subbasin – median monthly system storage, Historical and HD climates.

4.1.2 Variability under Hybrid-Delta Climates

Discussion now switches to the second question asked in this RMJOC effort: how does operational variability differ for the various RMJOC climate scenarios? In focusing on typical conditions, the preceding section offered a simple multi-metric narrative on how Yakima River operations change during relatively typical years under future HD climates relative to historical climate. This section broadens the view to consider changes in operational variability. This requires a more complex depiction of operations, revealing the range and distribution of various metrics under different climates. To develop this depiction, results were assessed using a distribution view, which offers a condensed way of summarizing operations variability within a climate and across climates.

To introduce distributional information, results are first presented for one metric using a time series view and then transitioning to distribution view. Figure 22 shows the time series of annual diversion above Parker for historical and HD 2040s climate (top panel), and the change in annual diversion from historical to a given HD climate (bottom panel). Diversions vary from year to year under each climate, which each express as a sequence of climatic variability similar to historical. For example, top panel on Figure 22 shows that for each climate the indexed simulation year 1977 generally involves relatively low diversion volume. Results show that while diversion volumes are expected to decrease during typical years, some years experience severe decreases while others experience increases.

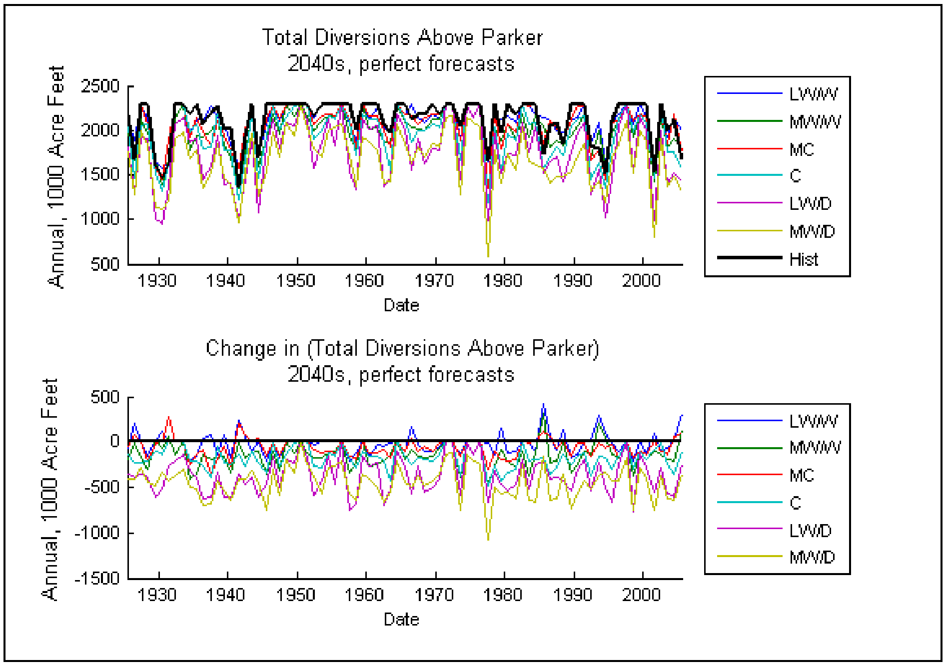


Figure 22. Yakima River subbasin – time series of annual diversions above Parker, Historical and HD 2040s climates.

If we permit ourselves to ignore the timing of conditions and simply focus on the distribution of conditions pooled during the simulation, and repeat this for each climate, then the conditions from Figure 22 can be equally shown using box plots as shown on Figure 23. Focusing on historical climate as an example (black box plot, top panel), the annual diversion is shown to vary within the same minimum and maximum limits under both portrayals (time series on Figure 22 and box plot on Figure 23). The merits of the box plot is that percentile conditions are more easily inferred based on the placement of the box: the bottom and top of the box represent the 25th and 75th percentiles, respectively, and the box midline represents the median or 50th percentile. The symbols above and below a box correspond to cases outside the interquartile range (i.e., above the 75th percentile and below the 25th percentile). So for example, in the 2040s, focusing on the values below the boxes or 25th percentile, there are reduced diversions in the relatively dry years of simulation under the MW/D climate compared to the historical climate. This makes sense given that the climate features warmer and drier conditions relative to historical, and thus there is generally less water available, including during relatively dry years.

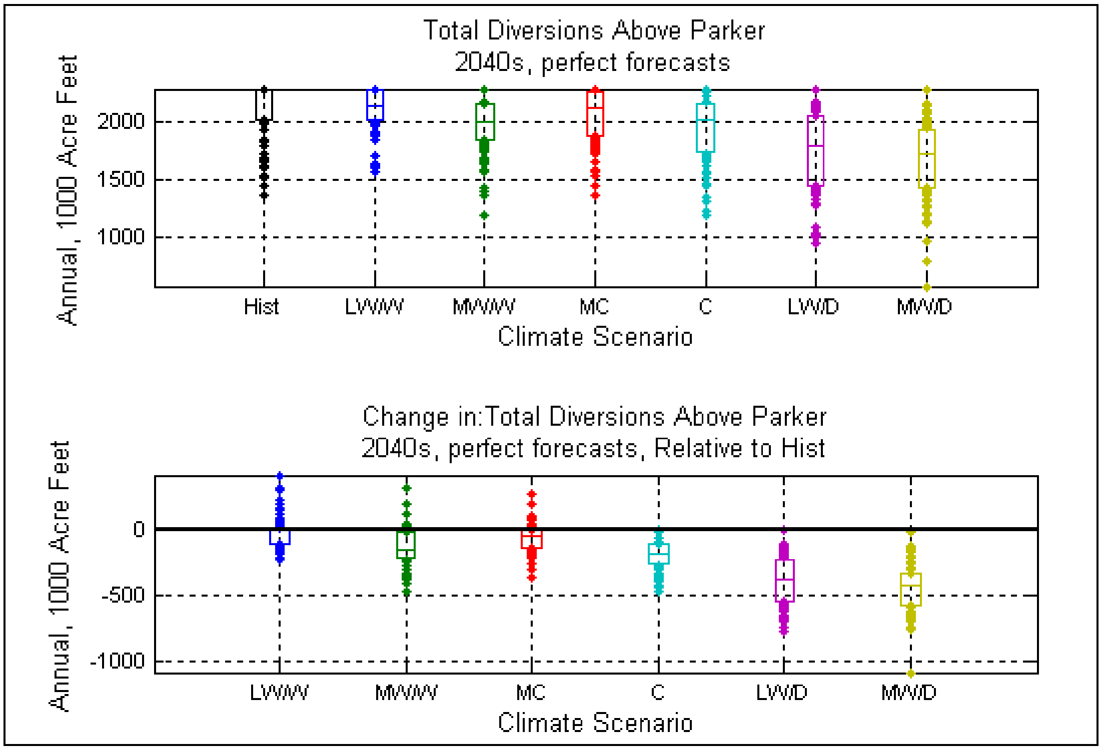


Figure 23. Yakima River subbasin – distributions of annual diversion volume above Parker, Historical and HD 2040s climates.

Switching from annual to monthly view and maintaining the distribution perspective, it is possible to compare monthly envelopes of operations variability. This also sets up assessment of the second central question on how operational extremes are portrayed differently under future HD climates compared to historical climate.

The following sequence of figures (Figure 24 through Figure 27) show monthly envelopes of operations variability for four of the ten metrics discussed under Typical Conditions (Section 4.1.1): average daily TWSA, target regulated flows at Parker, average daily proration, and system storage at the end of the water year (carryover system storage). Focus is placed on Group 1 simulation results where operations are informed by *perfect* water supply forecasts. Based on these results, effects on operations variability and extremes might be characterized as follows:

- *Average daily TWSA for April 1 and July 1*: Figure 24 shows monthly average daily TWSA variability for historical and HD 2040s climates. Given that the figure shows monthly average TWSA, the results are more resemblant of about April 15 and July 15 TWSA. Focusing on April and July distributions, all climates show a reduction in the median average daily TWSA. Under historical climate, the median conditions were roughly 2.9 MAF in April and about 1.3 MAF in July. Under the relatively optimistic 2040s climate (LW/W), the median values were roughly 2.6 MAF in April and 1.1 MAF in July. Under the relatively pessimistic 2040s climate (MW/D), these values respectively diminish to roughly 2.2 MAF and 0.8 MAF. Focusing on variability and relatively drier year conditions (i.e., the bottom quartile of cases under each climate), there appears to be a 1 in 4 chance that April and July TWSA values could be less than roughly 2.2 MAF and 1.0 MAF, respectively, under historical climate (i.e., roughly the bottoms of the historical boxes in April and July). Under the optimistic 2040s climate (MW/W), these values are roughly 2.2 MAF and 0.9 MAF. Under the pessimistic climate scenario (LW/D), these values are roughly 1.3 MAF and 0.6 MAF.

- *Target regulated flows in the Yakima River at Parker on July 1*: Figure 25 shows monthly average regulated flow variability at this location for historical and HD 2040s climates. Given that the figure shows monthly flow rate conditions, the results are more resemblant of mid-month rather than first-of-month flows. The July distribution of targets under historical climate suggests a median July target of 385 cubic feet per second (cfs) and a 1 in 4 chance that the flow target may be set at 465 cfs or greater. Switching to the 2040s climates, each future climate shows a trend toward lower July flow targets relative to historical. For example, all climates except LW/W show results where the box is not visible, meaning that 25 percentile to 75 percentile values are all 385 cfs (i.e., the minimum value shown). This means that in at least three-quarters of the Julys, for all climates except LW/W, the July-flow target is set at 385 cfs. On the higher flow side of the target flow schedule which depends on TWSA, the results show that maximum target flows vary across climates as follows: 655 cfs for historical, 655 cfs for LW/W, 465 cfs for MW/W, 565 cfs for C, 565 cfs for MC, 465 cfs for LW/D, and 385 cfs for MW/D.

- *Average daily proration level (DPL) on July 1 and September 1*: Figure 26 shows monthly average DPL variability for historical and HD 2040s climates. Given that the figure shows monthly average DPL, the results probably are more resemblant of mid-July and mid-September DPL. Focusing on July and September distributions, all climates show a reduction in the median average DPL. While historical median proration levels are 100 percent during these months, the median values range from above 90 percent under the relatively optimistic 2040s climate (LW/W) to below 50 percent under the relatively pessimistic 2040s climate (MW/D). Focusing on variability and the optimistic scenario, results show that proration expectations are similar under the historical and future MW/W climates, given that there appears to be a 3 in 4 chance that July and September prorations will be greater than roughly 70 percent to 75 percent under both climates, based on the bottoms of the blue and black boxes for these months. Switching to the pessimistic scenario (MW/D), the above statement must be modified to say that there is a 3 in 4 chance that July and September prorations will be greater than only about 20 percent. Or the corollary statement might be offered that there is a 1 in 4 chance that July and September prorations will be 20 percent or less.

- *System storage at the end of summer irrigation or carryover system storage*: This storage condition is sometimes referred to as carryover storage, as it represents residual system water supplies from the present water year that might be used to support system water uses during the following water year. Figure 27 shows monthly average daily storage variability for historical and HD 2040s climates. Given that the figure shows monthly average daily storage, the results probably are more resemblant of about mid-month storage. Focusing on October distributions permits an assessment of carryover storage variability across climates. Under historical climate, median and 25th percentile values of mean October-system storage are about 220 TAF and 140 TAF, respectively (i.e., box midline and bottom of box). Relative to these values, all HD2040s climates show a reduction in median and 25th percentile October storage, ranging from relatively smaller reductions under the optimistic 2040s climate (LW/W, having median and 25th percentile values of roughly 170 TAF and 110 TAF, respectively) to relatively greater reductions under the pessimistic 2040s climate (MW/D, having median and 25th percentile values of about 100 TAF).

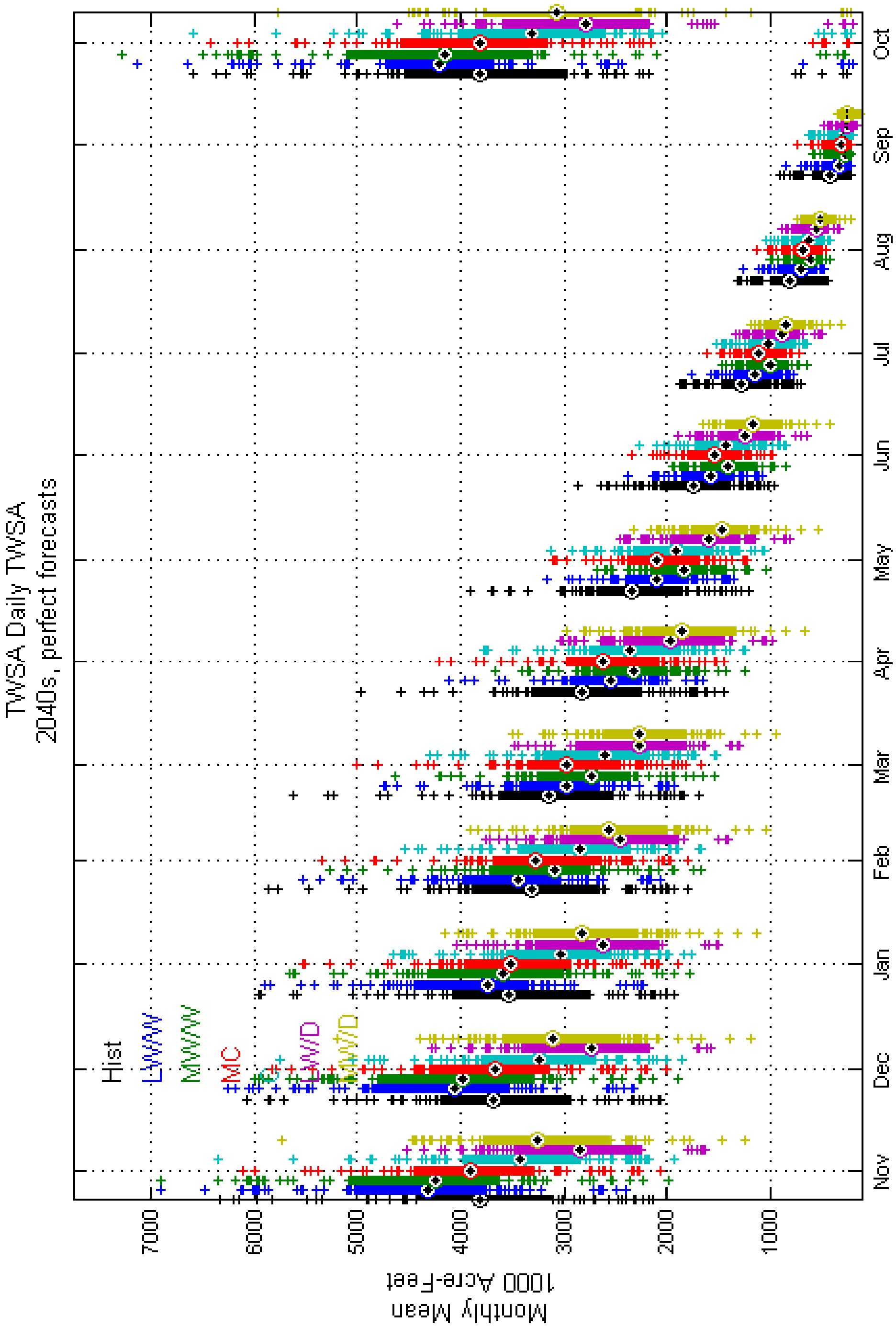


Figure 24. Yakima River subbasin – distributions of monthly total water supply available (TWSA), Historical and HD 2040s climates.

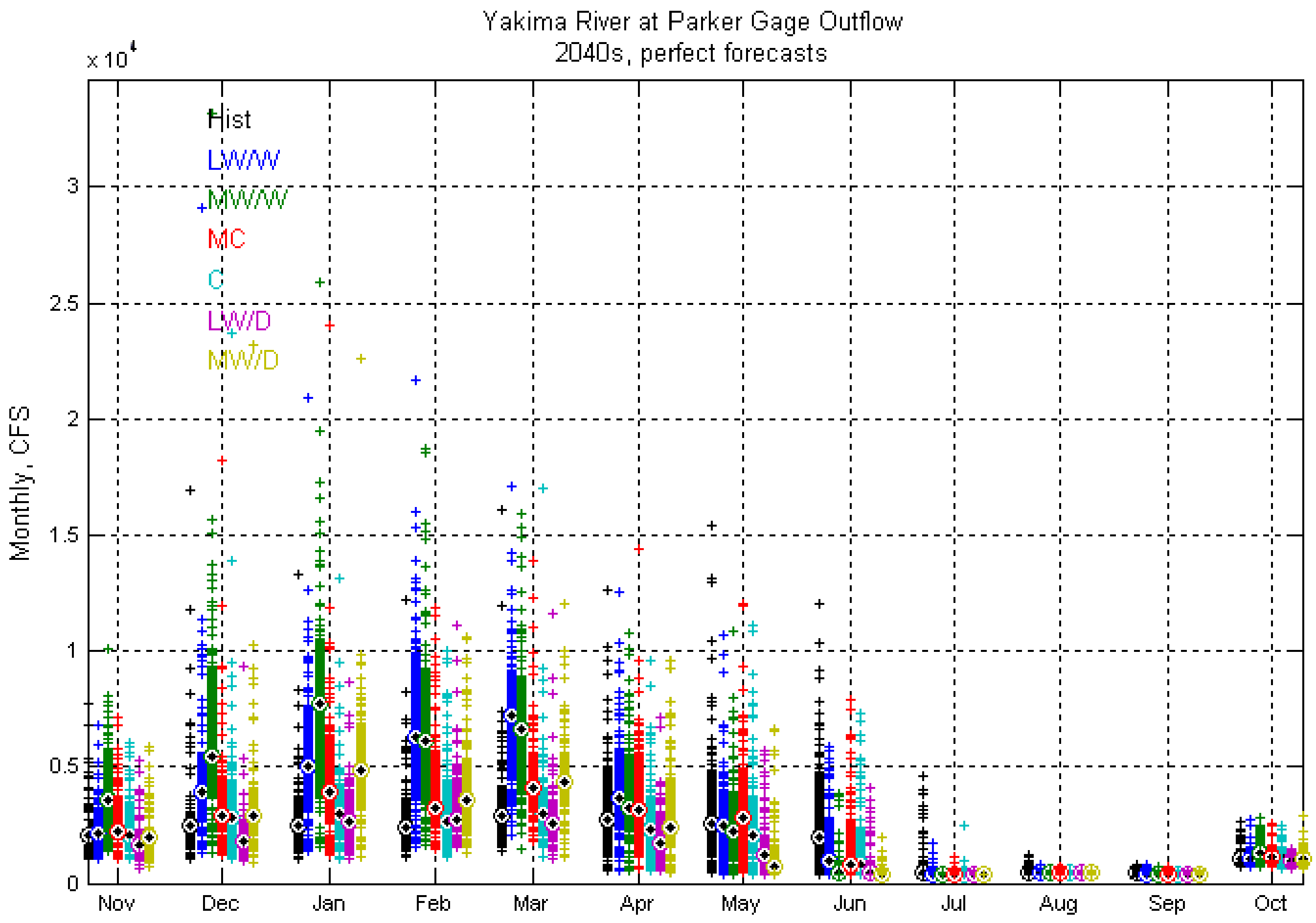


Figure 25. Yakima River subbasin – distributions of monthly Yakima River flow at Parker, Historical and HD 2040s climates.

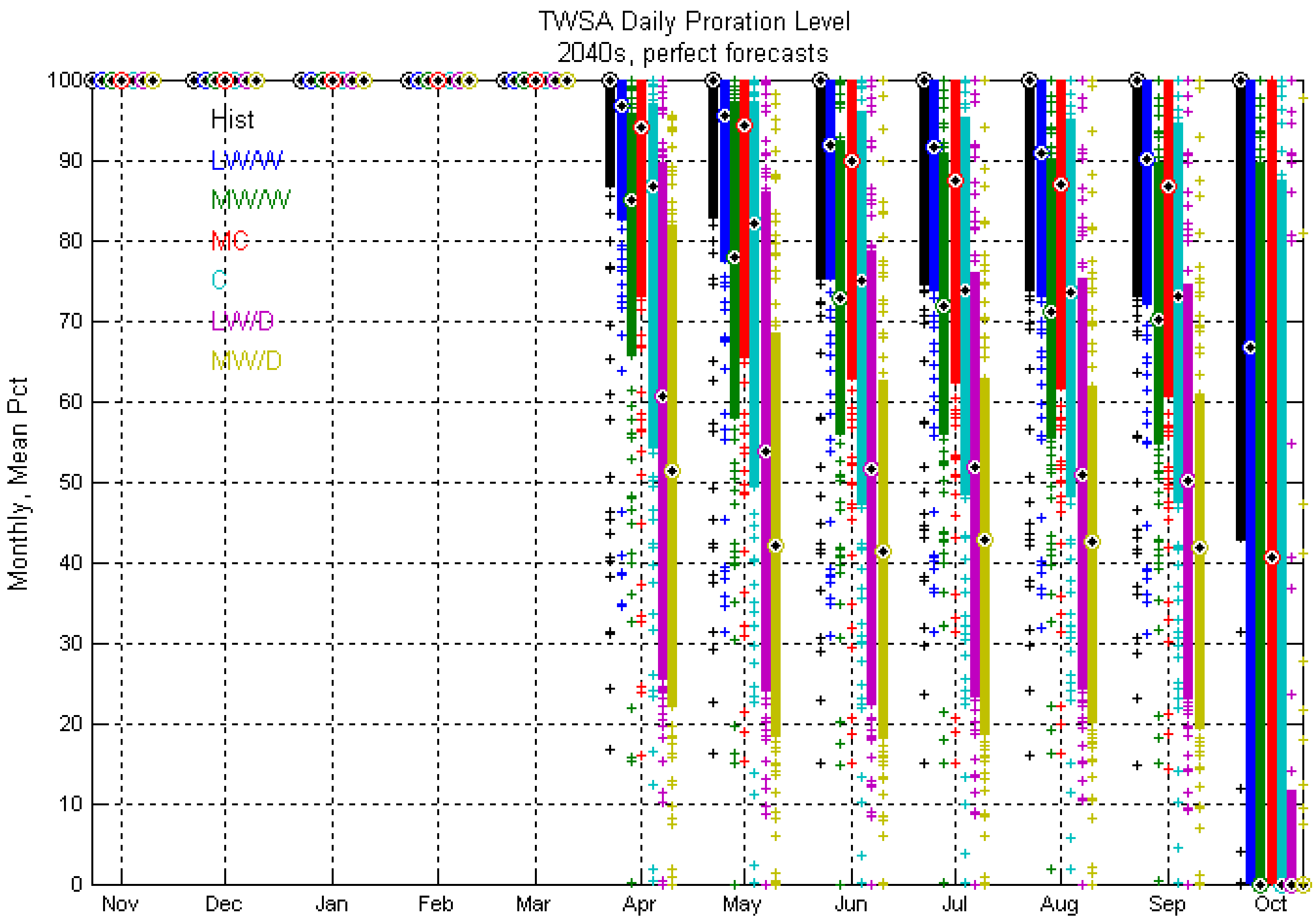


Figure 26. Yakima River subbasin – distributions of monthly average daily proration level (%), Historical and HD 2040s climates.

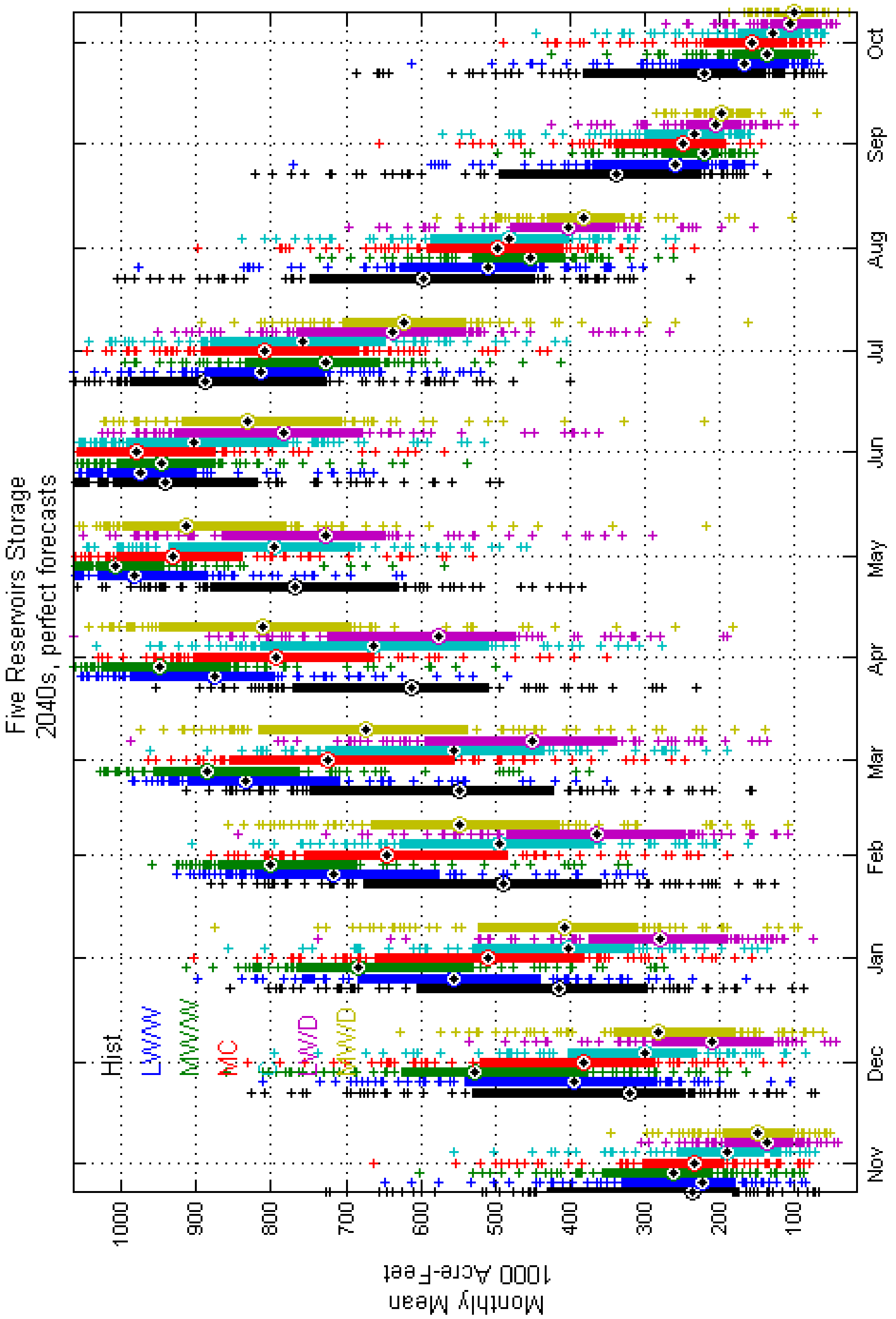


Figure 27. Yakima River subbasin – distributions of monthly system storage, Historical and HD 2040s climates.

4.1.3 Effect of Analytical Design Choices on Simulated Operations

This section addresses the final operations question posed in this RMJOC effort, which is about uncertainties in operations portrayal introduced by two aspects of analytical design. For each aspect, operations results are assessed to explore how the portrayal of climate change impacts on operations are sensitive to the analytical design choice. The two choices concern:

- Type of water supply forecast (*perfect* versus *imperfect*)
- Type of future climate scenario (Hybrid-Delta versus Transient)

4.1.3.1 Type of Water Supply Forecasting: *Perfect* versus *Imperfect*

During the scoping of this RMJOC effort, it was questioned whether the loss of snowpack might affect not only runoff seasonality, but also the ability to accurately forecast seasonal runoff volumes. As has been discussed in previous sections, the YPM calculation of TWSA is informed by forecasts of seasonal runoff volume on the Yakima River at Parker (PARW based on Reclamation Hydromet I.D., YAPAR based on UW CIG HB2860 I.D.). The resultant TWSA affects simulated decisions concerning instream flows targets, water demands prorationing, and storage targets.

The concern about forecasting stemmed from awareness that snowpack has historically served a role as a winter and early spring indicator of PARW runoff volume during April-September. As warming continues, snowpack should diminish and the utility of this indicator would theoretically diminish. This raises the questions of when this diminishment might occur and what it could mean for operations in addition to the impacts caused by runoff change.

To explore this question, YPM simulations were conducted for the historical and HD climates where TWSA calculations are informed by both *perfect* and *imperfect* forecasts of PARW irrigation-season runoff volume. *Perfect* forecasts are annually computed as the volume of PARW runoff during the upcoming irrigation season. *Imperfect* forecasts, described in the Part I Report, Section 5, were developed for this effort to reflect real-world seasonal runoff forecasting procedures and the climate-specific relationship between forecast-period runoff (Q), antecedent seasonal precipitation (P), and subbasin snow water equivalent at the time of forecast issue (SWE). For example, for the situation of issuing a January 1 forecast of April-September PARW runoff volume, the relationship might involve $Q_{\text{Apr-Sep}}$, $P_{\text{Oct-Dec}}$, and $SWE_{\text{Jan 1}}$. Following traditional model-development procedures, regression-based forecast models were built specific to each climate and the seven forecast situations at PARW (i.e., time of issue, forecast period). Model development details are described in the Part I Report, Section 5.

Figure 28 and Figure 29 show the quality of regression models for each forecast situation and for 13 climates: one historical, six HD 2020s, and six HD 2040s climates. Quality is measured by the calibration r^2 value for each climate-specific regression model. Results for the HD 2020s climates (Figure 28) show that regression model quality begins to slightly deteriorate at PARW during early and late season issues (January and July). This is intuitive given that warming might be expected to initially affect early season snowpack development and late season snowpack presence. These shoulder-season effects become more developed under the 2040s HD climates (Figure 29).

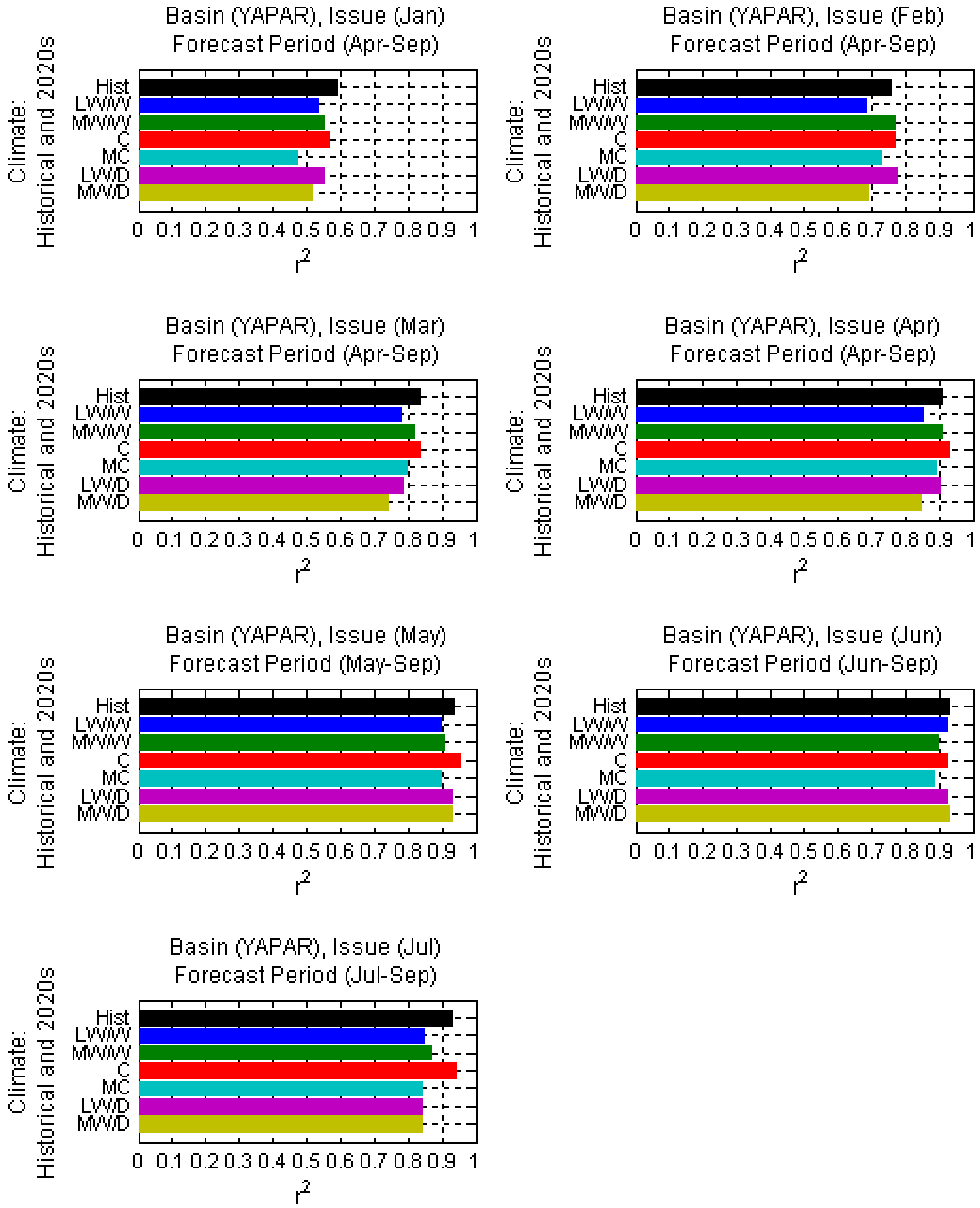


Figure 28. Yakima River subbasin – quality of regression models (r^2) used to generate *imperfect* forecasts of seasonal runoff volume on the Yakima River at Parker, Historical and HD 2020s climates.

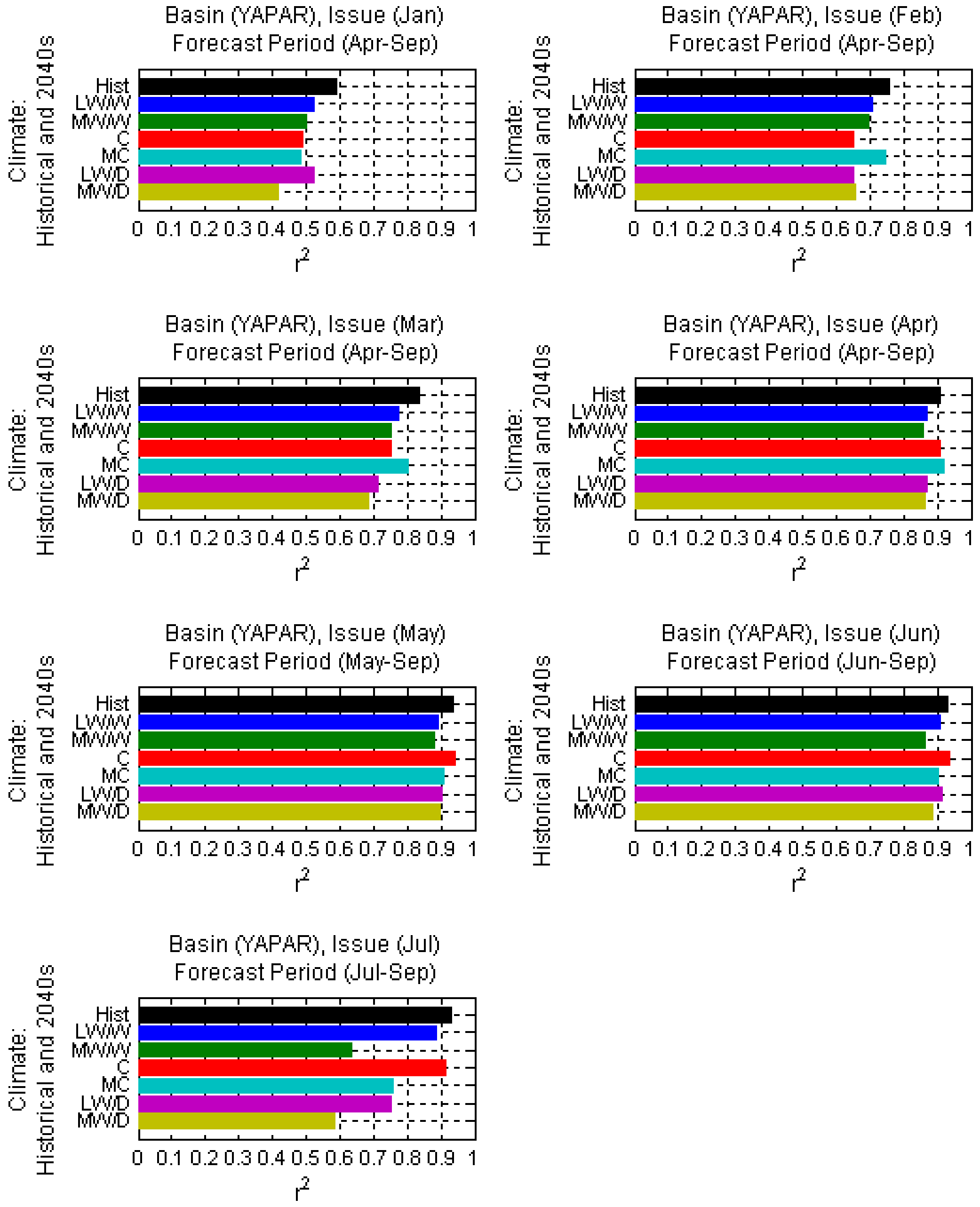


Figure 29. Yakima River subbasin – quality of regression models (r^2) used to generate *imperfect* forecasts of seasonal runoff volume on the Yakima River at Parker, Historical and HD 2040s climates.

Moving to YPM simulation results, the central question is whether Yakima River operational changes from historical to future HD climates are different when simulated using *perfect* or *imperfect* forecasts. Results suggest that the simulated operations are not very sensitive to type of water supply forecast. Further, it appears that the differences in operations portrayal introduced by choice of water supply forecast type are very small relative to differences in operations portrayal introduced by choice of climate. This is illustrated on Figure 30, which shows change in median monthly diversions above Parker relative from historical to HD 2040s climates: top panel showing changes based on YPM simulations using *perfect* forecasts, and the bottom panel based on simulations using *imperfect* forecasts. Comparing top and bottom panel results shows that the change in median monthly diversions are nearly insensitive to type of water supply forecasting, and vary considerably across the mix of six HD 2040s climates. Switching from change in typical conditions to change in variability, comparison of Figure 31 and Figure 32 shows that the distributed changes in monthly diversions is very similar using either forecast type. As with period-medians, the distributed changes in monthly diversions contrast more sharply when comparing distributions from different climates.

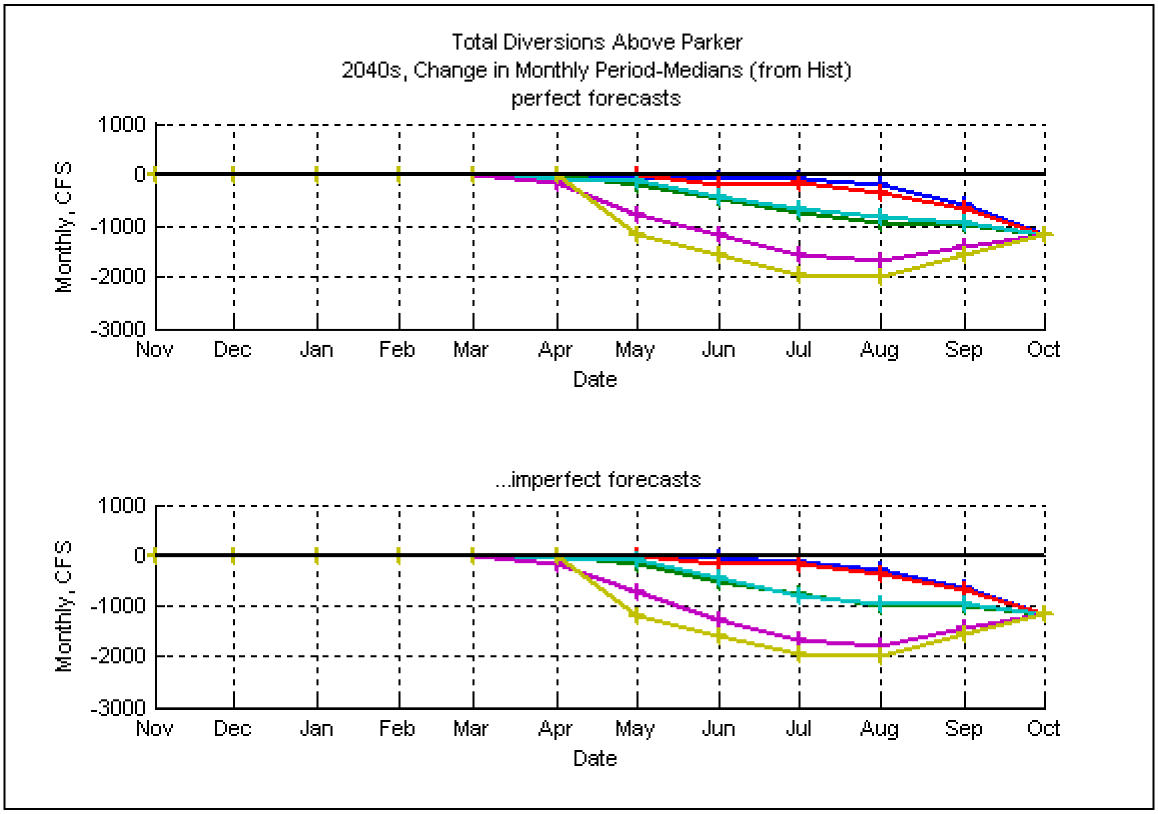


Figure 30. Yakima River subbasin – change in median monthly total diversions above Parker, HD 2040s climates relative to Historical, simulated using *perfect* and *imperfect* water supply forecasts.

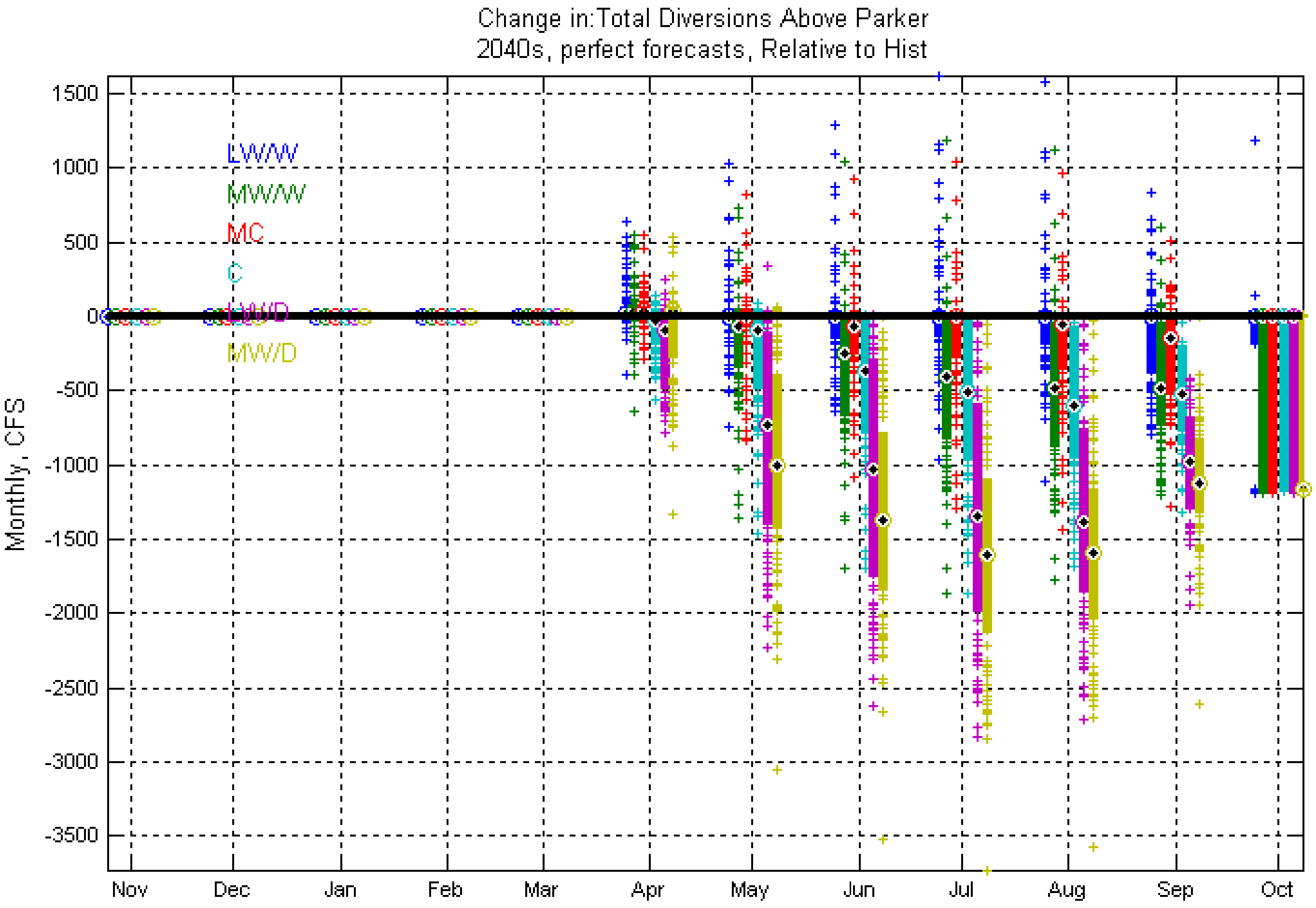


Figure 31. Yakima River subbasin – change in monthly distributions of total diversions above Parker, HD 2040s climates relative to Historical, simulated using *perfect* water supply forecasts.

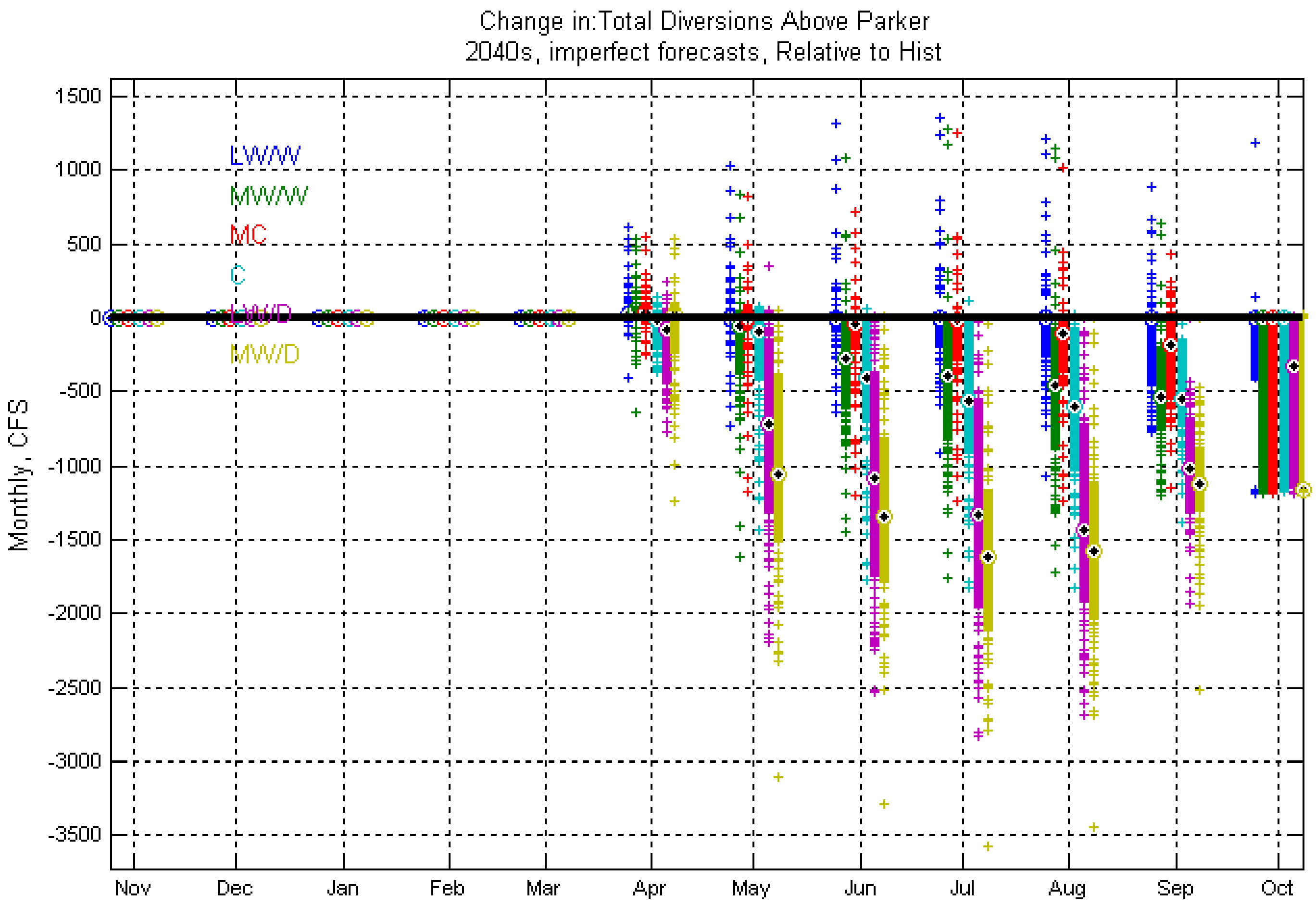


Figure 32. Yakima River subbasin – change in monthly distributions of total diversions above Parker, HD 2040s climates relative to Historical, simulated using *imperfect* water supply forecasts.

In summary, it appears that Yakima River operations portrayals under HD 2020s and 2040s climates are not significantly sensitive to using *perfect* or *imperfect* PARW forecasts in YPM simulation. This is could be due to a couple of reasons. First, the degree of climate change featured in the HD 2020s and HD 2040s climates may not be substantial enough to diminish snowpack to the point of causing enough impact on PARW (YAPAR) seasonal-runoff volume forecasting, TWSA assessment, and dependent operational decisions (at least during the period of March-May when PARW forecasts quality under HD 2020s and 2040s climates remains similar to historical). Second, the YPM 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 does 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* YAPAR water supply forecasts developed for these scenarios.

It should be noted that another factor contributing to this impression is how the forecasts were used. In the case of Yakima River operations analysis, a 50 percent exceedence estimate of PARW seasonal runoff volume was fed into YPM simulation, where the 50 percent exceedence estimate equals the regression estimate for a given forecast situation and year. An alternative way of using these regression models would be to also consider the model error characteristics and estimate a conservative estimate of YAPAR seasonal runoff volume, tiering from the regression estimate. This is done by some operations groups, reacting to real-world regression forecasts, and factoring in the risk attitudes of the given operations situation. So for example, rather than use 50 percent exceedence estimates directly from the regression models, the model estimate and model error characteristics might have been used to generate runoff estimates that have a 90 percent or 95 percent exceedence probability.

To illustrate, consider the historical-climate regression models from Figure 28 (model r^2 indicated by black bars). Figure 35 illustrates application of these models to estimate historical seasonal runoff volumes at PARW (blue line estimate compared to red line actual, where actual is from the hydrologic simulation under historical climate). The figure also illustrates the 80 percent confidence intervals about each regression estimate (time series of light blue area). If a risk-neutral attitude is taken and 50 percent exceedence forecasts are used, then it can be expected that half the time the coming water supply will be either under- or over-estimated. Given that the spring and early-summer issue forecast models are of pretty good quality (high r^2 values), the degree of under- or over-estimation should be minor and the effect on TWSA and dependent operating decisions should also be minor. If a risk-averse attitude is taken and a conservative forecast estimate is derived (e.g., 90 percent or 95 percent exceedence), then water supply should be more consistently under-estimated (e.g., use of 90 percent exceedence forecasts should lead to under-estimation in 9 out of 10 years).[14] When conservative forecast use is coupled with uncertain forecast models (e.g., January and February issues when the regression model is more error prone), then the degree of under-estimation might be more significant. To the extent that operations are sensitive to water supply anticipation in these situations, there might be more effect witnessed in the operations results depending on whether they're based on *perfect* or *imperfect* forecasts.

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[14] Note, Reclamation's real-world scheduling of operations for any particular year is informed by water supply forecasts reflecting several risk attitudes about inflow during coming months (e.g., consideration of 50 percent, 90 percent, and 95 percent exceedence forecasts for a given forecast situation). In contrast, the YPM simulates one risk attitude that is used for each year of simulation when relating system operating targets and decisions to PARW forecasts. The choice to use 50 percent exceedence PARW forecasts in the RMJOC effort's YPM simulations is subjective; other exceedence levels could have been used.

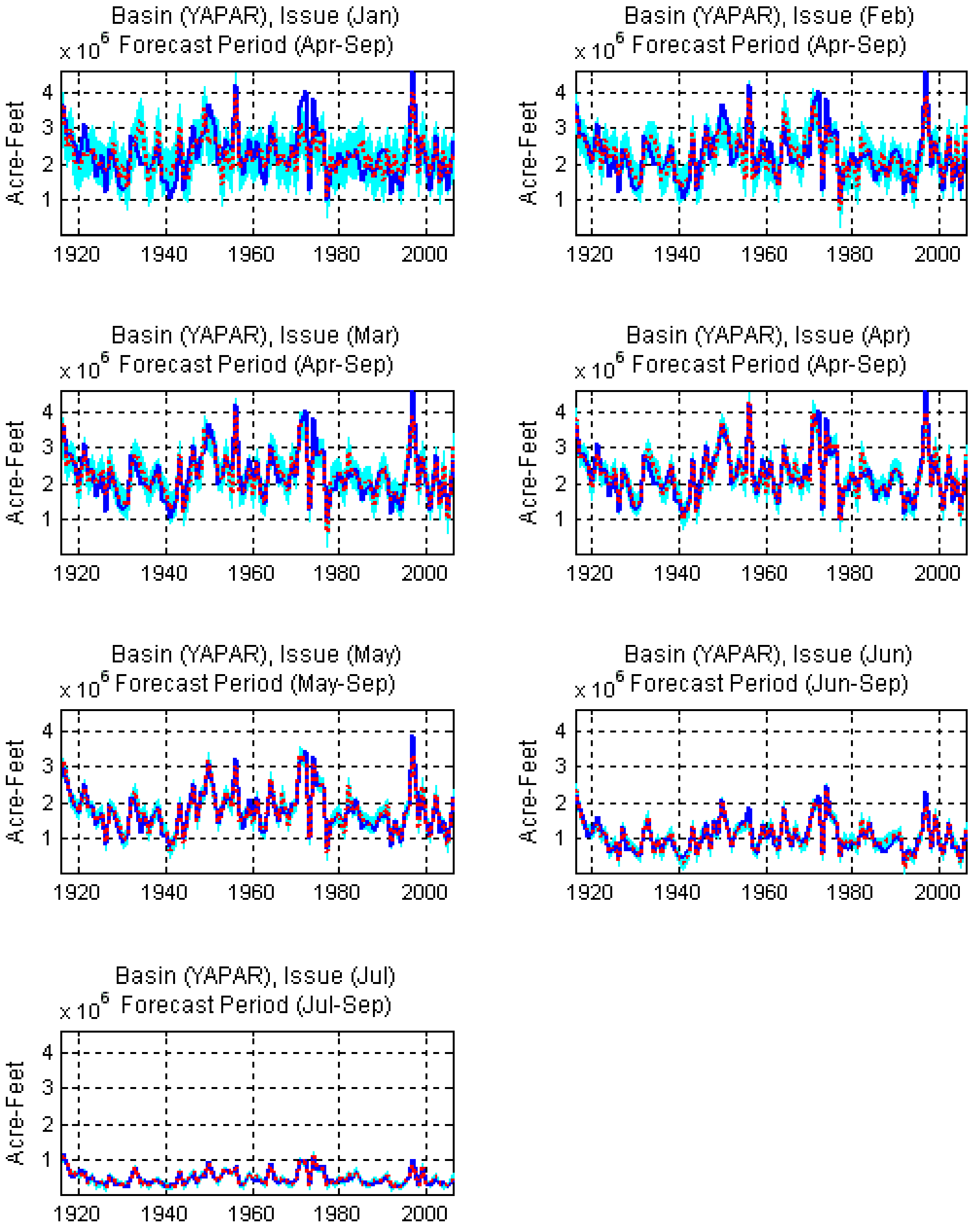

Figure 33. Yakima River subbasin – application of regression models under Historical climate. *Note about the figure: red line is the actual or predict and runoff volume, blue line is the regression-estimated runoff volume, and light blue area is the 80 percent confidence interval about the estimate (90 percent to 10 percent exceedence).*

4.1.3.2 Type of Future Climate Scenario: Hybrid-Delta (HD) versus Transient

During the scoping of this RMJOC effort, the technical workgroup decided to utilize two of the information types being developed for the UW CIG HB2860 effort: information that roughly reflects a step-change in climate from historical to future periods (i.e., HD scenarios) and information that reflects time-developing climate continuously from simulated historical to projected future periods (i.e., Transient scenarios). The purpose of considering both types is to gain understanding on which type is more appropriate for a given type of longer-term planning effort conducted by RMJOC agencies.

These two information types offer fundamentally different portrayals of future climate conditions and set up different types of longer-term operations analyses. The HD scenario “climate change” data are useful for studies meant to reveal system operational sensitivity to incremental change in climate. The Transient Climate Projection data are useful for revealing time-developing climate and operational performance, which can be useful for adaptation planning where there is interest in the timing, onset, and intensification of impact (Brekke et al. 2009). However, the latter involves more complex use of regional climate projection information and would seem to have limited applicability to planning at more local and sub-monthly scales (Elsner et al. 2009). The Part I Report, Section 3, offers additional discussion comparing and contrasting HD versus Transient information. Briefly:

- HD scenarios express the same year-to-year climate variations as observed historically, by definition of how HD scenarios are constructed. Thus, drought and flood events still occur during the familiar historical sequence, but with intensities adjusted based on the given HD climate change scenario.

- Transient scenarios do not express the same year-to-year variations as observed historically. This is because the month to month and year to year temperature and precipitation sequences of a given Transient scenario are generated using global climate models simulating global climate, with output then downscaled over the Pacific Northwest region (Part I Report, Section 3). These global climate simulations start from ocean conditions that do not correspond to actual ocean states (e.g., year 1900 ocean state at the beginning of 20th Century climate simulations or year 2000 ocean state at the beginning of 21st Century climate simulations). Because ocean states can drive sequences of regional climate variability, this permits these regional sequences to not align with historical. For example, flood and drought events (or relatively wet and dry years) still occur, but during simulated-historical years different than those from observed- historical years that respectively contained floods and droughts. That said, the first 50 years of Transient scenarios (simulated 1950-1999) have been adjusted in each scenario to be statistically consistent with the envelope of observed climate variability over the Columbia-Snake River Basin (Part I Report, Section 3). So although the simulated-historical hydrology and operations sequences may look unfamiliar under Transient scenarios, they should exhibit similar envelopes of variability as observed-historical.

- This section uses results on a single operations metric (annual diversions above Parker) to highlight differences in portrayed operations impacts when using the two types of future climate information. To begin, Figure 34 shows the time-series view of annual diversions for historical climate[15] (black line indexed from climate-observed WY 1926 to 2006) and transient climates (colored lines indexed from climate-simulated WY1950 to 2098). The figure also shows the time-series of transient ensemble-median annual diversions, where transient conditions are pooled each year and the median is computed each year from this pool of conditions (dashed black line indexed from WY 1950 to 2098).

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[15] These YPM-simulated diversions are from simulation 1, listed at the beginning of Section 4.

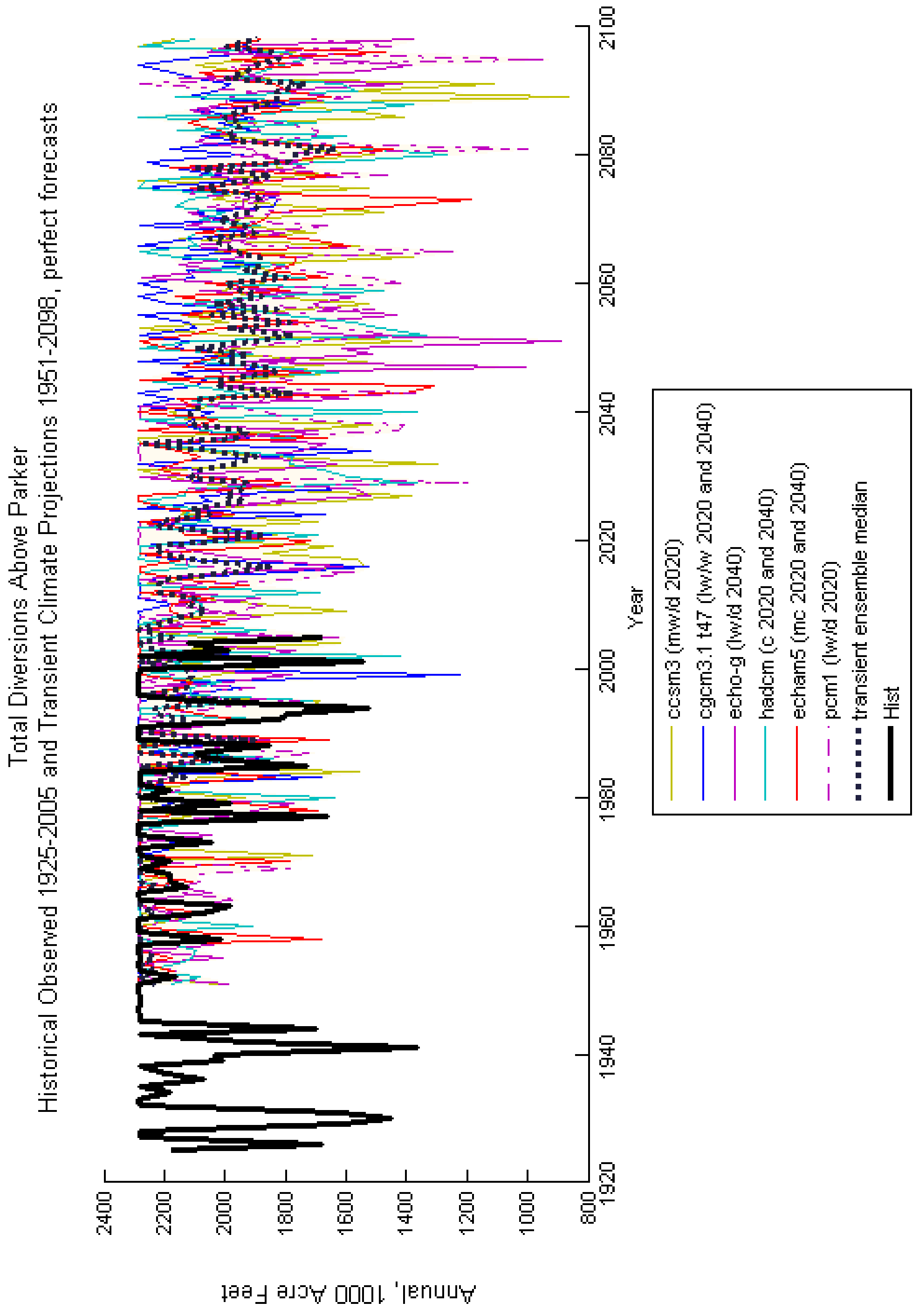

Figure 34. Yakima River subbasin – annual diversions above Parker, Historical and Transient climates.

There are several ways to interpret the transient information. A common way is to track the ensemble spread and central tendency through time. This speaks to the adaptation view and wanting to understand the timing of impacts. The central tendency is indicated by the ensemble median (dashed black line) and the spread is indicated by the spread of members through time (which reflects a mix of future climate variability told by the underlying climate projections and uncertainties in developing such projections). Interpreting these aspects of Figure 34, the central tendency of annual diversions tends to diminish with time. The decreasing trend begins during the Transient scenarios' late 20th Century period and continues throughout the 21st Century. In this sense, the Transient results are consistent with the HD results on change in typical annual diversions (Section 4.1.1). The Transient results differ in that they also characterize the trend in annual diversions in a time-evolving fashion through a time-period that extends before and after a given HD scenario. Granted, multiple period-specific HD scenarios could be viewed to offer a similar effect, but perhaps with less ease of depicting time-evolving results.

Ideally, the Transient information could also be used to support year-specific assessments, where the ensemble of information is sampled at a specific year-stage and viewed using a distribution perspective. This might be interpreted as the range of future climate variability or uncertainty at that point in time. For example, this system projection view has been featured in several recent risk assessments concerning climate change and variability implications for Colorado River Basin water management (e.g., Barnett and Pierce 2009, Rajagopalan et al. 2009, Reclamation 2007). To support such a view, the ensemble should have a sufficiently large set of ensemble members to support characterizing such distributions. As it is, this RMJOC effort features only six transient members, and therefore, it is inadvisable to characterize time-stage distribution informed by only six transient scenarios and six corresponding cases at each year-stage. Even then it, it may be preferable to build time-stage distributions using a decade of years centered on the time-stage. For example, to represent 2040 distribution of possibilities, one might pool 2035 to 2045 conditions from each transient trace to construct the 2040 distribution.

One benefit of using the Transient information is that it can be used to reveal decadal to multidecadal variability within climate projections. The matter of decadal to multidecadal variability affects our interpretation of the RMJOC HD scenarios, which are sampled as changes in 30-year climates from climate projections. The goal is to be able to interpret HD scenarios as climate change possibilities and not misunderstood multidecadal variability. It is possible that some of the RMJOC HD scenarios were selected in part because of the time period chosen (2020s or 2040s) and the climatic excursions happening within the climate projections during these periods. To explore this issue, consider the transient example, but smoothed through time using 10-year and 30 year moving means (Figure 35 and Figure 36, respectively). The 30-year period underlying 2040s HD scenario definition was 2030-2059. Now consider the selected LW/D 2040s HD scenario: this scenario is sampled from the same climate projection that underlies the Transient scenario labeled “echo-g” (see legend on Figure 35). Inspection of echo-g annual diversions during 2030-2059 reveals that a low-diversions decade happens roughly during the 2050s and relates to relatively dry conditions during this decade within this climate projection. Outside of this decade, the echo-g annual diversions track rather closely to the ensemble-median (e.g., 2000-2040). Thus it is fair to question whether the LW/D 2040s HD scenario is truly climate change, or perhaps a sampling of decadal climate variability from the echo-g projection.

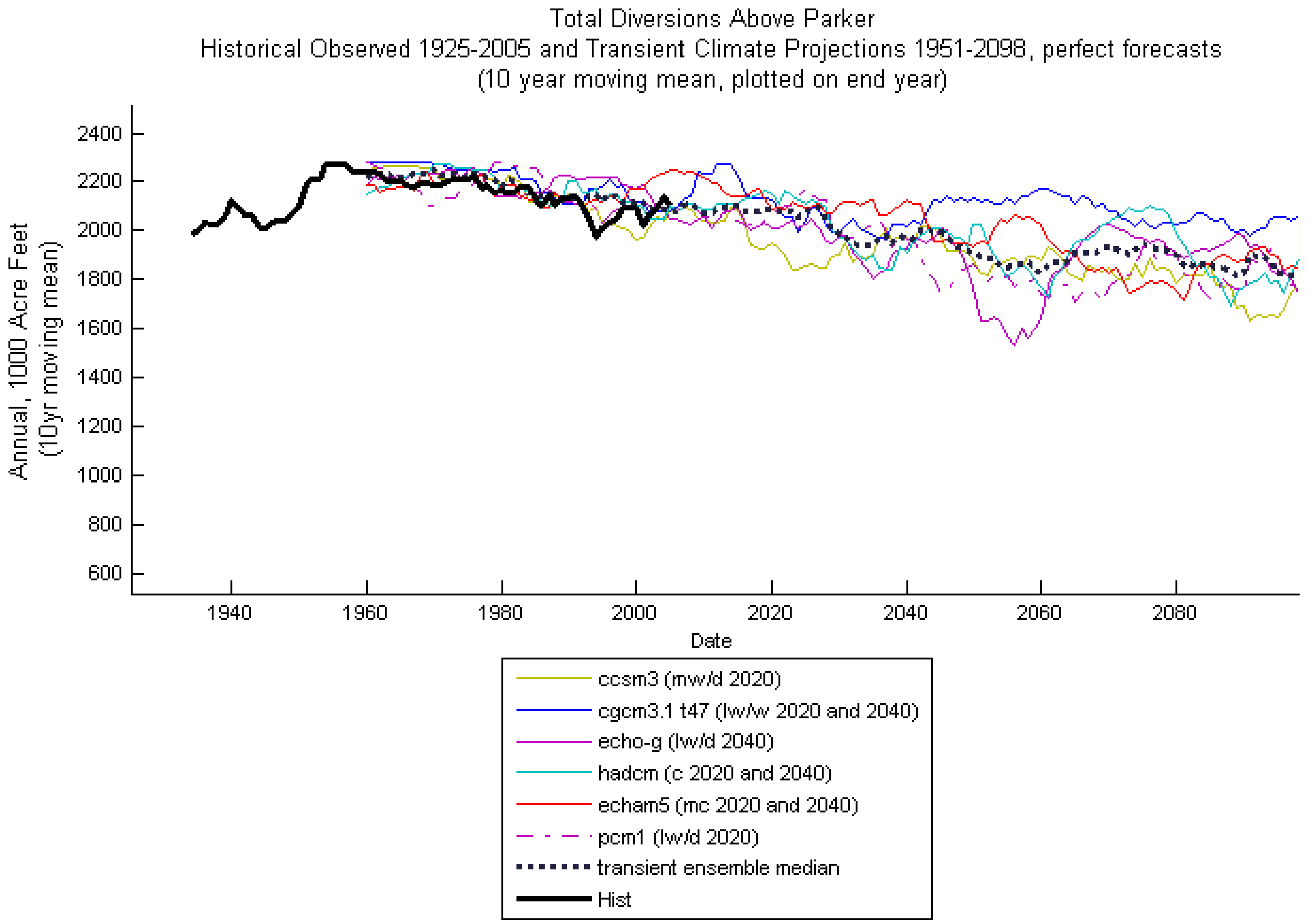

Figure 35. Yakima River subbasin – running 10-year mean-annual diversions above Parker, Historical and Transient climates.

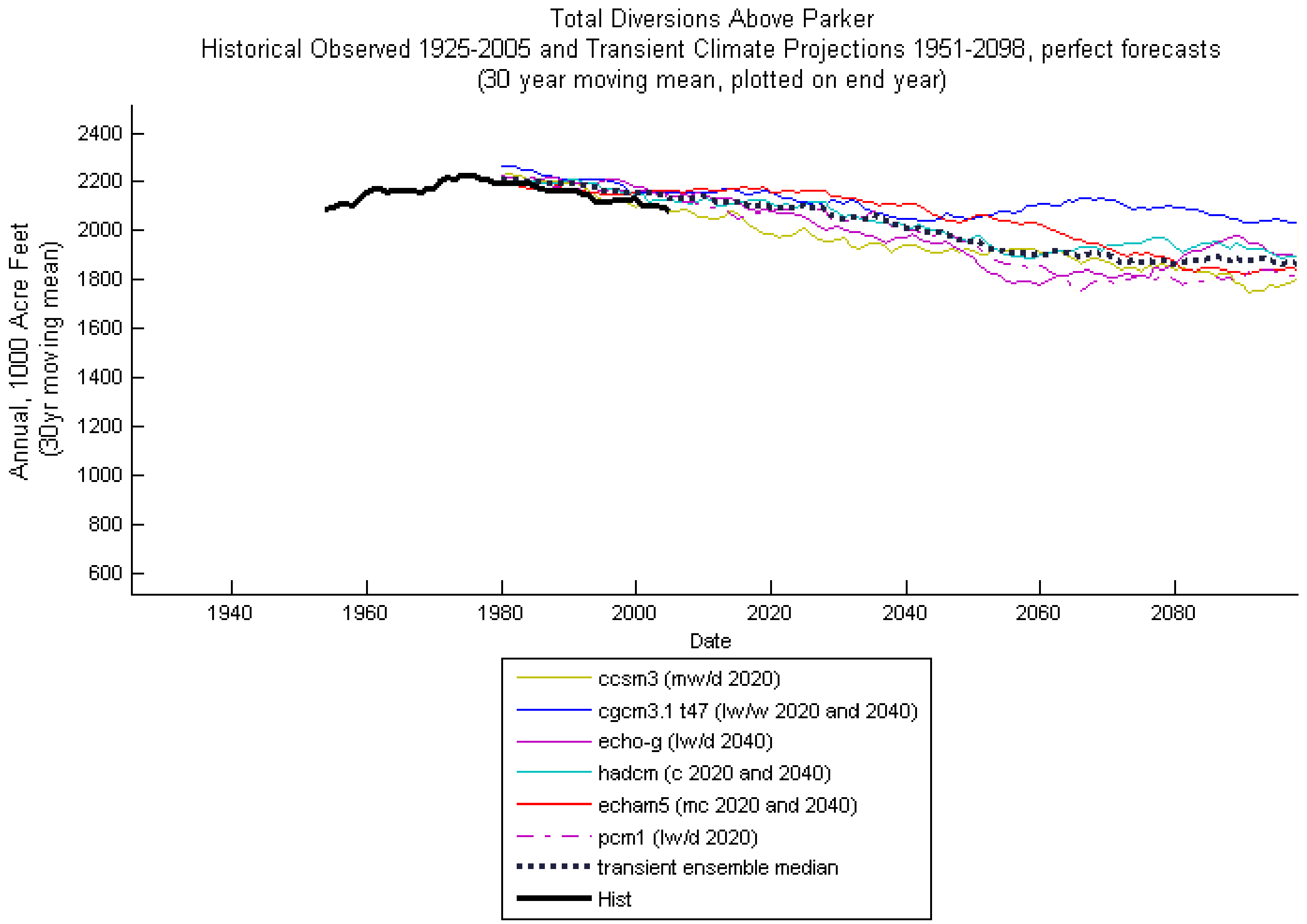

Figure 36. Yakima River subbasin – running 30-year mean-annual diversions above Parker, Historical and Transient climates.

One concern about misunderstanding the HD scenarios as being climate change only or misunderstood decadal to multidecadal variability stems from how the HD scenarios are used in subsequent hydrologic analysis. Recall that an HD climate change scenario reflects a change in 30-year monthly climate. This change is then superimposed on a 91-year envelope of historical weather variability to construct an adjusted 91-year envelop to create climate changed weather (Part I Report, Section 4). If the HD scenario actually reflects sampled multidecadal variability rather than climate change, then there is a risk of double-counting such variability if the base envelope of weather variability already includes multidecadal variability. If this is the case, then the operations variability portrayed by the pooling of HD scenarios (e.g., six HD 2040s climates) might offer an artificially broadened view of future operations uncertainty.

Review of YPM operations results suggests that this may be a possibility when using RMJOC HD scenarios, but it appears to be a minor concern. Keeping the focus on annual diversions above Parker, Figure 37 shows a pooling of Transient and HD results during the future HD periods (2010-2039 and 2030-2059): the top row of figure panels shows Transient information for these two periods (from Figure 34); the bottom row of figure panels shows the HD information (from Figure 14). The top panel features light-blue lines to highlight the 30-year maximum, minimum and median annual diversions when period results are pooled from the six transient simulations (i.e., n = 6 x 30 = 180 cases for computing these statistics). Those same statistics are indicated on the bottom panel (light-blue lines). Focusing on the bottom panel, the range of Transient annual extremes during this 30-year period is similar to the range indicated by the pooling of HD climate results. The range of extremes based on the HD climates is slightly broader in this comparison, which supports the concern described above. However, the extent that it is broader is minor and could be due to the Transient ensemble having few members and thus a smaller defined range.

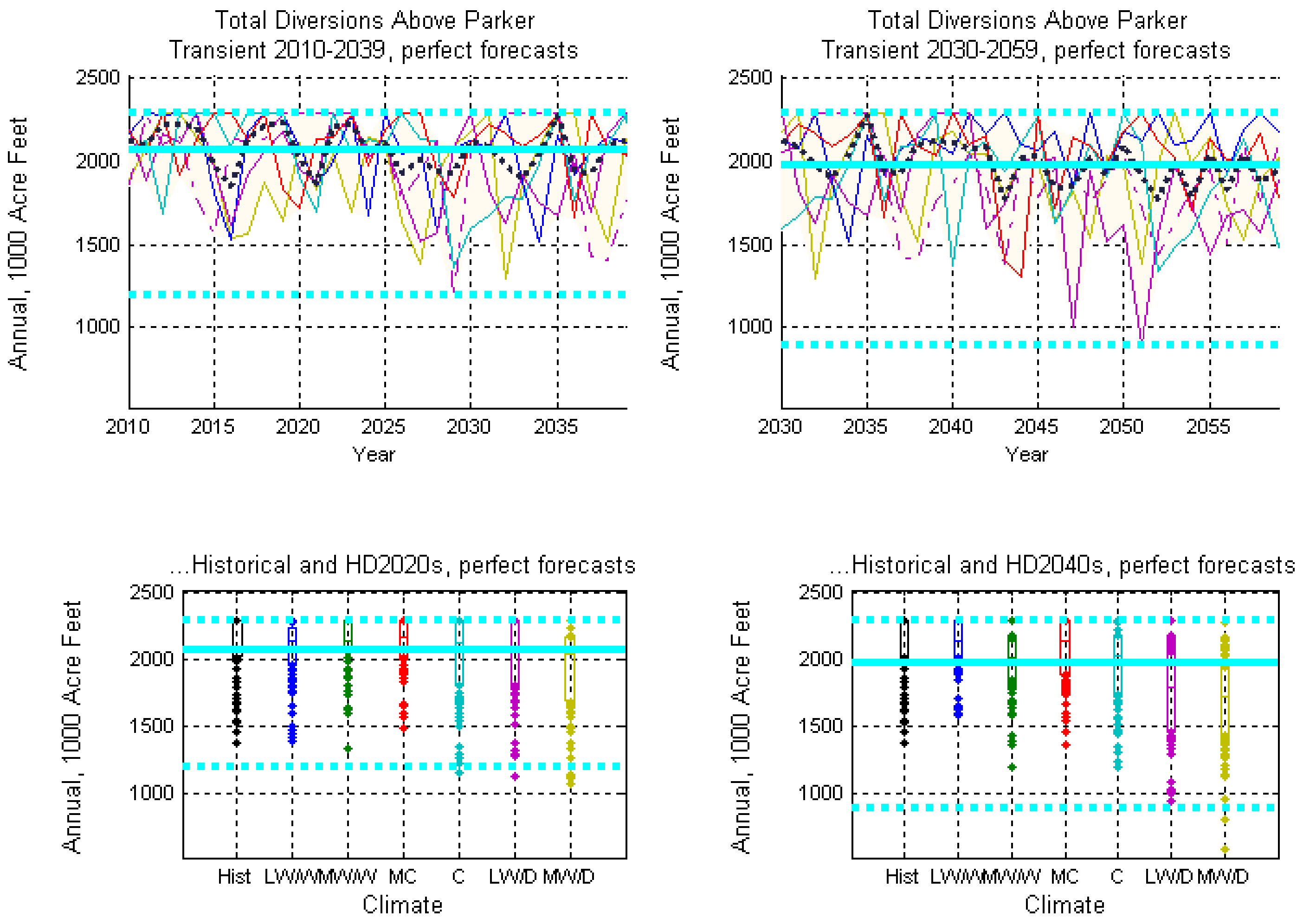

Figure 37. Yakima River subbasin – annual diversions variability above Parker, comparing HD Climates and Transient climates.

4.1.4 Summary

In summary, the three operations questions posed in this RMJOC effort might be answered for the Yakima River subbasin as follows:

1. *How do typical operating conditions vary across RMJOC climate scenarios?* Water supply conditions were found to have season-specific impacts under the future RMJOC HD climates, generally featuring increased cool-season inflow (during November through March) and decreased warm season inflow (during April through September). Season-specific changes in system inflow affect the assessment of TWSA during the months of March through September, which affects operating decisions related to river flow targets, water demand prorationing, and storage targets. For example, results show that March-September TWSA reductions lead 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) lead to corresponding changes in regulated flows. Switching attention to water deliveries, another consequence of March-September TWSA reductions is a reduction of water supply available for delivery to junior water users in the system. For both flow and delivery metrics, results vary considerably across future HD climates during a given period (2020s or 2040s), where more degree of change generally trends with the type of HD climate change (e.g., less warm-season flow or delivery reduction for the wetter HD climates, and more reduction for the drier climates). Lastly, the increase in cool-season system inflow and reduction in March-September TWSA leads to an increase in typical cool-season storage and a decrease during the warm-season and a decline in end of season storage, an indication of less manageable water in the subbasin.

2. *How does operational variability differ for the various RMJOC climate scenarios?* Operations variability was depicted in this section as envelopes of monthly or annual conditions that were simulated to occur under each climate scenario (Figure 23 through Figure 27). Qualitatively, the envelopes appear to be similar in breadth and distribution from climate to climate, meaning that the range of variability is similar. However, depending on the quality of the climate change (i.e., more or less warming, wetter or drier), the envelopes are shifted accordingly (e.g., shift towards reduced storage conditions for scenarios that involve drier conditions). This has implications for extremes, such as high-inflow months or droughts. Based on example results shown on Figure 23 through Figure 27, the shift in extreme monthly minimum or maximum conditions generally follows the shift in typical conditions (or median conditions). Thus, for scenarios involving drier conditions, not only would typical delivery and storage conditions be reduced, but drought year delivery and storage conditions would also be reduced relative to historical climate conditions.

3. *How does the portrayal of future operations depend on two analytical design choices*:

    a. *Type of water supply forecast?* It appears that Yakima River operations portrayals under the RMJOC HD climates are not very sensitive to use of *perfect* or *imperfect* PARW forecasts in operations simulation. This is could be due to a couple of reasons. First, the degree of climate change featured in the HD 2020s and HD 2040s climates may not be substantial enough to diminish snowpack to the point of causing enough impact on PARW (YAPAR) seasonal-runoff volume forecasting, TWSA assessment, and dependent operational decisions (at least during the period of March-May when PARW forecasts quality under HD 2020s and 2040s climates remains similar to historical). Second, the YPM 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 does 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* YAPAR water supply forecasts developed for these scenarios. It should be noted that another factor contributing to this impression is how the forecasts were used. An alternative way of using these regression models would be to also consider the model error characteristics and estimate a conservative PARW seasonal runoff volume.[16] Such conservative use of *imperfect* forecasts might lead to more substantial differences in portrayed operations, particularly those based on the relatively uncertain early issues (e.g., January and February issues of April-September PARW volume).

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[16] Note for YPM portrayal of operations possibilities, that this may not be the preferred approach, particularly with respect to the matter of simulating water shortage events. For example, if TWSA and prorationing were estimated this way in YPM, then the system would likely tend to have extra unused water at the end of the season. This is not favorably looked upon when farmers are experiencing water shortage hardships. The extra water could have been used to ease the negative impacts. We also do not want to over allocate the water either and come up short at the end of the season. In real-world scheduling of operations and making monthly updates to such schedules, early season issues may be based on more conservative usage of water supply forecasts. As the season progresses into July and August, scheduling tends to be based on a more risk-neutral use of water supply forecasts (e.g., 50 percent exceedence, meant to reflect a non-conservative best estimate).

   b. *Type of future climate scenario?* The HD and Transient information types offer fundamentally different portrayals of operation under future climate. The HD scenarios are useful for studies meant to reveal system operational sensitivity to incremental change in climate. The Transient Climate Projection data are useful for revealing time-developing climate and operational performance, which can be useful for adaptation planning where there is interest in the timing, onset, and intensification of impact. Based on comparison of Transient and HD operations results (those shown and not shown), the portrayal of typical operational conditions is similar under both operations types when the Transient results are viewed from an ensemble-median perspective and assessed during periods associated with HD climates. The Transient results differ from HD climates in that they also characterize the trend in operating conditions in a time-evolving fashion through periods that extend before and after a given HD scenario.

4.2 Deschutes River Subbasin

The three primary questions addressed in the Yakima River section were addressed for the Deschutes River as well. These primary questions are:

1. How do typical hydrologic conditions vary across RMJOC climate scenarios?
2. How does hydrologic variability differ for the various RMJOC climate scenarios?
3. How does the portrayal of future operations depend on two analytical design choices:
   a. Type of water supply forecast?
   b. Type of future climate scenario?

Each of these questions was addressed by metric rather than by question as, which was the approach in the Yakima River. Because the results for the impact of forecasting mode selection (i.e., *perfect* or *imperfect*) and distribution of data are similar regardless of metric, the forecasting results are addressed in the Inflow to the System metric only.

4.2.1 Metrics

4.2.1.1 Naturalized Model

Comparisons between the bias-corrected (BC) flow output from the VIC hydrologic model and the naturalized flow data that was provided to UW CIG by Reclamation were reported in the Part 1 Report, Section 4.4. As described in Subsection 4.4.3, BC was completed to match month-specific flow biases first, and then annual flow. However, the BC process did not result in a very close match to the Reclamation naturalized monthly time series runoff conditions. This poor calibration is in part due to the BC process, but may also be attributed to the VIC hydrologic model's inability to accurately simulate ground water and surface water interactions. With a system like the Deschutes River subbasin that is dominated by these interactions (Gannett et al. 2001), the resultant affect on the mass balance of the system generated by the VIC hydrologic model was an increase in flow of almost 3.5 percent over the entire period of record. This is further discussed in Section 4.2.2.1.

For the Naturalized Flow Deschutes Planning Model (DPM) simulations, comparisons of overall volumes at key locations between Reclamation observed naturalized historical data (i.e., Reclamation naturalized data) and CIG VIC simulated historical data (i.e., VIC simulated naturalized data) were made. These comparisons were made to:

1. Understand baseline differences in output between Reclamation naturalized flows and VIC simulated historical flows in the Naturalized Flows DPM

2. Understand the influence of disaggregating VIC inflow that was provided at a coarse scale into finer scale nodes in either DPM

3. Understand how the Naturalized Flows DPM might respond to significant changes in flow volumes in adjacent time steps and prepare the Modified Flows DPM input to account for these changes

4. Ensure that the volumes at each VIC location (12 total locations in the Deschutes River) and in total were similar to Reclamation volume at that same location and if not, document those differences

4.2.1.2 Modified Flow Model

For the Modified Flows DPM (i.e., the MODSIM model with reservoirs operating at 2010 reservoir protocols and irrigation demand) comparison, several metrics were used to evaluate the potential impact of HD climate change projections on the Deschutes River subbasin including system inflows to reservoir groups, flows at several key locations in the subbasin, surface water delivery,[17] and storage target levels. In addition, an analysis of potential impacts to the ability to operate to the current Biological Opinion (BiOp) objectives for each climate change projection was reported using a surrogate monthly approach for daily objectives in the BiOp. Transient results were not compared to Reclamation naturalized flows because variability in climate patterns (e.g., dry years in the Transient do not match dry years in the Reclamation naturalized dataset) is not retained in the Transient scenarios (Part 1 Report).

4.2.1.2.1 Inflow to the Deschutes River System

Total inflow to the Deschutes River system was determined for all major reservoirs up to and including Lake Billy Chinook, which is below the confluence of the Deschutes and Crooked rivers (Figure 38). Inflows are totaled for each reservoir group (i.e., those on the Crooked River, those on the upper Deschutes River, and then all major reservoirs up to and including Lake Billy Chinook) on a monthly time step and reported for the entire period of record. Inflow presented is a cumulative summation of reservoir inflow. So, the volume of inflow to each reservoir group is not the true summation of inflow to each individual reservoir, but a cumulative summation of inflow to all reservoirs in that reservoir group. This approach allows general trend comparison between the VIC simulated historical and simulated future climate projections. Comparison of the absolute value or volume for an individual reservoir is not appropriate.

Results on inflow to each tributary (i.e., upper Deschutes River and/or Crooked River) are reported only if noteworthy variations from the total inflow above Lake Billy Chinook are found. Inflow to Crane Prairie, Wickiup, and Crescent were summed on the upper Deschutes River and inflows were summed and reported for Prineville and Ochoco reservoirs on the Crooked River.

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[17] Impacts on future diversions as affected by climate change are difficult to determine. This difficulty is because the MODSIM model self-adjusts the diversion quantities to reflect past irrigation practices. MODSIM is programmed to change the diversion patterns based on historical diverter behavior. This hydrologic state reflects runoff conditions from very wet to very dry and is adjusted at every time step, which in turn causes diverter behavior to change based on that state at every time step.

One concern about misunderstanding the HD scenarios as being climate change only or misunderstood decadal to multidecadal variability stems from how the HD scenarios are used in subsequent hydrologic analysis. Recall that an HD climate change scenario reflects a change in 30-year monthly climate. This change is then superimposed on a 91-year envelope of historical weather variability to construct an adjusted 91-year envelop to create climate changed weather (Part I Report, Section 4). If the HD scenario actually reflects sampled multidecadal variability rather than climate change, then there is a risk of double-counting such variability if the base envelope of weather variability already includes multidecadal variability. If this is the case, then the operations variability portrayed by the pooling of HD scenarios (e.g., six HD 2040s climates) might offer an artificially broadened view of future operations uncertainty.

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[16] Note for YPM portrayal of operations possibilities, that this may not be the preferred approach, particularly with respect to the matter of simulating water shortage events. For example, if TWSA and prorationing were estimated this way in YPM, then the system would likely tend to have extra unused water at the end of the season. This is not favorably looked upon when farmers are experiencing water shortage hardships. The extra water could have been used to ease the negative impacts. We also do not want to over allocate the water either and come up short at the end of the season. In real-world scheduling of operations and making monthly updates to such schedules, early season issues may be based on more conservative usage of water supply forecasts. As the season progresses into July and August, scheduling tends to be based on a more risk-neutral use of water supply forecasts (e.g., 50 percent exceedence, meant to reflect a non-conservative best estimate).

  b. *Type of future climate scenario?* The HD and Transient information types offer fundamentally different portrayals of operation under future climate. The HD scenarios are useful for studies meant to reveal system operational sensitivity to incremental change in climate. The Transient Climate Projection data are useful for revealing time-developing climate and operational performance, which can be useful for adaptation planning where there is interest in the timing, onset, and intensification of impact. Based on comparison of Transient and HD operations results (those shown and not shown), the portrayal of typical operational conditions is similar under both operations types when the Transient results are viewed from an ensemble-median perspective and assessed during periods associated with HD climates. The Transient results differ from HD climates in that they also characterize the trend in operating conditions in a time-evolving fashion through periods that extend before and after a given HD scenario.

4.2 Deschutes River Subbasin

The three primary questions addressed in the Yakima River section were addressed for the Deschutes River as well. These primary questions are:

1. How do typical hydrologic conditions vary across RMJOC climate scenarios?
2. How does hydrologic variability differ for the various RMJOC climate scenarios?
3. How does the portrayal of future operations depend on two analytical design choices:
    a. Type of water supply forecast?
    b. Type of future climate scenario?

Each of these questions was addressed by metric rather than by question as, which was the approach in the Yakima River. Because the results for the impact of forecasting mode selection (i.e., *perfect* or *imperfect*) and distribution of data are similar regardless of metric, the forecasting results are addressed in the Inflow to the System metric only.

surface water delivery,[17] and storage target levels. In addition, an analysis of potential impacts to the ability to operate to the current Biological Opinion (BiOp) objectives for each climate change projection was reported using a surrogate monthly approach for daily objectives in the BiOp. Transient results were not compared to Reclamation naturalized flows because variability in climate patterns (e.g., dry years in the Transient do not match dry years in the Reclamation naturalized dataset) is not retained in the Transient scenarios (Part 1 Report).

4.2.1.2.1 Inflow to the Deschutes River System

Total inflow to the Deschutes River system was determined for all major reservoirs up to and including Lake Billy Chinook, which is below the confluence of the Deschutes and Crooked rivers (Figure 38). Inflows are totaled for each reservoir group (i.e., those on the Crooked River, those on the upper Deschutes River, and then all major reservoirs up to and including Lake Billy Chinook) on a monthly time step and reported for the entire period of record. Inflow presented is a cumulative summation of reservoir inflow. So, the volume of inflow to each reservoir group is not the true summation of inflow to each individual reservoir, but a cumulative summation of inflow to all reservoirs in that reservoir group. This approach allows general trend comparison between the VIC simulated historical and simulated future climate projections. Comparison of the absolute value or volume for an individual reservoir is not appropriate.

Results on inflow to each tributary (i.e., upper Deschutes River and/or Crooked River) are reported only if noteworthy variations from the total inflow above Lake Billy Chinook are found. Inflow to Crane Prairie, Wickiup, and Crescent were summed on the upper Deschutes River and inflows were summed and reported for Prineville and Ochoco reservoirs on the Crooked River.

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[17] Impacts on future diversions as affected by climate change are difficult to determine. This difficulty is because the MODSIM model self-adjusts the diversion quantities to reflect past irrigation practices. MODSIM is programmed to change the diversion patterns based on historical diverter behavior. This hydrologic state reflects runoff conditions from very wet to very dry and is adjusted at every time step, which in turn causes diverter behavior to change based on that state at every time step.

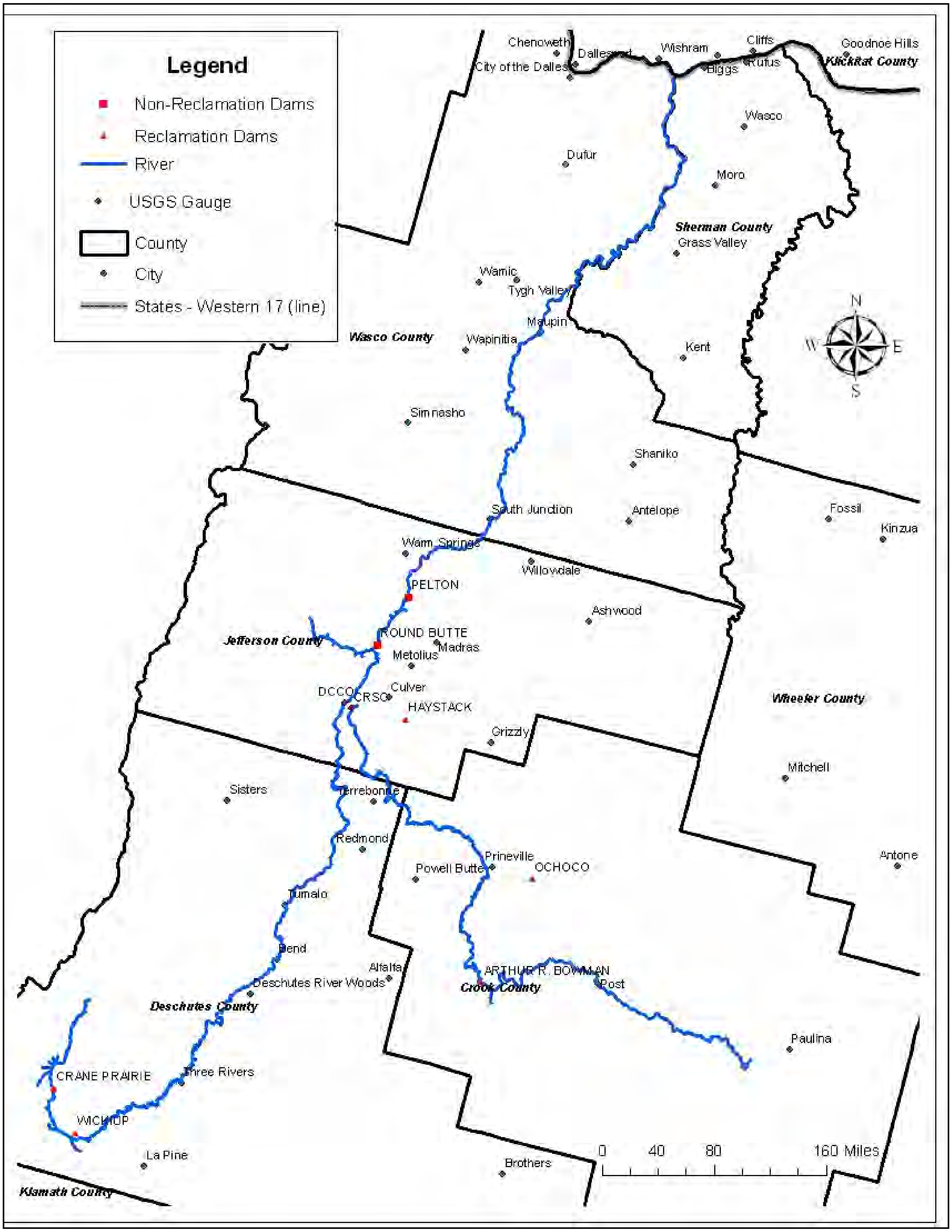

Figure 38. Deschutes River subbasin gage and reservoir locations.

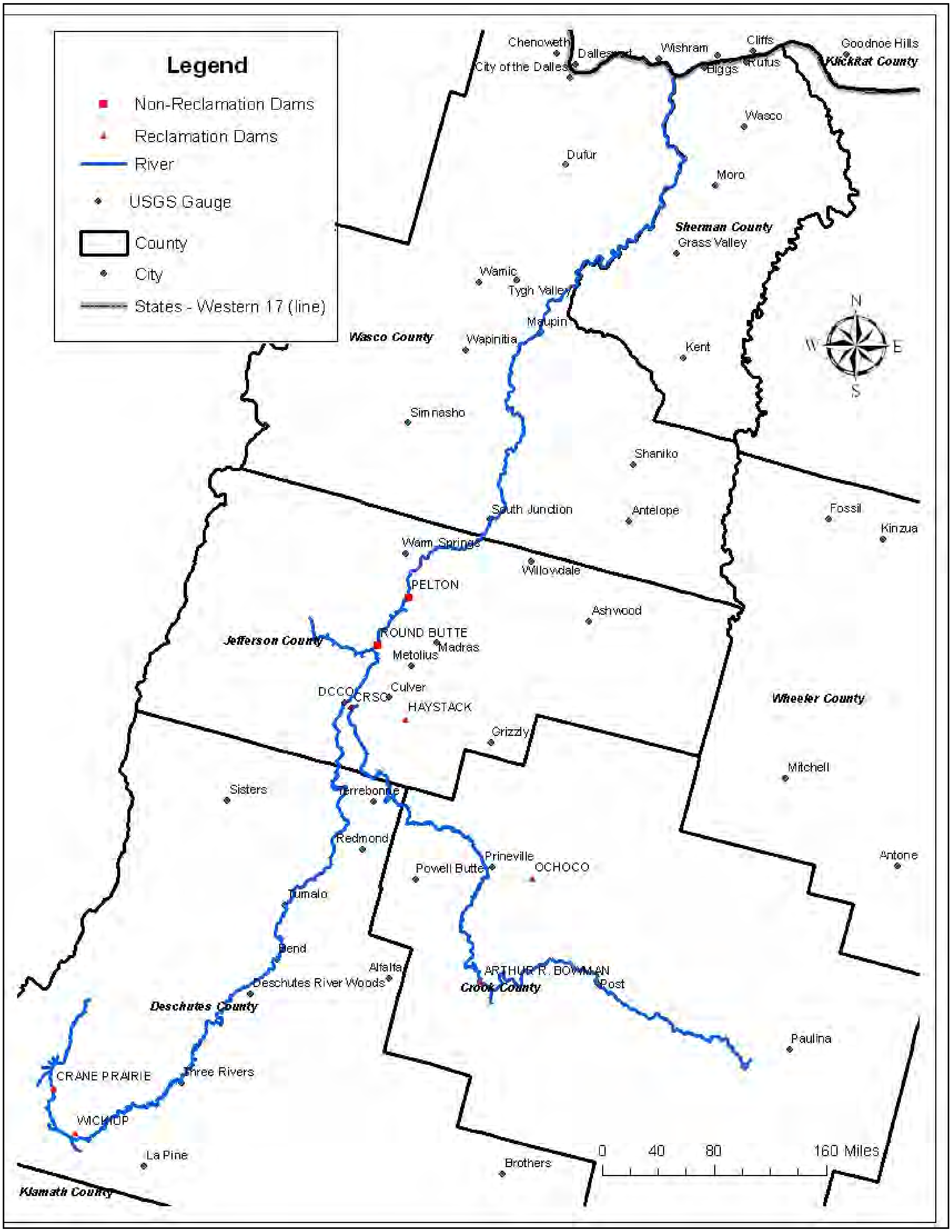

Figure 38. Deschutes River subbasin gage and reservoir locations.

One concern about misunderstanding the HD scenarios as being climate change only or misunderstood decadal to multidecadal variability stems from how the HD scenarios are used in subsequent hydrologic analysis. Recall that an HD climate change scenario reflects a change in 30-year monthly climate. This change is then superimposed on a 91-year envelope of historical weather variability to construct an adjusted 91-year envelop to create climate changed weather (Part I Report, Section 4). If the HD scenario actually reflects sampled multidecadal variability rather than climate change, then there is a risk of double-counting such variability if the base envelope of weather variability already includes multidecadal variability. If this is the case, then the operations variability portrayed by the pooling of HD scenarios (e.g., six HD 2040s climates) might offer an artificially broadened view of future operations uncertainty.

Review of YPM operations results suggests that this may be a possibility when using RMJOC HD scenarios, but it appears to be a minor concern. Keeping the focus on annual diversions above Parker, Figure 37 shows a pooling of Transient and HD results during the future HD periods (2010-2039 and 2030-2059): the top row of figure panels shows Transient information for these two periods (from Figure 34); the bottom row of figure panels shows the HD information (from Figure 14). The top panel features light-blue lines to highlight the 30-year maximum, minimum and median annual diversions when period results are pooled from the six transient simulations (i.e., n = 6 x 30 = 180 cases for computing these statistics). Those same statistics are indicated on the bottom panel (light-blue lines). Focusing on the bottom panel, the range of Transient annual extremes during this 30-year period is similar to the range indicated by the pooling of HD climate results. The range of extremes based on the HD climates is slightly broader in this comparison, which supports the concern described above. However, the extent that it is broader is minor and could be due to the Transient ensemble having few members and thus a smaller defined range.

4.1.4 Summary

In summary, the three operations questions posed in this RMJOC effort might be answered for the Yakima River subbasin as follows:

1. *How do typical operating conditions vary across RMJOC climate scenarios?* Water supply conditions were found to have season-specific impacts under the future RMJOC HD climates, generally featuring increased cool-season inflow (during November through March) and decreased warm season inflow (during April through September). Season-specific changes in system inflow affect the assessment of TWSA during the months of March through September, which affects operating decisions related to river flow targets, water demand prorationing, and storage targets. For example, results show that March-September TWSA reductions lead 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) lead to corresponding changes in regulated flows. Switching attention to water deliveries, another consequence of March-September TWSA reductions is a reduction of water supply available for delivery to junior water users in the system. For both flow and delivery metrics, results vary considerably across future HD climates during a given period (2020s or 2040s), where more degree of change generally trends with the type of HD climate change (e.g., less warm-season flow or delivery reduction for the wetter HD climates, and more reduction for the drier climates). Lastly, the increase in cool-season system inflow and reduction in March-September TWSA leads to an increase in typical cool-season storage and a decrease during the warm-season and a decline in end of season storage, an indication of less manageable water in the subbasin.

2. *How does operational variability differ for the various RMJOC climate scenarios?* Operations variability was depicted in this section as envelopes of monthly or annual conditions that were simulated to occur under each climate scenario (Figure 23 through Figure 27). Qualitatively, the envelopes appear to be similar in breadth and distribution from climate to climate, meaning that the range of variability is similar. However, depending on the quality of the climate change (i.e., more or less warming, wetter or drier), the envelopes are shifted accordingly (e.g., shift towards reduced storage conditions for scenarios that involve drier conditions). This has implications for extremes, such as high-inflow months or droughts. Based on example results shown on Figure 23 through Figure 27, the shift in extreme monthly minimum or maximum conditions generally follows the shift in typical conditions (or median conditions). Thus, for scenarios involving drier conditions, not only would typical delivery and storage conditions be reduced, but drought year delivery and storage conditions would also be reduced relative to historical climate conditions.

   b. *Type of future climate scenario?* The HD and Transient information types offer fundamentally different portrayals of operation under future climate. The HD scenarios are useful for studies meant to reveal system operational sensitivity to incremental change in climate. The Transient Climate Projection data are useful for revealing time-developing climate and operational performance, which can be useful for adaptation planning where there is interest in the timing, onset, and intensification of impact. Based on comparison of Transient and HD operations results (those shown and not shown), the portrayal of typical operational conditions is similar under both operations types when the Transient results are viewed from an ensemble-median perspective and assessed during periods associated with HD climates. The Transient results differ from HD climates in that they also characterize the trend in operating conditions in a time-evolving fashion through periods that extend before and after a given HD scenario.

4.2 Deschutes River Subbasin

The three primary questions addressed in the Yakima River section were addressed for the Deschutes River as well. These primary questions are:

1. How do typical hydrologic conditions vary across RMJOC climate scenarios?
2. How does hydrologic variability differ for the various RMJOC climate scenarios?
3. How does the portrayal of future operations depend on two analytical design choices:
    a. Type of water supply forecast?
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Each of these questions was addressed by metric rather than by question as, which was the approach in the Yakima River. Because the results for the impact of forecasting mode selection (i.e., *perfect* or *imperfect*) and distribution of data are similar regardless of metric, the forecasting results are addressed in the Inflow to the System metric only.

4.2.1 Metrics

4.2.1.1 Naturalized Model

Comparisons between the bias-corrected (BC) flow output from the VIC hydrologic model and the naturalized flow data that was provided to UW CIG by Reclamation were reported in the Part 1 Report, Section 4.4. As described in Subsection 4.4.3, BC was completed to match month-specific flow biases first, and then annual flow. However, the BC process did not result in a very close match to the Reclamation naturalized monthly time series runoff conditions. This poor calibration is in part due to the BC process, but may also be attributed to the VIC hydrologic model's inability to accurately simulate ground water and surface water interactions. With a system like the Deschutes River subbasin that is dominated by these interactions (Gannett et al. 2001), the resultant affect on the mass balance of the system generated by the VIC hydrologic model was an increase in flow of almost 3.5 percent over the entire period of record. This is further discussed in Section 4.2.2.1.

For the Naturalized Flow Deschutes Planning Model (DPM) simulations, comparisons of overall volumes at key locations between Reclamation observed naturalized historical data (i.e., Reclamation naturalized data) and CIG VIC simulated historical data (i.e., VIC simulated naturalized data) were made. These comparisons were made to:

1. Understand baseline differences in output between Reclamation naturalized flows and VIC simulated historical flows in the Naturalized Flows DPM

2. Understand the influence of disaggregating VIC inflow that was provided at a coarse scale into finer scale nodes in either DPM

3. Understand how the Naturalized Flows DPM might respond to significant changes in flow volumes in adjacent time steps and prepare the Modified Flows DPM input to account for these changes

4. Ensure that the volumes at each VIC location (12 total locations in the Deschutes River) and in total were similar to Reclamation volume at that same location and if not, document those differences

4.2.1.2 Modified Flow Model

For the Modified Flows DPM (i.e., the MODSIM model with reservoirs operating at 2010 reservoir protocols and irrigation demand) comparison, several metrics were used to evaluate the potential impact of HD climate change projections on the Deschutes River subbasin including system inflows to reservoir groups, flows at several key locations in the subbasin,

4.2.1.2.2 End-of-Month Storage at Major Reservoirs

As with inflows, end-of-month storage was determined for the total system that includes Lake Billy Chinook (534 KAF) as well as at the three major reservoirs (Figure 38) on the upper Deschutes River (total available storage capacity of 342,200 acre-feet), and two on the Crooked River (total available capacity of 187,633 acre-feet). These results reflect possible impacts on irrigation and potential flooding. Figures are provided on the tributary results when they vary from the subbasin trends.

4.2.1.2.3 Flow at Key Locations in the River Subbasin

Key locations evaluated for flow were current U.S. Geological Survey (USGS) gage locations including the Deschutes River near Culver, Oregon (DCCO) and the Crooked River below Opal Springs near Culver, Oregon (CSRO). They are also the two gage locations selected for ESA objectives in the Modified Flows DPM (Section 4.3.1.2.6).

4.2.1.2.4 Surface Water Delivered

Surface water delivered to major diversions was summed on the upper Deschutes River, separately on the Crooked River, and then in total for the entire Deschutes River. This metric can be used to compare the volume of water that will be delivered to users in the future as compared to current (2010) conditions. Major diversions on the upper Deschutes River include Lone Pine (1900 water right), Swalley (1899), Arnold (1905), COID (1900 and 1907), and Walker (1897, 1900, and 1902). The Crooked River Pumping Plan, owned by the North Unit Irrigation District (1939), is on the Crooked River and shown as “NU diversion” in the lower right corner of Figure 39. Figure 5 also provided a geographic view of the major irrigation districts.

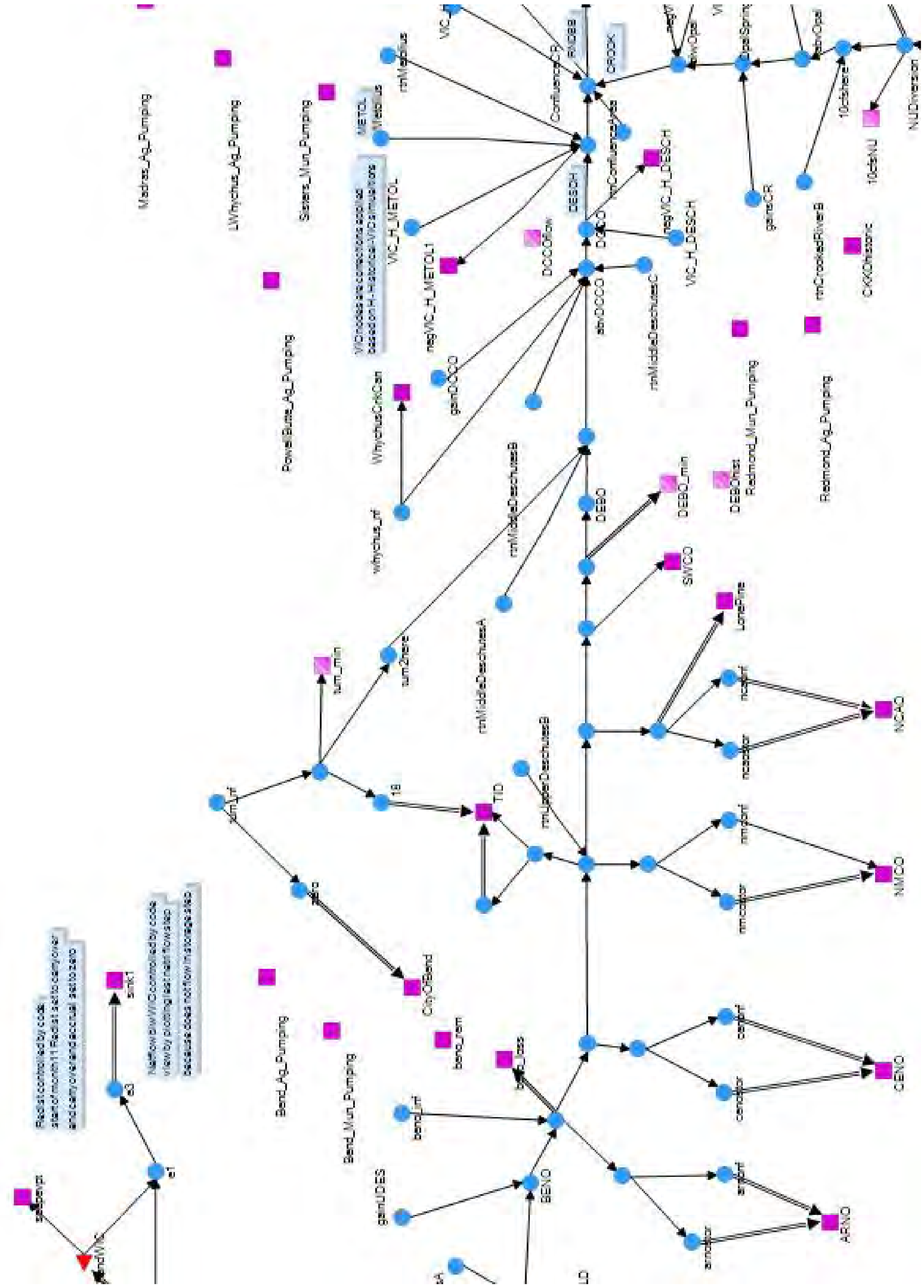


Figure 39. Locations of major diversions on the upper Deschutes River and on the Crooked River in the Deschutes Modified Flow Model.

While water supply is the only major parameter that is adjusted in this study, some built-in or hard-coded metrics in the Modified Flows DPM are such that other metrics change automatically based on that varying water supply. The Modified Flows DPM uses hydrologic states to signal the use of different demand patterns for major diversions on the river. These demand patterns are based on historical observations on how water users have behaved in the past, including during drought periods or extremely wet conditions. For irrigation demands, farmers typically adjust crop type, water use, and even irrigation methods (flood irrigation versus sprinkler) when drought conditions prevail. This adjustment is typically reflected in the amount of water consumed and the timing of that demand. These hard-coded demand patterns are based on historical observed demand patterns and will need to be adjusted in future climate change studies such that they are based on potential future diversion patterns.

Diversion volumes vary by month (La Marche 2001) and by individual diverter. Because the scale of this study was not such that individual diversions could be confidently evaluated, overall patterns were reported.

4.2.1.2.5 ESA Environmental Objectives

Several federally-listed ESA species exist in the Deschutes River subbasin. In 2005, a Biological Assessment was completed by Reclamation in which terrestrial, aerial, and aquatic species were considered. For the purposes of this study, only potential impacts to aquatic species were considered using VIC simulated historical and future climate change scenarios. In 2005, the NOAA Fisheries Service completed a BiOp on the operation and maintenance (O&M) of Reclamation projects in the Deschutes River subbasin, including an Incidental Take Statement to minimize take of Mid-Columbia steelhead. The Incidental Take Statement requires one of the following be true from October 1 through November 15:

1. 7-day moving average flow for the Crooked River below Opal Springs (CROO QD7), which is a Reclamation Hydromet gauge must be greater than or equal to 1,200 cfs

2. 7-day moving average for a combined flow of the Deschutes River near Culver gage (CULO) plus Crooked River below Opal Springs (CROO) must be greater than or equal to 1680 cfs. This combined flow is listed on the Reclamation Hydromet system as CULVER QD7

3. If neither 1 nor 2 are true, then the average Bowman Dam release (PRVO QD) must be greater than or equal to 215 cfs

Because the Modified Flows DPM is a monthly time step model and flow data provided for the study are in monthly units, the flow value for the month of October was evaluated instead of the required daily moving average in the Incidental Take Statement. In addition, the gages used to address the BiOp as described above are USGS gages and do not correspond directly to the node location or nomenclature in the Modified Flows DPM. Therefore, the corresponding MODSIM link in the Modified Flows DPM used to evaluate this flow are as follows:

1. For the first requirement, the link CRSO on the Crooked River was used to evaluated the flow at the CROO gage with a surrogate volume of 73,785 acre-feet per month for the month of October

2. For the second requirement above, the link DCCO on the Deschutes River was used to evaluate the flow for the CULO gage. The summation of the DCCO and CRSO gages were used to evaluate the Biological Assessment objective with a surrogate volume of 103,299 acre-feet per month for the month of October

3. For the Bowman Dam release, the PRVO link was used with a surrogate volume of 13,220 acre-feet per month used for this analysis

Results are reported using a monthly time step. The results may indicate trends or potential issues in the future based on the climate change projections under consideration in this study. However, the scale of the analysis does not enable a full understanding of Reclamation’s ability to meet the BiOp requirements in the future.

4.2.2 Results

4.2.2.1 Naturalized Model Results

Results from the Naturalized Flows DPM simulations indicated that while bias-corrected VIC annual mean data for the period of record correlated well with Reclamation naturalized annual mean (reported in Part I), the volume on a monthly basis did not. This had an impact on model stability and output.

In Table 5, the average monthly volumes near Lake Billy Chinook are shown. On an average monthly basis, VIC simulated naturalized flow volume was overestimated by almost 3.5 percent for the entire period of record when compared to Reclamation naturalized flow volume. Overestimates on a monthly average varied from almost 2 percent in May to less than 4.5 percent in August and November.

Table 5. Differences between period average monthly VIC-historical simulated data and Reclamation historical observed data in the Deschutes River subbasin above Lake Billy Chinook.

	Data		
Month	**Average of Reclamation Observed Historical Model Results**	**Average of VIC Simulated Historical Model Results**	**Percent different**
Jan	277,250	288,592	4.09%
Feb	285,566	297,237	4.09%
Mar	334,700	346,606	3.56%
Apr	344,332	354,330	2.90%
May	344,772	350,455	1.65%
Jun	311,042	318,495	2.40%
Jul	272,505	283,100	3.89%
Aug	249,430	259,977	4.23%
Sep	243,189	252,733	3.92%
Oct	249,363	257,807	3.39%
Nov	238,665	248,858	4.27%
Dec	263,482	274,199	4.07%
Grand Total Volume	3,414,296	3,532,389	3.46%

On an annual basis, the variation between the two datasets varied considerably in some years as well. Figure 40 shows the largest change in annual volume occurred in 1995 with over 30 percent more volume in the VIC naturalized data than in the Reclamation naturalized data. In several years, annual average flow volume were more than 10 percent less in the VIC simulated naturalized data than in the Reclamation naturalized data. Overall, increases in volume averaged almost 10 percent for the period of record and decreases in volume averaged almost 5 percent.

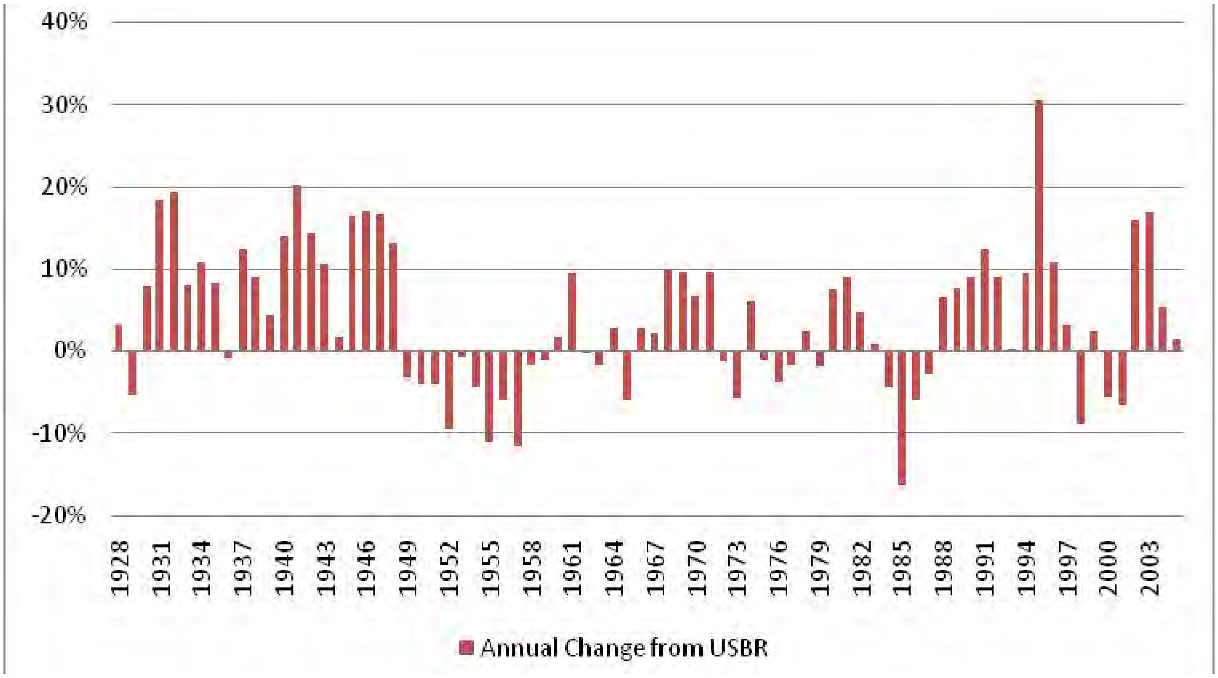


Figure 40. Percent annual change in flow volume from USBR historical observed data at Lake Billy Chinook on the Deschutes River.

These significant changes in volume on an annual average and period monthly basis affected the model in a number of ways. When changes in adjacent monthly time steps varied greatly, model stability (or the model's ability to converge to a reasonable solution) was an issue. This instability resulted in greater use of the local_gains and local_losses described in Section 3.2.2.3 to reduce the large swings in volume between adjacent time steps. While direct comparisons can be made between VIC simulated naturalized or modified flow model results and VIC simulated future naturalized or modified model results, caution must be used when making direct comparisons to Reclamation modeling results (in either the naturalized or the modified flow models).

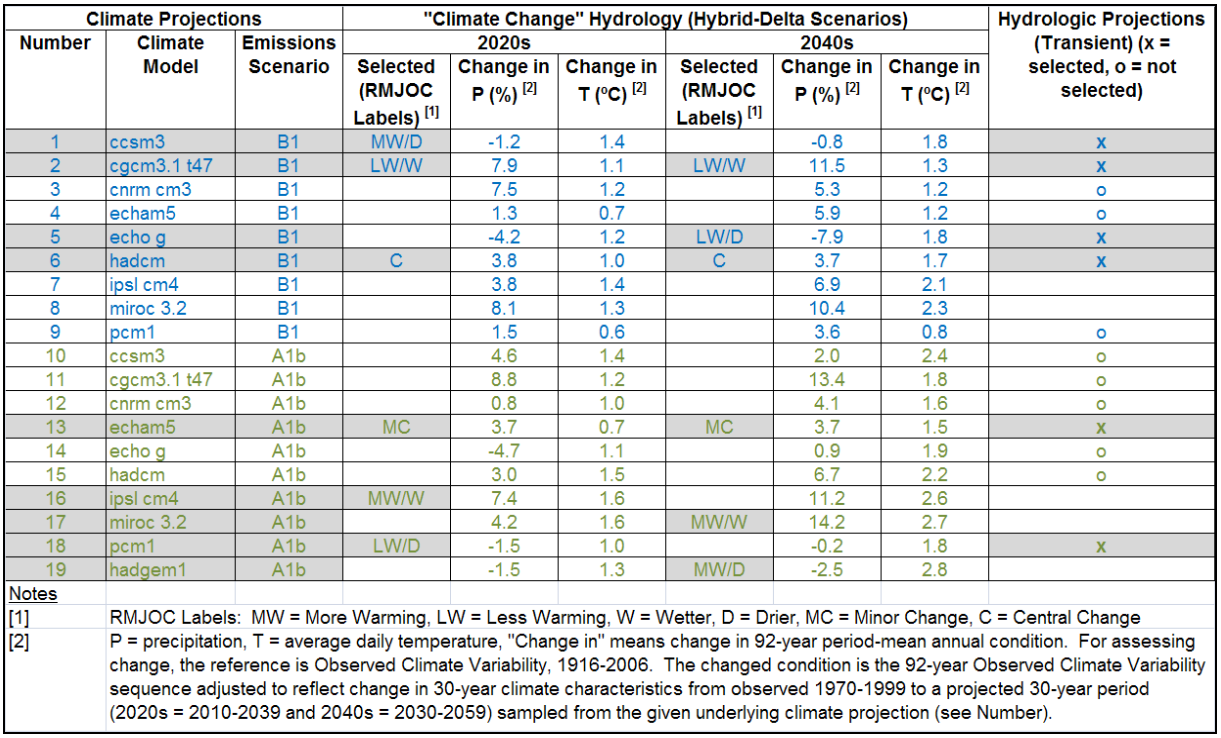
The possible reason for differences in volumes varies. The VIC hydrologic model used by UW CIG to develop the flows is unable to accurately simulate flow in subbasins that are heavily influenced by ground water. Because the Deschutes River flow is heavily impacted by ground water flows (Gannett et al. 2001), the VIC hydrologic model may not be the best model for this subbasin.

The BC approach may also have an impact on the flow results (described in Part 1, Section 4.4). While BC was focused on calibrating the annual and the monthly averages, it poorly calibrated with the monthly time series. It may be necessary to recalibrate the VIC hydrologic model or use another hydrologic model other than VIC in subbasins where ground water has such a large influence rather than depend on the BC process.

4.2.2.2 Modified Flow Model Results

Results from the metrics used to evaluate potential impacts on Reclamation operations using the Modified Flows DPM due to climate change are summarized in the following sections. All three questions posed earlier are addressed for each metric and an overall summary of the results is presented at the end of the Deschutes River section. Table 6 (extracted from the Part I Report, Section 3.0) lists the climate change models selected for evaluation in this study at the Columbia River Basin scale. The numbers on the left side of the table were assigned to each climate model and used in the plots on the following pages (Figure 41 and Figure 42) to illustrate comparisons of climate model results against other climate models at the subbasin scale in the Columbia River Basin.

Table 6. List of UW CIG HB2860 climate projections and Hybrid-Delta and Transient climate change scenarios.



Climate Projections			"Climate Change" Hydrology (Hybrid-Delta Scenarios)						Hydrologic Projections (Transient) (x = selected, o = not selected)
			2020s			2040s			
Number	Climate Model	Emissions Scenario	Selected (RMJOC Labels) [1]	Change in P (%) [2]	Change in T (°C) [2]	Selected (RMJOC Labels) [1]	Change in P (%) [2]	Change in T (°C) [2]	
1	ccsm3	B1	MW/D	-1.2	1.4		-0.8	1.8	x
2	cgcm3.1 t47	B1	LW/W	7.9	1.1	LW/W	11.5	1.3	x
3	cnrm cm3	B1		7.5	1.2		5.3	1.2	o
4	echam5	B1		1.3	0.7		5.9	1.2	o
5	echo g	B1		-4.2	1.2	LW/D	-7.9	1.8	x
6	hadcm	B1	C	3.8	1.0	C	3.7	1.7	x
7	ipsl cm4	B1		3.8	1.4		6.9	2.1	
8	miroc 3.2	B1		8.1	1.3		10.4	2.3	
9	pcm1	B1		1.5	0.6		3.6	0.8	o
10	ccsm3	A1b		4.6	1.4		2.0	2.4	o
11	cgcm3.1 t47	A1b		8.8	1.2		13.4	1.8	o
12	cnrm cm3	A1b		0.8	1.0		4.1	1.6	o
13	echam5	A1b	MC	3.7	0.7	MC	3.7	1.5	x
14	echo g	A1b		-4.7	1.1		0.9	1.9	o
15	hadcm	A1b		3.0	1.5		6.7	2.2	o
16	ipsl cm4	A1b	MW/W	7.4	1.6		11.2	2.6	
17	miroc 3.2	A1b		4.2	1.6	MW/W	14.2	2.7	
18	pcm1	A1b	LW/D	-1.5	1.0		-0.2	1.8	x
19	hadgem1	A1b		-1.5	1.3	MW/D	-2.5	2.8	

Notes

[1] RMJOC Labels: MW = More Warming, LW = Less Warming, W = Wetter, D = Drier, MC = Minor Change, C = Central Change

[2] P = precipitation, T = average daily temperature, "Change in" means change in 92-year period-mean annual condition. For assessing change, the reference is Observed Climate Variability, 1916-2006. The changed condition is the 92-year Observed Climate Variability sequence adjusted to reflect change in 30-year climate characteristics from observed 1970-1999 to a projected 30-year period (2020s = 2010-2039 and 2040s = 2030-2059) sampled from the given underlying climate projection (see Number).

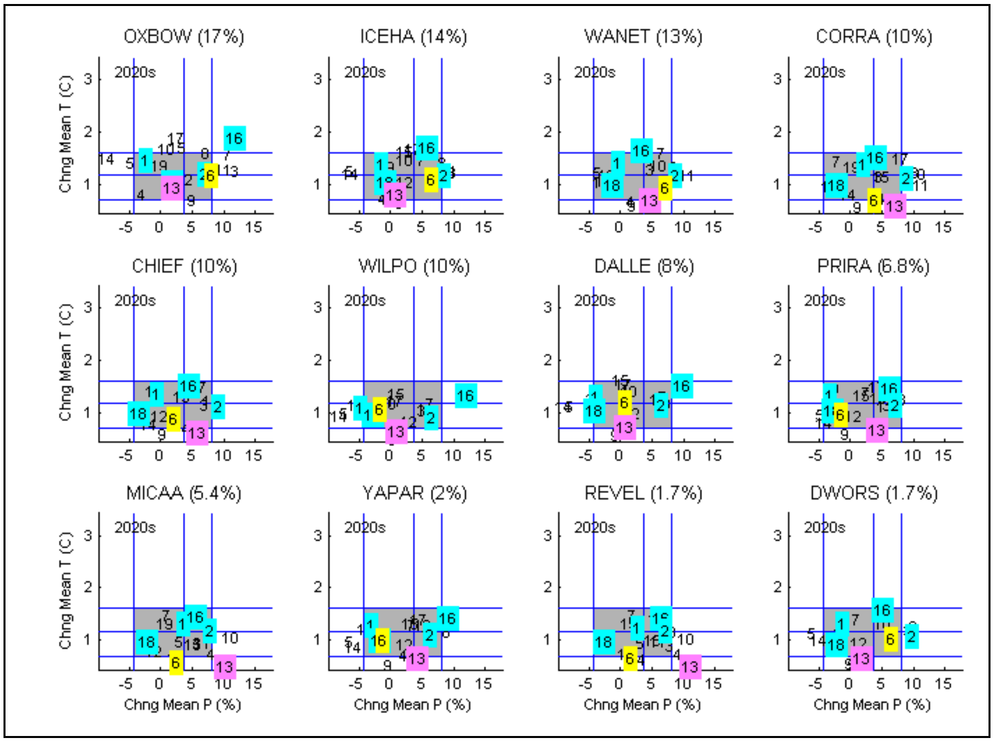


Figure 41. Spread of HD 2020 changes by subbasin (number colors represent global climate model shown in Table 5).

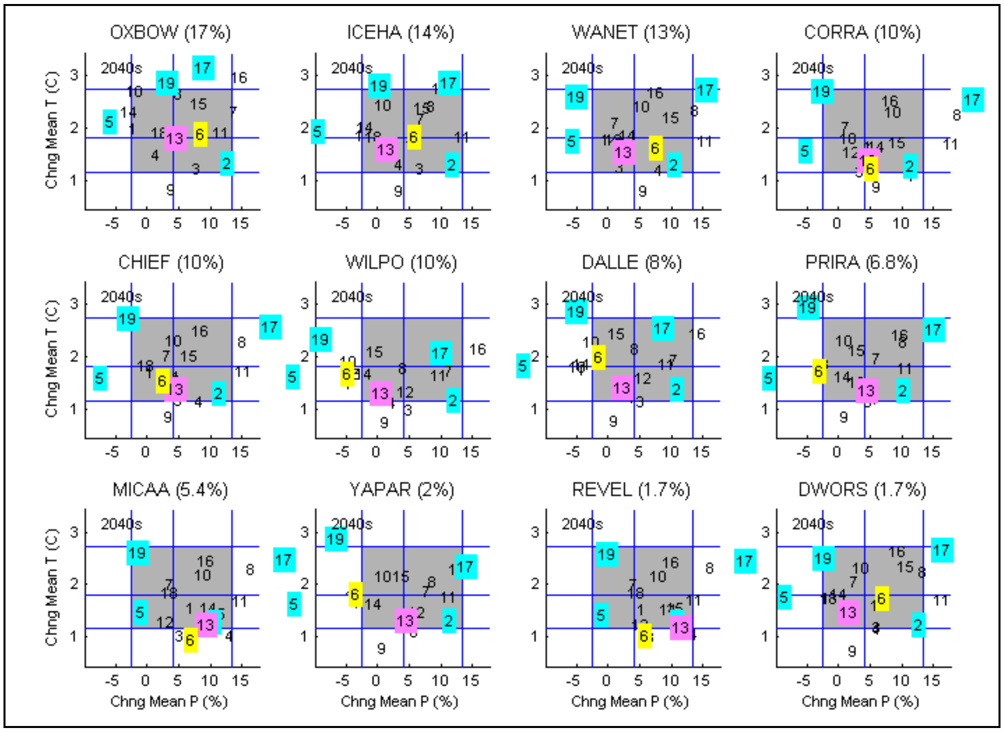


Figure 42. Spread of HD 2040 changes by subbasin.

As shown in Figure 41, the MW/W projection is the wettest GCM scenario used for HD2020 in the Dalles River subbasin (of which the Deschutes River subbasin is part), indicating a 10 percent increase in mean annual precipitation and an almost 1.5 degree Celsius (˚C) increase in mean annual temperature (#16 in the DALLE plot corresponding to "ipsl_cm4" in Table 6). In that same figure, the MW/D projection (#1) was the driest climate used in the HD 2020 scenario, indicating a 5 percent decrease in mean annual precipitation and slightly more than a 1˚C increase in mean annual temperature in the Dalles River subbasin.

In Figure 42, MW/W climate had higher mean annual temperature increases than did the LW/W climate, but the LW/W climate (#2 in the DALLE plot) had over a 10 percent increase in mean annual precipitation whereas the MW/W climate (#17) only suggested about a 7 or 8 percent increase. As described in the Part 1 Report Section 3.0, precipitation increases tended to have a greater influence on projections than did temperature changes. HD 2040 LW/D climate (#5) was the driest GCM model, indicating more than a 10 percent decrease in mean precipitation and a nearly a 2˚C increase in mean temperature for the Dalles River subbasin.

4.2.2.2.1 Inflow to System

Inflow results for each tributary (i.e. upper Deschutes River and/or Crooked River) were reported only if noteworthy variations from the total inflow above Lake Billy Chinook were found. Inflow to Crane Prairie, Wickiup, and Crescent reservoirs were summed on the upper Deschutes River (cumulative inflow for all three reservoirs) and inflows were summed and reported for Prineville and Ochoco reservoirs on the Crooked River (cumulative).

4.2.2.2.1.1 Typical Conditions and Variability

Monthly median total and change in median inflow into Lake Billy Chinook, upper Deschutes River summed for Crane Prairie, Wickiup, and Crescent Lake, and to the Crooked River summed for Ochoco and Prineville were plotted for the HD 2020 and HD 2040 climate change scenarios (Figure 43, Figure 44, and Figure 45). The peak inflow in the historical condition (black line in top panels) occurs in April in both HD scenarios. Peak timing of the inflow for the climate change projects appears to shift by one month earlier to March in all climate projections in both scenarios. In addition to the peak inflow timing occurring one month earlier, the volume of the inflow also changes. During the wetter winter months, inflow volume is much higher than in historical conditions in all but the LW/D projection in the HD 2040 scenario. However, during the summer months, lower inflow volumes are found to occur. For example, a maximum decrease of approximately 15 percent in the HD 2020 and 30 percent in the HD 2040 scenario is anticipated in the MW/D projection in June.

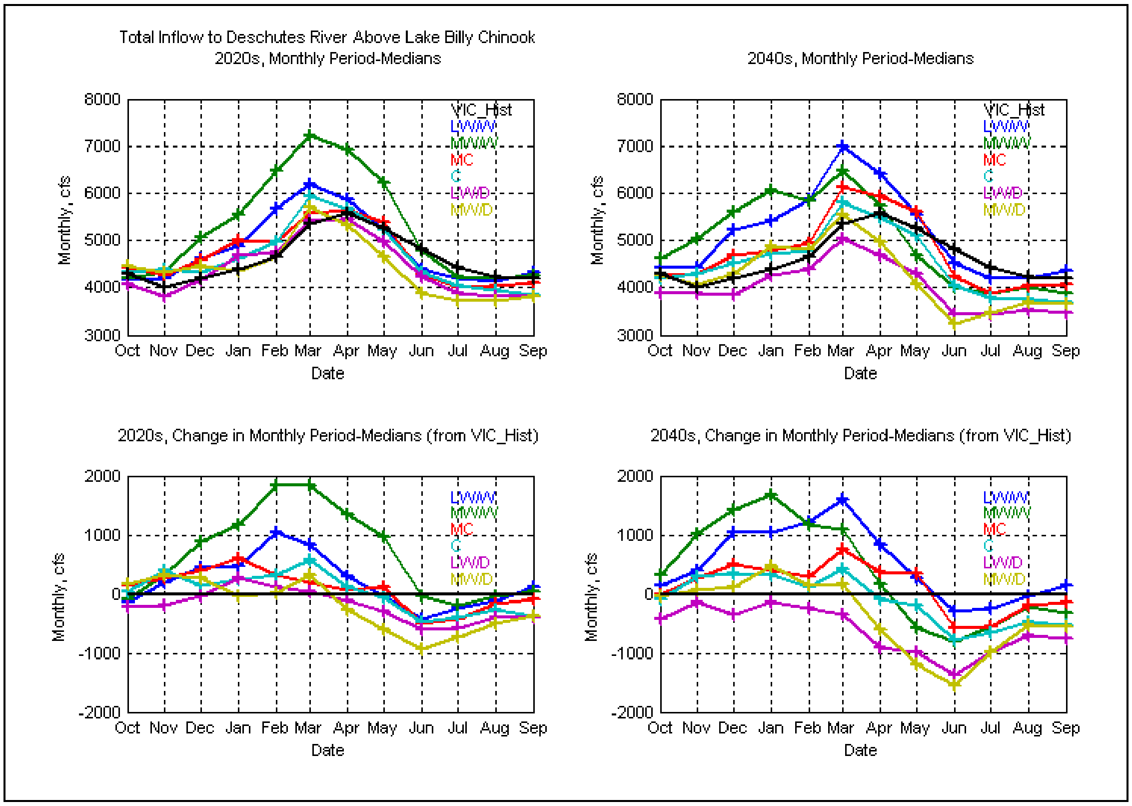


Figure 43. Monthly median (top plates) and change in monthly median inflow from VIC simulated inflow (bottom plates) for the HD 2020 and HD 2040 climate change projections above Lake Billy Chinook on the Deschutes River.

In upper Deschutes River, inflow to Crane Prairie, Wickiup and Crescent reservoirs was evaluated. The MW/D projection in the HD 2040 scenario has the largest decrease (Figure 44). Unlike total inflow above Lake Billy Chinook, peak flow timing shifts by two months (from May to March) in only the wettest climate projections in the HD 2020s and in four of the six projections in the HD 2040 scenario. The inflow volume for the MW/W climate projection peak is almost 40 percent greater in March when compared to historical inflow for that same month in both HD scenarios (about a ten percent increase in peak inflow). However, as with Lake Billy Chinook, a decrease below historical conditions in the summer months is expected.

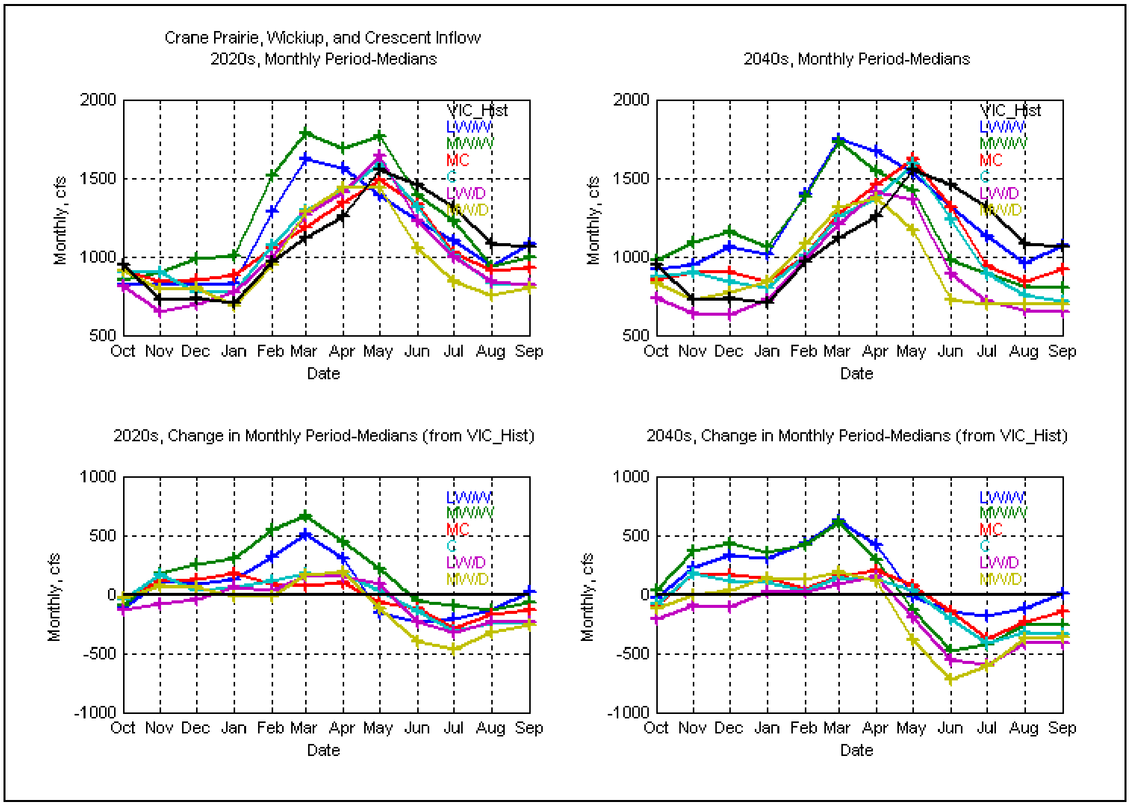


Figure 44. Monthly median (top plates) and change in monthly median inflow from VIC simulated historical (bottom plates) for the HD 2020 and HD 2040 climate change projections into major reservoirs on the upper Deschutes River.

Inflow to Prineville and Ochoco reservoirs on the Crooked River reflected similar results as reported in the previous two locations (Figure 45). However, the timing of the peak inflow volume does not shift on the Crooked River in any of the climate projections in either scenario. In addition, while a slight increase in volume is expected in the winter months and a decrease below historical inflow in the summer months, these changes are not as significant as the previous two locations. The maximum increased inflow volume change occurs in April during which a 35 percent increase in inflow is observed in the MW/W climate projection in the HD 2020 scenario and less than 10 percent in the HD 2040 scenario when compared to the historical inflow (the black line).

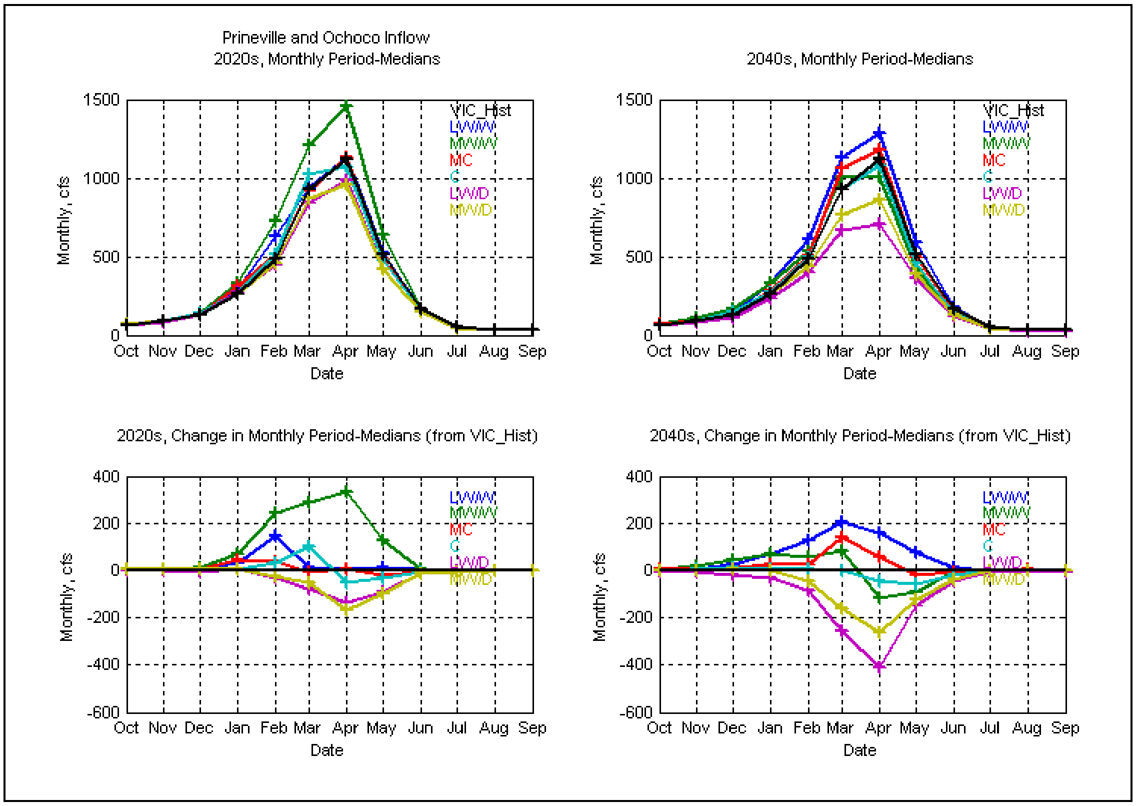


Figure 45. Monthly median (top plates) and change from VIC simulated historical in monthly median inflow (bottom plates) for the HD 2020 and HD 2040 climate change projections into major reservoirs on the Crooked River.

To address inflow variability results were assessed using a distribution view, which offers a condensed way of summarizing operations variability within a climate and across climates. To introduce distributional information, results are first presented for one metric using a time series view and then transitioning to distribution view.

Figure 46 shows the time series of annual inflow above Prineville and Ochoco for historical and HD 2020s climate (top panel), and the change in annual diversion from historical to a given HD climate (bottom panel). Inflow varies from year to year in each climate. For example, the top panel of Figure 45 shows that for each climate the indexed simulation year 1983 generally involves relatively low inflow volume. Results show that while inflow volumes are expected to decrease during typical years, some years experience severe decreases while others experience increases.

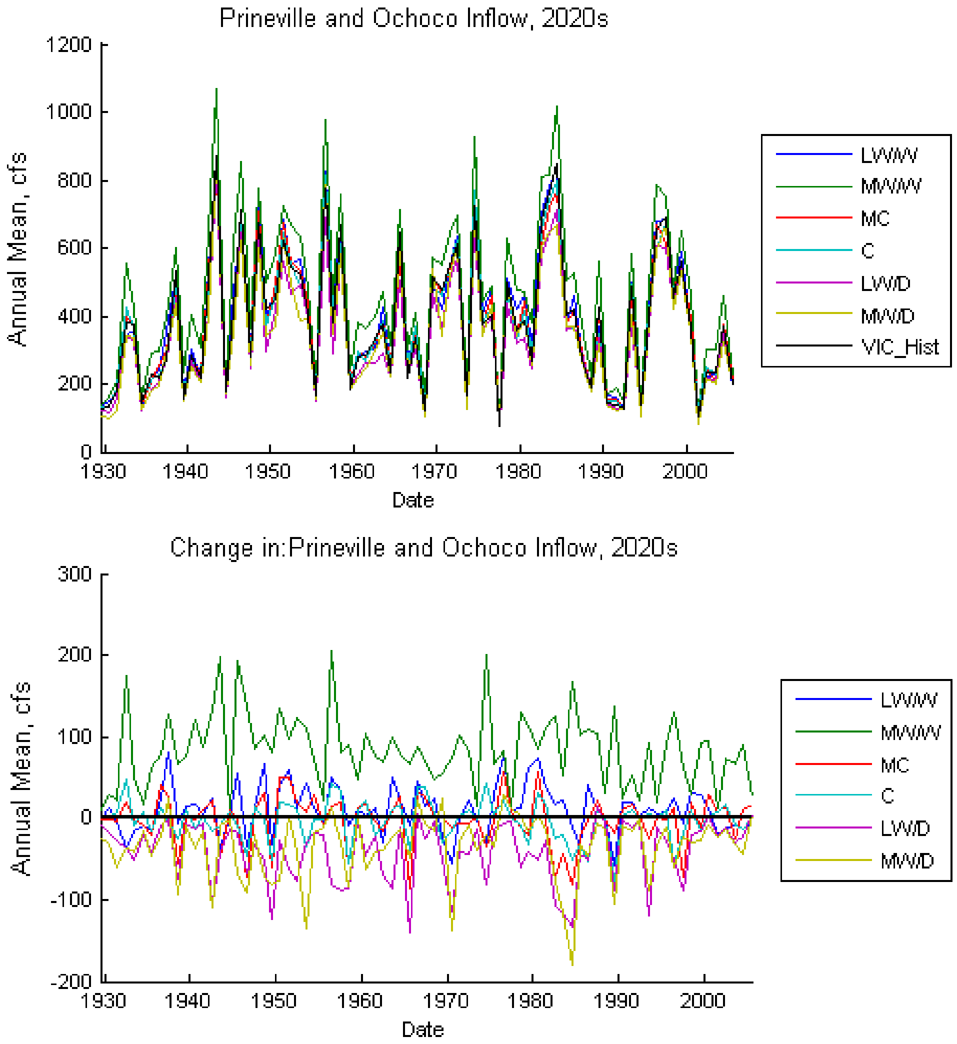


Figure 46. Inflow into Prineville and Ochoco reservoirs on the Crooked River for VIC simulated historical and HD 2020s Climates.

The distribution of inflow during the simulation for each climate can also be shown using box plots as shown on Figure 47. For example, the historical climate (black box plot, top panel) annual inflow is shown to vary within the same minimum and maximum limits under both the time series view on Figure 46 and the box plot view on Figure 47. However the merits of the box plot is that percentile conditions are more easily inferred based on the placement of the box: the bottom and top of the box represent the 25th and 75th percentiles, respectively, and the box midline represents the median or 50th percentile. The symbols above and below a box correspond to cases outside the interquartile range (i.e., above the 75th percentile and below the 25th percentile).

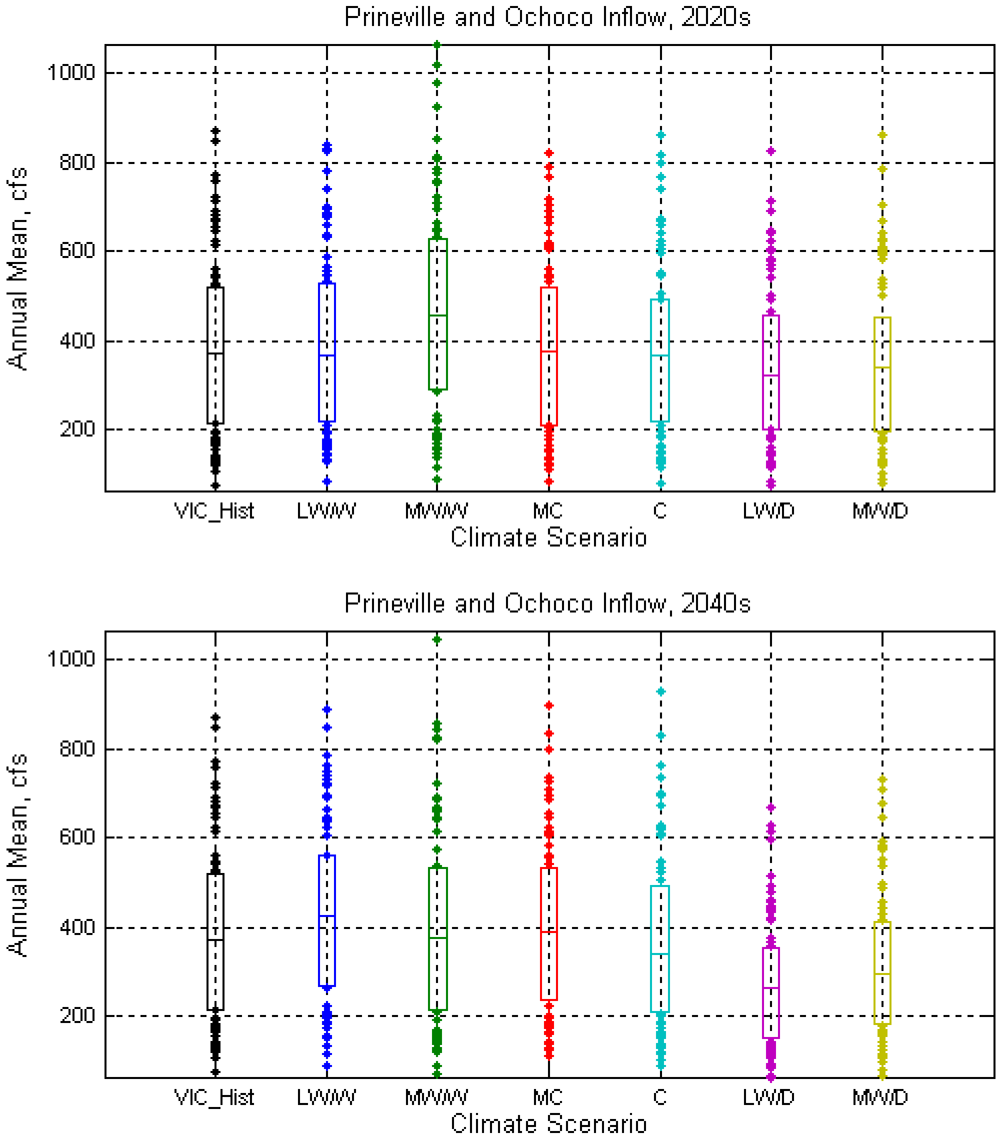


Figure 47. Total annual mean distribution compared to VIC simulated historical inflow to Prineville and Ochoco for the HD 2020 and 2040 scenarios.

4.2.2.2.1.2 Effect of Forecasting Method Selection on Simulated Operations

As described in Section 4.1.2, the original scoping of the RMJOC effort questioned the impact of the loss of snowpack and its effect on runoff timing and volume. To evaluate this question, simulations were conducted using *perfect* and *imperfect* forecasting on the Deschutes River. Evaluating different forecasting methods stemmed from awareness that snowpack has historically served a role as a winter and early spring indicator of runoff volume during April-September in snowmelt driven subbasins. As warming continues in the future, snowpack would diminish and have less affect on runoff. It was hoped by comparing forecast methods that the timing of when that diminishment occurs could be better understood. In short, *perfect* forecasting assumes knowledge of future runoff using known observed flow. *Imperfect* forecasting reflects the uncertainties (and errors) in forecast equations that use the relationship between precipitation and subbasin snow water equivalent to predict runoff on any given date (Section 5 of the Part 1 Report and Section 3.1.3 of this report).

Figure 48 shows the quality of regressions for each forecast situation for VIC simulated historical and six HD 2020s climates at the Prineville Reservoir on the Crooked River. A forecast situation reflects a specific location a forecast is given, the time period of the forecast (e.g., January to June), and the issue time. The quality of the regression model or r^2 value reflects represents how closely the simulated forecasts reflect the actual data. In the case of the Prineville Reservoir location, the quality was poor with r^2 values generally less than 0.3 (where 1 is a good representation). Simulated forecasts using the VIC model output adjusted to the Prineville and Ochoco inflow locations are generally not as good as the forecasts done in real-time by Reclamation hydrologists for reasons explained in the Part 1 Report.

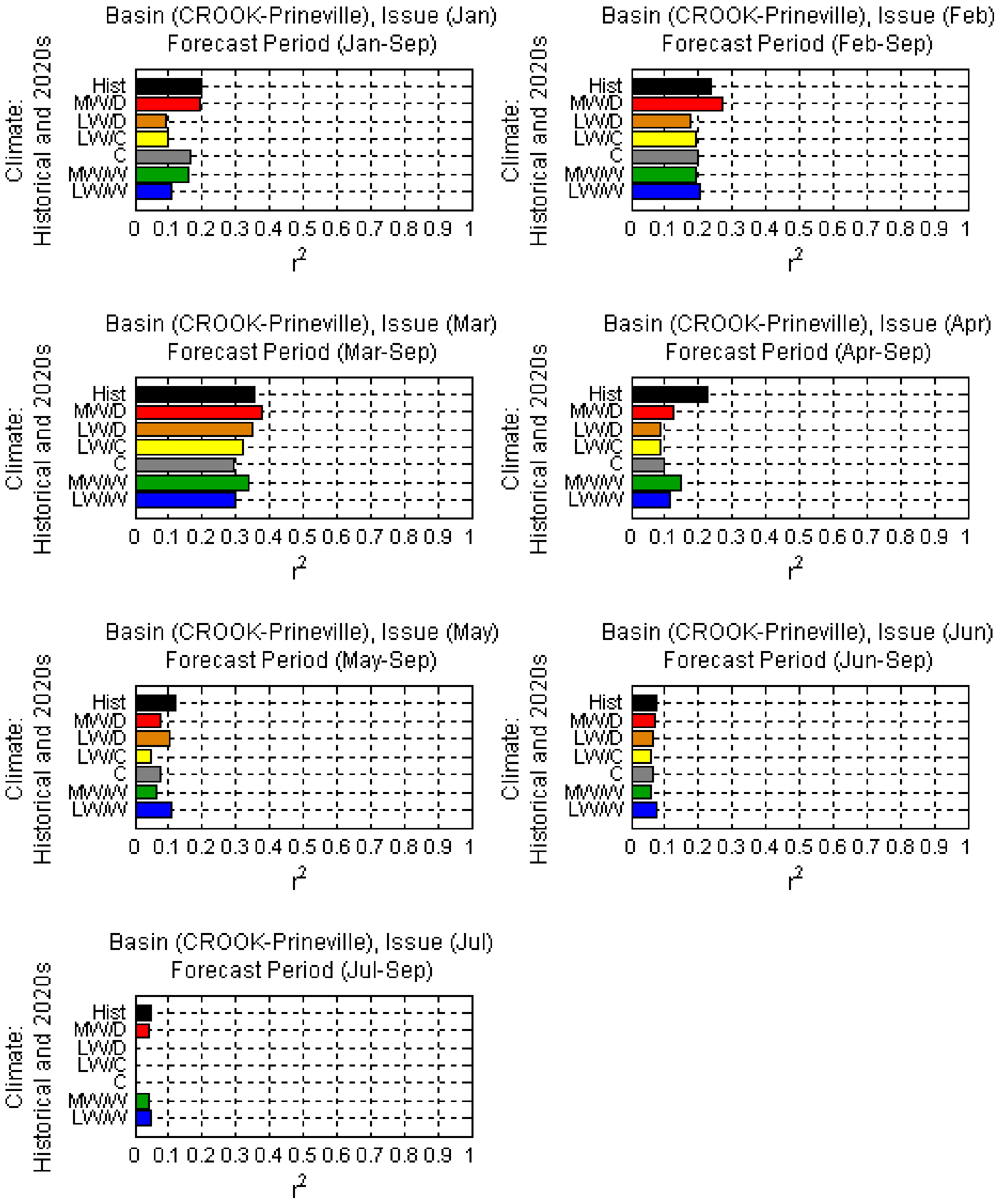


Figure 48. Quality of regression models (r^2) at Prineville on the Crooked River used to generate *imperfect* forecasts of seasonal runoff volume, Historical and HD 2020s climates.

While quality of simulated forecasting is better at the Crescent forecasting location on the upper Deschutes River (Figure 49), the overall quality remains generally poor with r^2 values less than 0.6 in most situations. Note that only the HD 2020 forecasts on the upper Deschutes River are presented here because the r^2 results in the HD 2040 are similar to the HD 2020.

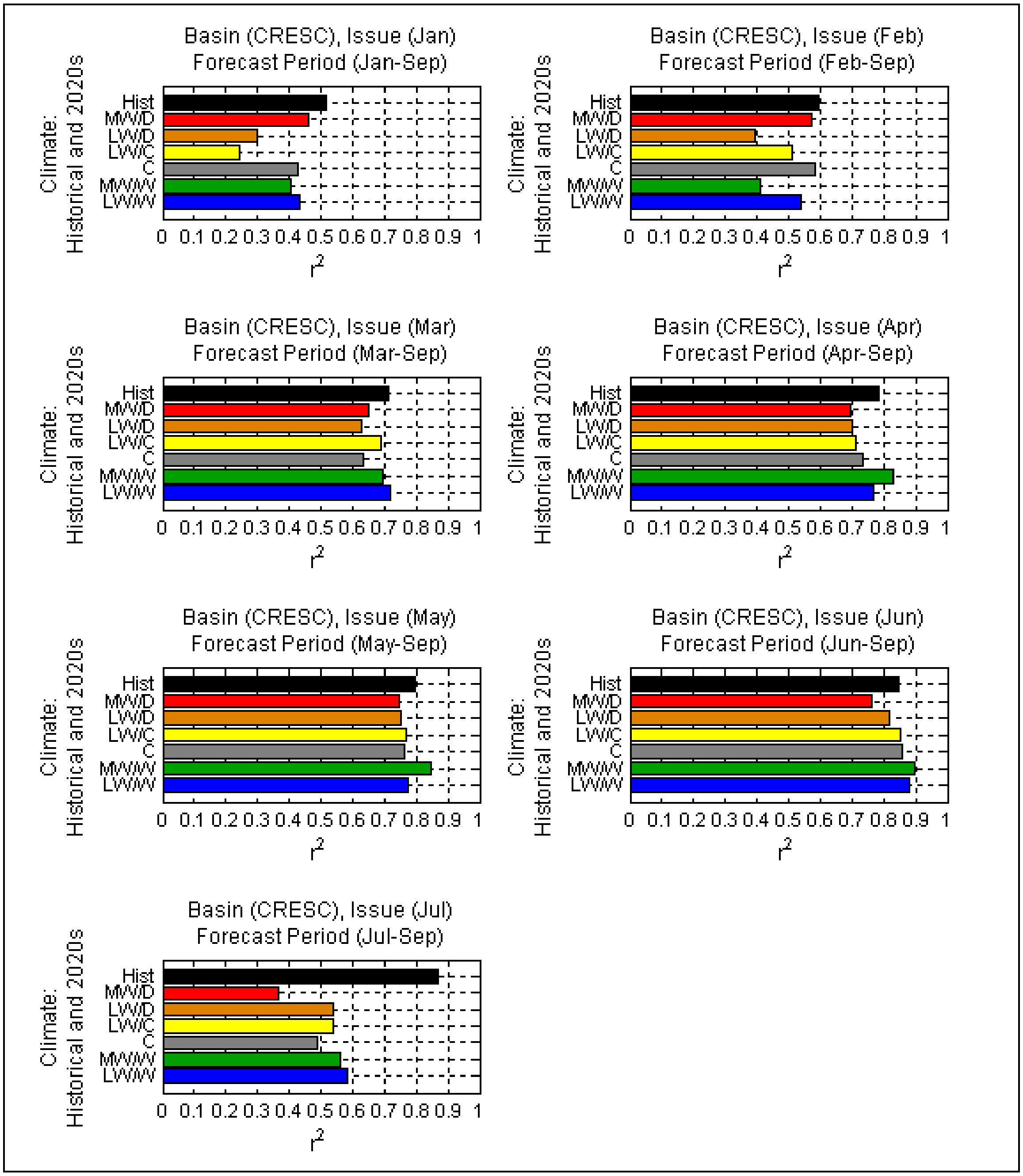


Figure 49. Quality of regression models (r^2) at Crescent on the upper Deschutes River used to generate *imperfect* forecasts of seasonal runoff volume, Historical and HD 2020s climates.

Despite the poor quality of the forecasting, the impact on the overall results on the Deschutes River metrics was negligible. Figure 50 depicts results for the Deschutes River subbasin above Lake Billy Chinook using *perfect* forecast mode and Figure 51 shows the results at the same location, but using *imperfect* forecast mode. Both total volume and change in median values remained generally unchanged between the two HD scenarios and among any of the 12 climate change projections as compared to VIC simulated historical. The negligible change in results between *perfect* and *imperfect* results is found in all of the metrics presented. Because of that, only *perfect* forecasting mode results will be presented in the remaining metrics.

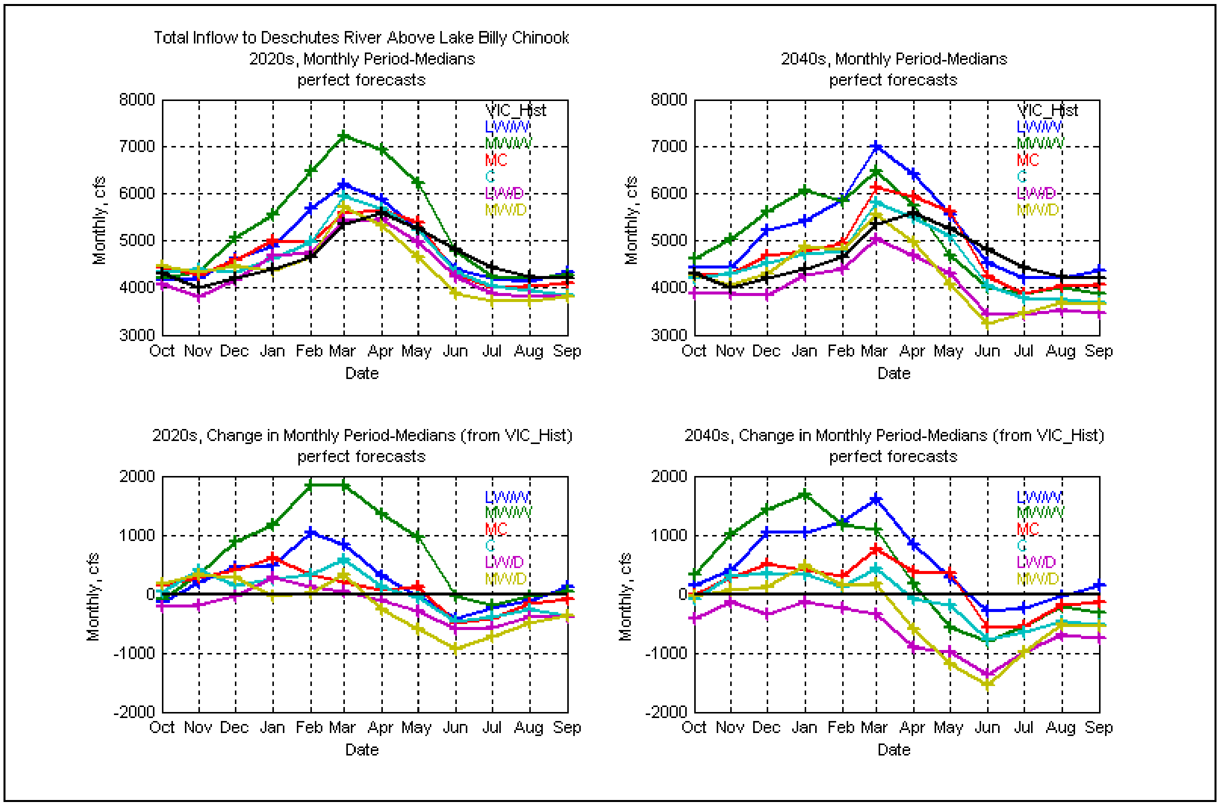


Figure 50. Total in monthly period-median and change from VIC simulated historical in monthly period-medians inflow above Lake Billy Chinook on the Deschutes River in the HD 2020 and HD 2040 climate projections using *perfect* water supply forecasts.

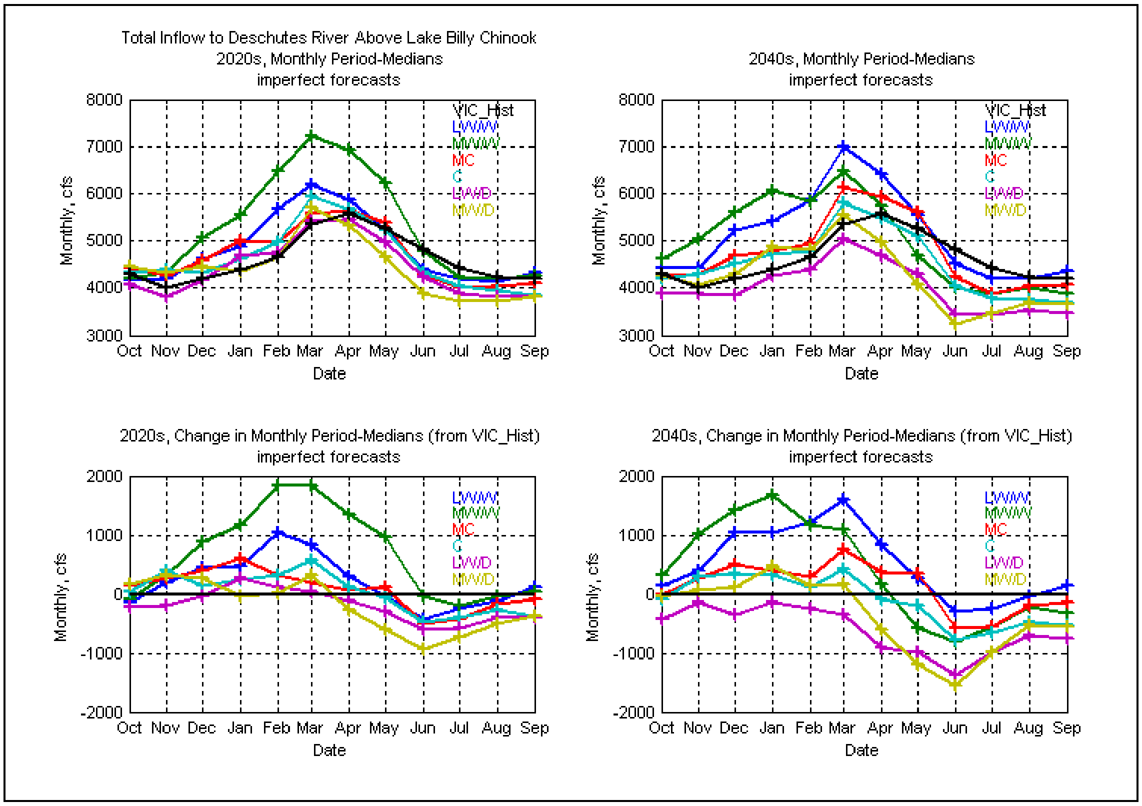


Figure 51. Total monthly period-median and change from VIC simulated historical inflow in monthly period-median above Lake Billy Chinook on the Deschutes River in the HD 2020 and HD 2040 climate projections using *imperfect* water supply forecasts.

4.2.2.2.1.3 Effect of Transient Climate Projections on Simulated Operations

Total system inflow above Lake Billy Chinook for the Transient scenario is presented in Figure 52. Inflow is presented as a 30-year moving mean for each climate change projection in the Transient scenario. As shown, the cgcm3.1 (i.e., the dark blue line representing the MW/W climate projection) and the echo5 GCM (pink line representing the LW/D climate projection) bound the remaining four projections. The solid thick black line is the 30-year moving average of the VIC simulated historical trend. The transient ensemble median is the median of all six climate change projections and is shown in the dashed black line. The ensemble median suggests that the general trend of inflow above Lake Billy Chinook remains relatively unchanged over time.

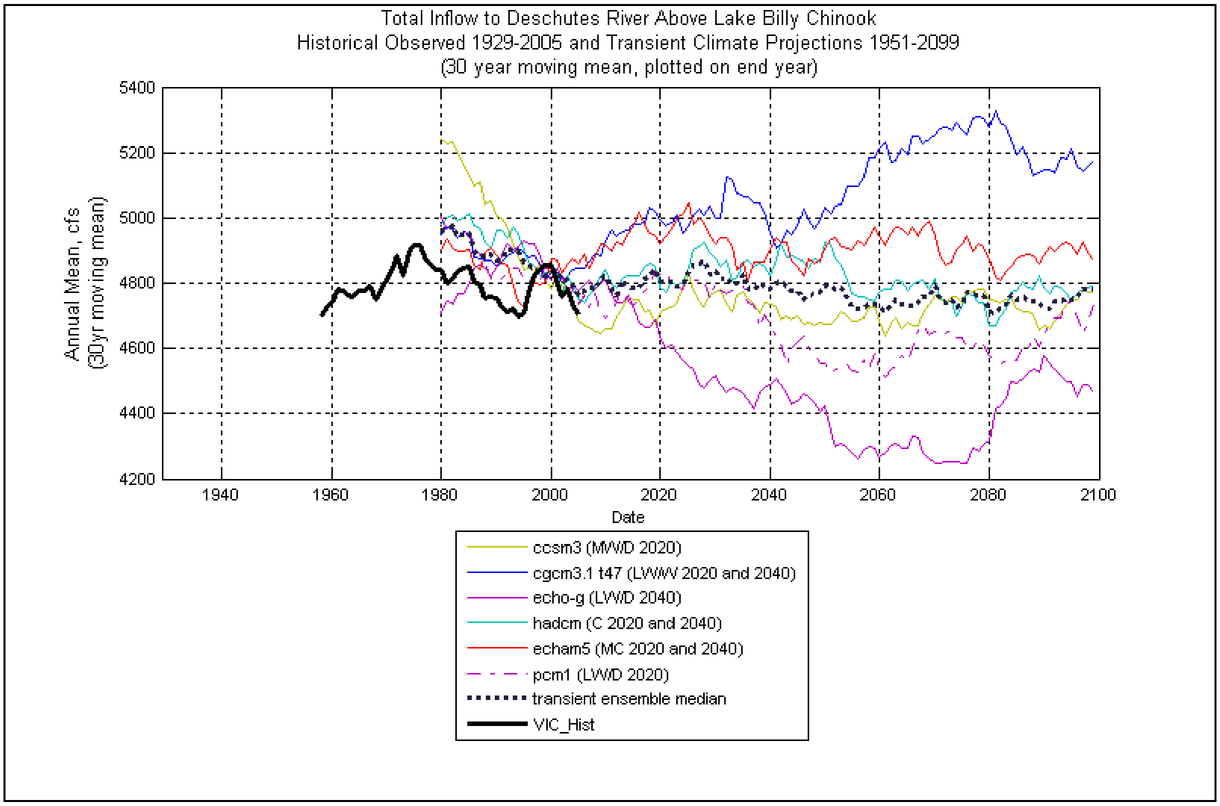


Figure 52. Transient 30-year moving mean of annual mean for 150 years and the Transient ensemble median of total inflow to the Deschutes River above Lake Billy Chinook.

4.2.2.2.2 End-of-Month Storage at Major Reservoirs

End-of-month storage was summed at Prineville and Ochoco reservoirs on the Crooked River, Wickiup, Crescent, and Crane Prairie reservoirs on the upper Deschutes River, and at Lake Billy Chinook on the Deschutes River below the confluence with the Crooked River.

4.2.2.2.2.1 Typical Conditions and Variability

End-of-month storage at Prineville and Ochoco is shown in Figure 53 for both HD scenarios. Generally, the Crooked River reservoirs were expected to refill in May and June in almost all of the climate change projections in both HD scenarios. The only exception is in the two driest climate changes projections (LW/D and MW/D) in the HD 2040 scenario. In these two climate projections, the end-of month storage was consistently less than the historical storage volume. In addition, deeper reservoir drafts (or drawing the reservoir to a lower water surface elevation by removing increased volumes of water from it) were expected in both of these climate projections to the extent that it is impossible for the reservoir storage levels to fully recover the following spring.

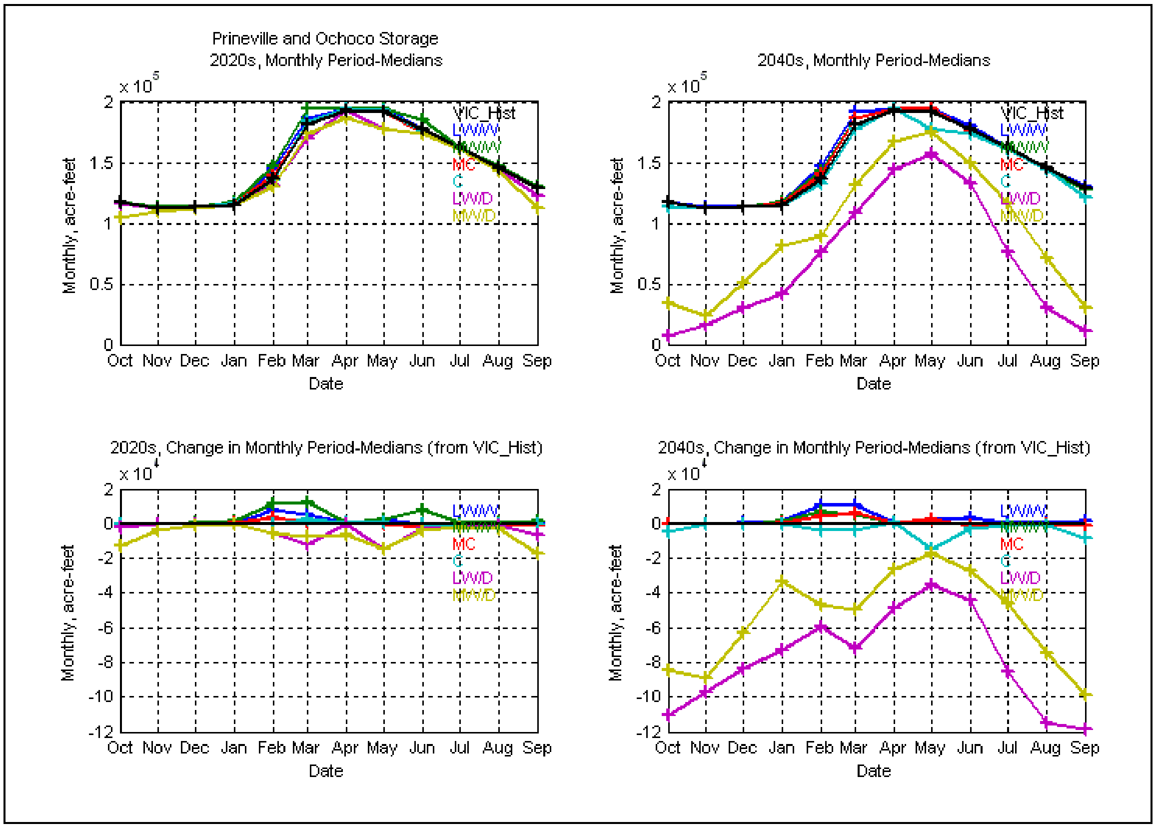


Figure 53. Total and change in monthly period-median storage for the HD 2020 and 2040 scenarios on storage on the Crooked River reservoirs.

The end-of-month storage for all six reservoirs is shown in Figure 54. Generally, storage volume is higher than historical storage in the winter months and in almost all of the projections, deeper drafts in the summer and fall result in decreased storage volumes during those months when compared to historical end-of-month storage. The two driest climates (LW/D and MW/D) in both HD scenarios continue to require deeper drafts of the reservoirs in the Deschutes River system later in the irrigation season to meet demands and deplete reservoir storage levels such that the reservoir storage levels do not fully recover the following year. A decrease of almost 25 percent of end-of-month storage occurs in the LW/D projection in the HD 2040 scenario in September. At the peak of the storage (April), the LW/D projection is almost 20 percent less than historical peak storage for that same month. For the remaining climate projection simulations, earlier runoff refills the system by April, but the reservoirs start to draft earlier in the season, usually by June.

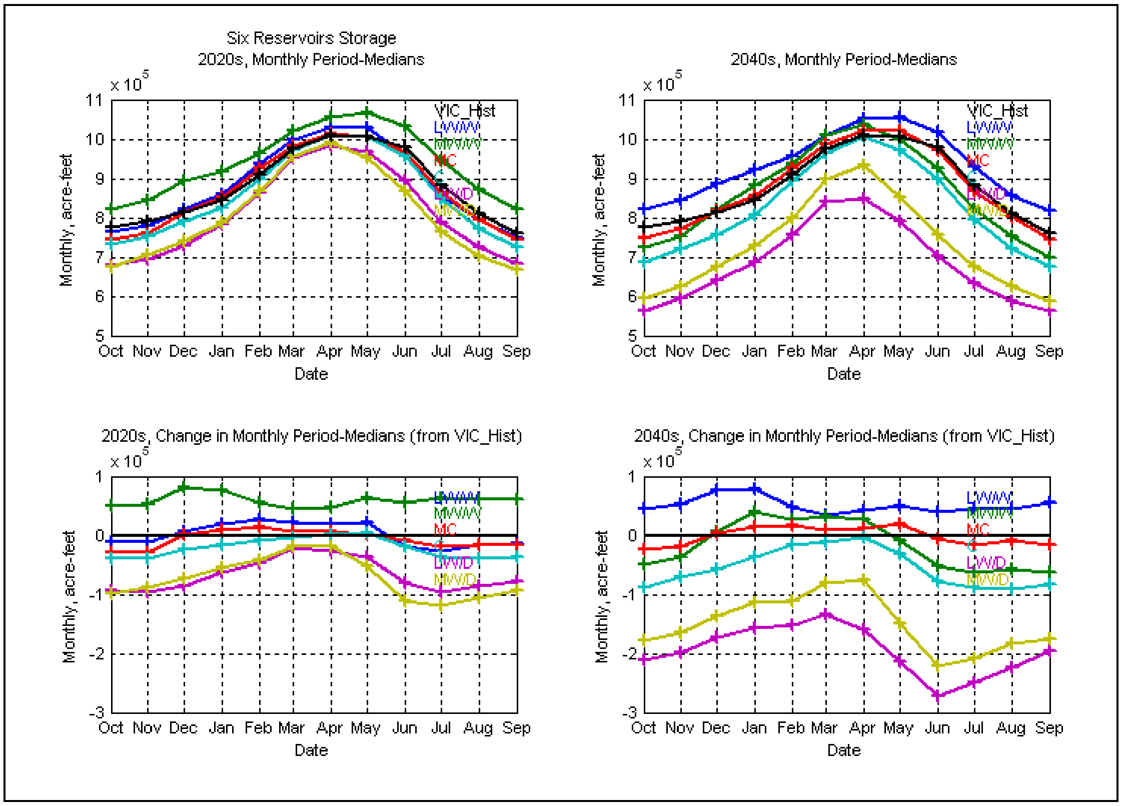


Figure 54. Change in monthly period-median storage for the HD 2040 projections for all reservoirs storage on the Deschutes River.

4.2.2.2.2.2 Effect of Transient Climate Change Projections on Operations

End-of-month storage for the Transient scenario 30-year moving mean is shown for reservoirs on the Crooked River (Figure 55), upper Deschutes River (Figure 56), and both subbasins combined (Figure 57). The ensemble median (dash black line) of the end-of-month storage decreases by more than 20 percent over the next 150 years in the Crooked River system, by approximately 35 percent in the upper Deschutes, and more than 10 percent in the entire Deschutes River system. These trends indicate that it could be a challenge to fill the reservoirs should the climate change patterns in the Deschutes River subbasin become much drier than the subbasin currently experiences.

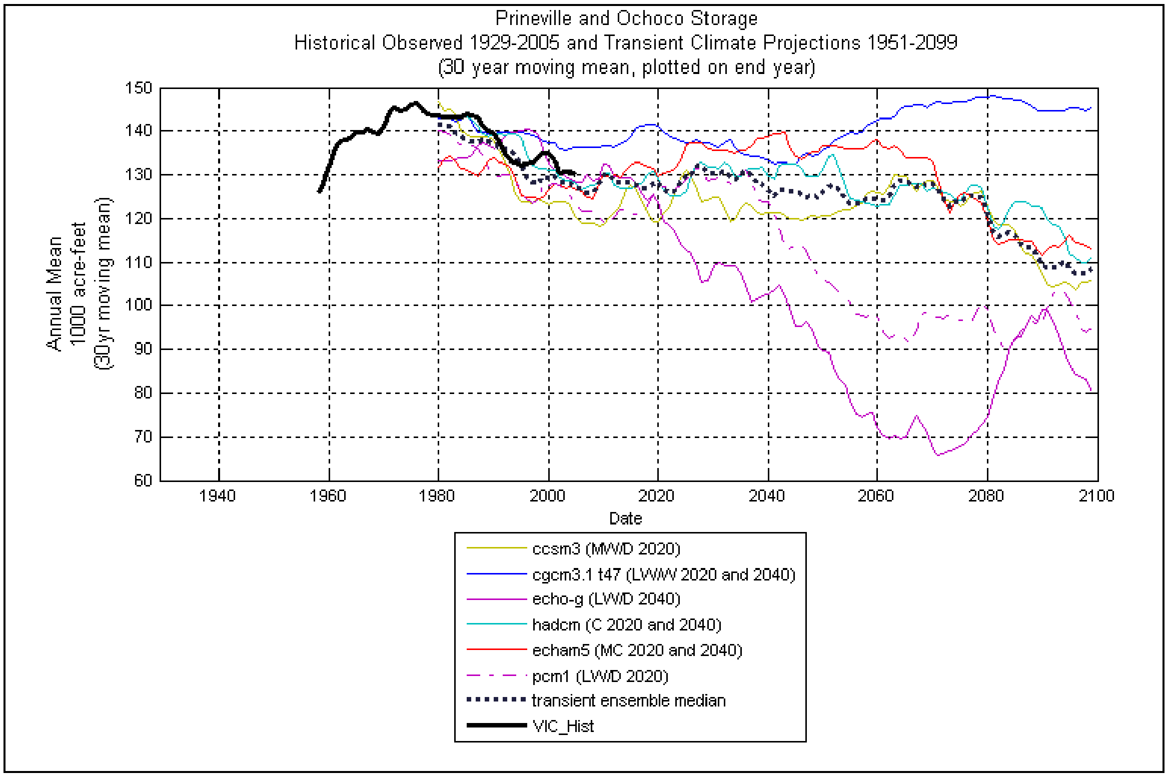


Figure 55. 30-year moving mean of the annual mean for 150 years of end-of-month storage summed for Prineville and Ochoco reservoirs on the Crooked River.

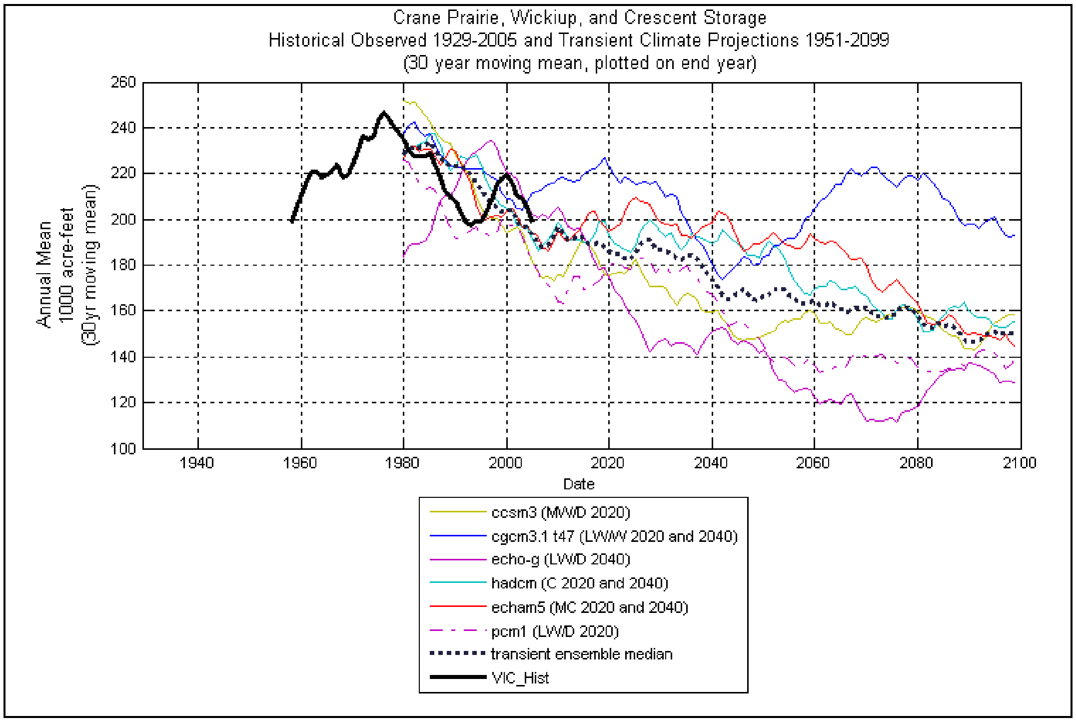


Figure 56. 30-year moving mean of the annual mean for 150 years of end-of-month storage summed for Crane Prairie, Wickiup, and Crescent reservoirs on the upper Deschutes River.

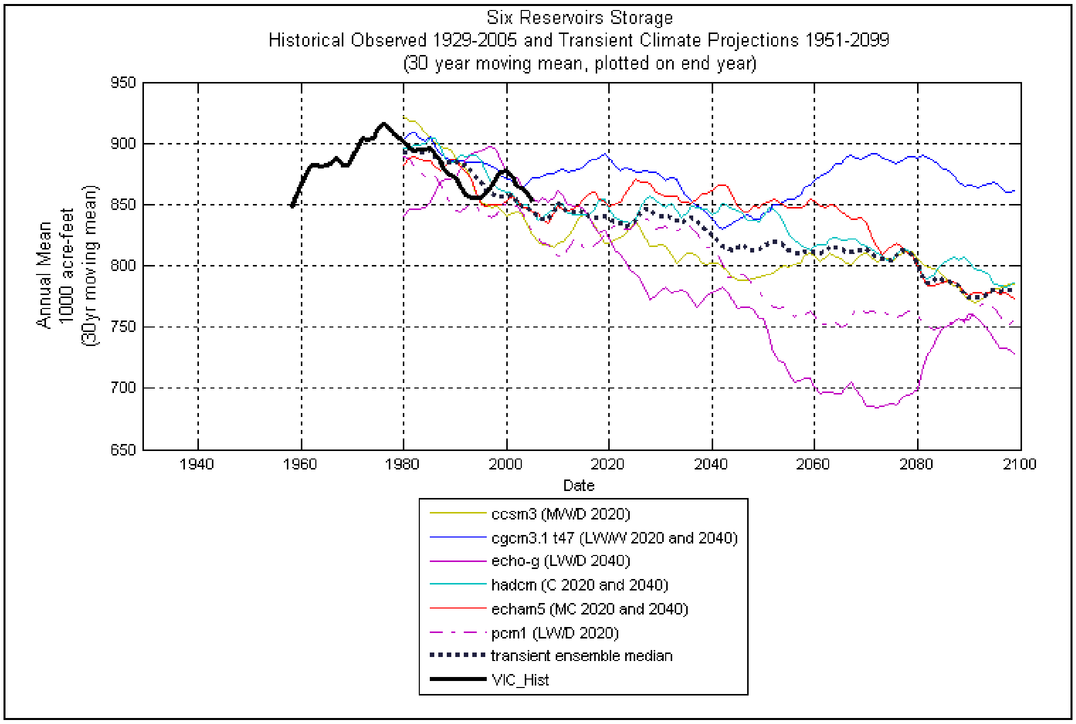


Figure 57. 30-year moving mean of the annual mean for 150 years of end-of-month storage summed for all six major reservoirs (including Lake Billy Chinook) on the Deschutes River.

4.2.2.2.3 Flow at Key Locations in the Subbasin

Crooked River below Opal Springs (CRSO) and the upper Deschutes River above Lake Billy Chinook (DCCO) were selected to evaluate flow in the channel over the entire period of record. These two locations were chosen because they are the major gages on the Deschutes River and they are used to determine ESA objectives (Section 4.2.1.2.5).

4.2.2.2.3.1 Typical Conditions and Variability

The median monthly flow at CRSO was generally increased above historical monthly flow beginning in January and extending into June in the wetter climate projections in both HD scenarios (Figure 58). At the peak flow in April in the HD 2020 MW/W projection, flow is projected to increase more than 40 percent. In the HD 2040 scenario, the LW/W and MC projections have the greatest increases during the peak month of April with more than 10 percent.

The two driest climates are consistently below historical levels for most of the year in both HD scenarios. In the HD 2020 dry projections, the peak in April is between 15 and 20 percent less than historical flow in April for the MW/D and LW/D, respectively. Greater decreases are observed in the HD 2040 dry projections with more than a 40 percent decrease from historical flow.

The increased ability to store water during with winter months because of greater rainfall and less snow will somewhat offset the decrease in river flows in late summer and fall. Irrigators that are solely dependent on natural flow rights will likely feel the effects of climate change more than those who possess storage water rights.

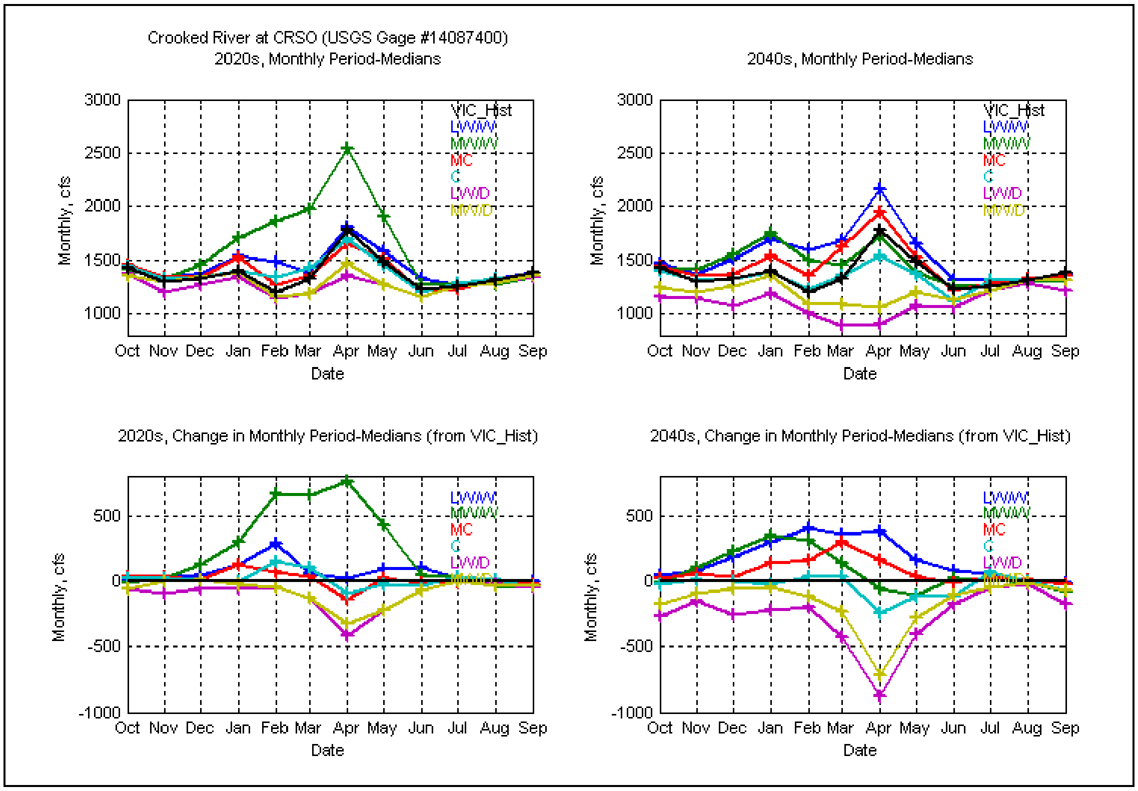


Figure 58. Flow in total and change in total (from VIC Historical) monthly period-medians at USGS Gage 14087400 (CRSO) on the Crooked River.

Changes in monthly median flow for the drier scenarios on the upper DCCO were less variable than they were on the Crooked River (Figure 59). However, unlike the peak timing on the Crooked River, the timing of the peak flow on the Deschutes River is expected to shift one month earlier from April (the black line) to March in the two wetter climate projections and in the MC projection in the HD 2040 scenario. The flow in the LW/W projections in both HD scenarios in March is almost 70 percent higher than historical flow during that same month. Flow at DCCO generally returns to more historical levels by June. The increase volume of flow during the spring has obvious implications for flood control and an increased need for reservoir storage.

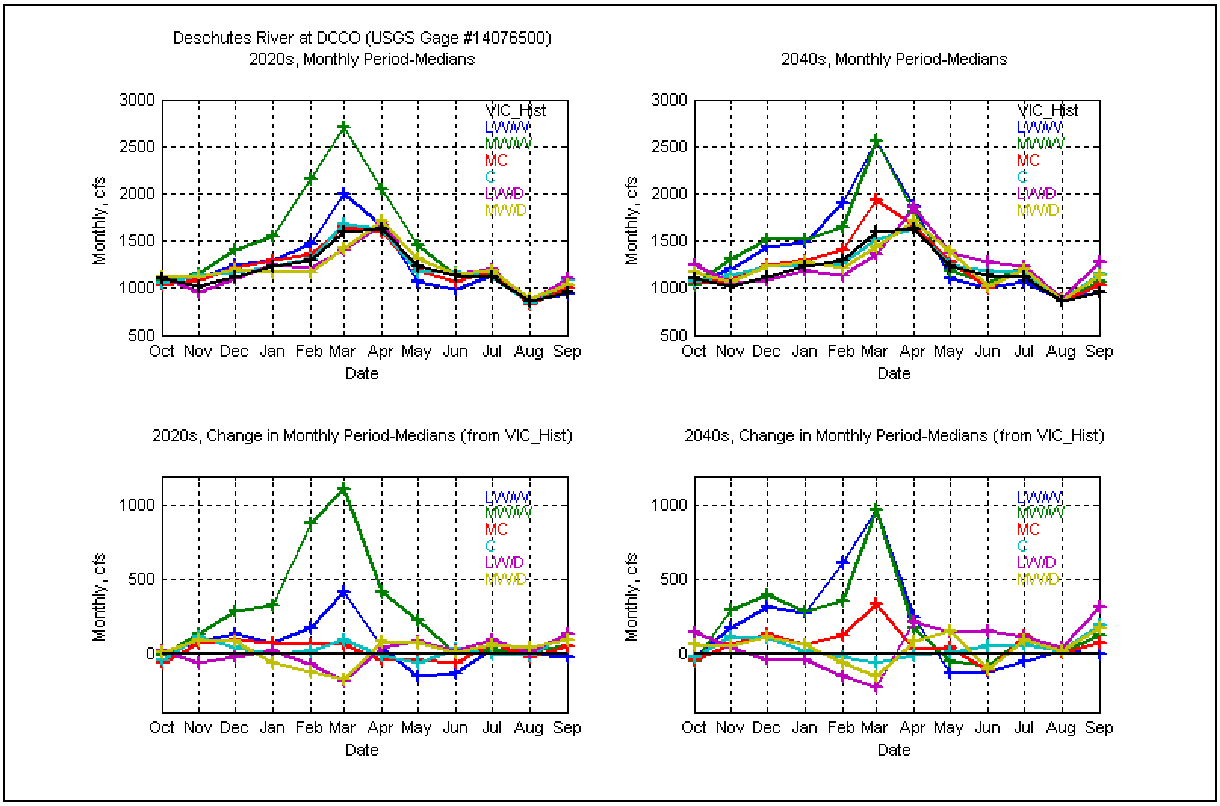


Figure 59. Flow in total and change in total (from VIC Historical) monthly period-medians at USGS Gage 14076500 (DCCO) on the Deschutes River.

4.2.2.2.3.2 Effect of Transient Climate Projections on Simulated Operations

The ensemble median of the 30-year moving mean of flow at the CRSO gage on the Crooked River shows a slight decreasing trend in the regulated in-stream flows (Figure 60) over the 150-year period. A decrease of less than 5 percent is observed over that time frame.

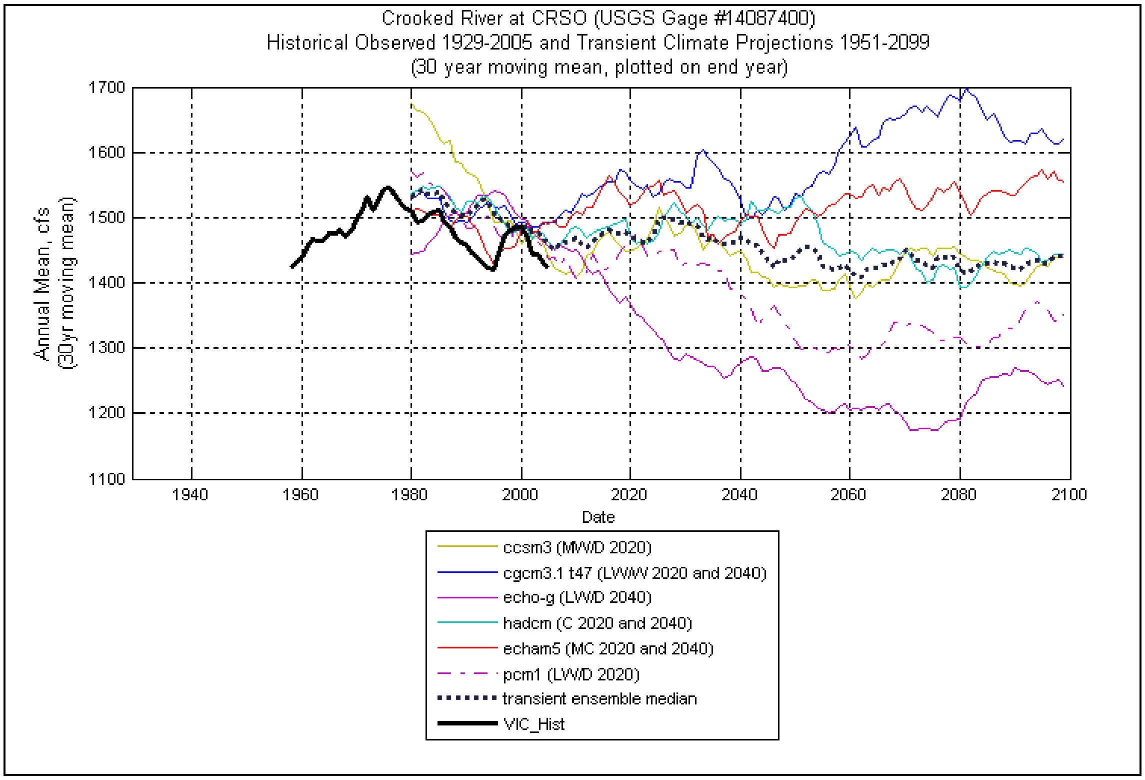


Figure 60. 30-year moving mean of the annual mean for 150 years of flow at the CRSO gage on the Crooked River.

The ensemble median on the upper Deschutes River at the DCCO gage shows a slightly increasing annual flow trend (Figure 61) of less than 8 percent. This gage is just upstream of the confluence of the upper Deschutes River and the Crooked River. It is not completely clear why this trend takes place in the Deschutes River subbasin.

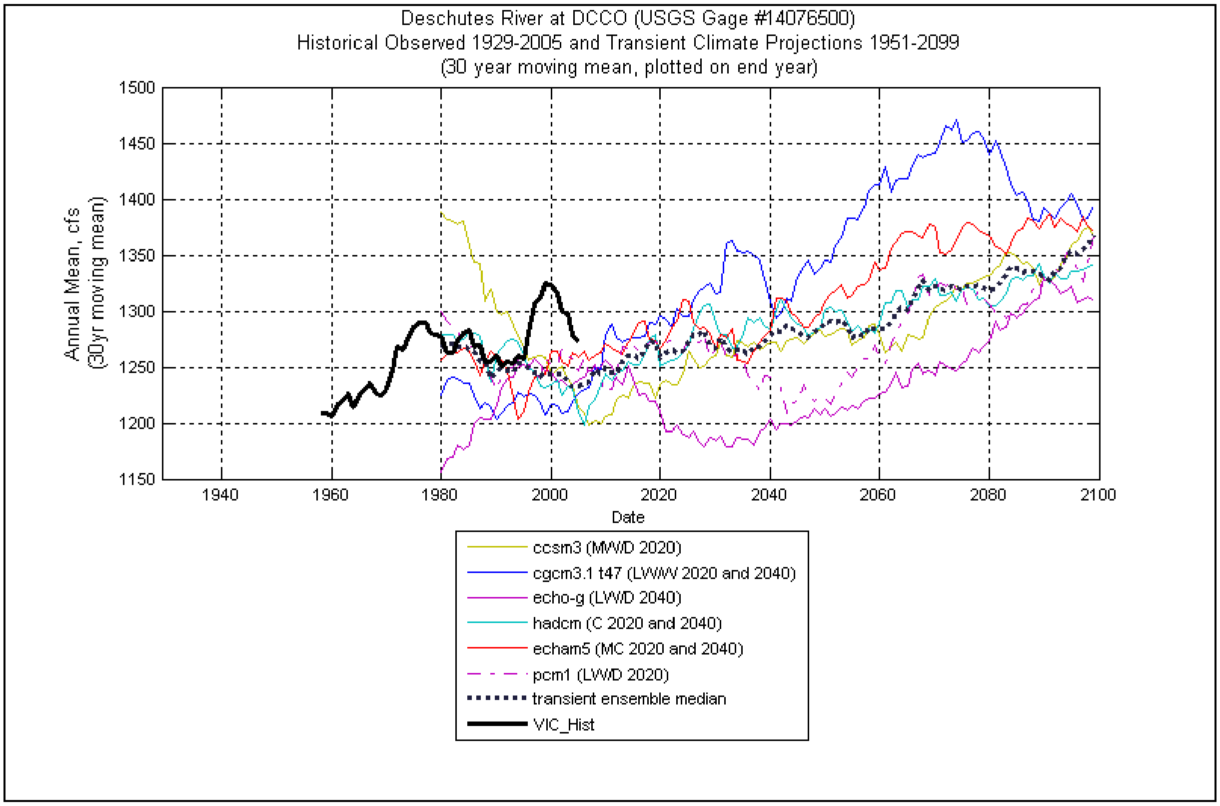


Figure 61. 30-year moving mean of the annual mean for 150 years of flow at the DCCO gage on the upper Deschutes River.

4.2.2.2.4 Surface Water Delivered

4.2.2.2.4.1 Typical Conditions and Variability

Total surface water delivered is equal to the irrigation demand minus the irrigation demands not met. In the HD 2020 and 2040 scenarios, total surface water delivered decreases slightly in the dry and central climate change projections. Because the surface water delivery volumes on the upper Deschutes River (Section 4.2.1.2.4) are much greater than those on the Crooked River (Figure 62), changes observed in the entire system were similar to those on the upper Deschutes River (Figure 63) and so changes on the upper Deschutes River are not shown.

Generally, surface water deliveries remain unaffected except in the two driest projections on the Crooked River (Figure 62). In both HD scenarios, decreased surface water deliveries are observed during the peak of the irrigation season. In the HD 2040 dry projections, surface water deliveries are consistently below historical deliveries throughout the entire irrigation season. This pattern suggests that demands are not met during extremely dry conditions on the Crooked River.

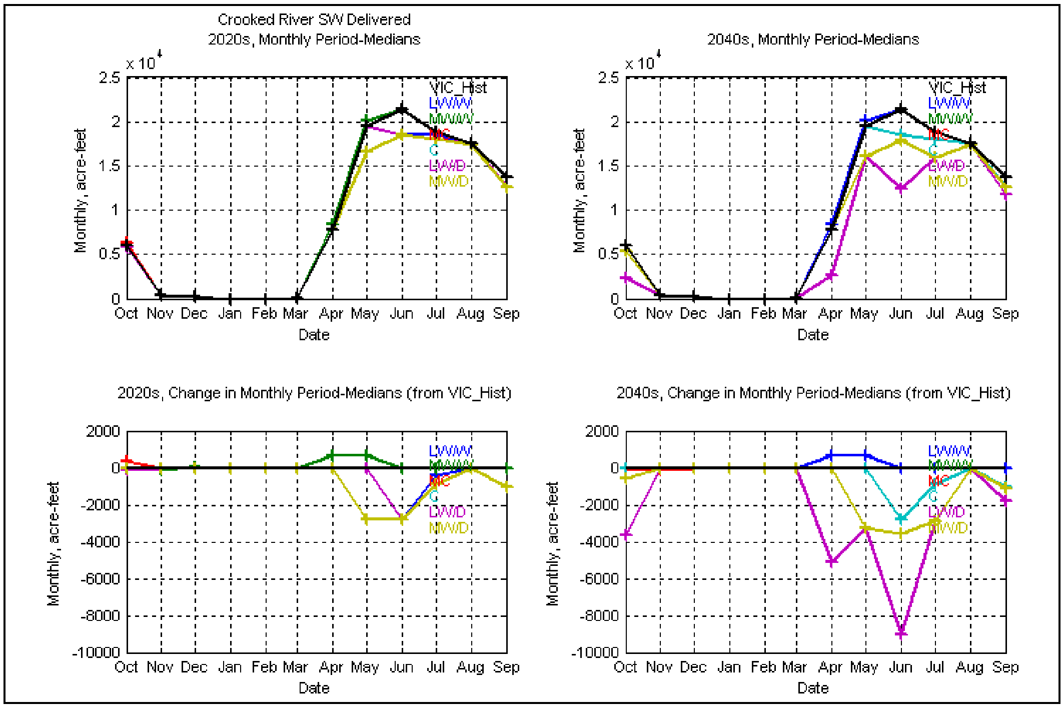


Figure 62. Total and change in monthly-period medians (from VIC simulated Historical) of surface water delivered from the Crooked River.

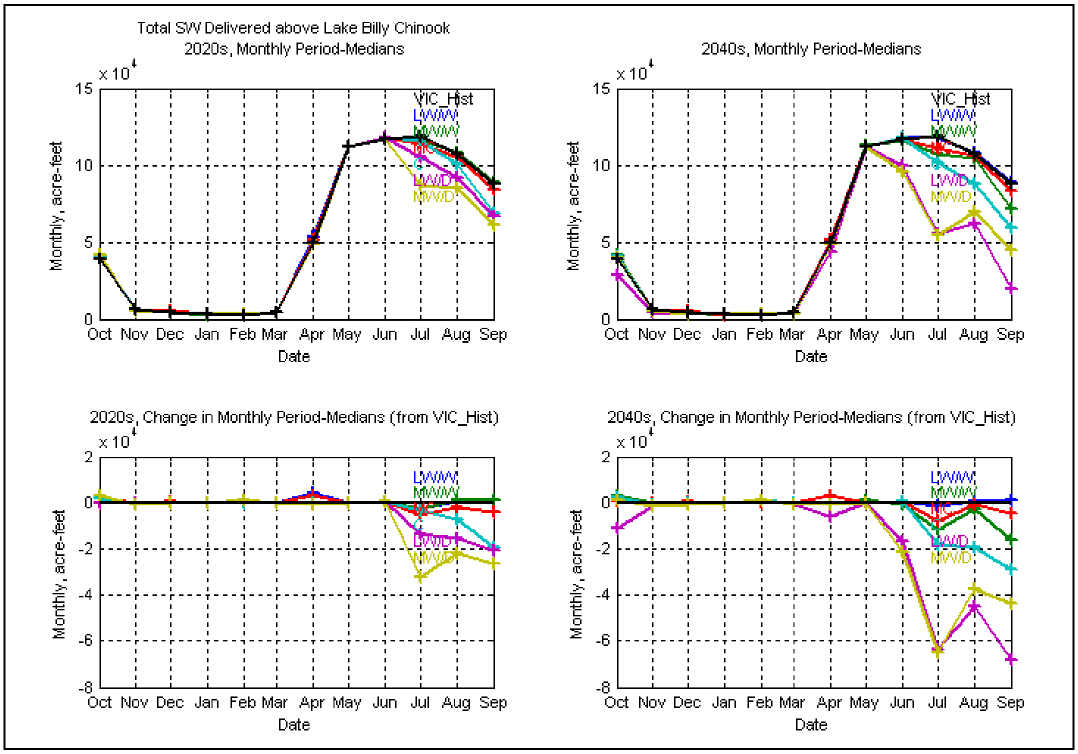


Figure 63. Total and change in monthly-period medians (from VIC Historical) of surface water delivered above Lake Billy Chinook.

System water surface deliveries suggest that in dry conditions, demands may be unmet during extremely dry conditions during the peak of the irrigation season. Both HD scenarios show decreases in deliveries during the summer, but in the HD 2040 dry projections, deliveries are 50 percent less in July than historical deliveries.

4.2.2.2.4.2 Effect of Transient Climate Change Projections on Simulated Operations

Overall deliveries of water in the Deschutes River subbasin have a slight decreasing trend over time (with the exception of LW/W climate) as shown in the 30-year moving average for the Deschutes River above Lake Billy Chinook (Figure 64). The ensemble median experienced an approximate 17 percent decrease in surface water delivered. This downward trend is attenuated when viewed at a 30-year moving average scale, but was still visible.

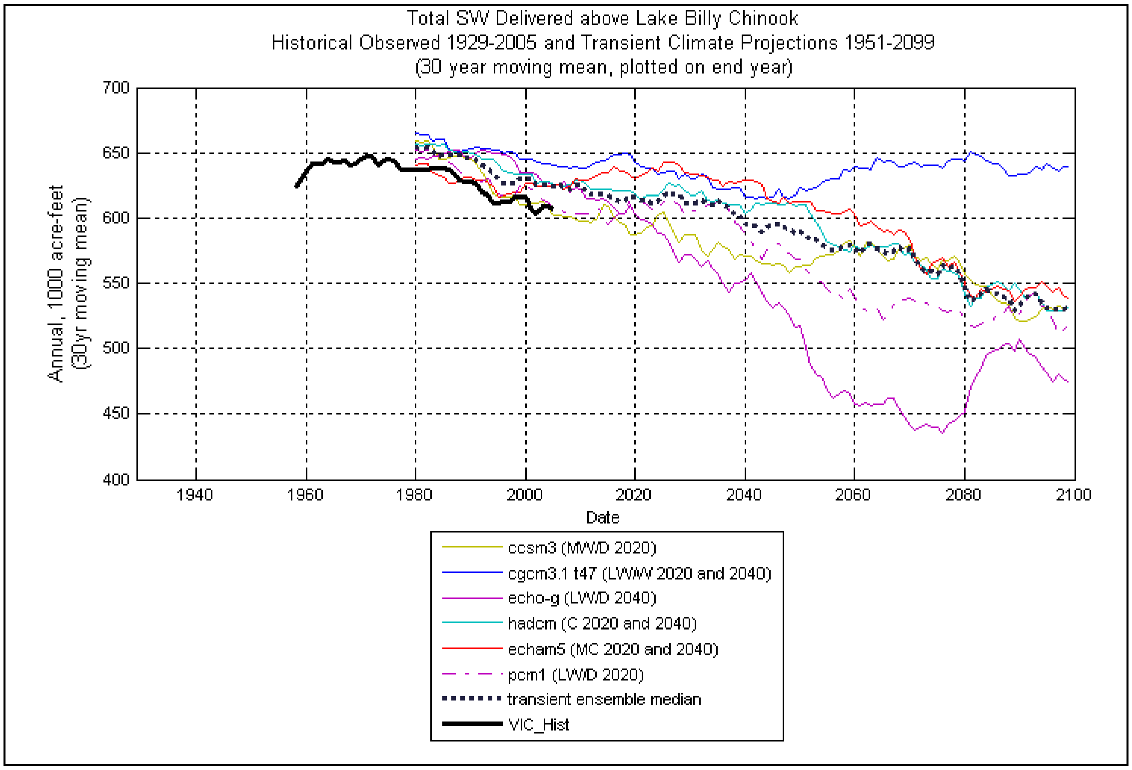


Figure 64. 30-year moving mean of the annual mean for 150 years of surface water delivered on the Deschutes River above Lake Billy Chinook.

Results for the two tributaries (upper Deschutes River and Crooked River) were similar to those presented for the Deschutes River subbasin above Lake Billy Chinook (Figure 65 and Figure 66). An approximate 14 percent decrease from the beginning of the time period in surface water delivered was predicted for the upper Deschutes River and nearly a 21 percent decrease was predicted in the Crooked River.

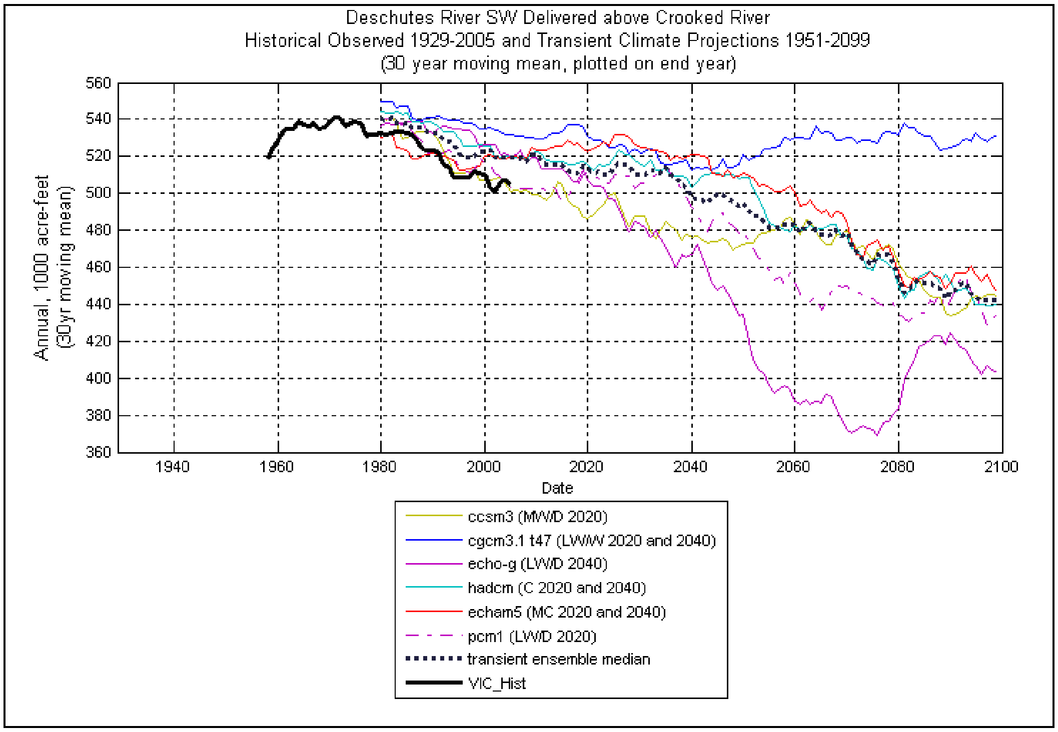


Figure 65. 30-year moving mean of the annual mean for 150 years of surface water delivered on the upper Deschutes River.

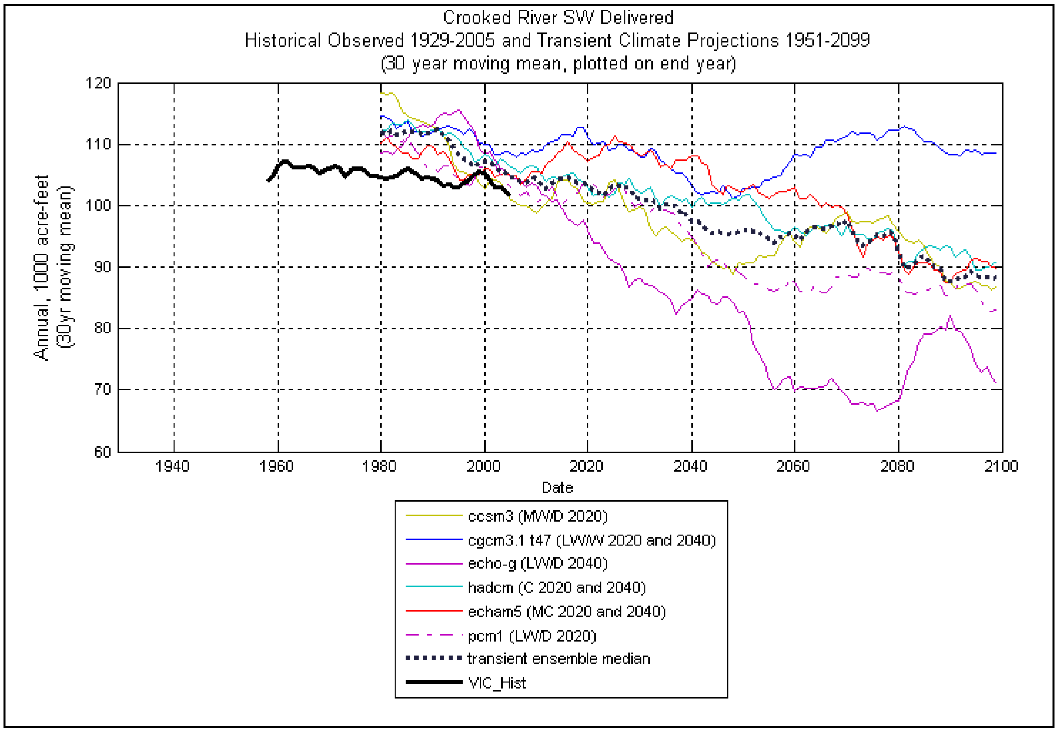


Figure 66. 30-year moving mean for 150 years of surface water delivered on the Crooked River.

4.2.2.2.5 ESA Environmental Objectives

4.2.2.2.5.1 Typical Conditions and Variability

Analysis on the ESA objectives was completed using the October monthly volume as a surrogate for the 7-day moving average flow volume to evaluate if the climate change scenarios would impact the ESA requirement. The surrogate approach was developed for use in this study because the actual BiOp objectives are in a daily measurement measured from October through mid-November, but the MODSIM model is only in a monthly time step. This approach was developed to see if a trend could be observed. Each flow requirement presented in Section 4.2.1.2.5 was evaluated independently. For example, Requirement 1 was evaluated to see when and how often CROO was less than 73,785 acre-feet per month in October. The number of times that occurred in the modeling of current operations was then compared to the future scenarios.

The result was that 12 deviations from the surrogate value of 73,785 acre-feet for the month of October occurred at the CROO location (Table 7 and Table 8). When using the flow data generated by the VIC hydrologic model (and modeled using the Modified Flows DPM), 11 deviations from the monthly surrogate value were predicted. The variation between the VIC simulated historical and the Reclamation modeling results further suggested poor VIC model calibration.

Table 7. Comparison of HD 2020s simulated historical and future climate change projections to Reclamation observed historical for surrogate ESA Requirement 73,785 acre-feet for the month of October at CROO (CRSO in MODSIM) on the Deschutes River.

	USBR Observed historic	**VIC Simulated historical at CRSO**	**cgcm3_B1 (LW/W)**	**Ipsl_cm4_A1B (MW/W)**	**echam5_A1B (MC)**	**hadcm_B1 (C)**	**pcm1_A1B (LW/D)**	**ccsm3_B1 (MW/D)**
Count of Times Deviation Occurred	13	11	11	7	12	16	18	21
Delta from USBR Observed Historic	0	-2	-2	-6	-1	3	5	8

Table 8. Comparison of HD 2040s simulated historical and future climate change projections to Reclamation observed historical for surrogate ESA Requirement of 73,785 acre-feet for the month of October at CROO (CRSO in MODSIM) on the Deschutes River.

	USBR Observed historic	VIC Simulated historical	cgcm3_B1_ (LW/W)	miroc_32_A1B (MW/W)	echam5_A1B (MC)	hadcm_B1 (C)	echo_B1 (LW/D)	hadgem1_A1B (MW/D)
Count of Times Deviation Occurred	12	17	5	6	9	20	49	22
Delta from USBR Observed Historic	0	5	-7	-6	-3	8	37	10

Each of the six HD 2020 climate change projections generally resulted in what would be expected. Drier climate projections (e.g., LW/D and MW/D) had increased deviations from historical conditions than did wetter projections. Similar predictable patterns were observed in the HD 2040 climate change projections as well. Similar patterns were observed in each HD scenario for the remaining two requirements outlined in Section 4.2.1.2.5. For example, Requirement 2 states that a combined flow on the Deschutes River near Culver gage (CULO) plus Crooked River below Opal Springs (CROO) must be greater than or equal to 1680 cfs.

Using the surrogate flow of 103,230 acre-feet for the month of October, results showed that increased deviations at CROO and CULVE (summed) were observed in drier climate projections. Similar results at the PRVO site were observed as well.

Because BiOp and ESA deliveries are generally given a higher priority in the Modified Flows DPM, these ESA and environmental objectives are generally met in the model. As indicated in this analysis, there were times when the model indicated no water was available either in the reservoir or in the channel during extremely dry conditions in the future. Further study and a daily model would be needed to better understand the actual daily requirements as outlined in the BiOp, but the patterns suggest that during dry conditions, water availability may be an issue.

4.2.3 Summary

Six HD climates from the 2020s, six HD climates from the 2040s, and six Transient climates were evaluated in the Deschutes River subbasin. The HD scenario represented a change from historical conditions while the transient scenario represented a time evolving climate extending to 2099. In all of the climate change projections and in both the HD and Transient scenarios, a warmer future climate was indicated in the Deschutes River subbasin, increasing from 0.5 and 1.5 degree Celsius in annual mean temperature in the HD 2020 scenario and between a 1 and 3 degree Celsius increase in the HD 2040 scenario.

Predicted changes in precipitation reflected either wetter or drier future conditions. The HD 2020 climates change in mean annual precipitation from historical precipitation varied between a 5 percent decrease and almost 10 percent increase in precipitation. In the HD 2040 climates, the range was even larger from between almost a 10 percent decrease to a 15 percent increase.

For the Transient scenarios, temperature results were presented using the ensemble median of all six Transient climate change projections. Predicted increases in the annual mean temperature ranged from 0 to nearly 10 degrees Fahrenheit from the mid-1950s and 2099 in the Deschutes River subbasin were shown. However, the ensemble median for precipitation of the six transient climate projections generally remained unchanged. More information about the details of the climate projections selected and the changes that resulted can be found in the Part I Report.

The potential impact of climate change was evaluated using the Naturalized Flow DPM and the Modified Flow DPM. Inflow, generated by the UW CIG VIC hydrologic model, was evaluated for the 12 HD future climates using *perfect* and *imperfect* forecasting and in the Transient future climates, using only *perfect* forecasting. The HD results were compared to simulated historical flow generated by the VIC hydrologic model as well.

The Naturalized Flow DPM indicated that the VIC simulated flows were greater in total volume for the period of record than Reclamation naturalized flows. In addition, large fluctuations in annual average volumes between VIC simulated flows and Reclamation naturalized flow was found. This weak calibration between datasets may indicate that it is possible that the wetter climates over predicted water availability and the drier climates underestimate the extent of the dry volumes. As suggested in Section 2, modeling ground water dominated systems with a more appropriate model other than VIC and improved calibration to Reclamation naturalized flow data would likely narrow these differences.

The Modified Flow DPM was used to evaluate five metrics in the Deschutes River subbasin including inflow to reservoirs, storage, flow in the Deschutes River and in the Crooked River, surface water delivery, and Reclamation's ability to meet established ESA objectives. The Modified Flow DPM was used to evaluate these metrics and a summary of the results, by metric, follow:

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. In the HD climates, inflow into Lake Billy Chinook and into the three reservoirs on the upper Deschutes River increased above historical conditions. In addition, the peak of the inflow magnitude shifted at least one 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 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.

End-of-Month Storage

End-of-month storage for the Prineville and Ochoco reservoirs on the Crooked River, for the Wickiup, Crescent, and Crane Prairie reservoirs on the upper Deschutes River, and in total at Lake Billy Chinook on the Deschutes River was evaluated. Refill in both HD scenarios was higher than historical refill levels from October through March or April, but then increased reservoir drafts 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.

Flow

Flow in the channel was evaluated at two locations: one on the Crooked River upstream of its confluence with the Deschutes River and one upstream of Lake Billy Chinook on the Deschutes River. Generally, flow on the Crooked River upstream of its confluence increased in only the wetter climates and decreased in the neutral or dry climates. The driest climates had the highest decreased 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 flow 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. The ensemble median of all six Transient climate projections suggested only a slightly decreasing trend line in the flow along the Crooked River. However, an increasing flow trend line was shown on the Deschutes River above Lake Billy Chinook. It is unclear why this trend is occurring.

Surface Water Delivered

Surface water delivered was summed for all demands on the Crooked River, for those on the upper Deschutes River and then for all demands in the total system. 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, which had the driest climate models used, surface water delivered was be less than historical deliveries for the entire irrigation season. The change in supply occurs because of the shift to an earlier timing of peak flow runoff and a decrease in late summer instream flows. Reservoirs start drafts (removing water from the reservoir) earlier and are relied upon more heavily in the summer and late fall. Predicted changes appear 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.

ESA Environmental Objectives

In the Deschutes River subbasin, there are three ESA objectives (detailed in the 2005 Biological Opinion) and 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 Modified Flows DPM was a monthly model, a surrogate approach had to be developed to evaluate the potential impacts of climate change on these requirements. This approach evaluated the monthly equivalent of the ESA requirements for the month of October only. 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.

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 Section 4.2.2.1, forecasting quality done as part of the Deschutes River subbasin analysis was poor with r^2 values below 0.4 at most forecasting locations. This poor quality is consistent with real-time reservoir operations. Because very few reservoir operating decisions are made based on forecasts alone, it is not surprising that the model output was not significantly impacted either.

4.3 Snake River Subbasin above Brownlee Reservoir

4.3.1 Metrics

4.3.1.1 Naturalized Flow Snake Planning Model (SPM)

Naturalized flow simulations were completed using the Naturalized Flow Snake Planning Model (SPM) on the Snake River subbasin above Brownlee Reservoir. Comparisons were made between the natural flow volume generated by Reclamation and those simulated natural flows generated by the VIC hydrologic model and provided by the UW CIG.

4.3.1.2 Modified Flow Snake Planning Model

For the modified flow SPM (e.g., model with reservoirs, demands) comparisons, similar metrics were used in the Snake River system that were used to evaluate the potential climate change projection impacts in the Deschutes River subbasin, but with the addition of flow augmentation. The upper Snake River attempts to release up to 478,000 acre-feet (or 478 KAF) of water for flow augmentation every year. The water is to aid migration of ESA-listed juvenile salmonids in the lower Snake River and lower Columbia River.

The metrics from the VIC HD simulated future climate change projection results were compared to VIC simulated historical modeling results. In the Transient scenario, overlapping time periods with the HD results were also reported.

4.3.1.2.1 Inflow to Major Reservoirs

Inflow volumes to major reservoirs in the upper Snake River above Brownlee Reservoir (Figure 6) were summed for the purposes of comparing scenario results and 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. The inflow volumes were computed to illustrate general trend information within the Snake River system, between river systems or between climate change projections within the HD or Transient scenarios.

Inflows are totaled for each reservoir group or major subbasin (i.e., Boise River, Payette River, and the upper Snake River above Milner Dam, above Minidoka, and above Brownlee Reservoir) on a monthly time step and reported for the entire period of record. Because most of the reservoirs in the Snake River subbasin are in series on the river, the inflow presented here is a cumulative summation of reservoir inflow. This means that the volume of inflow to each reservoir group is not the true summation of inflow to each individual reservoir, but a cumulative summation of inflow to all reservoirs in that reservoir group. This approach allows general trend comparison between the VIC simulated historical and simulated future climate projections. Comparison of the absolute value or volume for an individual reservoir is not appropriate.

4.3.1.2.2 End-of-Month Storage at Major Reservoirs

As with inflows, end-of-month storage volumes were evaluated for the entire Snake River subbasin above Brownlee Reservoir. End-of-month storage is the remaining volume of water within each reservoir or system of reservoirs after water releases have been made based on inflow, irrigation demands, flood control, and current operational constraints. These end-of-month reservoir volumes are summed for each defined reservoir group (i.e., Boise River, Payette River, and the upper Snake River above Milner Dam, above Minidoka, and above Brownlee Reservoir) above Brownlee. Relative changes in reservoir storage between VIC simulated historical output and VIC simulated future climate projections under 2010 operational protocols of the system are compared.

4.3.1.2.3 Flow at Key Locations in the Subbasin

Several river flow locations were identified to compare results. These selected locations were chosen because they are used in operational decisions or considered information in other studies on the Snake River. Those evaluated for the Snake River included flow at Heise and Minidoka, on the Boise River at the confluence with the Snake, and on the Payette River at the confluence with the Snake. This evaluation provided patterns of flow through the period of record for both the HD and Transient projections.

4.3.1.2.4 Surface Water Deliveries

Surface water delivered (i.e., storage and natural flow) is defined as irrigation demands minus irrigation demands not met and was summed in a similar manner as described in the reservoir storage section. The summations include all modeled diversions above Brownlee Reservoir to assess the trend in surface water delivered. Water right holders' priority dates for senior and junior appropriators are included in the model such that water delivery is appropriately distributed. Similarly, storage water right holders and natural flow water right holders are differentiated in the model to represent water delivery operational protocols.

4.3.1.2.5 ESA Flow Augmentation for Anadromous Species

Reclamation began providing flows from the upper Snake River to aide in juvenile salmonid migration in 1991. Since 1992, consultations between Reclamation and NOAA Fisheries Service under Section 7(a)(2) of the ESA have included the consideration of flow augmentation from Reclamation's upper Snake Projects to augment flows in the lower Snake and Columbia rivers through acquisitions from willing sellers. Also as required by Section 8 of the Reclamation Act of 1902, flow augmentation must rely on State protection of augmentation flows under the provisions of State water law.

The 2008 NOAA Fisheries BiOp indicates that up to 487 KAF of water will be delivered to Brownlee Reservoir to benefit the migration of salmonids. If the full 487 KAF is not available through a willing seller in a particular water year, Reclamation can acquire water from their power headspace. However, if power head space, as defined within specific reservoirs, was needed to provide augmentation water, then the maximum augmentation volume that could be provided is 427 KAF.

In general, augmentation storage releases are made primarily during May through July. Some storage releases may occur in August as a result of water year type or operational constraints. Natural flow rights counting towards augmentation are provided in the April through August period.

Rental water is a substantial portion of the total augmentation water identified in the Snake River system. Actual augmentation volumes are predicated on the assumption that a willing seller (or renter) of reservoir storage water exists. The modeling for this study attempted to capture the historical pattern of those water districts that rented water to Reclamation for flow augmentation. This historical distribution assumption also incorporates the available rental water volume as a function of water year type and reservoir storage. It was assumed that the historical distribution and quantity rented to Reclamation would continue in the future under these model configurations.

The 487 KAF of salmon flow augmentation from the Snake River is one of several regional supplies of augmentation water used to help improve conditions for ESA-listed salmon and steelhead. In addition to Reclamation's Snake River supplies, other sources for flow augmentation within the Columbia River Basin include up to 1.2 MAF from Dworshak Reservoir and up to 237 KAF from Brownlee Reservoirs. Up to 2.428 MAF from reservoirs at Grand Coulee, Banks Lake, Libby, and Hungry Horse dams located on the upper Columbia River are released to help meet flow objectives on the lower Columbia River at McNary Dam. Up to 1.0 MAF from Canadian storage (negotiated annually) may also be available. However, for this modeling effort, the Snake River above Brownlee Reservoir flow augmentation metric was analyzed.

The accounting for flow augmentation from the Snake River above Milner takes place at Milner gage (river mile 638.7). During the flow augmentation season, Reclamation makes releases from American Falls Reservoir, which pass through Minidoka and Milner Dams. Reclamation's releases from Payette and Boise River systems are measured at Letha and Middleton gages, respectively. All of Reclamation's flow augmentation water is delivered to the Snake River at Brownlee Reservoir. That flow must pass through Idaho Power Company's Hells Canyon Dam before salmon and steelhead are benefited. Reclamation's flow augmentation flows are most important in the Snake River reach between the toe of Hells Canyon Dam to the confluence of the Snake and Clearwater Rivers. At this location a significant volume of Clearwater River water released from Dworshak Reservoir enters the river (Reclamation 2007).

Analysis of each climate change projection included a comparison of potential impacts on flow augmentation requirements above Brownlee only.

4.3.1.2.6 ESA for Resident Species and Other Environmental Objectives

Environmental objectives and ESA operational constraints for resident species have been given a higher priority in the Snake MODSIM model than other uses. Though the targets listed below are not necessarily first priority in the model, a higher priority means that the model will make automatic adjustments in storage or flow. For example, adjustments may be made by the model to ensure compliance with resident species ESA and other environmental objectives. These water quality targets and ESA objectives include:

- Targets (water quality and other)
    - Palisades Reservoir - minimum flow of 800 cfs below Palisades Dam for resident fish target during the winter (November through March) as recommended by the Idaho Department of Fish and Game.
    - Lake Cascade – preferred level of 400 KAF or more by the end of August for water quality.
    - American Falls Reservoir – minimum pool of 100 KAF for water quality purposes.
- ESA
    - American Falls Reservoir – a minimum pool of 50 KAF for ESA-list snail[18] habitat (USFWS 2005).

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[18] The snail Utah valvata (*Valvata utahensis*) was delisted by the USFWS during the course of this study (75 FR 52272). The effects of this delisting are not known at this time.

- Lake Walcott – minimum pool level of 4239.5 feet for ESA-listed snail habitat[19] in and along the reservoir as directed by the 2005 BiOp (USFWS 2005).
- Arrowrock Reservoir – minimum pool requirements for bull trout considerations as directed by the 2004 BiOp (NOAA Fisheries Service 2004):
    - Minimum pool of elevation 3,111 feet, July through September
    - Minimum pool level of elevation 3,100 feet, September 15 through October 31
    - Minimum pool level of elevation 3090.5 feet, year-round

4.3.2 Results

Results are summarized for the natural model simulations for the HD method transient methods. The natural flow model is presented to illustrate the model calibration to the VIC historical hydrology. This scenario represents the baseline from which the other model results will be compared. Once the model was calibrated to the historical hydrology, the climate projection hydrology was incorporated as new boundary conditions for the model scenarios.

4.3.2.1 Naturalized Model Results

Results from the Naturalized Flow SPM simulations indicated that VIC simulated historical model results correlated well with USBR observed historical model results on an average period monthly basis.

Table 9 shows the period average monthly volumes above Brownlee Reservoir. On a period average monthly basis, VIC simulated historical modeling results correlated well with Reclamation observed historical model results. Variations in period monthly average were generally less than 1 percent with the greatest increase in volume of 1.6 percent in July, but overall volume between VIC and Reclamation was only 0.17 percent. Likely due to the predominance of snowmelt driven watersheds in the Snake River subbasin, the VIC model was able to generate data that was similar in pattern to the observed conditions.

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[19] See previous footnote concerning 75 FR 52272.

Table 9. Total, live, and active capacity of major reservoirs in the Snake River subbasin.

	Total Capacity	Live Capacity	Active Capacity	Source of Data	Owner
Jackson	847,000	847,000	847,000	RCA	Reclamation
Palisades	1,401,000	1,357,000	1,200,000	RCA	Reclamation
Island Park	135,585	135,585	135,205	RCA	Reclamation
Grassy Lake	15,452	15,182	15,182	RCA	Reclamation
Ririe	100,500	96,500	90,500	RCA	Reclamation
American Falls	1,671,300	1,671,300	1,671,300	RCA	Reclamation
Minidoka	--	210,000	95,200	RCA	Reclamation
Subtotal for above Minidoka on the upper Snake River	*4,035,252*	*4,332,567*	*4,054,387*		
Anderson	474,942	450,030	413,074	RCA	Reclamation
Arrowrock	272,224	271,710	271,710	RCA	Reclamation
Lucky Peak	307,040	264,000	--	USGS	Corps
Subtotal for the Boise River	*1,054,206*	*721,740*	*684,784*		
Payette Lake	35,008	--	--	MODSIM	Private
Cascade	693,000	693,000	646,500	RCA	Reclamation
Deadwood	153,992	153,992	153,992	RCA	Reclamation
Subtotal for the Payette River	*882,000*	*846,992*	*800,492*		
Total reservoir storage volume above Brownlee on the upper Snake River	**5,971,458**	**5,901,299**	**5,539,663**		

- The volumes provided do not include all storage facilities or Reclamation projects in the Snake River subbasin. They are meant to provide general, but sufficient information to determine the potential impacts of the climate change study in this subbasin.
- RCA: Reservoir Capacity Allocation Manual

Table 10. Percent difference of period average monthly volumes between VIC historical simulated data and Reclamation historical observed data in the Snake River subbasin above Brownlee Reservoir.

Month	Average of USBR Observed Historical Model Results	Average of VIC Simulated Historical Model Results	Percent Difference
Jan	974,185	977,183	0.31%
Feb	995,144	1,005,467	1.04%
Mar	1,460,500	1,457,829	-0.18%
Apr	2,206,319	2,200,101	-0.28%
May	3,506,372	3,495,541	-0.31%
Jun	3,197,716	3,194,215	-0.11%
Jul	1,486,863	1,510,489	1.59%
Aug	894,383	904,072	1.08%
Sep	846,478	848,968	0.29%
Oct	963,064	966,929	0.40%
Nov	848,247	847,582	-0.08%
Dec	932,690	934,528	0.20%
Grand Total	18,311,961	18,342,904	0.17%

Statistically, the monthly representation of the VIC model output was comparatively less than 0.2 percent; however, on an annual basis, the variation between the two datasets was greater in some years. Figure 67 shows the largest change in annual average volume occurred in 2008 of just more than 32 percent increase in the VIC historical simulated modeled resulted than the Reclamation historical observed model results. However, overall the positive volume increases averaged 11 percent while negative volume decreases averaged 8 percent.

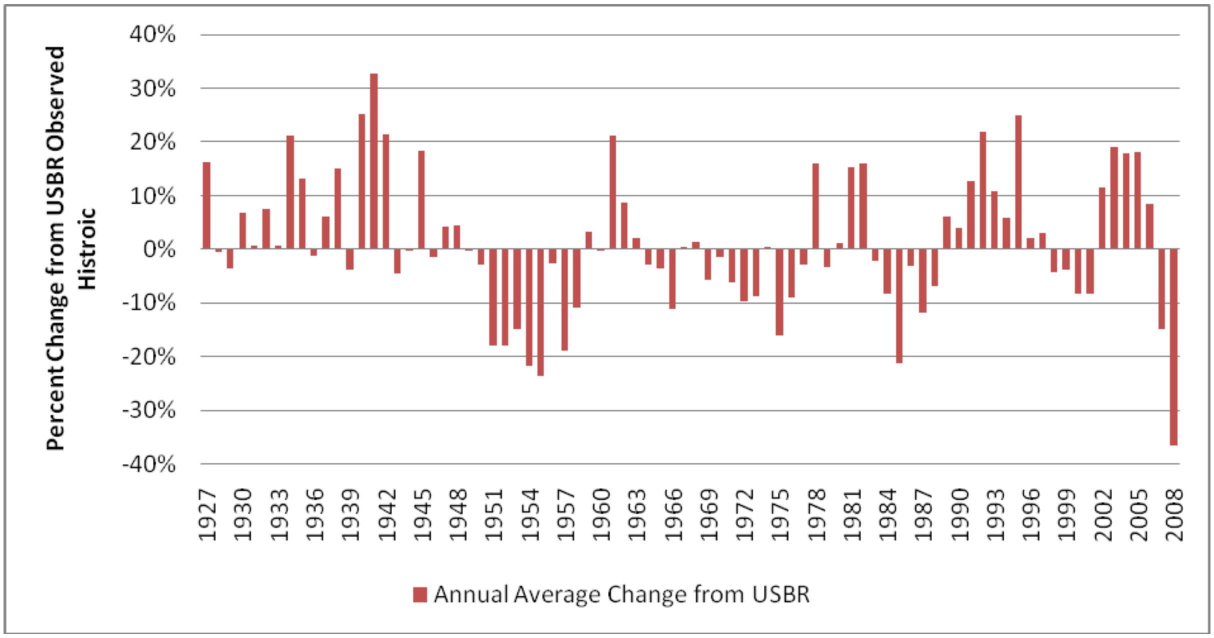


Figure 67. Annual average change in flow volume from USBR historical observed data at Lake Billy Chinook on the Deschutes River.

As with the Deschutes River modeling effort, when changes in adjacent monthly time steps varied greatly, model stability was an issue. To retain model stability and mass balance, adjustments of the local_gains and local_losses that were described in Section 3.2.2.3 to reduce the large swings in water volume between adjacent time steps were made. Because the monthly time series output from VIC hydrologic model do not closely match Reclamation's naturalized time series output, direct comparisons between years should not be made on a time series basis.

4.3.2.2 Modified Flow SPM Results

Climate change projections from the Snake River subbasin were generally wetter than originally anticipated (Part 1 Report, Section 4.5). The Snake River subbasin is part of the OXBOW and ICEHA subbasins in the climate change scenarios (Figure 41 and Figure 42). The global climate models selected for inclusion in this study were selected at a Columbia River Basin scale rather than at a subbasin scale. This selection approach inadvertently resulted in most of the climate change projections being wetter in the Snake River subbasin than current conditions.

In the Part 1 Report, Section 4.5, runoff results that were reported for 3 of the 28 VIC inflow locations on the Snake River subbasin are repeated here, including SNKHE (Figure 68), PAYET (Figure 69), and BROWN (Figure 70). As these figures show, four of the six climate change projections suggest wetter conditions (LW/W, MW/W, MC, and C climates). While the two dry climate change scenarios (e.g., LW/D and MW/D) are drier, the change in total annual runoff is generally less than 5 percent from Reclamation observed historical conditions. The selection of wetter climates in the Snake River subbasin is an artifact of the selection process (Part 1 Report, Section 3.3), but it should not be misconstrued to mean that the Snake River subbasin is only predicted to be wetter in the future or conversely, that drier climates are not predicted in the Snake River subbasin. It just so happens that in selecting six climate change scenarios that cover a wide range of possibilities from wet to dry or warm to less warm for the Columbia River Basin as a whole, the chosen scenarios were generally wetter in the Snake River subbasin on an annual average basis.

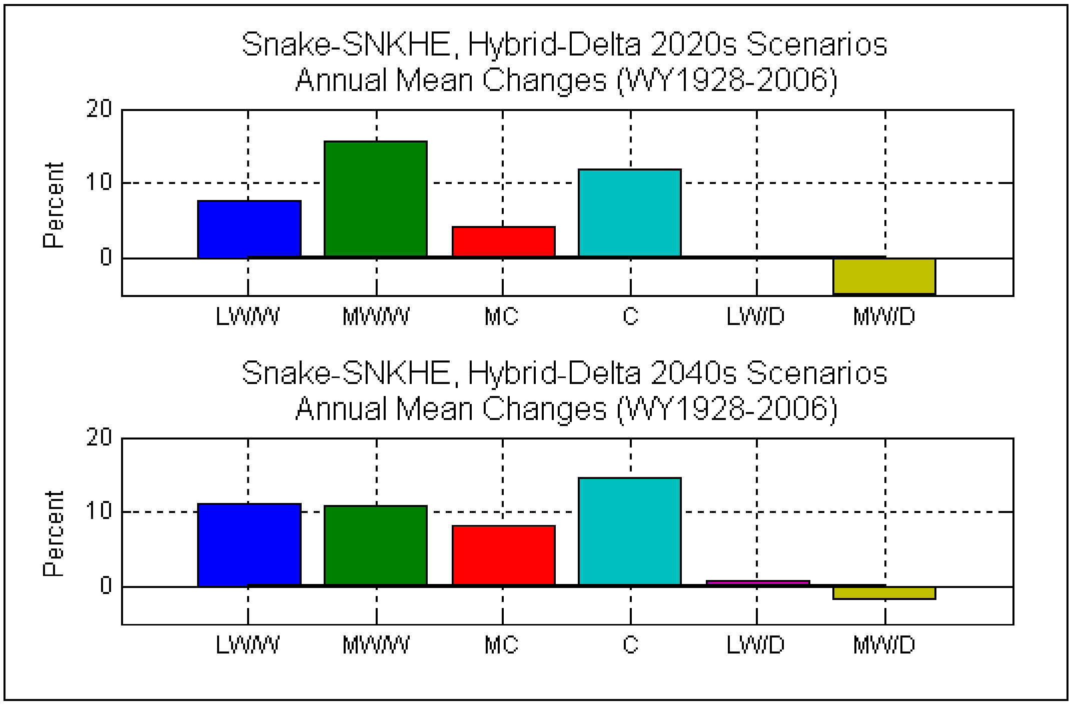


Figure 68. Snake River subbasin runoff under Hybrid-Delta 2020 and 2040 climate scenarios: change in annual mean at SNKHE.

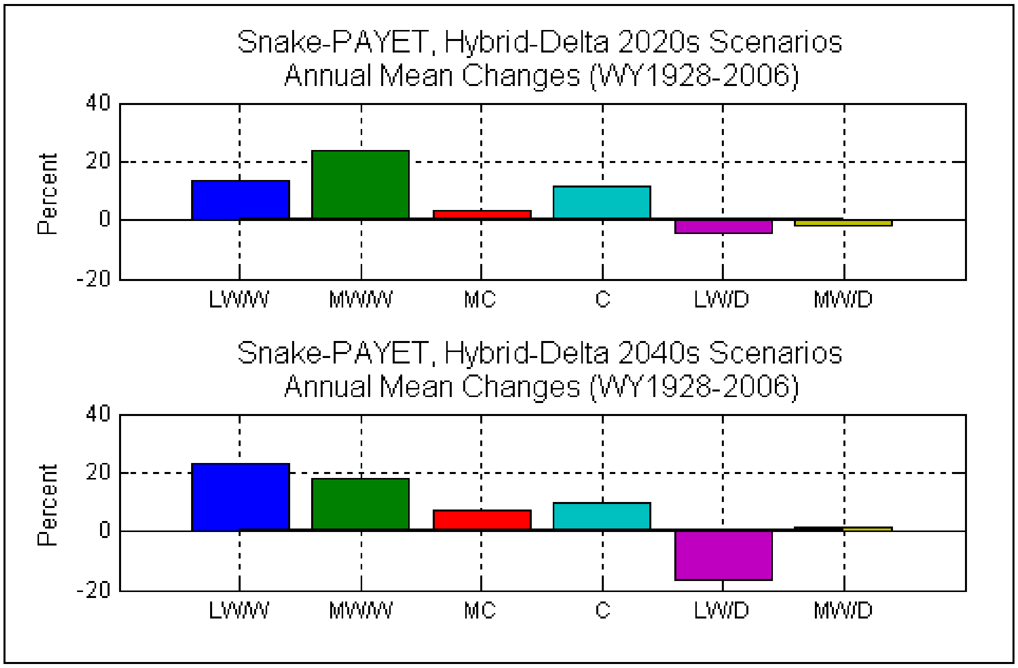


Figure 69. Snake River subbasin runoff under Hybrid-Delta 2020 and 2040 climate scenarios: change in annual mean at PAYET.

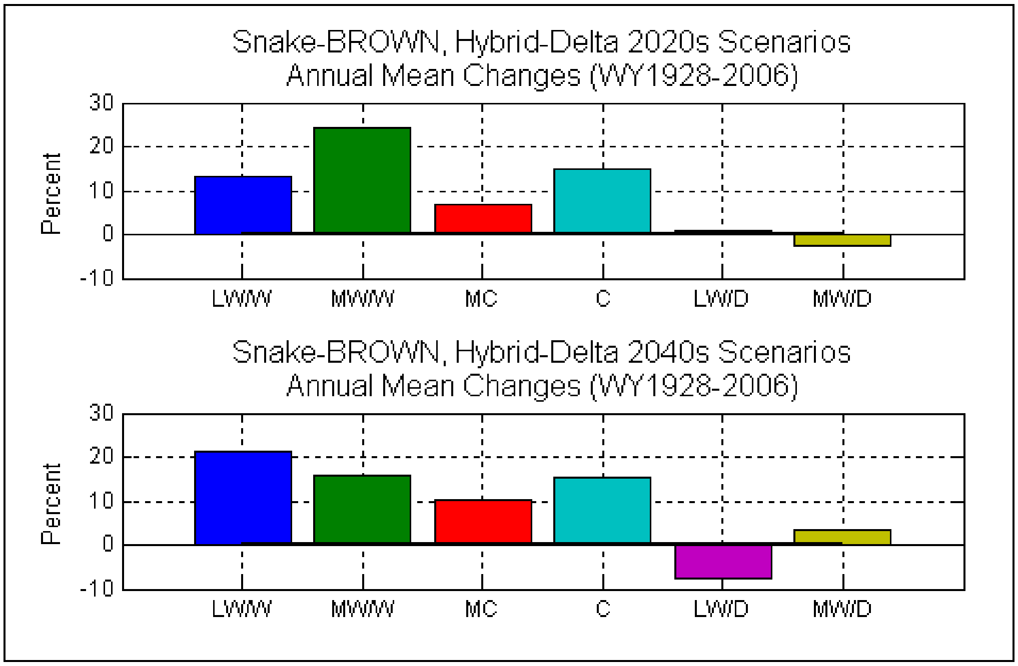


Figure 70. Snake River subbasin runoff under Hybrid-Delta 2020 and 2040 climate scenarios: change in annual mean at BROWN.

While the overall VIC simulated historical runoff results reflect wetter conditions, in the HD 2020 scenario, the higher (wetter) bounding projection alternated between either the more warming/wetter (MW/W) or central (C) and the lower (drier) bounding projection alternated between the either the LW/W or MW/D climates. The HD 2040 wetter scenarios generally included the LW/W or the C climate and the two drier climates for the lower boundary depending on the location of the VIC inflow point.

Model results were generated for several locations on the Snake River, but were generally reported for areas above Milner, above Brownlee Reservoir, and at the Boise and Payette rivers confluence with the Snake River. If changes between the above-Milner results and above-Brownlee results follow similar patterns, then only above-Brownlee results are reported. As with the Deschutes River subbasin section, results are reported by metric to evaluate potential impacts to current water delivery objectives as a result of climate change. Operational protocols of the system remained unchanged. The three questions posed in Section 5.0 are addressed for each metric. An overall summary of the metric results is provided at the end of the section.

4.3.2.2.1 Inflow to Major Reservoirs

4.3.2.2.1.1 Typical Conditions and Variability

Monthly inflow above Brownlee is shown in Figure 71 as described in Section 4.3.1.2.1 (note that inflow is calculated not by individual reservoir, but by reservoir group so suggested trends are reported, not actual values for this metric). Increased volume of inflow is projected in all of the climates and in both HD scenarios. As with the Deschutes River pattern that showed a shift in peak flow timing to earlier in the year, the peak timing of three of the projections also shift to earlier in the year in the HD 2020 scenario. Changes in monthly period-median flows in this scenario vary with the greatest change in inflow in the MW/W projection and the least variation in inflow in the MW/D projection when compared to the VIC simulated historical condition in the HD 2020 scenario.

In the HD 2040 scenario, all of the projections indicate both earlier (from June to May) and higher inflows during the cooler months (December to May) to the major reservoirs above Brownlee Reservoir. Almost all of the projections suggest increases in monthly period-median inflows above VIC simulated historical inflow. At the peak in the HD2020 scenario, an increase of about 15 percent above the historical peak flow was indicated, with a slightly smaller increase observed in the peak inflow of the projection in the HD 2040 scenarios. In addition to that, decreased inflow is observed during the summer months when compared to the same climates in both HD scenarios. Similar patterns were given in the scenarios for inflow to and above Milner Reservoir (not shown).

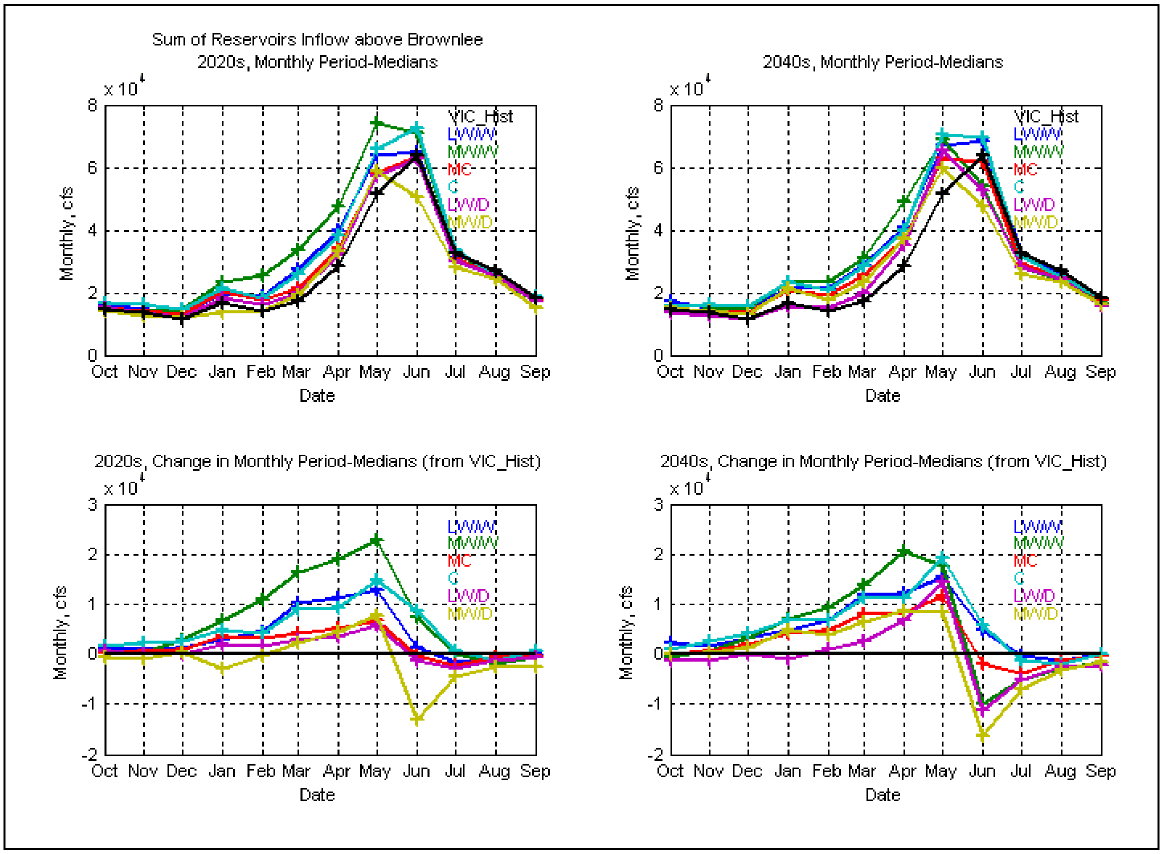


Figure 71. Total (top panel) and change in period-median monthly inflows (bottom panel) from VIC simulated historical above Brownlee Reservoir in the upper Snake River subbasin.

Figure 72 shows that on an annual average basis, the average inflow (represented by the line in the middle of each box) to reservoirs above Brownlee Reservoir increases (from VIC simulated historical) in all but the LW/D projection in the HD 2020 scenario and in four of the six climate change projections in the HD 2040 scenario. However, while the overall annual inflow volume above Brownlee Reservoir is greater, the magnitude of volume or flow during a portion of the irrigation season is less, particularly during the months of June through September.

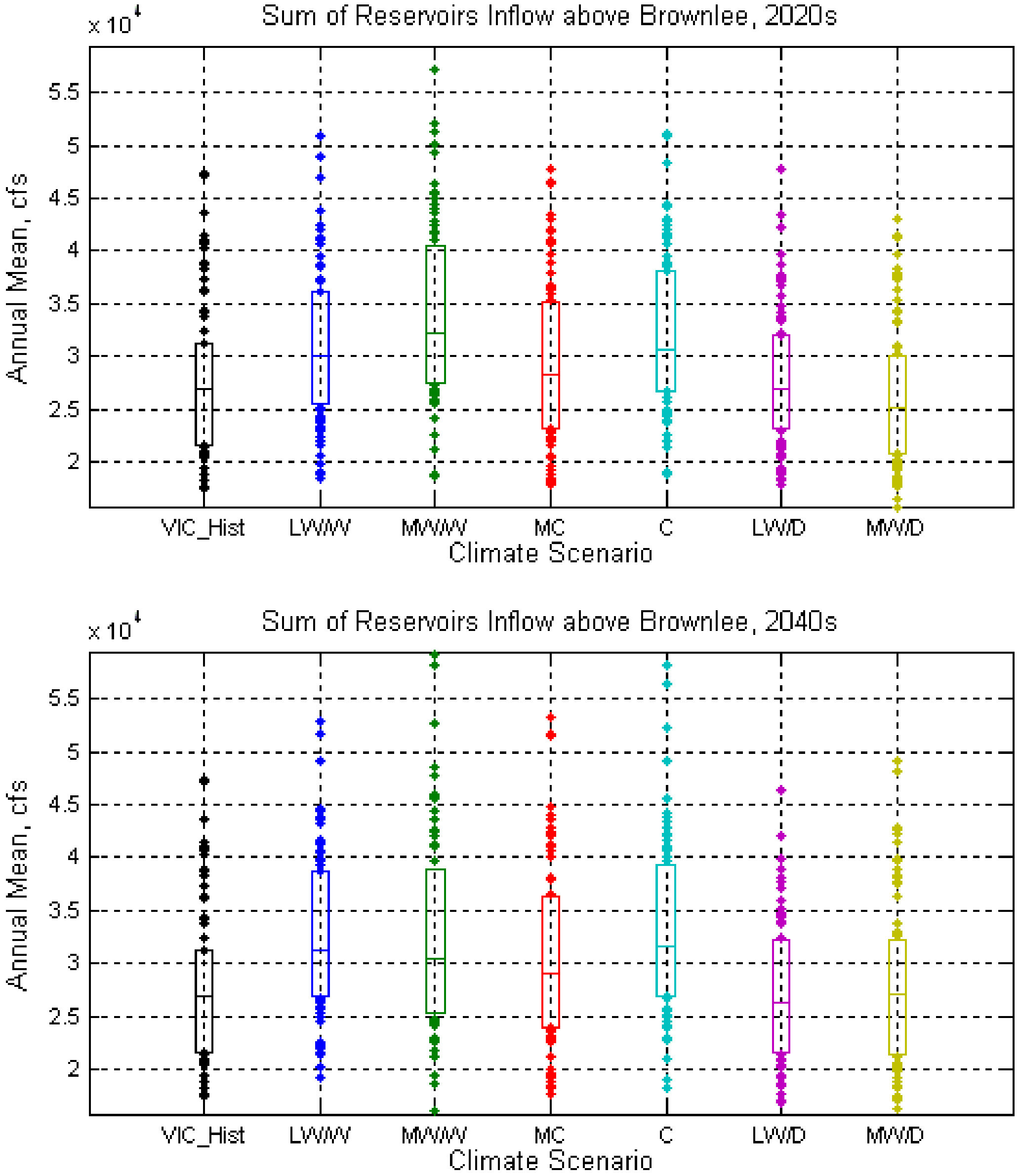


Figure 72. Annual average of monthly inflow for 81 years to reservoirs above Brownlee Reservoir on the Snake River in the HD 2020 and HD 2040 scenarios.

The peak of the monthly period median inflow on the Boise River reservoirs is greater in the VIC simulated historical condition (Figure 73). In general, peak inflow volume is not projected to vary much in any of the climate change projections except the MW/D projection. However, increased volume inflow occurs in all of the climate projections from January to June with the wetter projections in the Boise River reservoirs.

Minimal decreased inflow is predicted in all of the projections in the HD 2040 scenario except the MW/D projection when compared to VIC simulated historical. In the HD 2040 scenario, all of the projections show peak monthly period median inflow to the Boise River reservoirs to have the same timing as VIC simulated historical. However, greater decreased volume is occurs in all of the climate projections after the peak inflow in June through September.

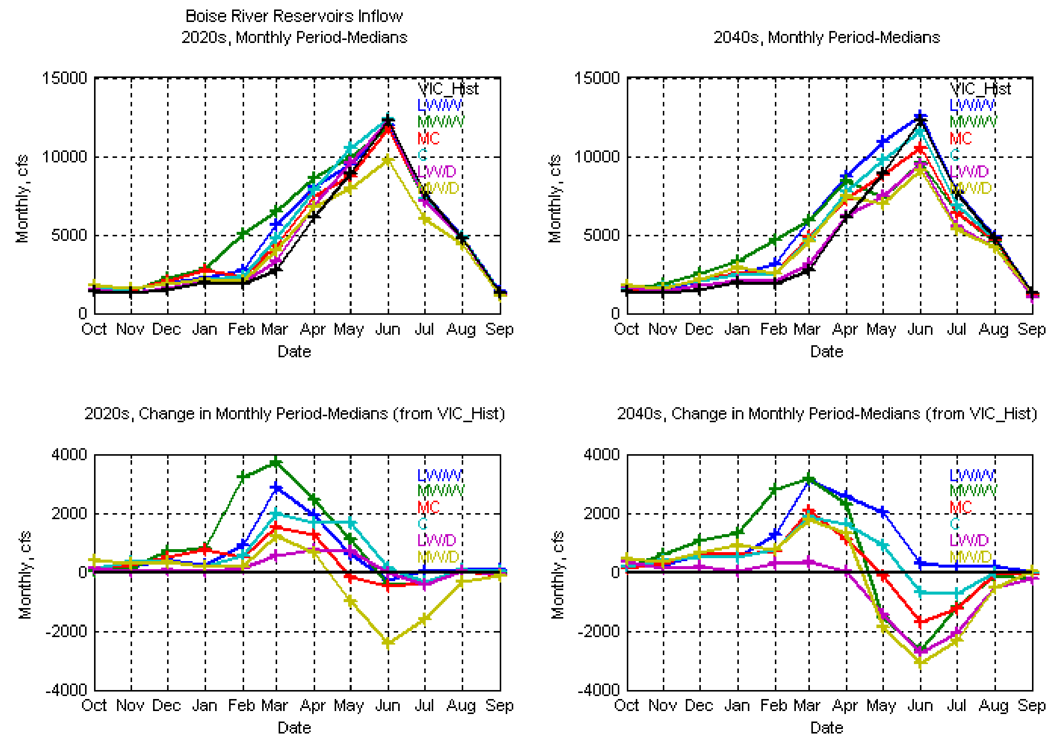


Figure 73. Total and change in monthly period-medians from VIC simulated historical on the Boise River in the Snake River subbasin.

On an annual average basis, change in inflow to the reservoirs on the Boise increases in all but the dry climates in both HD scenarios (Figure 74). Overall changes in inflow to reservoirs above the Boise River confluence with the Snake River in the HD 2020 scenario vary the most between the MW/W projection and the MW/D projection. As with the inflow to reservoirs above Brownlee Reservoir, the annual average inflow to reservoirs on the Boise River in the MW/D projection in the HD 2040 scenario is not expected to vary from the VIC simulated historical condition.

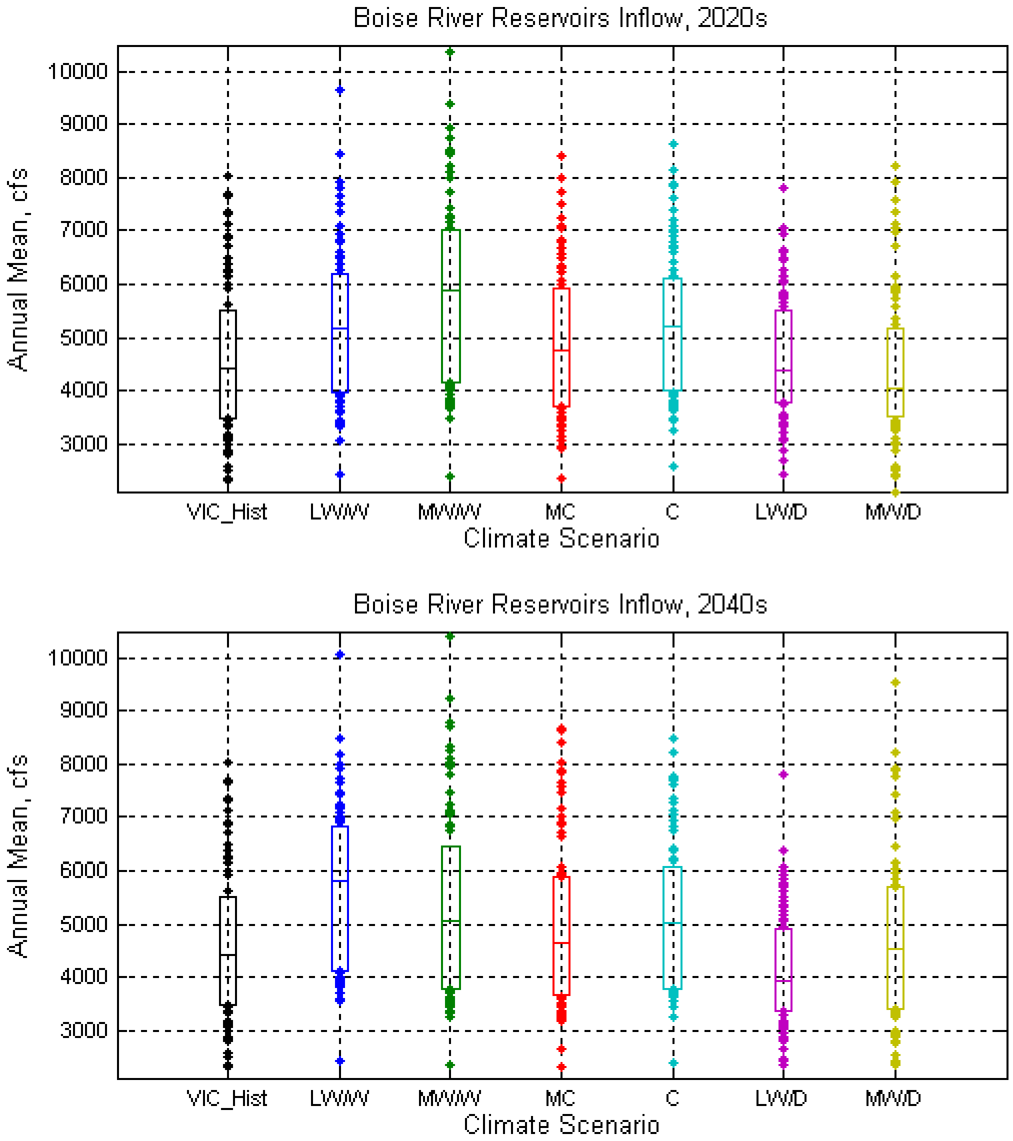


Figure 74. Annual mean of monthly inflow for 81 years to reservoirs on the Boise River in the HD 2020 and HD 2040 scenarios.

As in the Boise River results, the timing of the peak monthly period median inflow on the Payette River reservoirs does not vary much from VIC simulated historical inflow significantly. However, unlike the results reported for reservoir groups on the Boise River and the upper Snake River above Brownlee, the monthly inflow volume to Payette River reservoirs does not increase dramatically from the VIC simulated historical condition in either the HD 2020 or the HD 2040 scenario (Figure 75). Payette River reservoirs are predicted to experience decreased monthly period-median inflows in June in both HD scenarios.

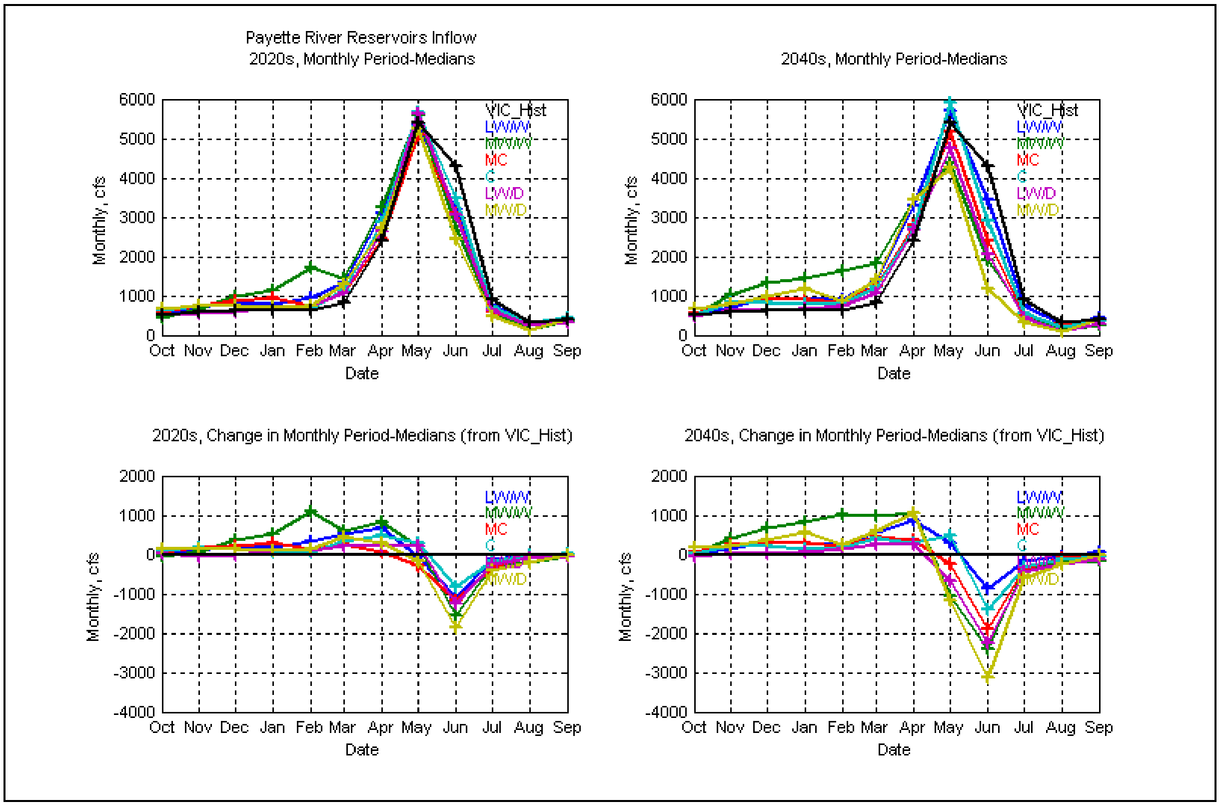


Figure 75. Total and change in monthly period-medians from VIC simulated historical on the Payette River in the Snake River subbasin.

As with the previous two subbasins, box plots were used to easily show inflow variability results and summarize operations variability within a climate and across climates. The bottom and top of the box represent the 25th and 75th percentiles, respectively, and the box midline represents the median or 50th percentile. On an annual mean basis (Figure 76), the 50th percentile change in inflow to the reservoirs on the Payette River does not vary significantly from the VIC simulated historical inflow in either the HD 2020 or the HD 2040 scenario. Increases in the wetter climate projections are predicted in both HD scenarios. In the HD 2040 scenario, the LW/D climate has the lowest inflow of all climates in both HD scenarios.

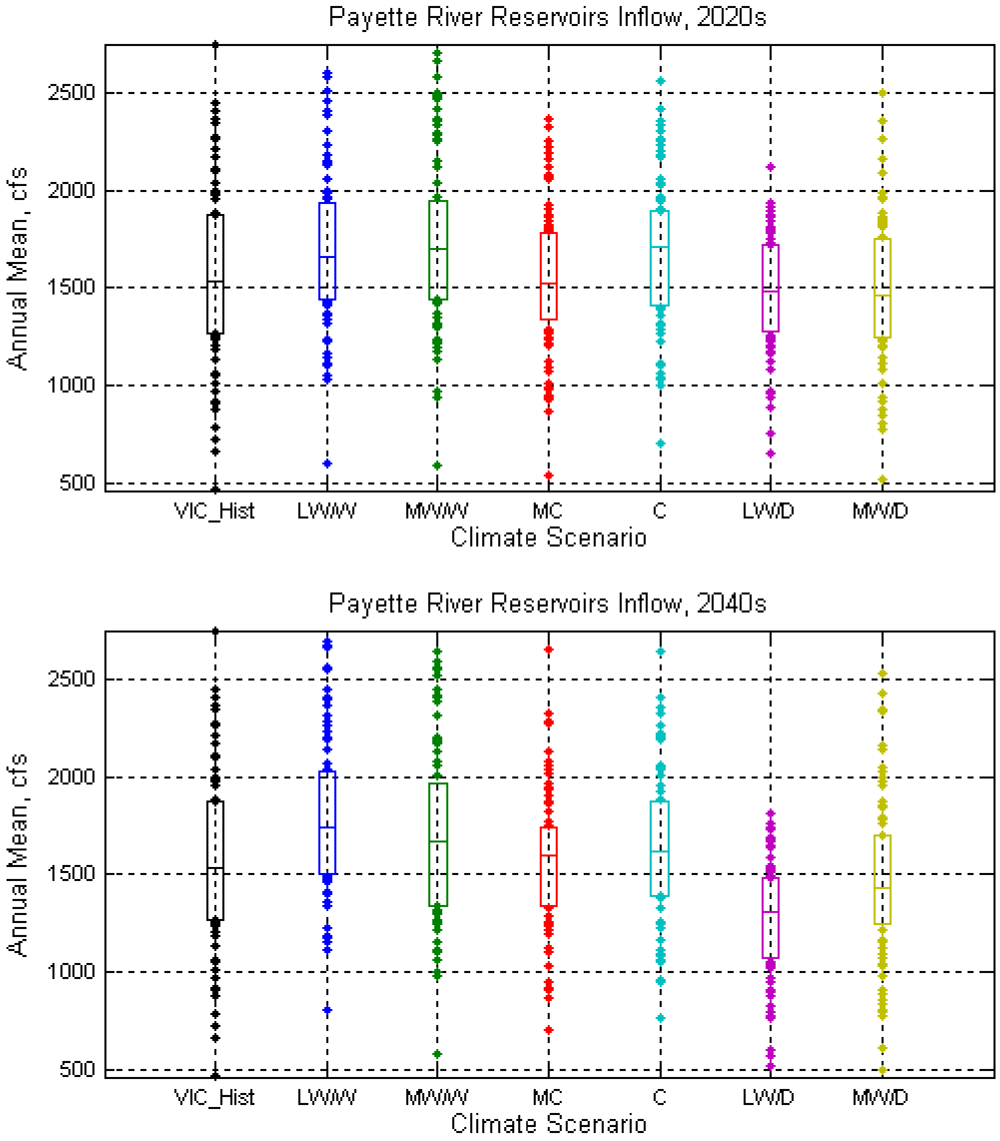


Figure 76. Annual mean of monthly inflow for 81 years to reservoirs on the Payette River in the HD 2020 and HD 2040 scenarios.

4.3.2.2.1.2 Effect of Forecasting Method Selection on Simulated Operations

As with the previous two subbasins to the Columbia River Basin, simulations were also conducted using *perfect* and *imperfect* runoff volume forecasting modes on the Snake River and as with the previous two subbasins, the results were similar. The *perfect* forecasting mode allows the model to set reservoir targets and irrigation demands knowing the exact volume of water entering the system during the forecast months. The *imperfect* forecasting mode allows for reservoir targets and irrigation demands to be determined on volumes of water, during the forecast period, with inherent errors, similar to real time operational procedures. The quality of the regression models for each *imperfect* forecast situation is significantly better than those reported in the Deschutes River. For the SNKHE location, the HD 2020 (Figure 77) and HD 2040 (Figure 78) quality as captured by coefficient of determination, r^2, was generally between 0.6 and 0.9 for any of the season issues (January through September). A higher r^2 number generally means a better fit of data to historical conditions.

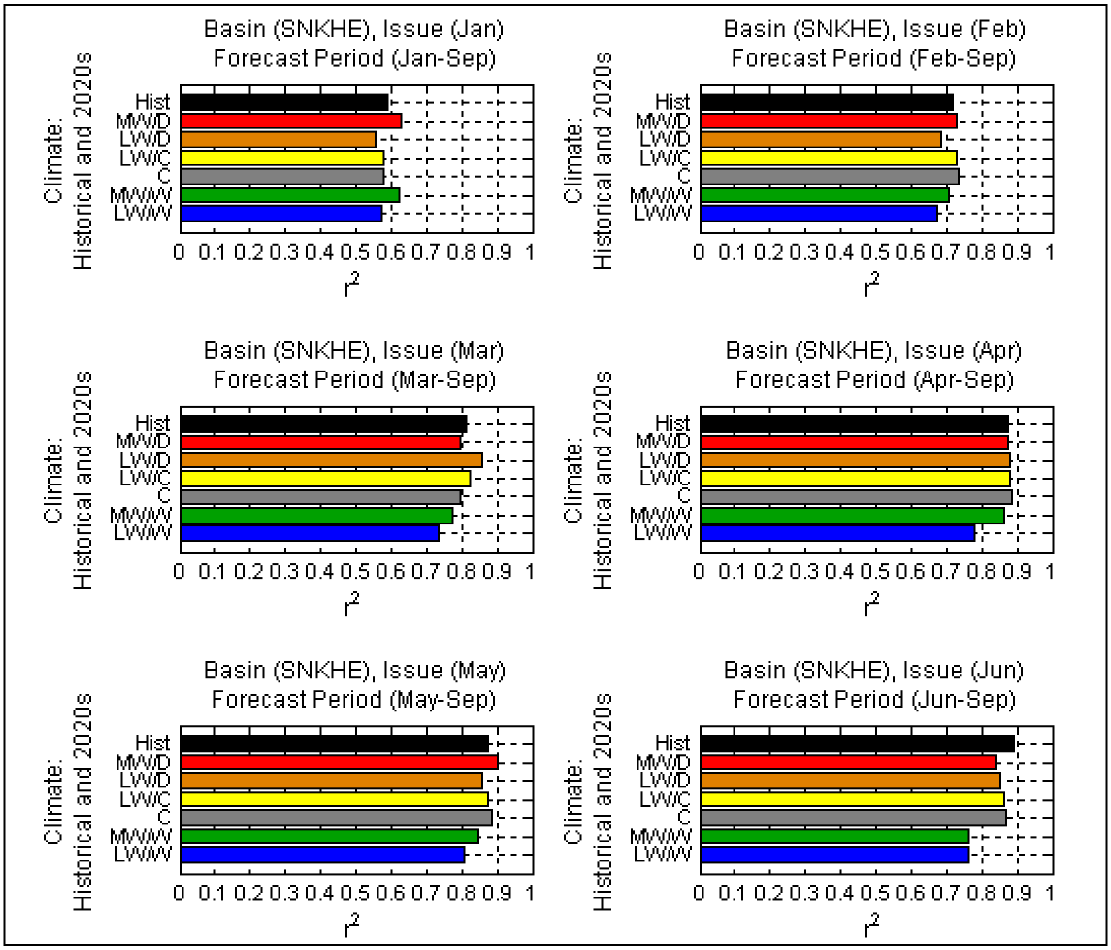


Figure 77. Quality of regression models (r^2) at Heise on the Snake River used to generate *imperfect* forecasts of seasonal runoff volume, historical and HD 2020s climates.

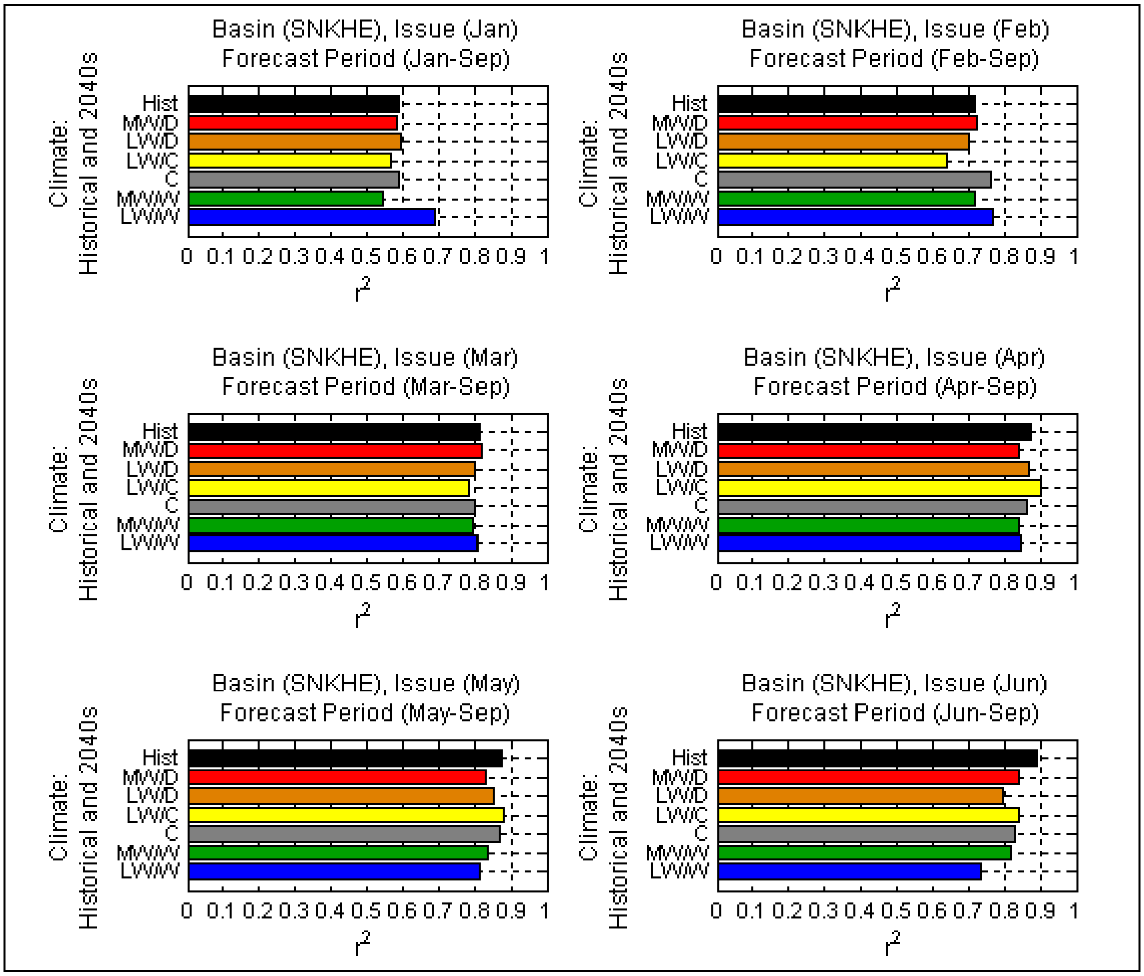


Figure 78. Quality of regression models (r^2) at Heise on the Snake River used to generate *imperfect* forecasts of seasonal runoff volume, historical and HD 2040s climates.

Even with improved quality of the forecasting when compared to the Deschutes River subbasin, the impact on the overall results was negligible. Figure 79 depicts results for the Snake River subbasin at Heise using *perfect* forecast mode and Figure 80 shows the results at the same location, but using *imperfect* forecast mode. Both total volume and change in monthly period-median values remained generally unchanged between the two HD scenarios and among any of the 12 climate projections.

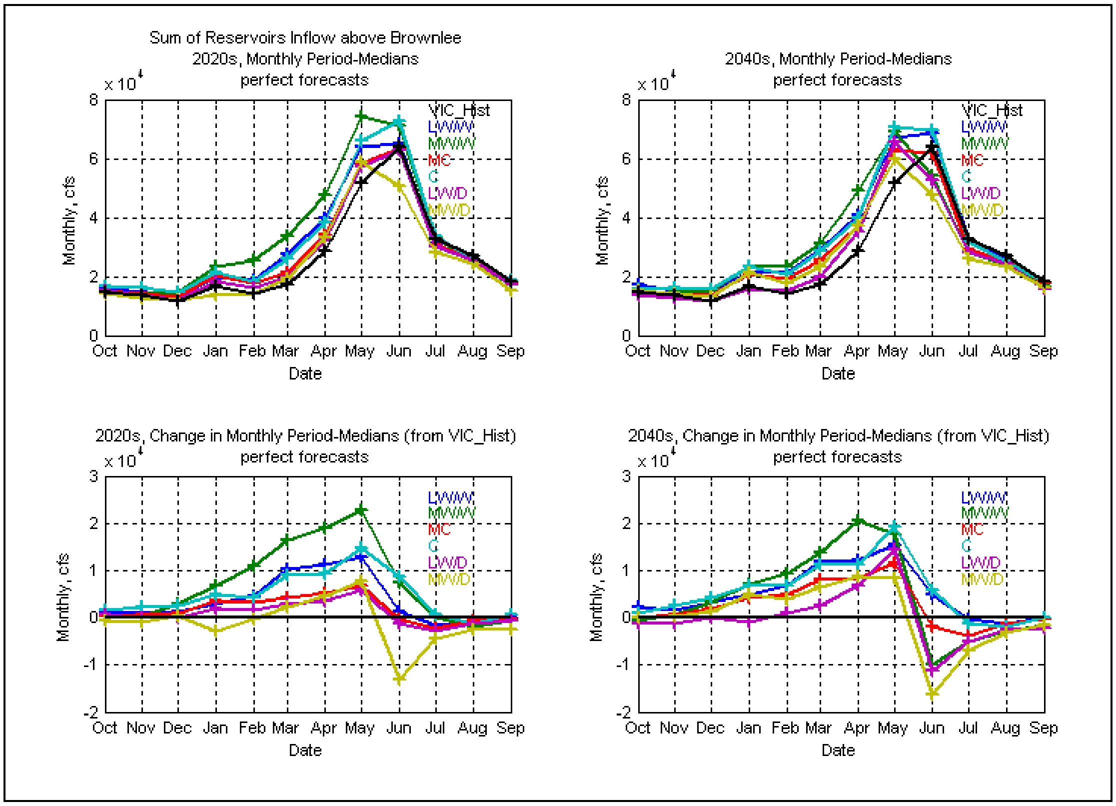


Figure 79. Total and change in monthly period-medians for the cumulative inflow to reservoirs above Brownlee in the HD 2020 and HD 2040 climates using *perfect* water supply forecast mode.

Because the results did not differ with forecasting mode selection, only *perfect* forecasting mode results are presented.

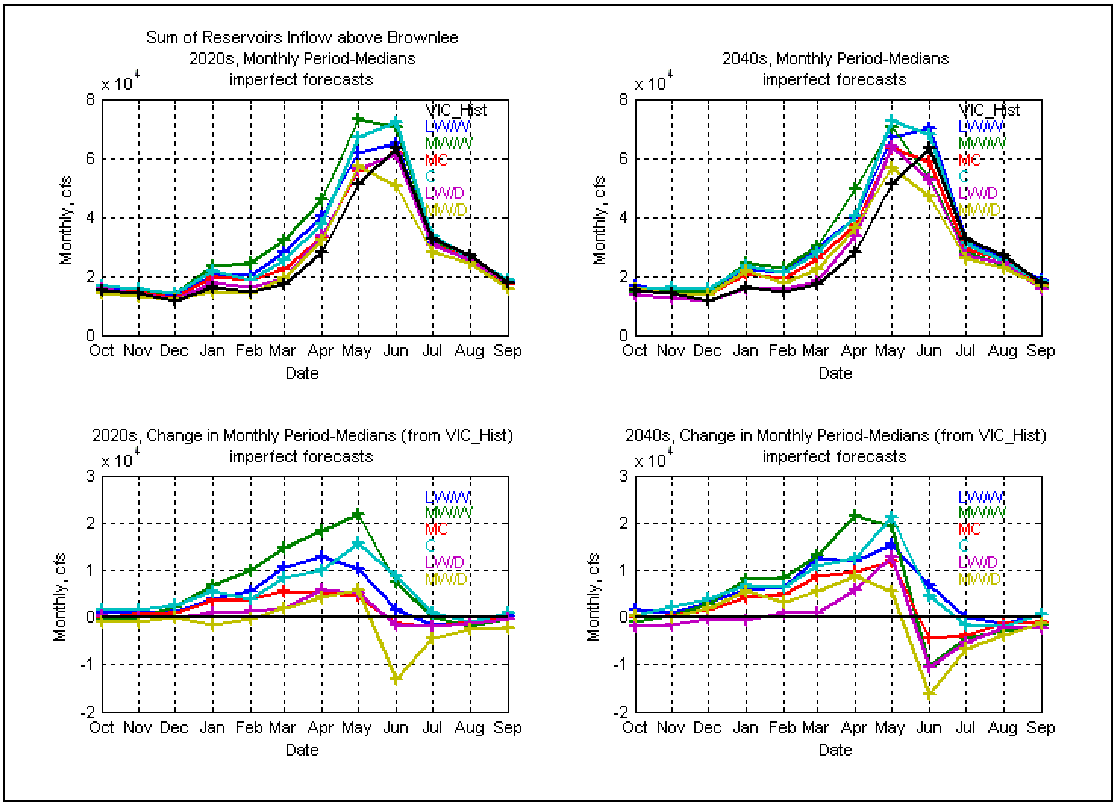


Figure 80. Total and change in monthly period-medians for the cumulative inflow to reservoirs above Brownlee in the HD 2020 and HD 2040 climates using *imperfect* water supply forecast mode.

4.3.2.2.1.3 Effect of Transient Climate Projections on Simulated Operations

In addition to determining if the type of forecasting mode (i.e., *perfect* or *imperfect*) had an impact on the results, six Transient (or time evolving) climate projections were also simulated to evaluate how inflow to Brownlee Reservoir may be affected. Inflow to reservoirs above Brownlee Reservoir on the Snake River and on each tributary were assembled for the 150-year time period through 2099. The sum of inflow to reservoirs on the Snake River above Brownlee is shown. The ensemble median trend (dashed black line) for the sum of reservoir inflow has a slight upward trend over time as shown in Figure 81. The reservoirs in the upper Snake and Boise rivers show this trend, but the ensemble median (dashed black line) inflow to the Payette River reservoirs shows a relatively flat trend over time (Figure 82).

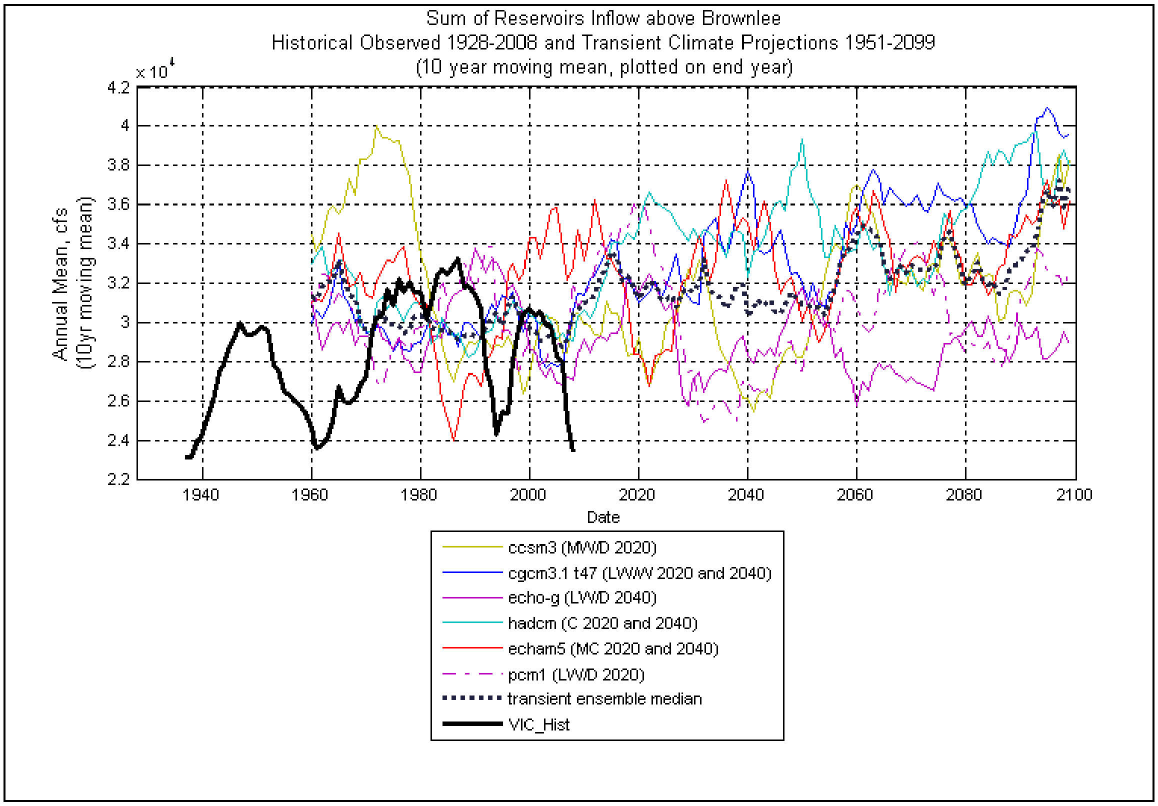


Figure 81. Transient 10-year moving average for 150 years of inflow all major reservoirs on the Snake River above Brownlee Reservoir.

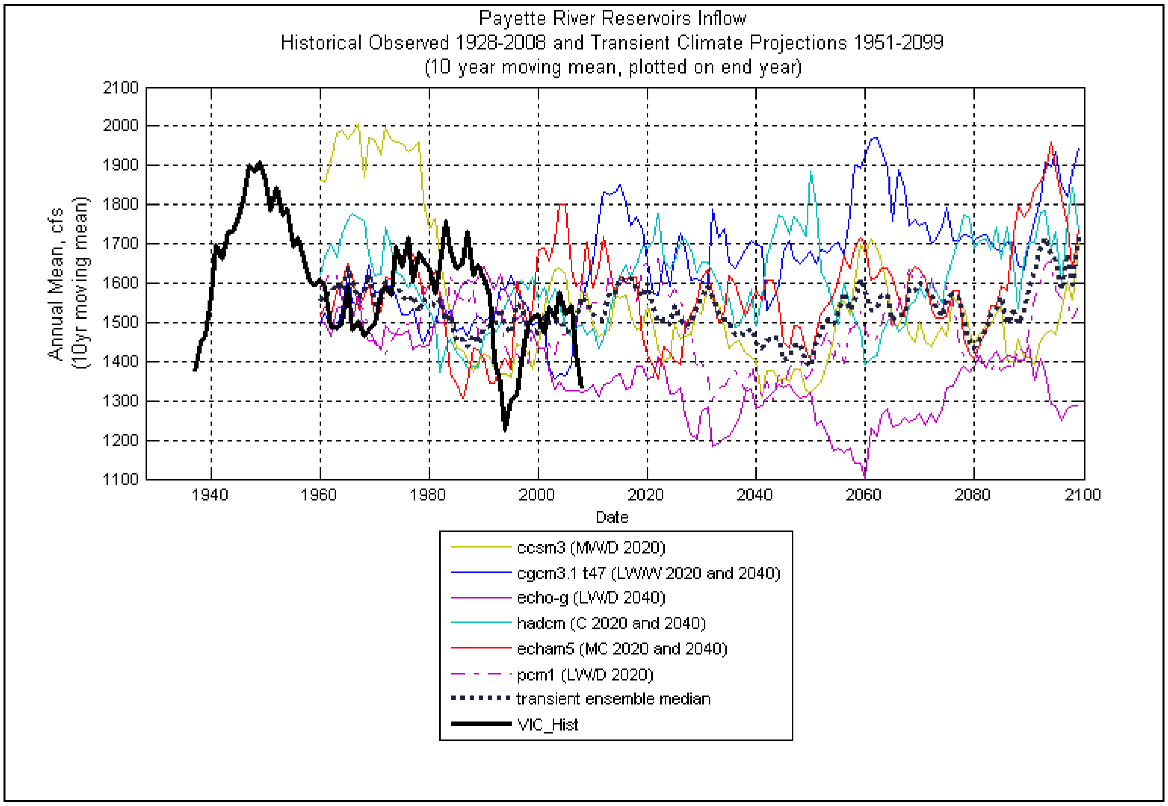


Figure 82. Transient 10-year moving average for inflow all major reservoirs on the Payette River at the confluence with the Snake River.

4.3.2.2.2 End-of-Month Storage at Reservoirs

Modeled results of the change in reservoir storage in the Snake River subbasin are presented for the climate change hydrology. Storage volumes are presented as a cumulative value of the reservoir volumes above the reporting point (i.e., Boise River, Payette River, Snake River above Minidoka, Snake River above Milner, and Snake River above Brownlee). For example, when the reporting location is on the Boise River, the values reported are the cumulative values for all three reservoirs (Anderson, Arrowrock, and Lucky Peak reservoirs) on the Boise River. This approach in reporting allows discussion of general trends as opposed to the comparison of actual values because the inflow numbers are cumulative and therefore, representative of the reservoir system above any reporting point. Operational constraints and assumptions were not changed between the VIC simulated historical condition and the VIC simulated future climate projections. This allowed for comparative analysis between the model simulations and possible trends in river system storage resources.

4.3.2.2.2.1 Typical Conditions and Variability

As inflow to the reservoirs on the overall Snake River system increase earlier in the year, end-of-month storage increases generally from the beginning of October through May or June when compared to VIC simulated historical end-of-month storage (Figure 83). The current forecasting methodology used in the model to set monthly flood control reservoir targets resulted in an increase in available reservoir storage during the months of January through March. While storage reliability increases due to wetter winter flows, deeper draft will be required during the irrigation season to meet irrigation demand as natural inflows drop.

As shown in Figure 83, end-of-month storage volume is greater than historical conditions from October or November through May above Brownlee. In the summer months, some projections suggest that storage volumes will be below VIC simulated historical end-of-month storage through September or October. In the HD 2040 scenario, almost all of the climate projections end the year in September with lower end-of-month storage volumes than historically. With the exception of the C and LW/W climates, at least a 5 percent decrease in end-of-month storage volume is observed in September.

In addition to volume, the timing of the peak end-of-month storage in all of the climate projections appears to be one month earlier (shifting from June to May) when compared to the timing in the VIC simulated historical end-of-month storage (at the scale of this study, daily or weekly shifts cannot be observed). This pattern is perceptible in both HD scenarios.

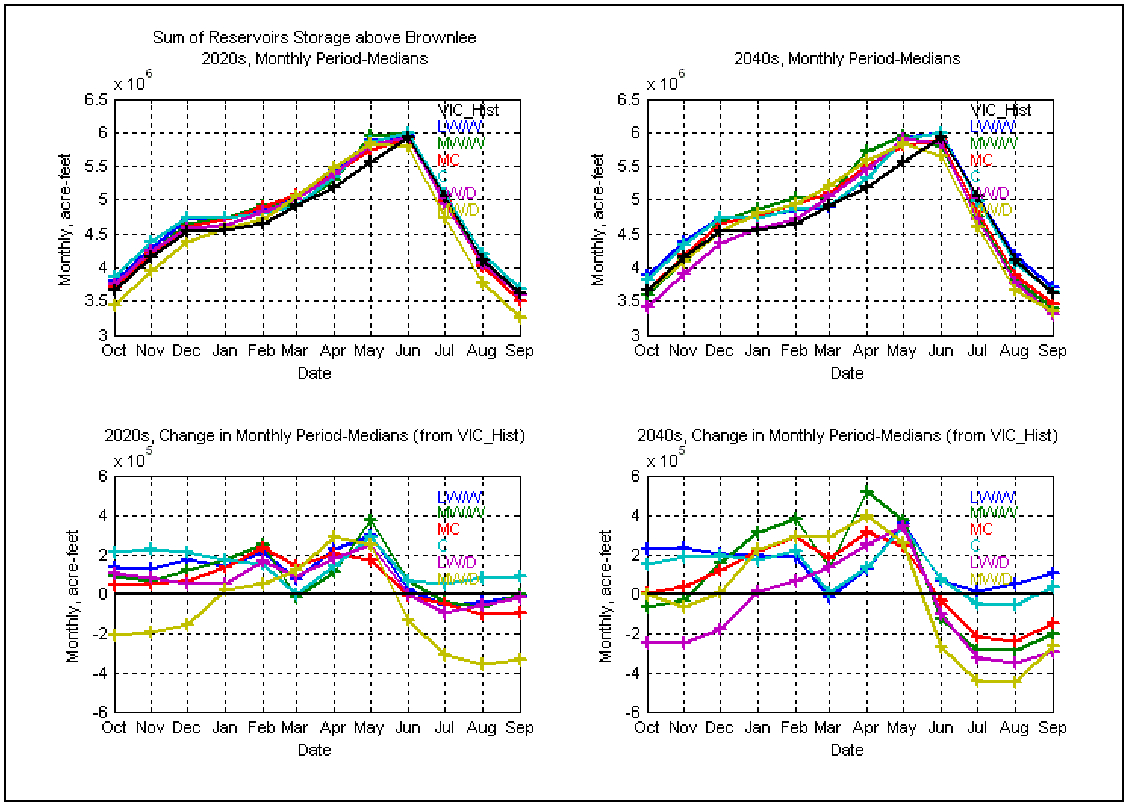


Figure 83. Total and change in monthly period-median (from VIC simulated historical) end-of-month storage above Brownlee Reservoir in the Snake River subbasin.

The change in end-of-month storage on the Boise River seems to follow a similar pattern as the total reservoir system above Brownlee Reservoir (Figure 84). Increases in end-of-month storage volume occur during the cooler months in the Boise River reservoirs when compared to VIC simulated historical end-of-month storage during the same timeframe.

Decreased volume below historical storage levels is also observed in both HD scenarios, but the HD 2040 scenario has four of the six climate projections projecting lower September end-of-month storage volumes than historically. The peak of the decrease is observed in the HD 2040 MW/D dry projection in June.

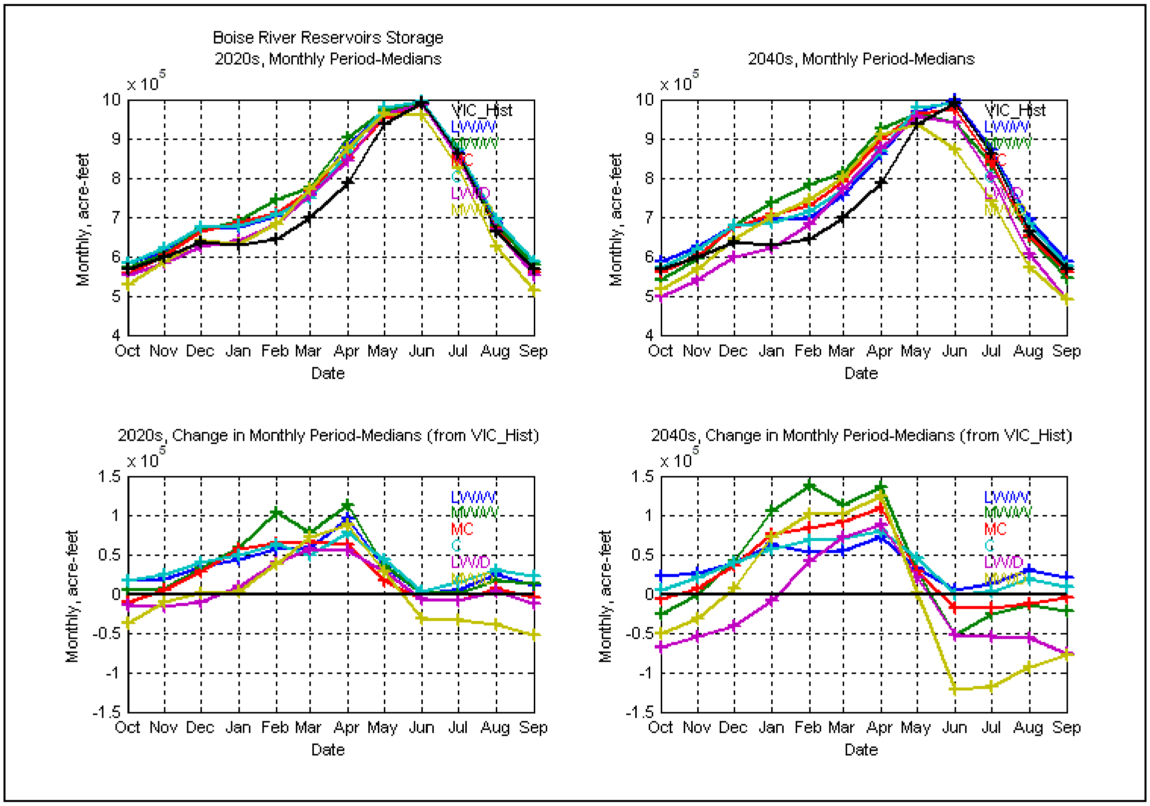


Figure 84. Total and change in monthly period-medians from VIC simulated historical in reservoir end-of-month storage on the Boise River.

The change in end-of-month storage on the Payette River appears to follow a similar pattern as the total reservoir system above Brownlee and on the Boise River (Figure 85). End-of-month storage in the spring was between 12 percent and 18 percent higher, depending on the climate projection, when compared to VIC simulated historical end-of-month storage during the same timeframe. By the end of September, end-of-month storage was predicted to be lower than historical storage levels by up to about 8 percent depending on the climate projection and the HD scenario.

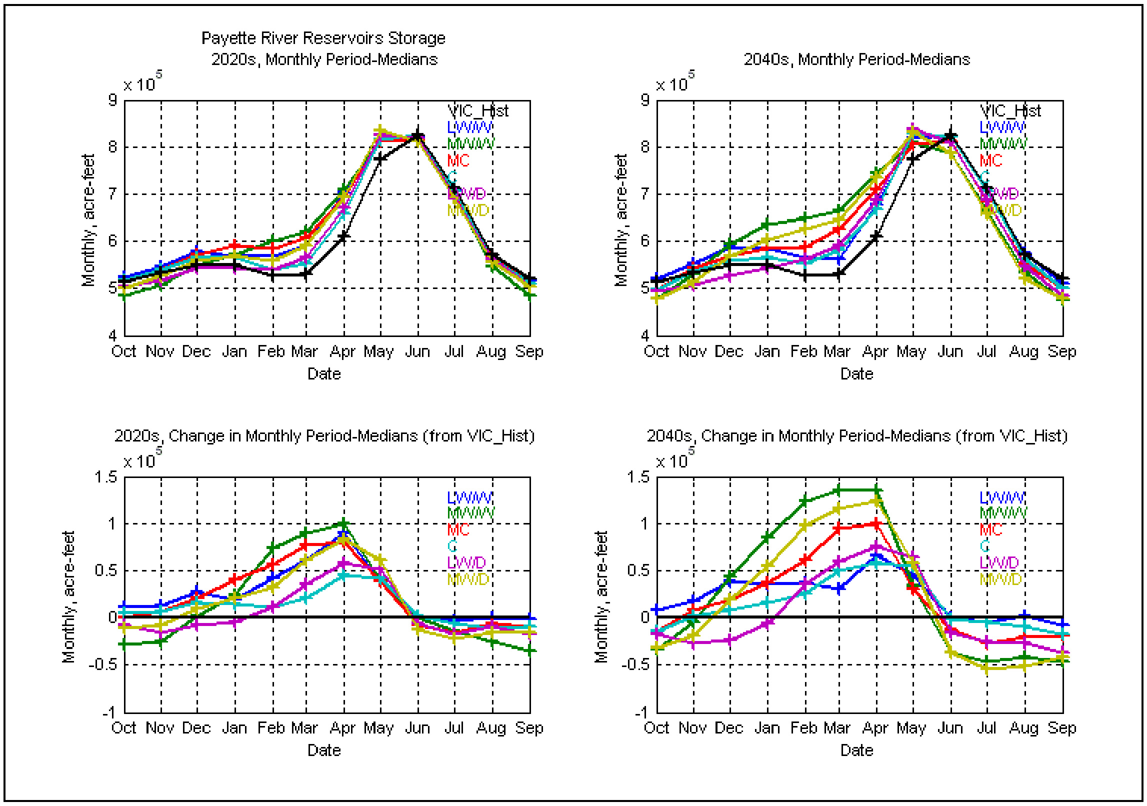


Figure 85. Total and change in monthly period-medians from VIC simulated historical in reservoir end-of-month storage on the Payette River.

While the Boise River reservoir system experienced a 10 to 15 percent decrease in end-of-month storage in late summer and fall in the HD 2040 MW/D projection, only minor decreases in end-of-month storage (maximum of 6 percent in the LW/D projection in the HD 2040 scenario in the same period) were shown in the Payette River reservoir system when compared to the VIC simulated historical condition.

4.3.2.2.2.2 Effect of Transient Climate Change Projections on Simulated Operations

The ensemble median end-of-month storage (the dotted line in Figure 86), which is the composite of the 10-year moving averages of the for all six Transient climate change projections, show similar patterns for the 150-year time frame for all reservoirs above Brownlee Reservoir and for reservoirs on the Payette River (Figure 87). The end-of-month storage ensemble median of the six Transient climate projections on the Boise River reservoir (Figure 88) appears to be on a slight upward trend suggesting that end-of-month storage in the Boise River reservoir system may increase over time.

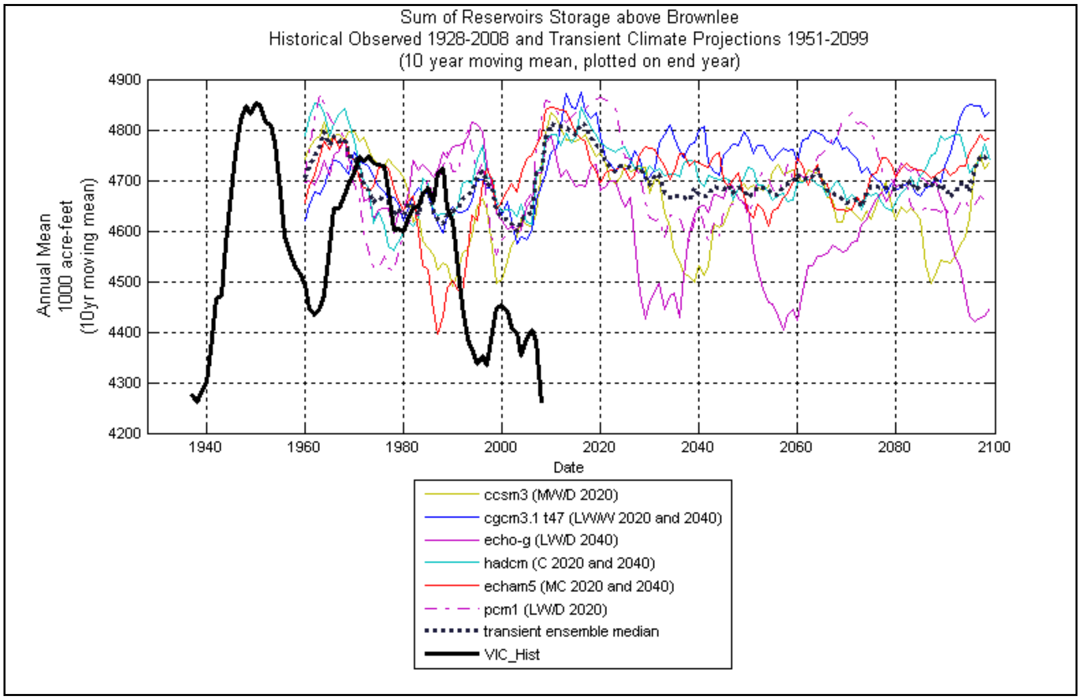


Figure 86. Transient 10-year moving average of the annual average for 150 years of end-of-month storage in all major reservoirs on the upper Snake River above Brownlee.

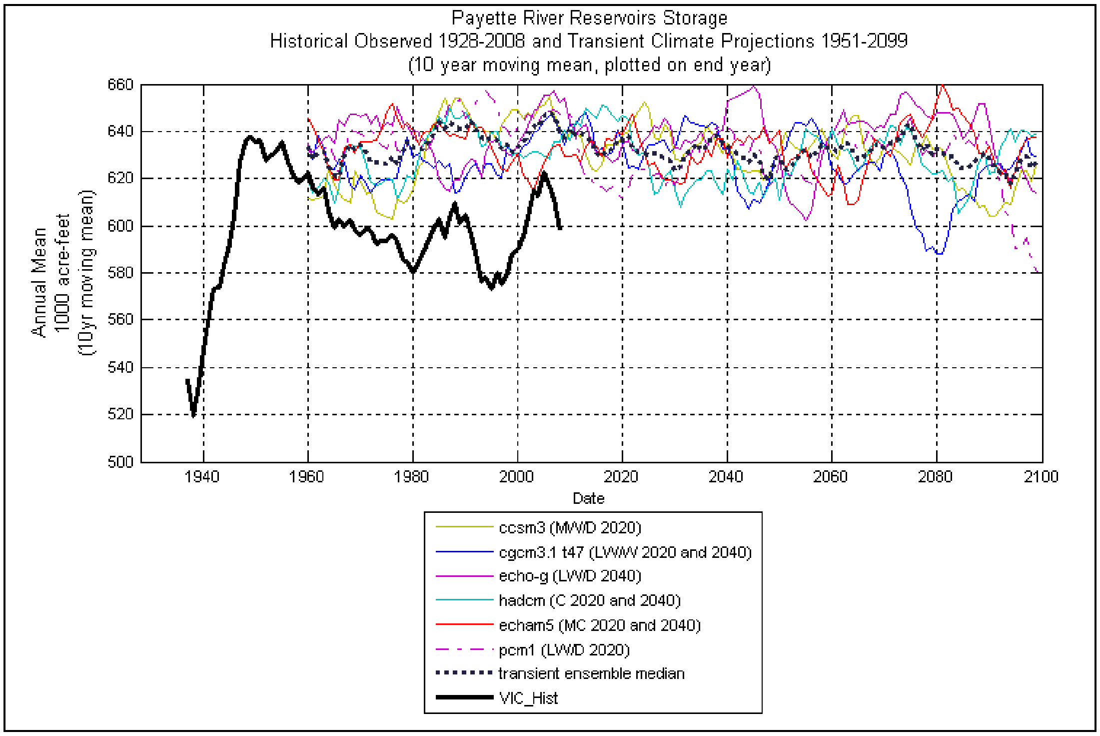


Figure 87. Transient 10-year moving mean of the annual average (for 150 years) of end-of-month storage in all major reservoirs on the Payette River in the Snake River subbasin.

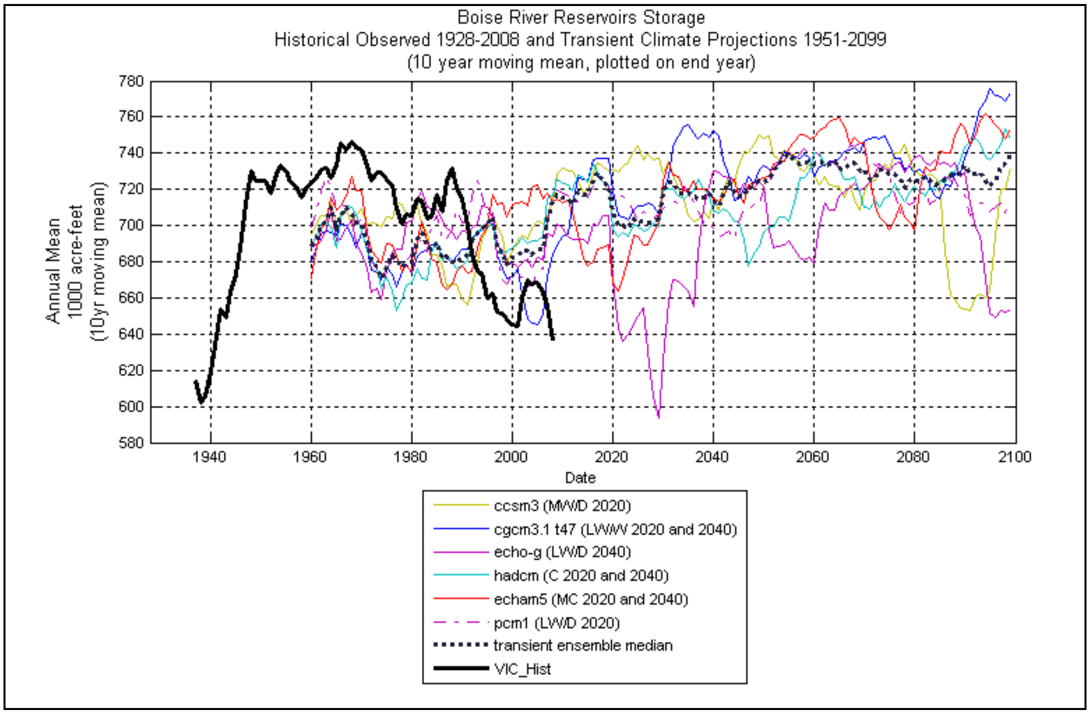


Figure 88. Transient 10-year moving average of the annual average for 150 years of end-of-month storage in all major reservoirs on the Boise River.

4.3.2.2.3 Flow at Key Locations in the Subbasin

4.3.2.2.3.1 Typical Conditions and Variability

The period median monthly peak flow on the Snake River at Brownlee Reservoir had a significant increase in the month of March in the HD 2020 MW/W climate change projection. In this climate change projection, the peak occurs two months earlier and with more volume in the month of March when compared to peak of the VIC simulated historical peak flow in May (Figure 89). The peak flow of the other climate projections also occurs two months earlier when compared to VIC simulated historical flow; however, the magnitude of these increases in volume is less than the MW/W projection in the HD 2020 scenario.

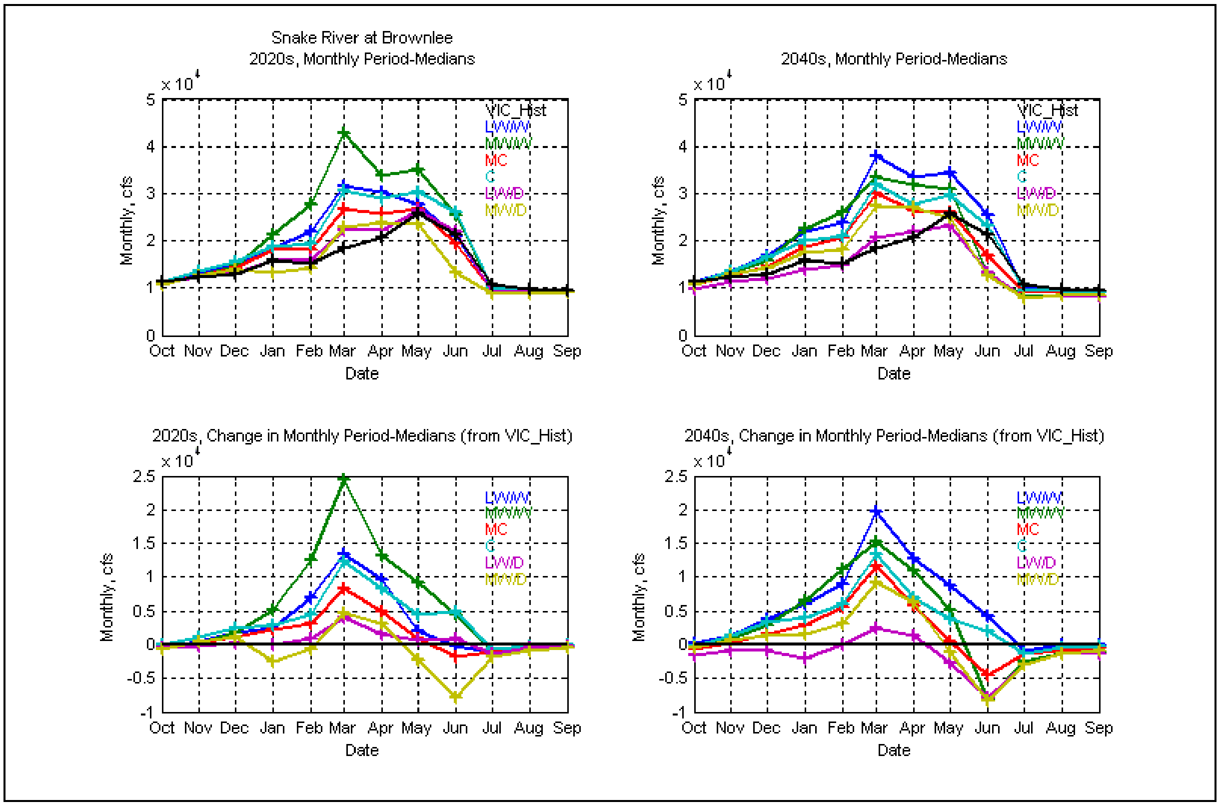


Figure 89. Total and change in total (compared to VIC simulated historical) monthly period-medians flow in at Brownlee Reservoir on the Snake River.

This increase in flow at the Brownlee Reservoir results in increased end-of-month storage on the Snake River as described in Section 4.4.2.2.2. The maximum decrease in period monthly median flow at Brownlee occurs in June in both HD scenarios.

Neither flow volume nor peak flow timing on the Snake River at Heise is predicted to change significantly when compared to the VIC simulated historical condition in either HD scenario (Figure 90 and Figure 92). Peak monthly period median flow for the MW/W and C climates is expected to experience minor increases above VIC simulated historical flow at Heise in the HD 2020 scenario and in the MW/Win the HD 2040 scenario.

As with the timing of the peak flow and volume of flow at Brownlee Reservoir, volume and timing of flow on the Snake River at Minidoka changes when compared to the VIC simulated historical condition (Figure 91 and Figure 92) in most projections. Flow increases in both HD scenarios and the timing of the peak shifts at least one month earlier at Minidoka in most of the climate projections.

Peak flow on the Boise River at the confluence with the Snake River does not shift to earlier in the year in any of the climate projections; however, the volume of flow in the winter and spring is expected to be much higher (Figure 92).

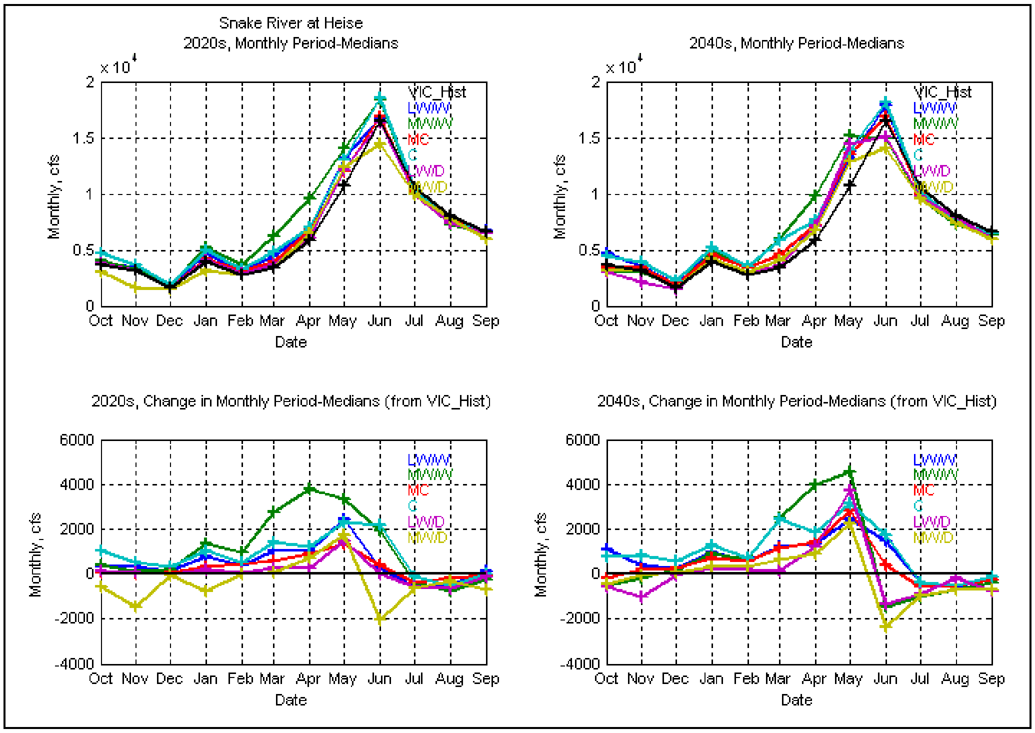


Figure 90. Total and change in total (compared to VIC simulated historical) monthly period-medians flow at Heise on the Snake River.

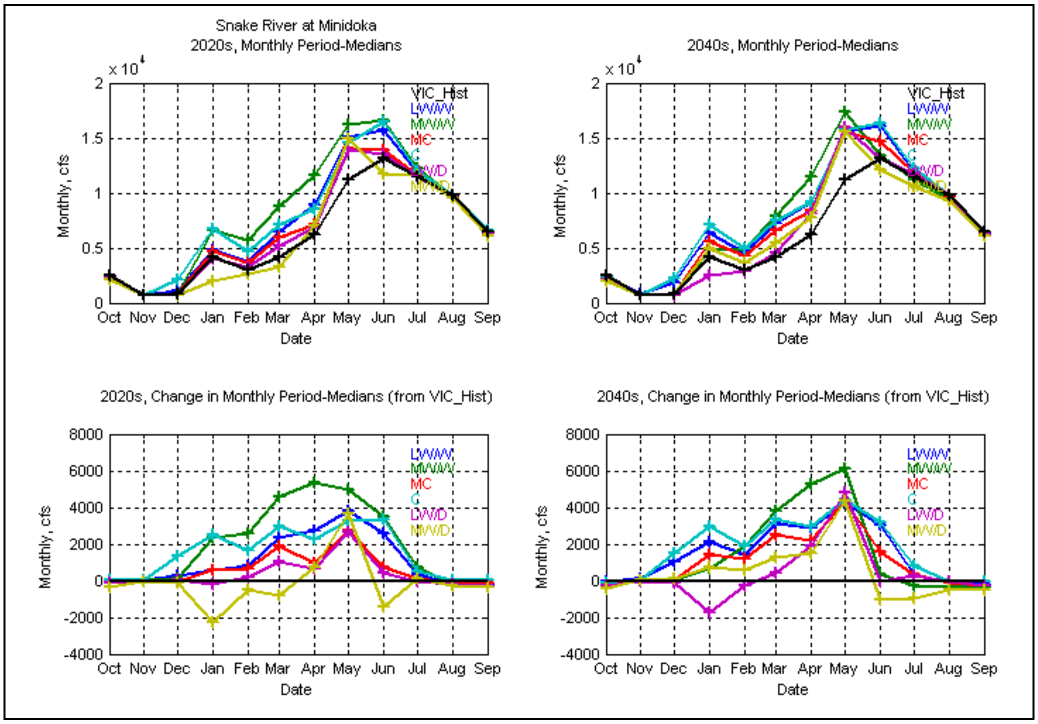


Figure 91. Total and change in total (compared to VIC simulated historical) monthly period-medians flow in at Minidoka Reservoir on the Snake River.

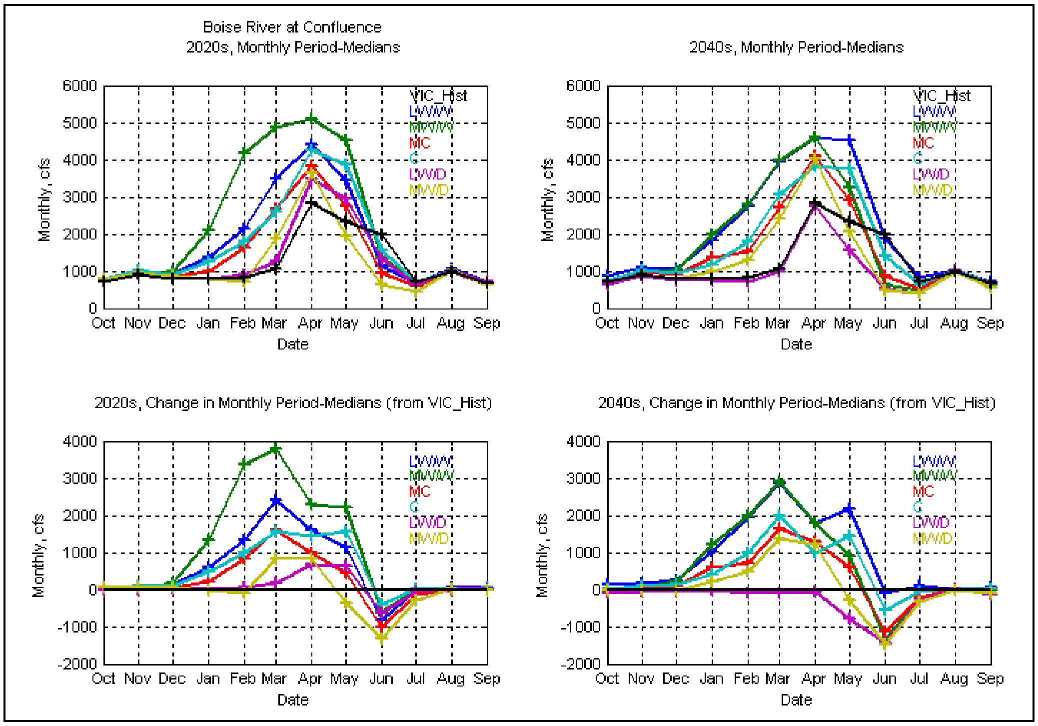
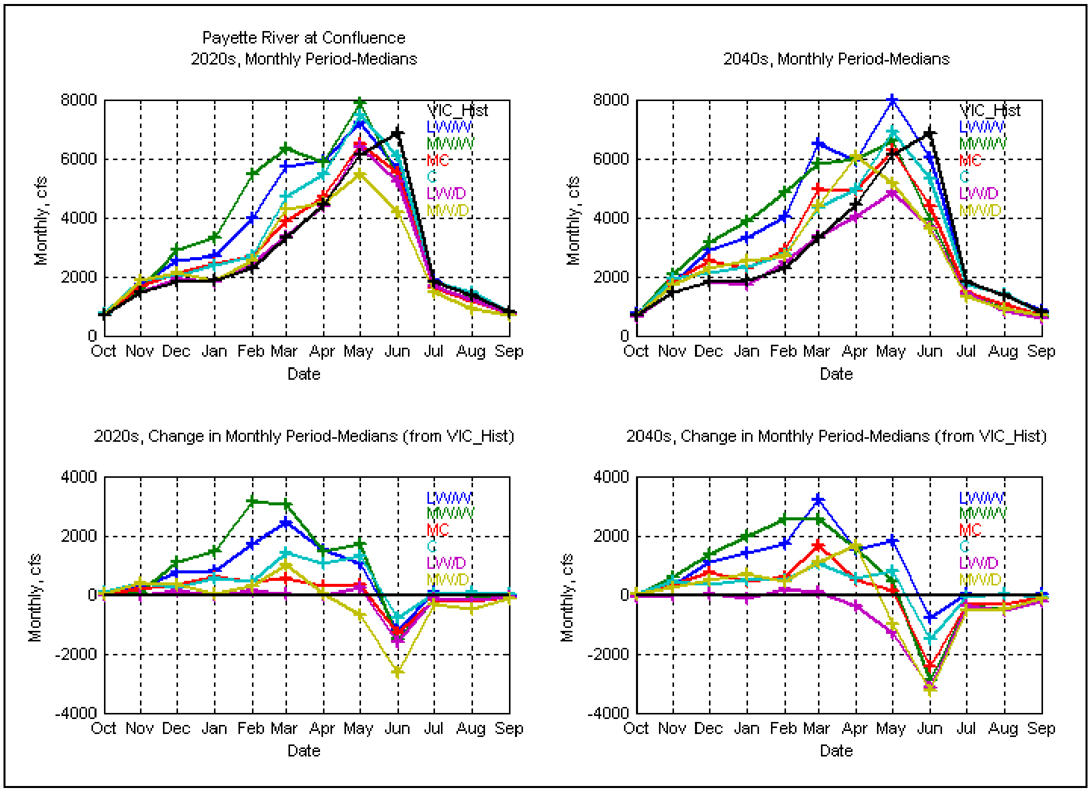


Figure 92. Total and change in total (compared to VIC simulated historical) monthly period-medians flow in at the Payette River confluence.

Peak flow timing on the Payette River at the confluence with the Snake River shifts from June to May in all projections and in both HD scenarios (Figure 93). In addition, the volume of flow in the winter and spring is expected to be higher through May in most projections in both HD scenarios when compared to VIC simulated historical flow. The peak flow of the LW/W projection in May is roughly 30 percent higher than the historical flow in that same month.


Payette River at Confluence
2020s, Monthly Period-Medians

2040s, Monthly Period-Medians

2020s, Change in Monthly Period-Medians (from VIC_Hist)

2040s, Change in Monthly Period-Medians (from VIC_Hist)

Figure 93. Total and change in total (compared to VIC simulated historical) monthly period-medians flow in at Brownlee Reservoir on the Snake River.

In both HD scenarios and in all projections, flow at the confluence is expected to be less than historical flow during the drier, summer months through September. These decreased flows during the summer will result in the increased need for dependence on stored water and may have serious implications for the river water temperature and natural water diversions off the river.

4.3.2.2.3.2 Effect of Transient Climate Change Projections on Simulated Operations

Transient scenario trends in flow at all gage locations described in this section are similar and because of that similarity, only results at Brownlee are presented below. The flow through the 150-year period shown as a 10-year moving average (Figure 94) and a 30-year moving average (Figure 95) show a slight increase in flow. This pattern is apparent at Heise and

Minidoka on the Snake River and on the Payette and Boise rivers tributaries. This pattern is likely an artifact of the fact that the projections that satisfied the needs of the entire Columbia River Basin as described in the Part 1 Report are primarily wetter projections in the Snake River subbasin.

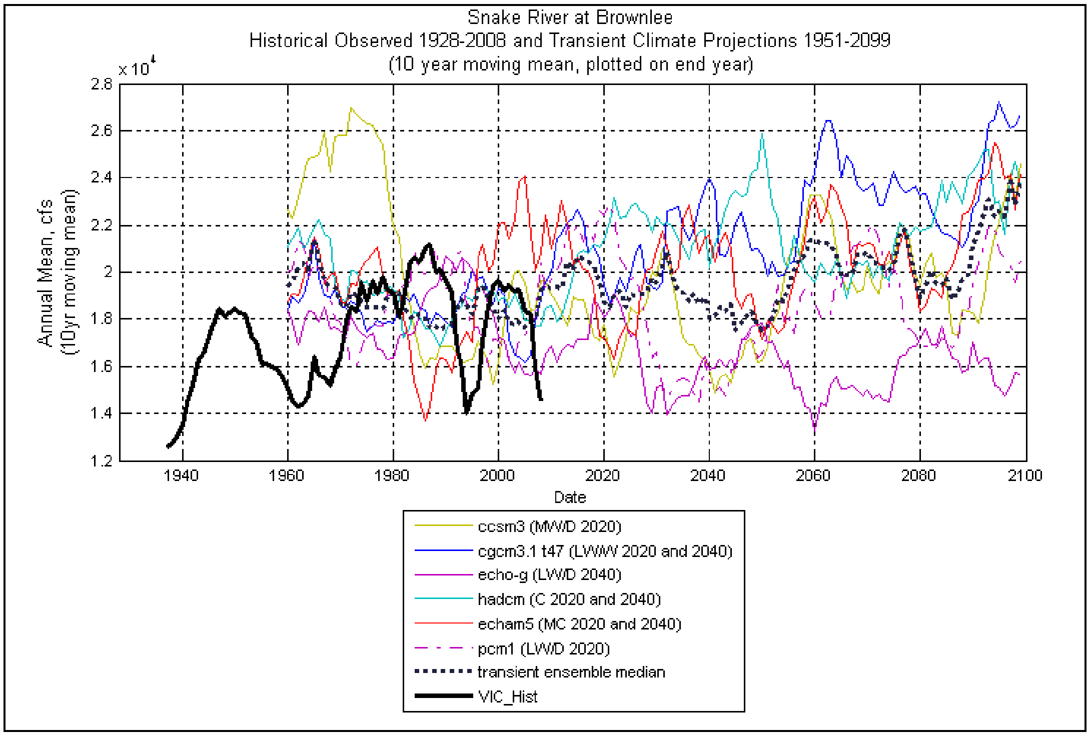


Figure 94. Transient method 10-year moving mean of the annual mean (for 150 years) of flow at Brownlee Reservoir on the Snake River.

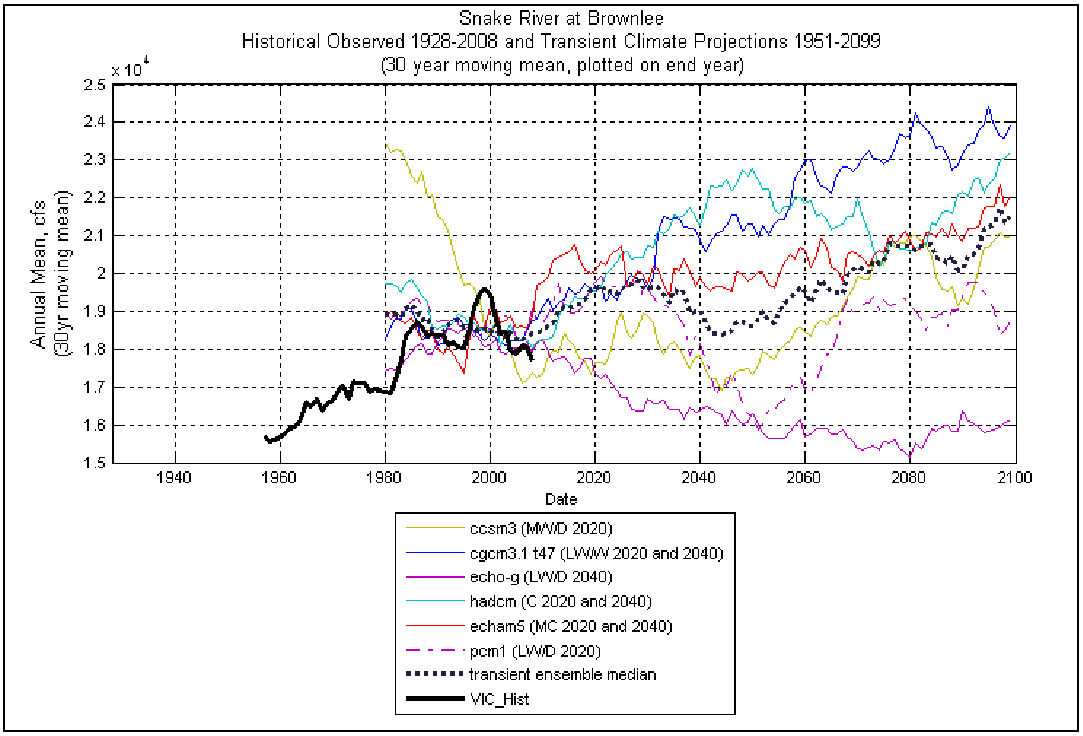


Figure 95. Transient method 30-year moving mean of the annual mean (for 150 years) of flow at Brownlee Reservoir on the Snake River.

4.3.2.2.4 Surface Water Delivered

Surface water delivered (natural flow and storage water) were evaluated above Brownlee Reservoir. The scale of this study is such that trends for the composite delivery were evaluated, but individual water rights were not.

4.3.2.2.4.1 Typical Conditions and Variability

For the purpose of this study, the irrigation season was generally defined as the months of April through September each year. Depending upon water year type (e.g., wet, dry) and weather (temperatures), the season may extend longer. The amount of surface water delivered (as opposed to storage water) above Brownlee Reservoir decreases slightly resulting in decreased overall water deliveries during the irrigation season (July and August) in both HD scenarios in most projections (Figure 96). The greatest decrease in surface water delivered is projected to occur in September near the end of the irrigation season, when stream flows will be the lowest in the MW/D projection in both HD scenarios. In the HD 2020, the largest monthly period median decrease of 40 KAF occurs in September and a decrease of 100 KAF occurs that same month in the HD 2040 scenario.

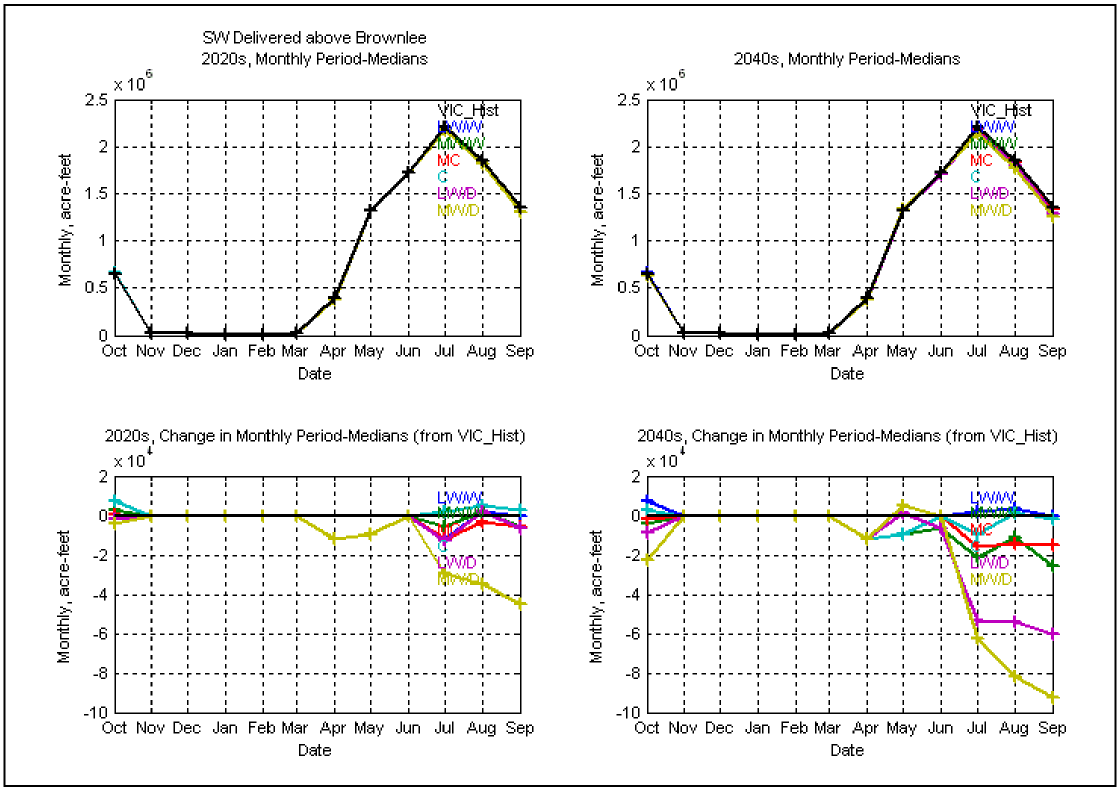


Figure 96. Total and change in surface water delivered above Brownlee Reservoir in the HD 2020 and HD 2040 scenarios.

These decreased surface water deliveries are more apparent in the annual average period median as shown in Figure 97. While most climate projections selected for analysis in the Snake River subbasin are wetter than historical conditions, the two dry projections in the HD 2040 scenario show that potential impacts to surface water deliveries can be significant if a drier climate prevails in the future.

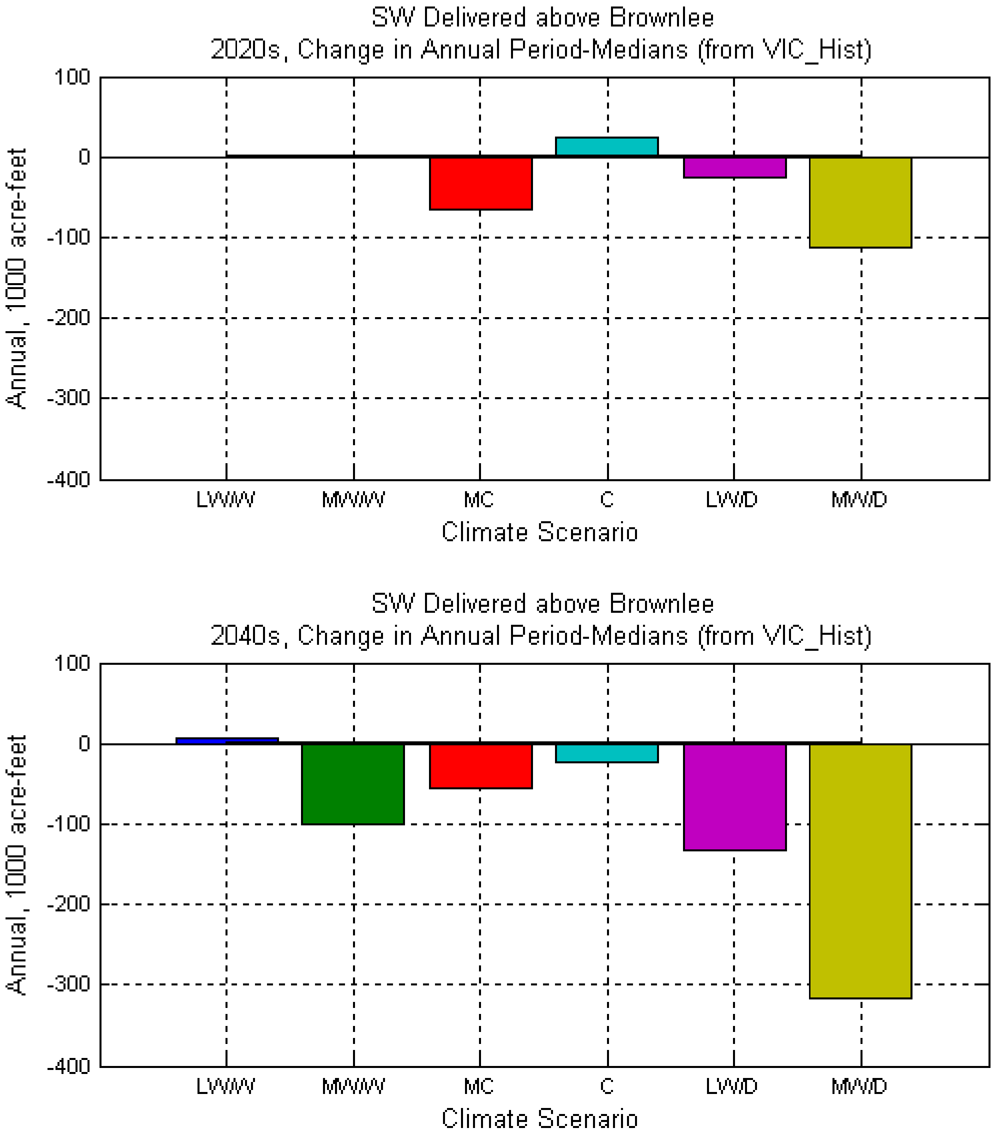


Figure 97. Annual median change in surface water delivered in the HD 2020 and HD 2040 scenarios above Brownlee Reservoir on the Snake River.

Surface water deliveries above Milner (Figure 98) account for the greatest percentage of those deliveries reported on the entire system (i.e., Snake River above Brownlee Reservoir).

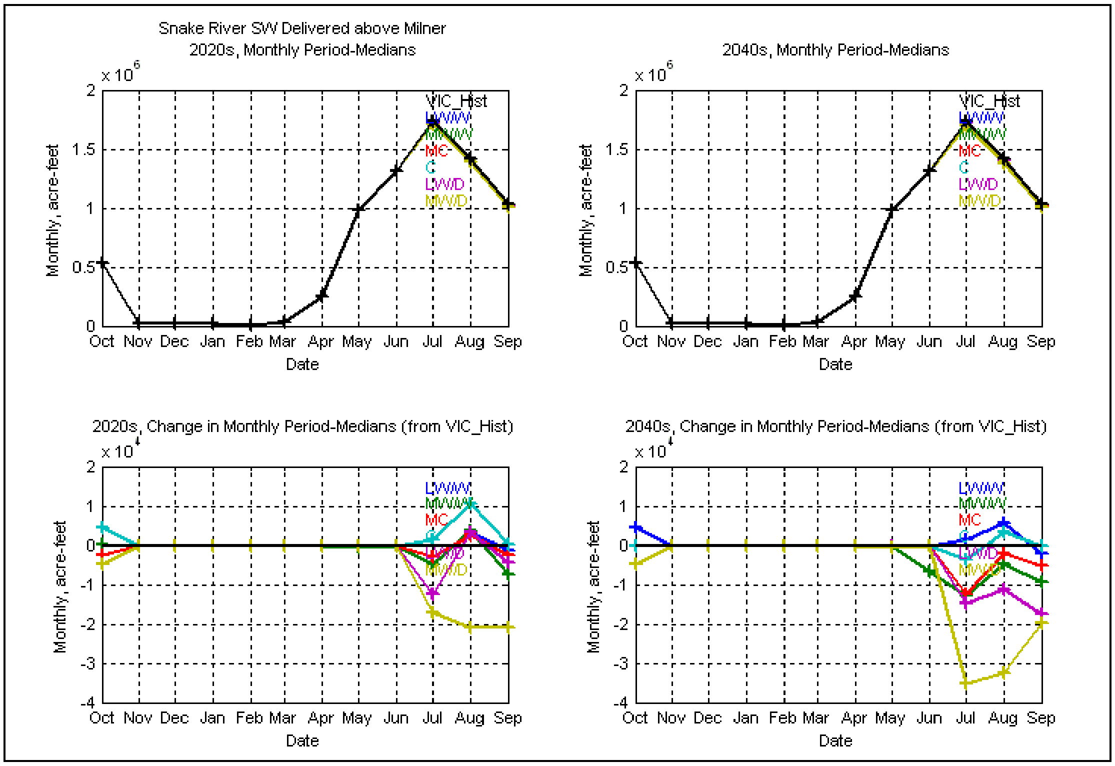


Figure 98. Total and change in surface water delivered above Milner Reservoir in the HD 2020 and HD 2040 scenarios.

On the Payette River subbasin, surface water deliveries are generally unaffected in most of the climate projections in both HD scenarios with the exception of the MW/D climate in the HD 2040 scenario (Figure 99).

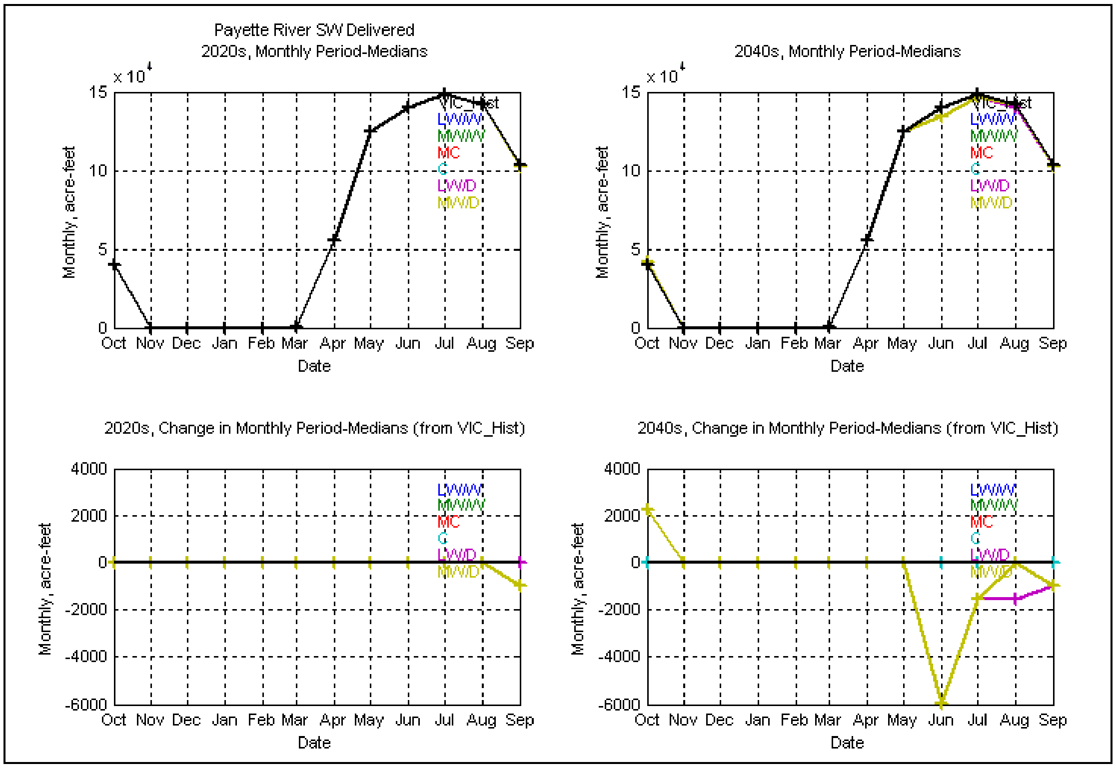


Figure 99. Total and change in surface water delivered on the Payette River above the confluence with the Snake River in the HD 2020 and HD 2040 scenarios.

On the Boise River, most surface water deliveries were generally unaffected in most of the climate projections in both HD scenarios with the exception of the MW/D climate in the HD 2040 scenario (Figure 100). In that scenario, a decrease of over 50 KAF (20 percent in surface water delivered) in September is indicated when compared to VIC simulated historical in that same month. This lowest volume of delivered water followed four months of declining deliveries in that climate projection. The Boise River reservoir system continued to have a high probability of refill except in the driest climate projections. Reservoirs were drawn down lower by the end of September in the HD 2040 dry scenarios as well.

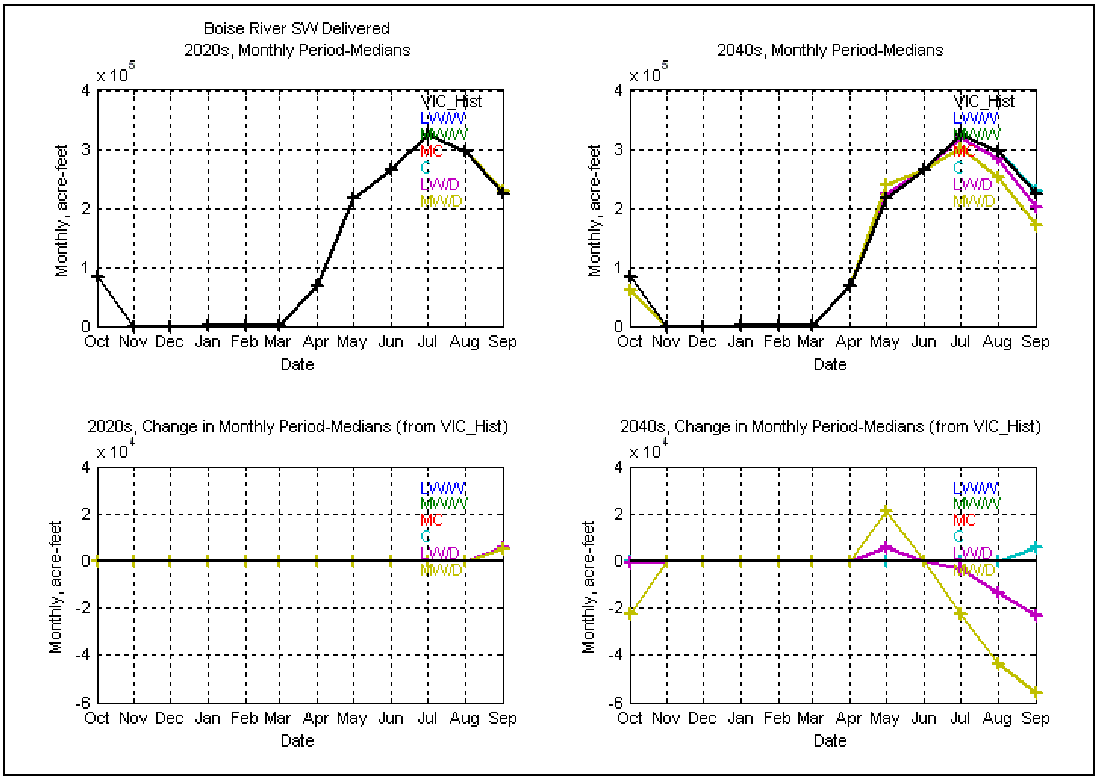


Figure 100. Total and change in surface water delivered on the Boise River above the confluence with the Snake River in the HD 2020 and HD 2040 scenarios.

While the modeled HD climate change projections are generally wetter in average annual volume, the flows during the irrigation months tend to be drier; consequently, surface water deliveries are reduced. The reduced water deliveries results in a shift in the source of the water used by irrigators. The ability of the reservoirs to fill with a warmer future climate is a function of warmer winters allowing reservoirs to capture winter runoff before senior natural flow diverters begin to call for water in April. Ultimately by mid-summer, water users with both natural flow and storage water rights shift water use from natural flow rights to storage rights. This change in system dynamics is shown in Figure 101 through Figure 104 where a shift from natural water rights to storage water rights in the modeling of one irrigation district is illustrated. The Northside Canal Company has senior natural flow water rights and storage water rights. These figures show how storage would take on a greater importance in the future, particularly in the HD 2040 scenarios. A general shift from natural flow right diversions to storage water rights was apparent in the drier climate projections when compared to VIC simulated historical use.

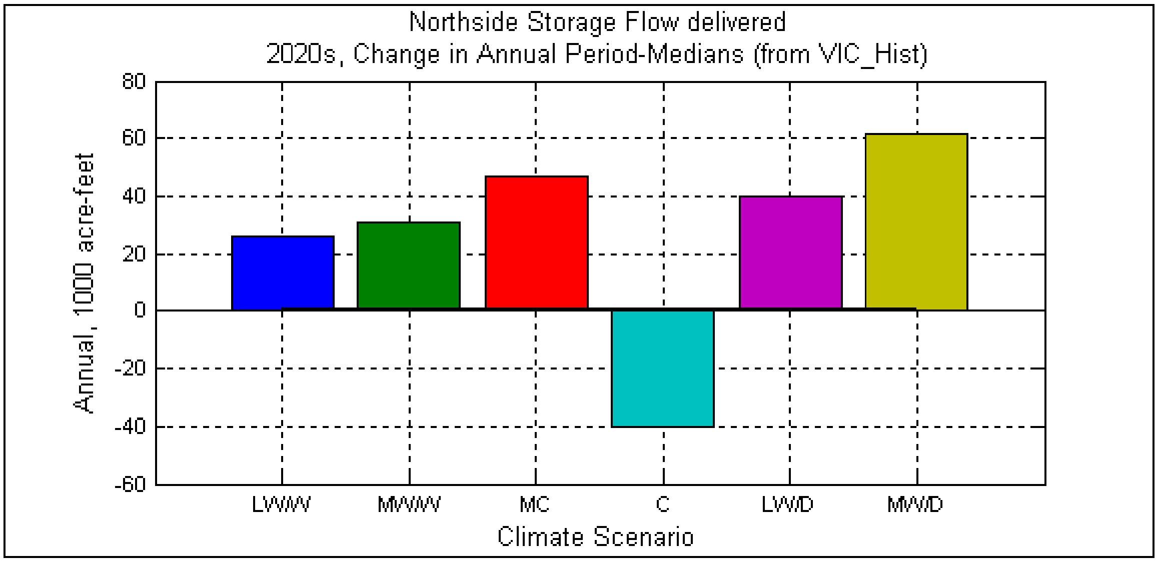


Figure 101. Change in Northside storage flow delivered in HD 2020 climates when compared to VIC Simulated Historical delivery.

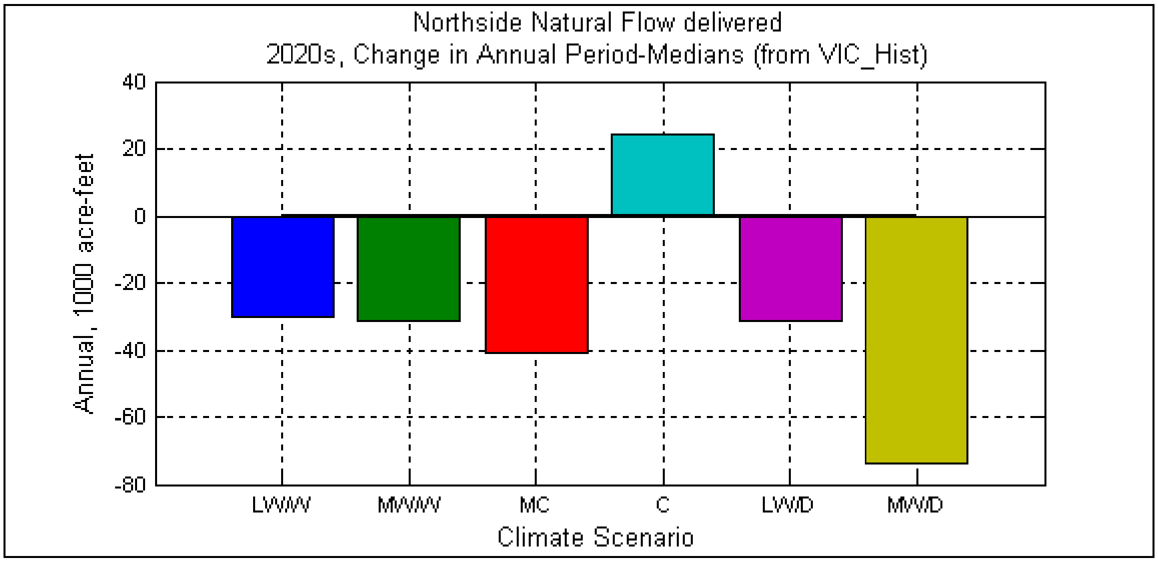


Figure 102. Change in Northside natural flow delivered in HD 2020 climates when compared to VIC Simulated Historical delivery.

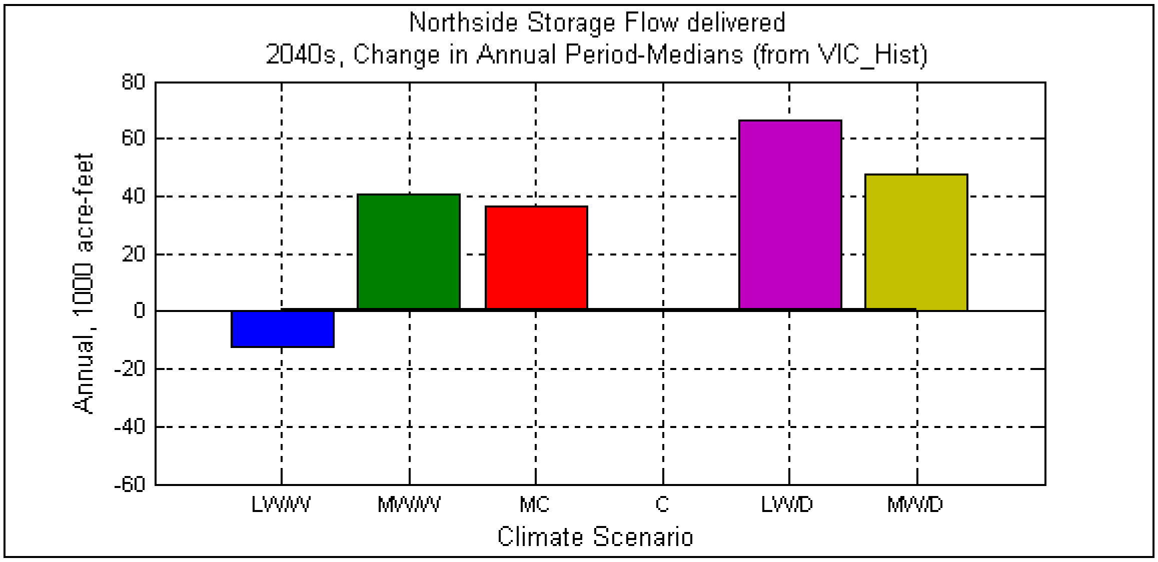


Figure 103. Change in Northside storage flow delivered in HD 2040 climates when compared to VIC Simulated Historical delivery.

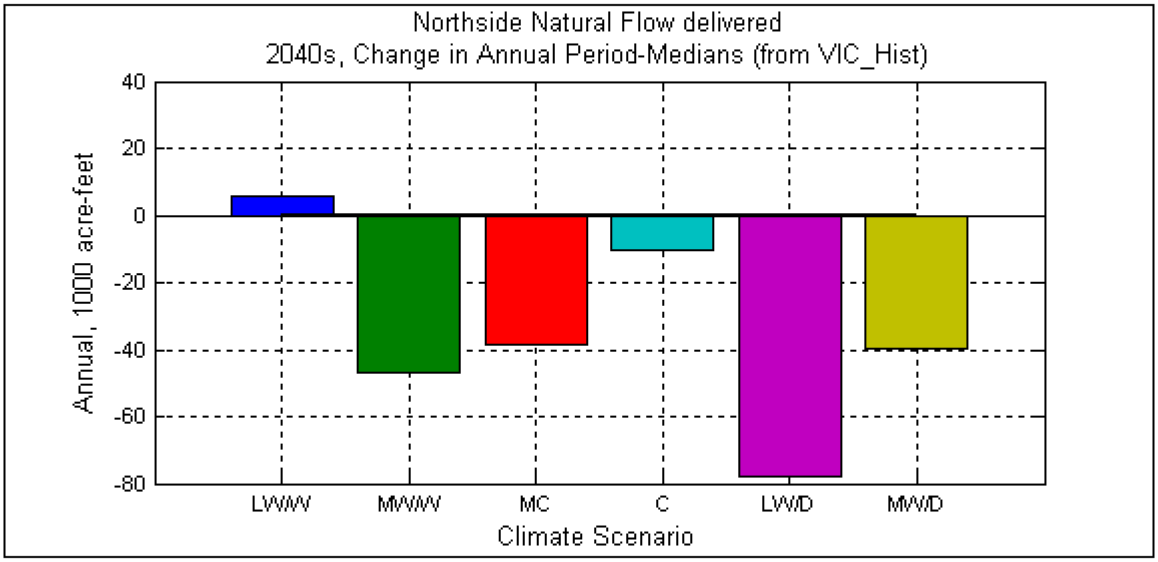


Figure 104. Change in Northside natural flow delivered in HD 2040 climates when compared to VIC Simulated Historical delivery.

4.3.2.2.4.2 Effect of the Transient Climate Change Projections on Simulated Operations

Overall changes in the Transient ensemble median (the dotted line on Figure 105) were similar at all locations on the Snake River in this section so only patterns for deliveries above Brownlee are presented. A gradual declining trend in surface water deliveries from 1950 to 2099 was indicated in all of the climate change projections as illustrated in the ensemble median.

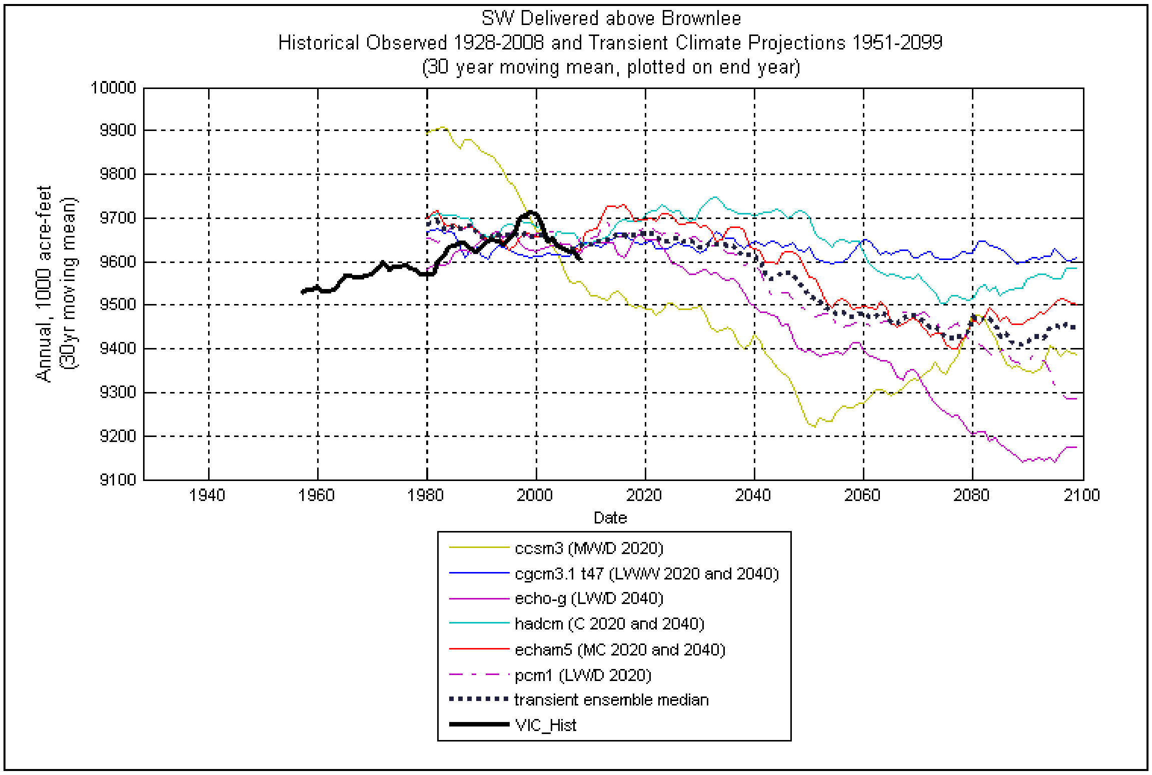


Figure 105. Transient method 30-year moving average (for 150 years) of surface water delivered above Brownlee Reservoir on the Snake River.

Overall changes in the ensemble median (dotted line on figure) of the 30-year moving average of surface water delivered in the Payette River and of the 10-year moving average on the Boise River (Figure 106 and Figure 107, respectively) are similar to the Snake River above Brownlee Reservoir. A gradual declining trend in surface water deliveries is illustrated in both systems (note y-axis scale is different).

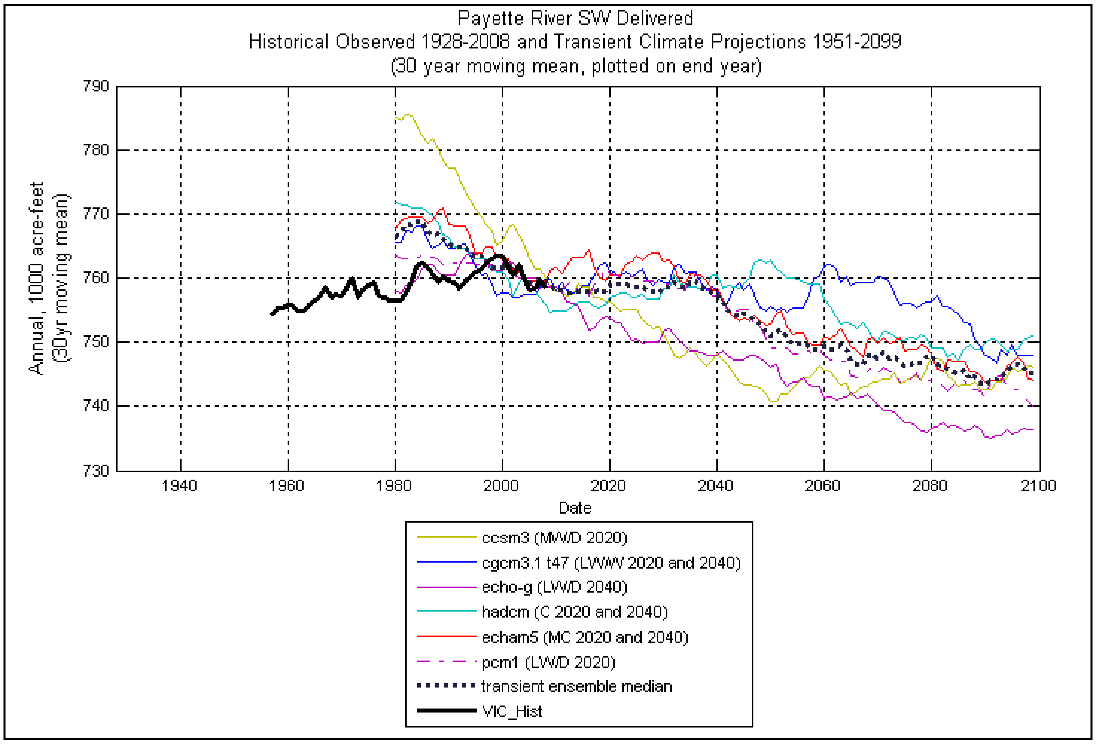


Figure 106. Transient method 30-year moving mean for 150 years of surface water delivered above the Payette River confluence with the Snake River.

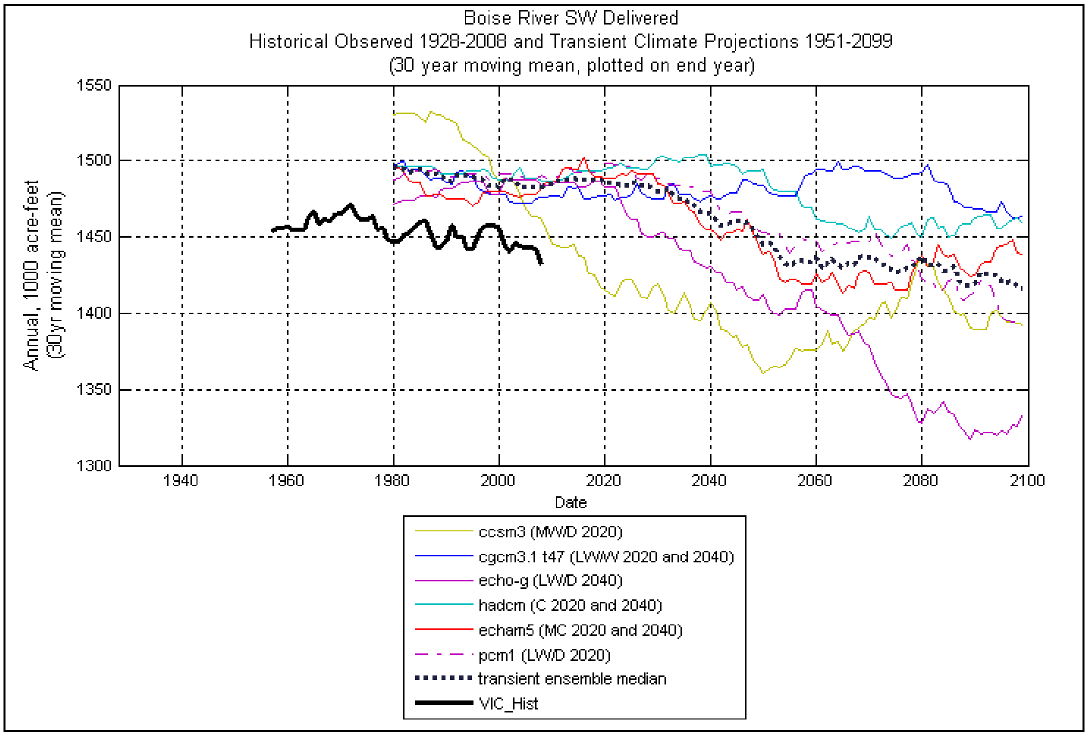


Figure 107. Transient method 30-year moving mean for 150 years of surface water delivered above the Boise River confluence with the Snake River.

4.3.2.2.5 ESA Flow Augmentation for Anadromous Species

As described in Section 4.3.1.2.5, up to 487 KAF of water is delivered to Brownlee Reservoir to benefit the migration of salmonids. If power head space was needed to provide augmentation water, then the maximum augmentation volume that is provided is 427 KAF. The following figures illustrate that in the future the 487 KAF of augmentation water may be less reliable in some of the scenarios, it is more reliable in others. The delivery of at least 427 KAF may occur more frequently in most of the HD 2020 and HD 2040 scenarios. This is due to the runoff characteristics or timing of the hydrology climate change projections. Storage water delivered from the reservoirs to meet demands causes lower reservoir elevations in the fall after irrigation season. In turn, the lower reservoir elevations in the fall result in less water being consigned to the Water District 1 rental pool for flow augmentation the following year. The Water District 1 flow augmentation contribution to the rental pool is based upon November 1 carryover from the previous year in conjunction with the anticipated spring runoff determined April 1 of the current year. Because less water is committed to the rental pool in dry years due to lower cumulative reservoir storage on November 1, Reclamation needs to rely on the use of powerhead space more often; however, if powerhead space is to be used, only up to 427 KAF can be delivered. Therefore, in some of the climate change projections, the opportunity to deliver up to 487 KAF is less in the future while the likelihood of delivering 427 KAF is greater. A benefit of the higher winter flows associated with these climate change projections is that reservoirs are more likely to fill, including Reclamation’s powerhead space. This results in the use of powerhead space more often, but with less volume under each occurrence, than the VIC simulated historical run.

Figure 108 illustrates the shift in augmentation deliveries when compared to the VIC simulated historical deliveries. While the 487KAF delivery may become less reliable, particularly under the HD 2040 scenario, an increase in total augmentation up to 427 KAF is realized as a result of filling the reservoirs with the increased winter inflows.

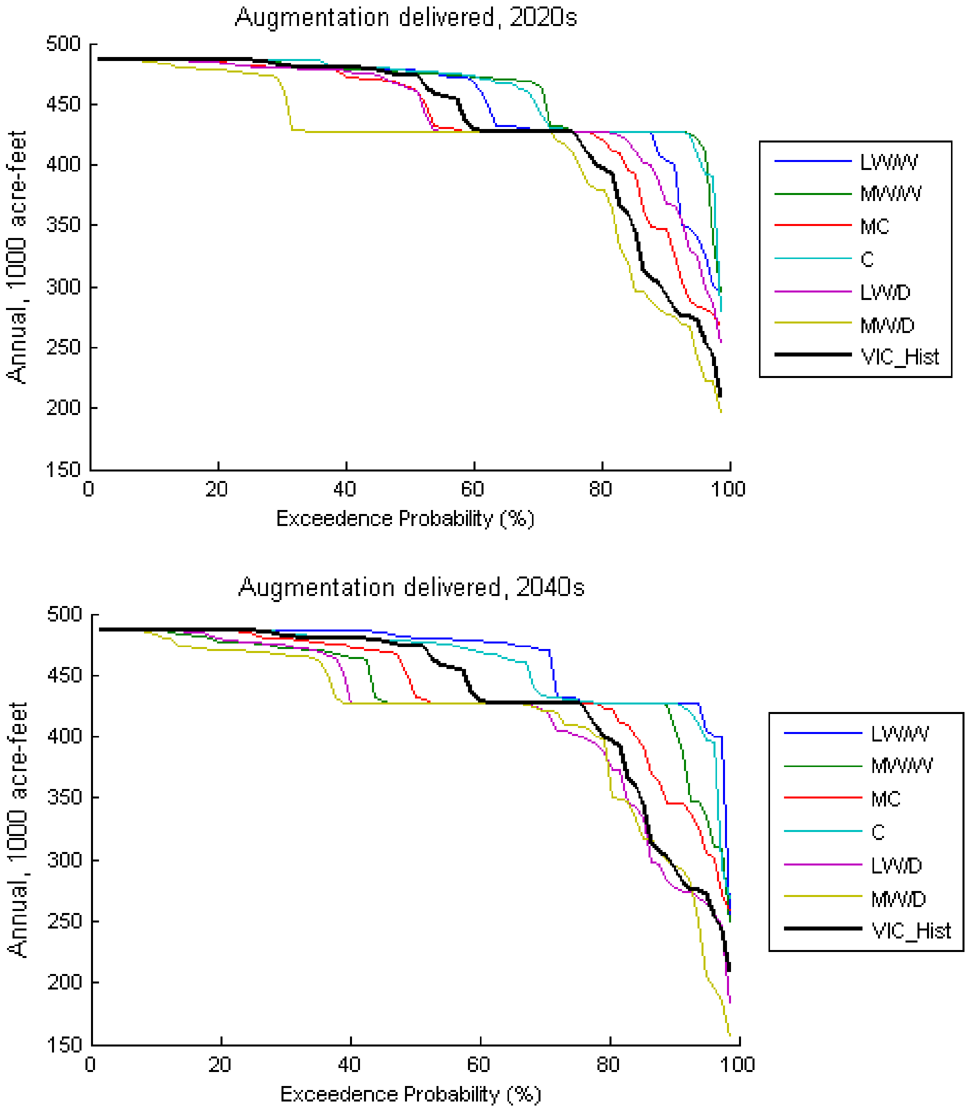


Figure 108. Flow augmentation delivered in the HD 2020 and HD 2040 climate change projections.

While augmentation volume deliveries up to 427 KAF are more reliable, this does not necessarily equate to increased instream flow conditions. Previous figures illustrated reduced flow at various key river gage locations during the late summer months (Section 4.3.2.2.3). The augmentation water delivery timing coincides with the reduced flows at several river gage locations. Therefore, while augmentation water is delivered more reliably and accounted for, there may be an overall decrease in total instream flow during the late summer months.

4.3.2.2.6 ESA for Resident Species and Other Environmental Objectives

Other environmental objections such as water quality minimum pools, minimum flows for the benefit of non-ESA-listed fish, and ESA requirements for ESA-listed snails and bull trout are a high priority in the model constraints that minimize or eliminate compliance violations occurring during model simulations. To meet these objectives, delivery of storage water or reduction in project discharges may be necessary. This in turn may have consequences for other uses.

Figure 109 through Figure 118 illustrate the frequency of meeting environmental targets and subsequent impact to resources.

1. The Palisades Reservoir's minimum flows objective of 900 cfs (54 KAF per month) are met between November and March for all of the climate change projections. The early fall appears to be drier in most instances, resulting in a longer duration of lower flows; however, the wetter winter months generally maintain higher flows than VIC simulated historical conditions.

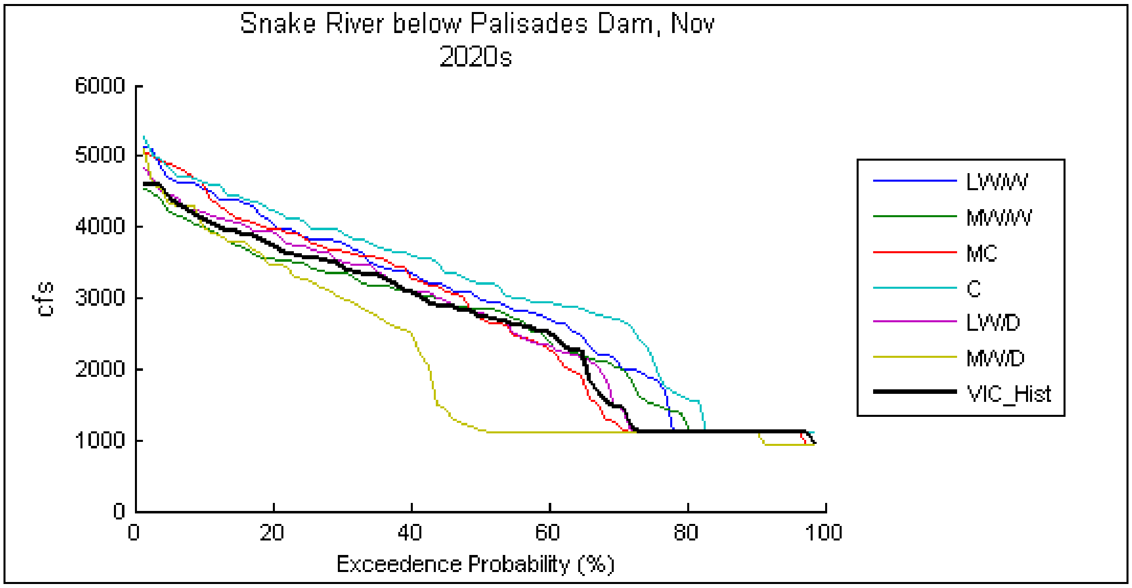


Figure 109. Exceedence probability Palisades discharge in November HD 2020 scenario, when compared to VIC simulated historical.

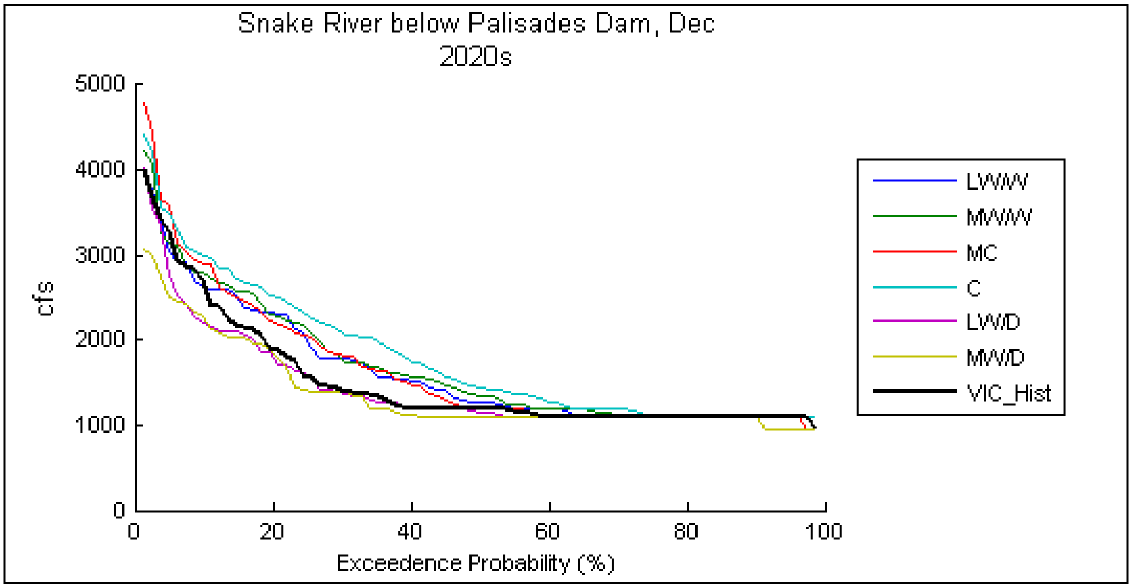


Figure 110. Exceedence probability Palisades discharge in December HD 2020 scenario, when compared to VIC simulated historical.

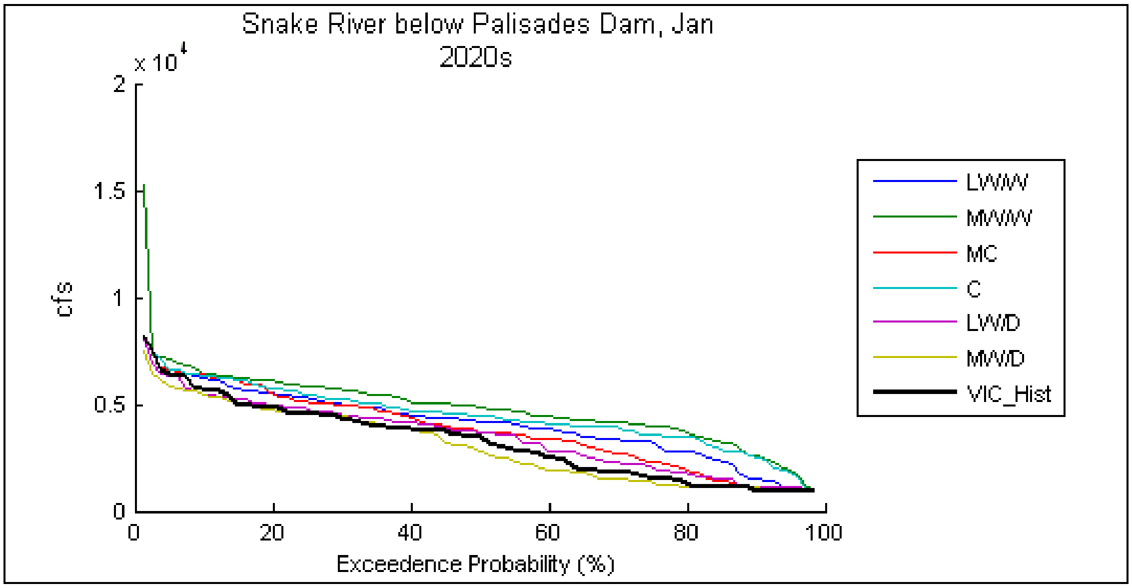


Figure 111. Exceedence probability Palisades discharge in January HD 2020 scenario, when compared to VIC simulated historical.

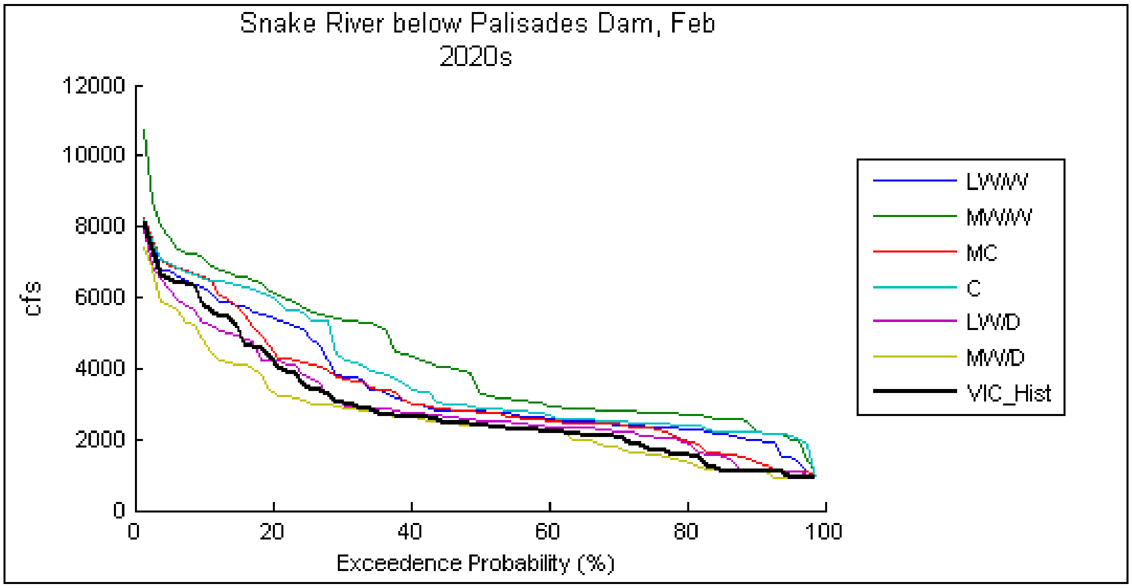


Figure 112. Exceedence probability Palisades discharge in February HD 2020 scenario, when compared to VIC simulated historical.

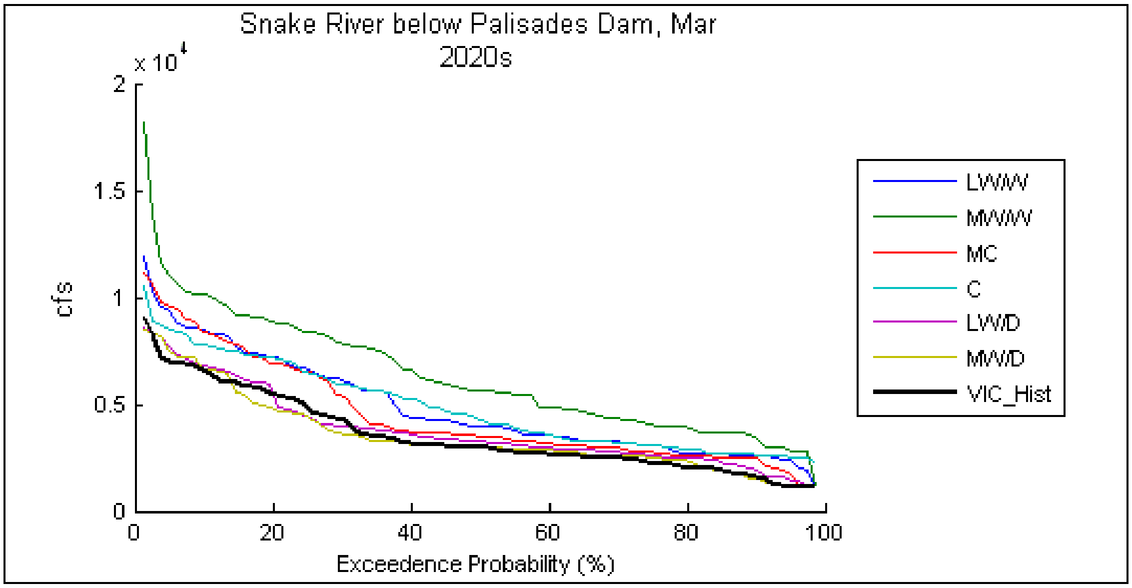


Figure 113. Exceedence probability Palisades discharge in March HD 2020 scenario, when compared to VIC simulated historical.

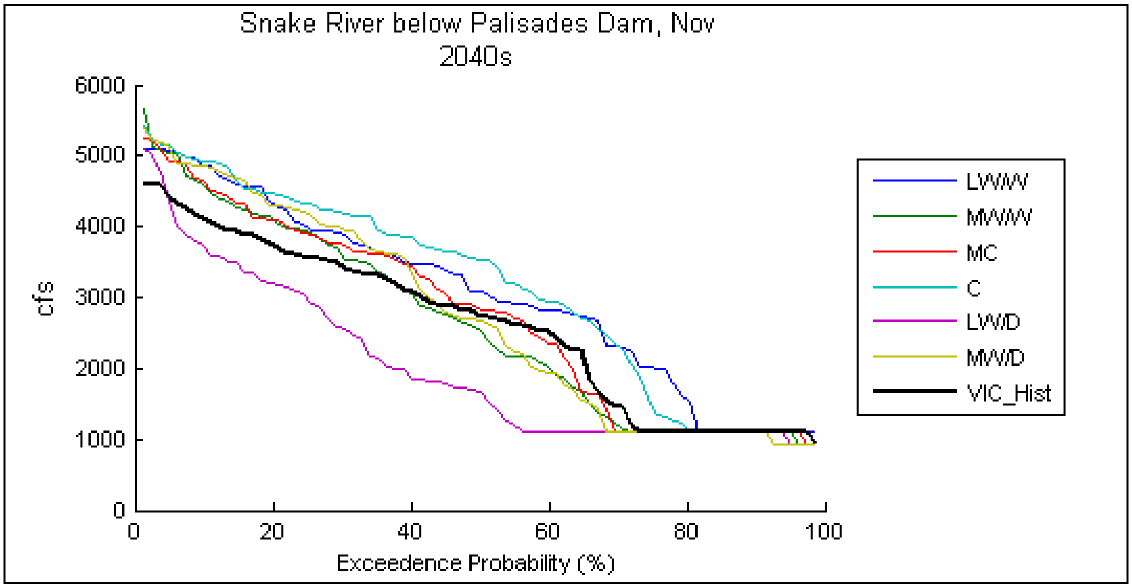


Figure 114. Exceedence probability Palisades discharge in November HD 2040 scenario, when compared to VIC simulated historical.

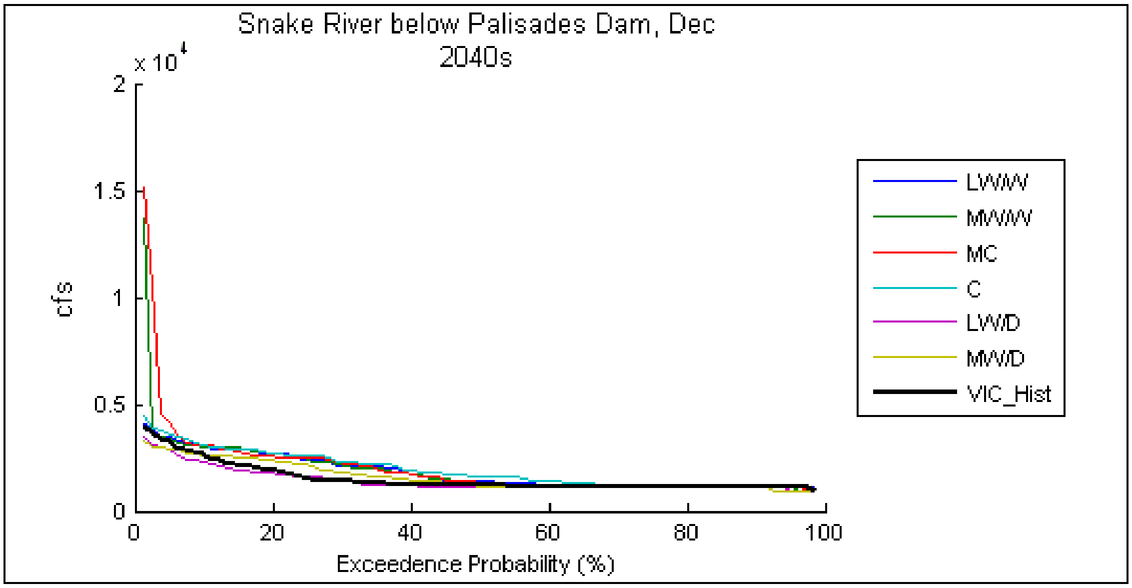


Figure 115. Exceedence probability Palisades discharge in December HD 2040 scenario, when compared to VIC simulated historical.

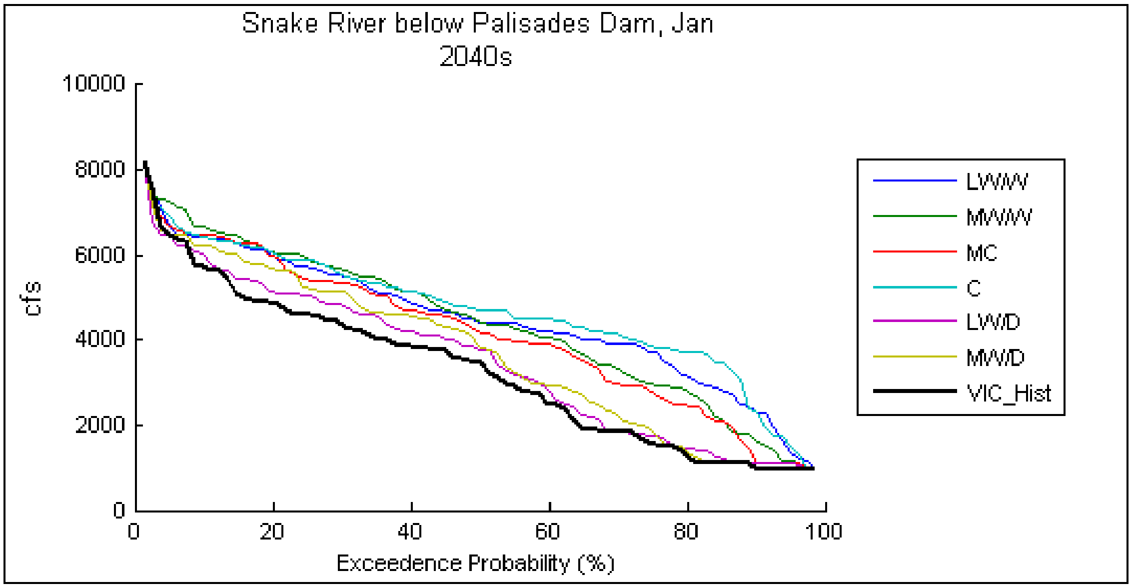


Figure 116. Exceedence probability Palisades discharge in January HD 2040 scenario, when compared to VIC simulated historical.

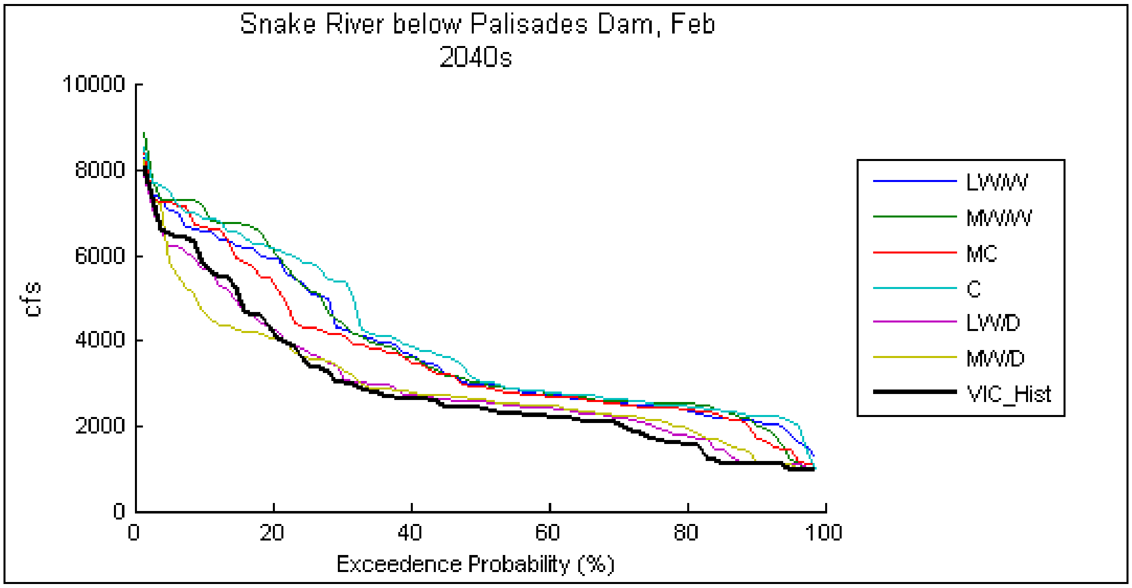


Figure 117. Exceedence probability Palisades discharge in February HD 2040 scenario, when compared to VIC simulated historical.

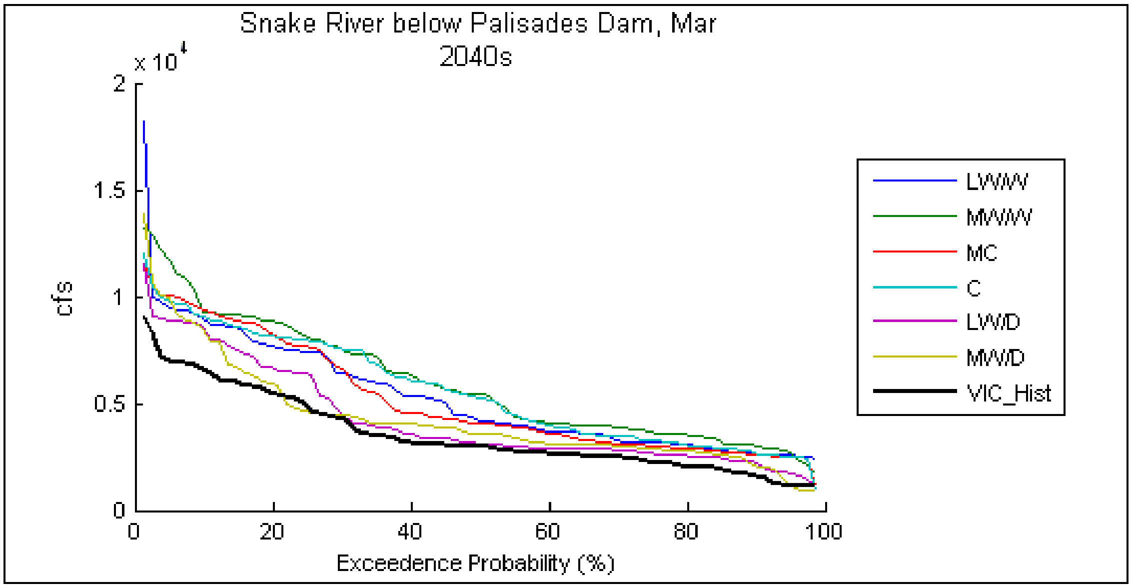


Figure 118. Exceedence probability Palisades discharge in March HD 2040 scenario, when compared to VIC simulated historical.

2. The minimum pool objective in Cascade Reservoir of 400 KAF per month to maintain satisfactory water quality conditions in the reservoir (Figure 119). However, other water demands currently have preference or a higher priority over this self-imposed constraint. Additionally, this occurrence results in reduced flows below the project, potentially impacting recreational needs as well. Therefore, a decrease in water quality conditions may be more frequent under the climate change hydrology conditions.

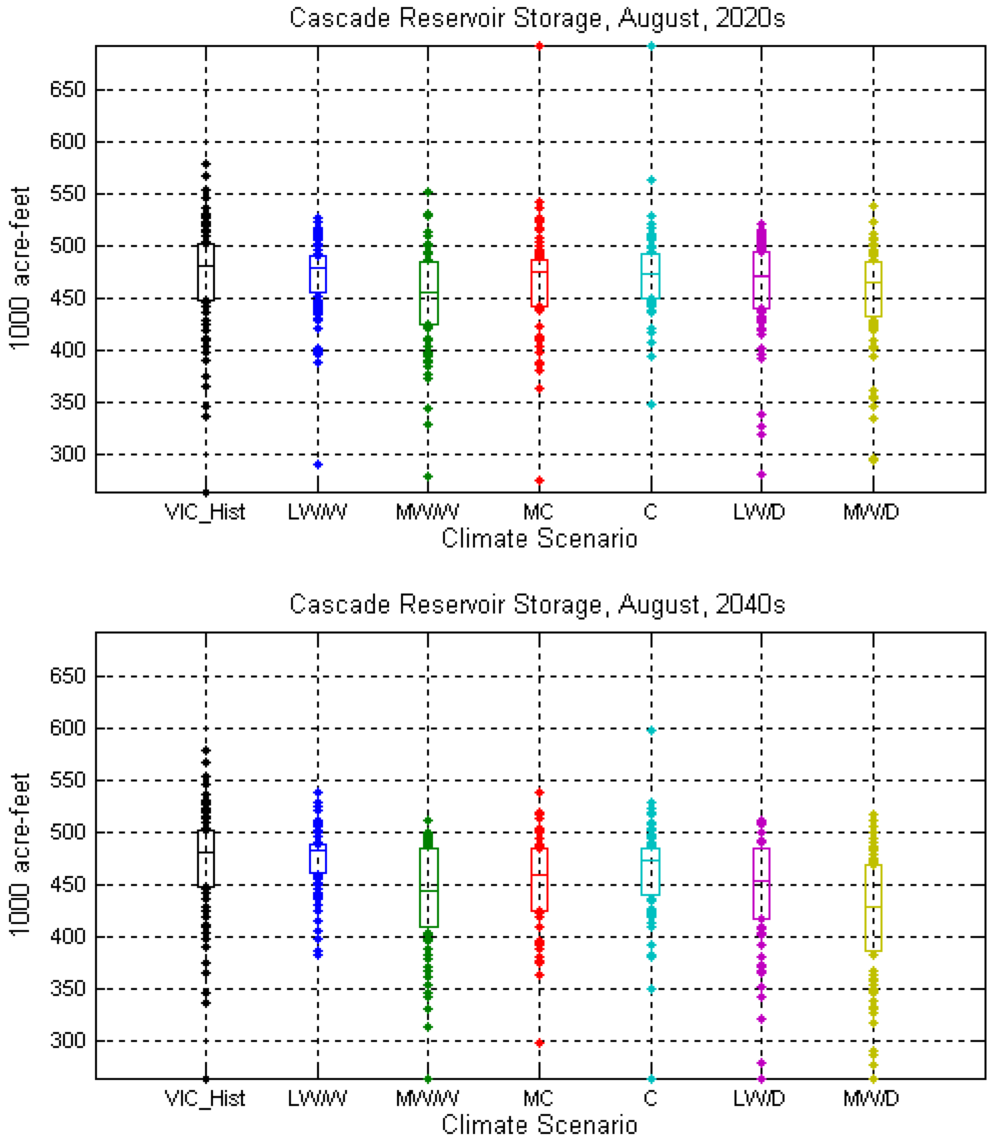


Figure 119. Cascade Reservoir storage comparisons, HD 2020 and HD 2040 scenarios.

3. Reclamation attempts to retain 100 KAF of storage in American Falls Reservoir during the months of September and October for water quality purposes (Figure 120 through Figure 127). Flows below the project are reduced in an attempt to retain the minimum volume and stay within water quality compliance standards for total dissolved solids downstream of the project. The occurrence of reduced flows during this time period is minimal to maintain water in American Falls Reservoir.

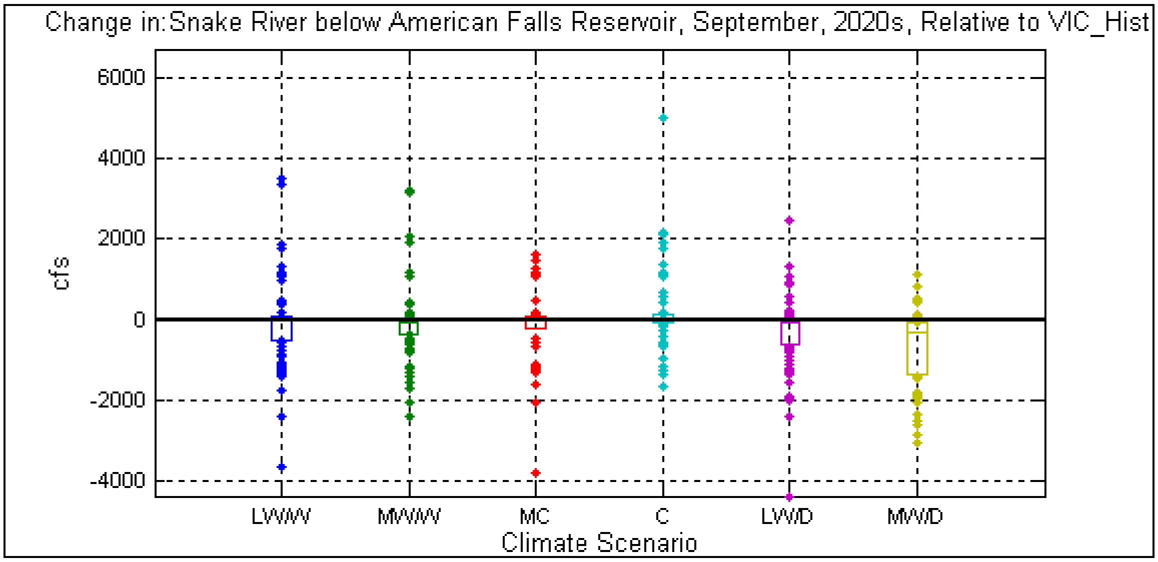


Figure 120. Change in Snake River flow below American Falls Reservoir in September HD 2020 when compared to VIC simulated historical flow.

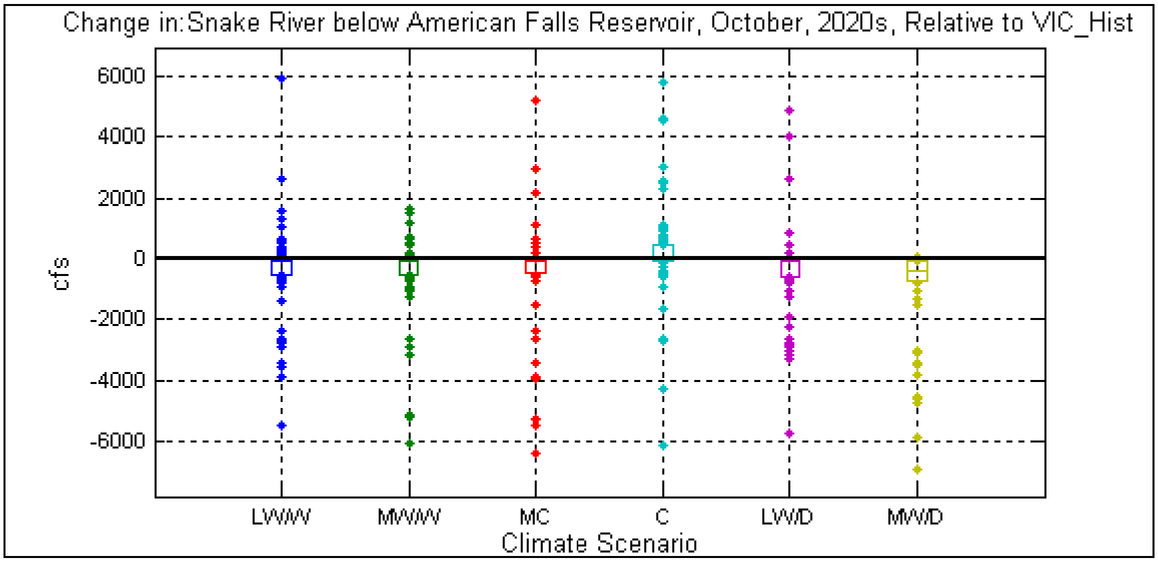


Figure 121. Change in Snake River flow below American Falls Reservoir in October HD 2020 when compared to VIC simulated historical flow.

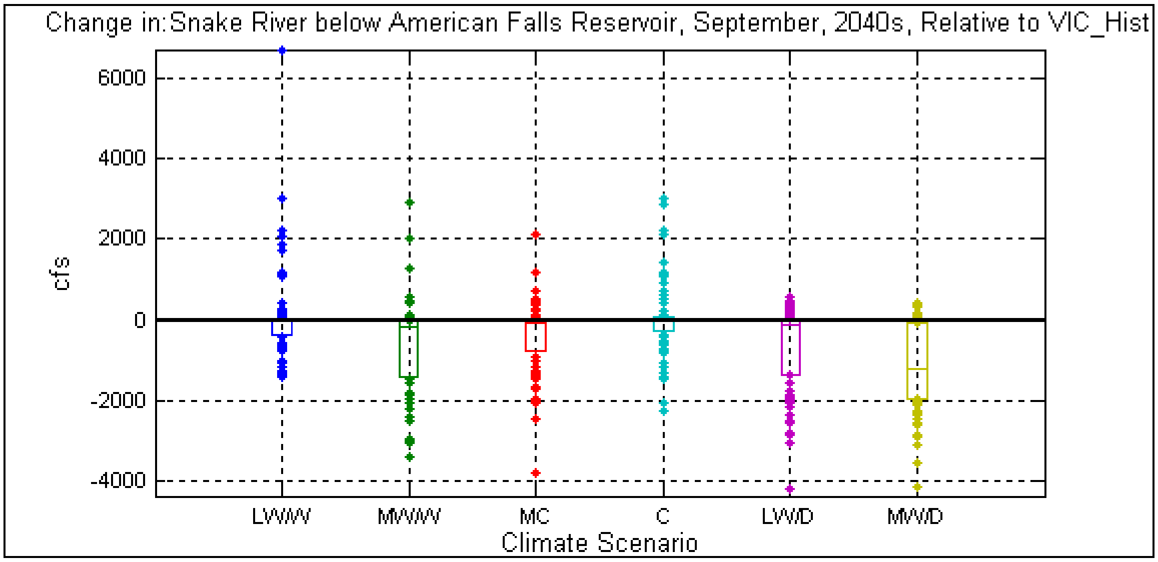


Figure 122. Change in Snake River flow below American Falls Reservoir in September HD 2040 when compared to VIC simulated historical flow.

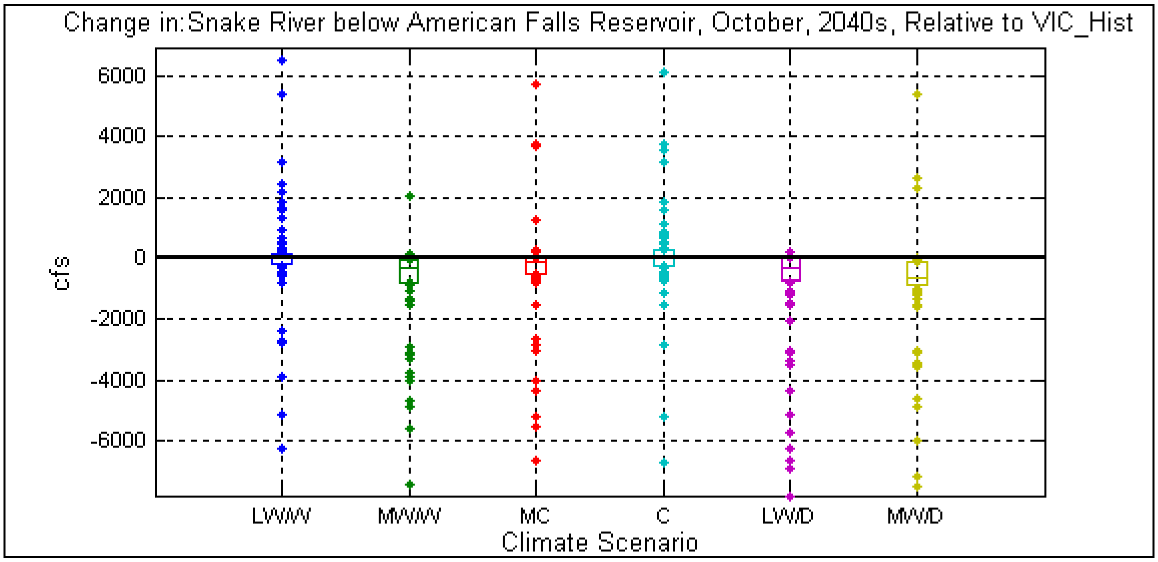


Figure 123. Change in Snake River flow below American Falls Reservoir in October HD 2040 when compared to VIC simulated historical flow.

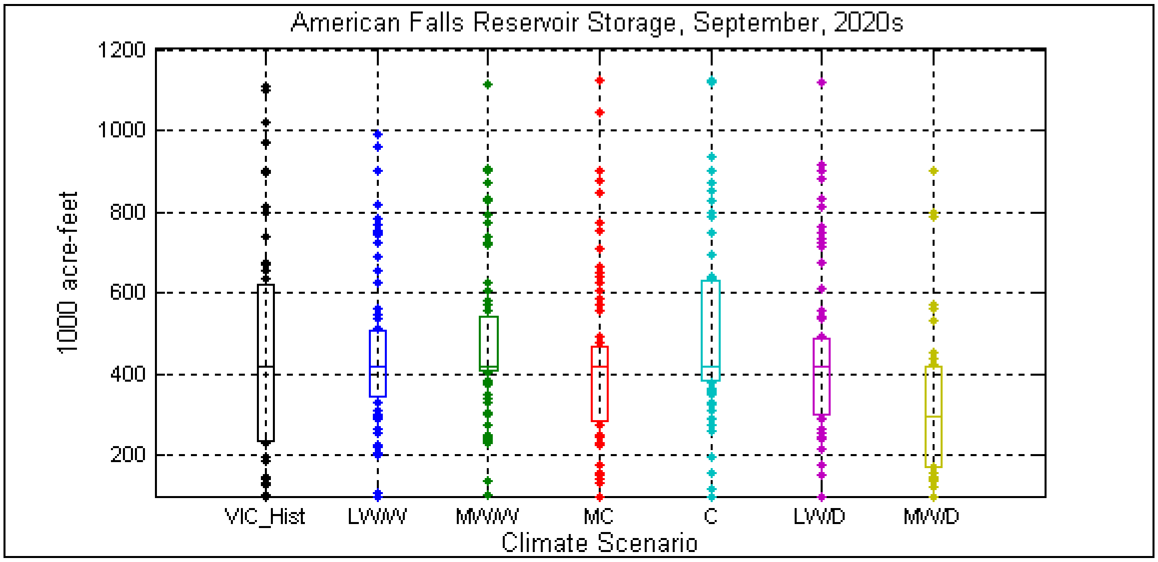


Figure 124. Change in American Falls Reservoir end-of-month reservoir content for September in the HD 2020 scenario when compared to VIC simulated historical.

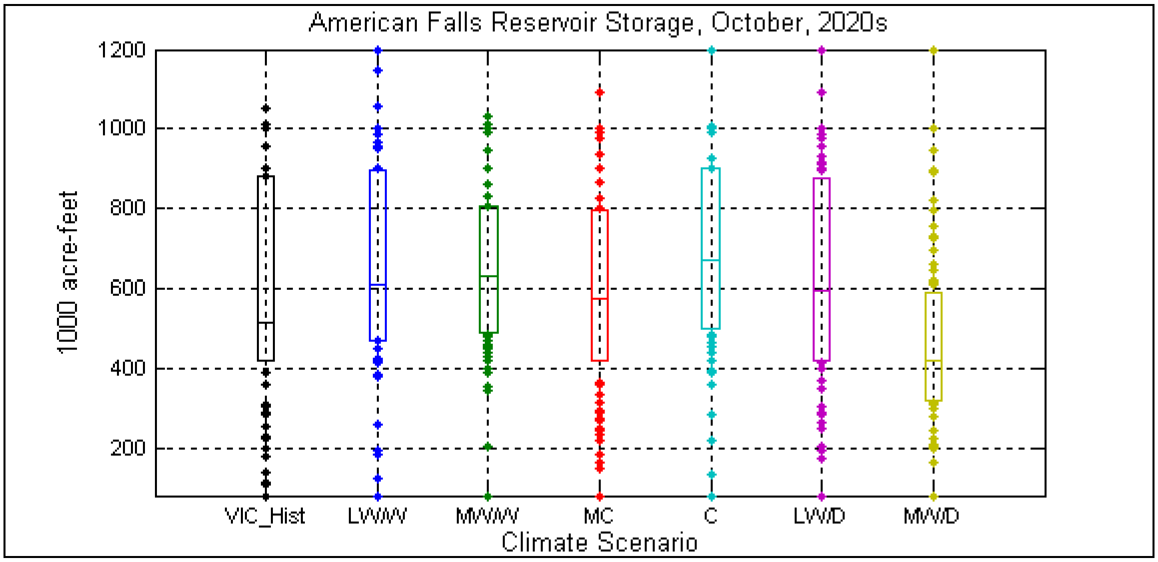


Figure 125. Change in American Falls Reservoir end-of-month reservoir content for October in the HD 2020 scenario when compared to VIC simulated historical.

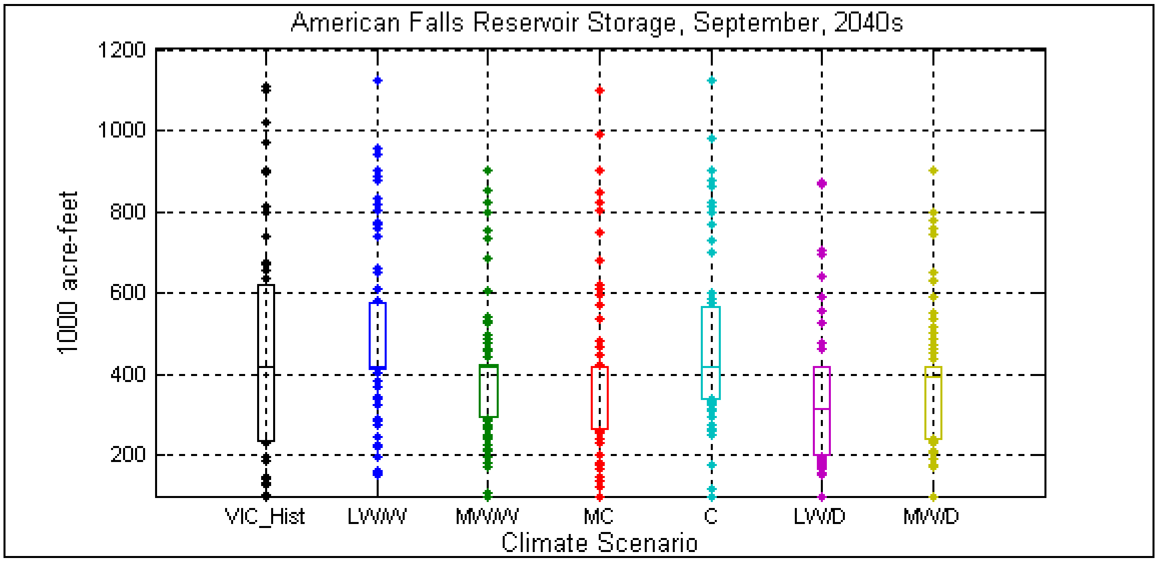


Figure 126. Change in American Falls Reservoir end-of-month reservoir content for September in the HD 2040 scenario when compared to VIC simulated historical.

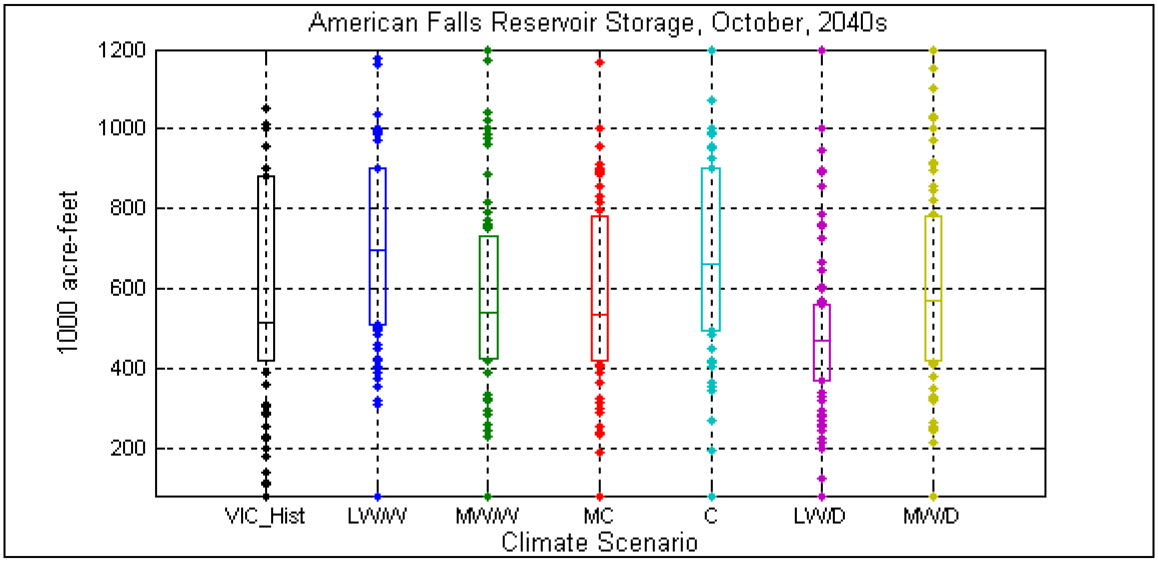


Figure 127. Change in American Falls Reservoir end-of-month reservoir content for October in the HD 2040 scenario when compared to VIC simulated historical.

4. There are several minimum pool objectives in Arrowrock Reservoir for ESA-listed bull trout as described in Section 4.3.1.2.6. Minimum pool elevation within Arrowrock Reservoir with climate change hydrology are not changed substantially over the VIC simulated historical conditions (Figure 128 through Figure 131). To meet the pool elevation objectives there are reduced flows below Arrowrock Reservoir. The change in flows is very slight in the all climate change projections (Figure 132 through Figure 135). The minimum pool objectives are generally achieved for bull trout needs under the changed conditions within current operating protocols.

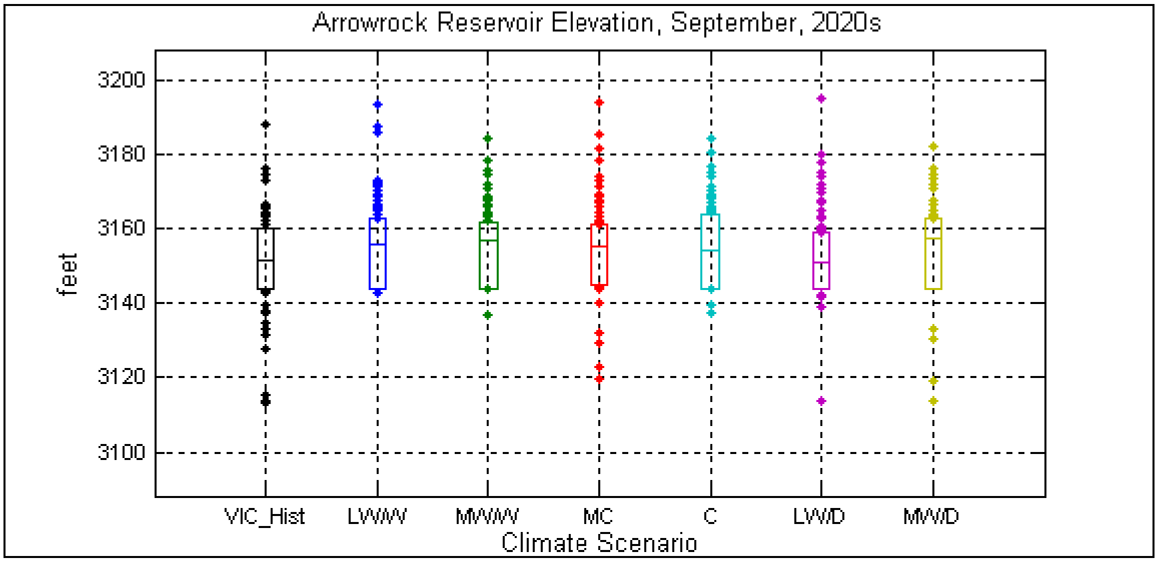


Figure 128. Change in Arrowrock Reservoir end of month pool elevation in September HD 2020 scenario when compared to VIC simulated historical.

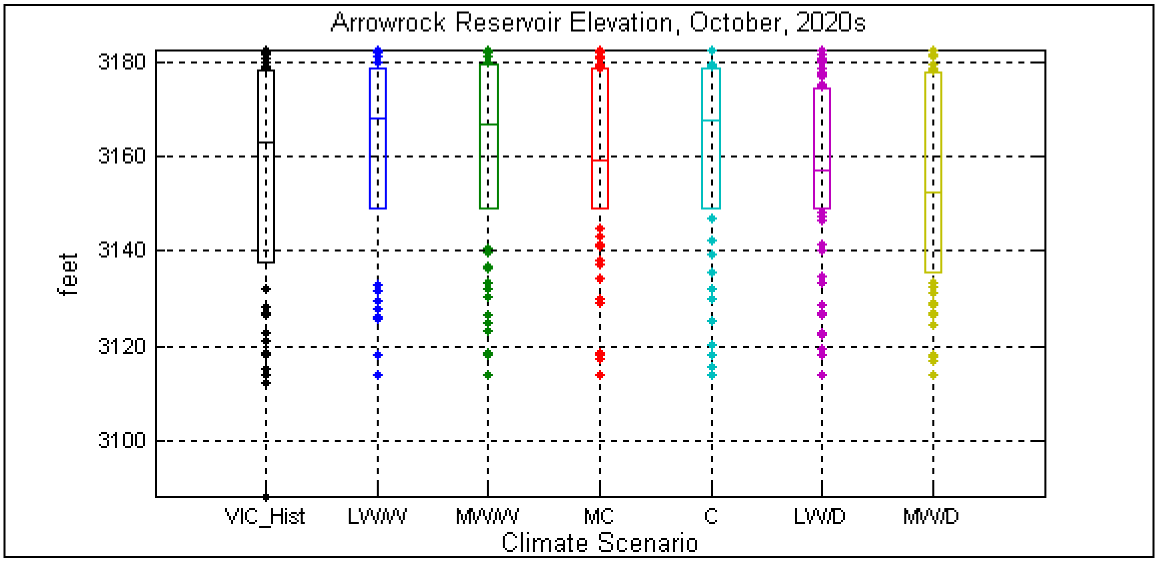


Figure 129. Change in Arrowrock Reservoir end of month pool elevation in October HD 2020 scenario when compared to VIC simulated historical.

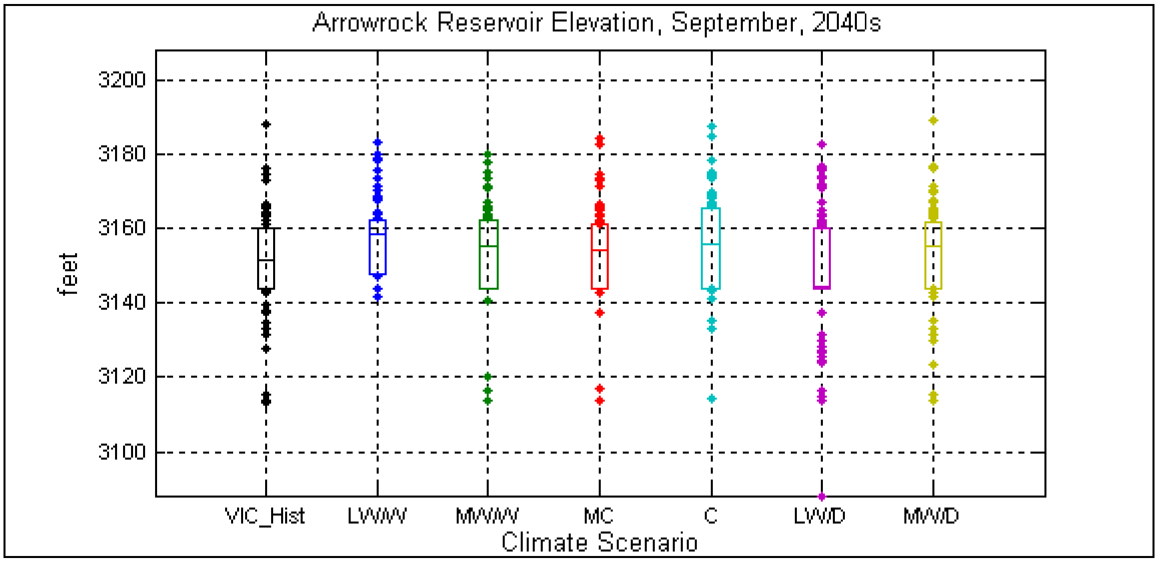


Figure 130. Change in Arrowrock Reservoir end of month pool elevation in September HD 2040 scenario when compared to VIC simulated historical.

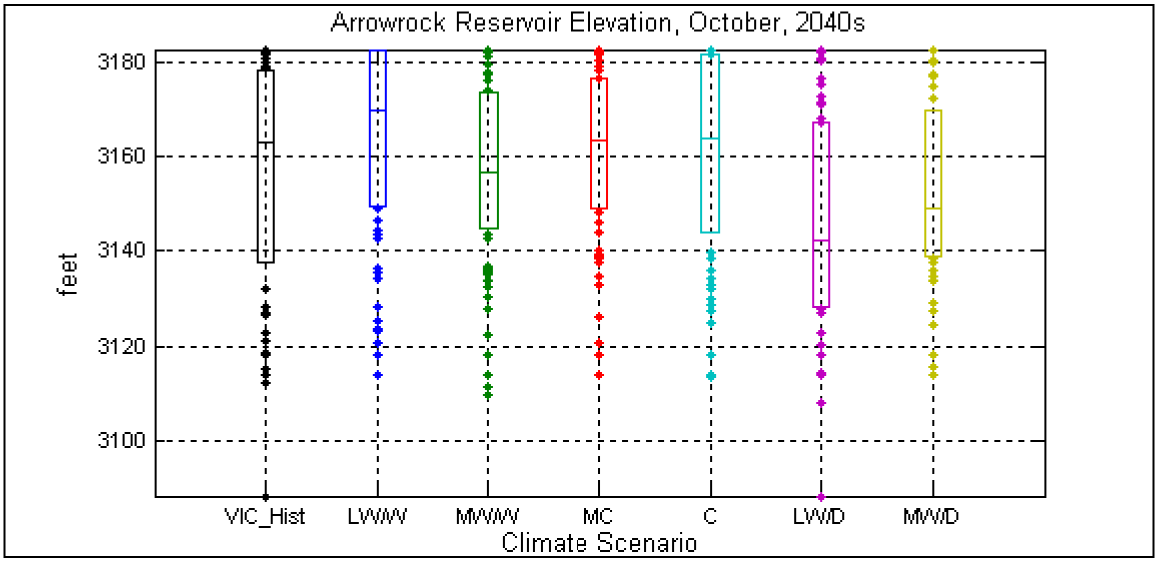


Figure 131. Change in Arrowrock Reservoir end of month pool elevation in October HD 2040 scenario when compared to VIC simulated historical.

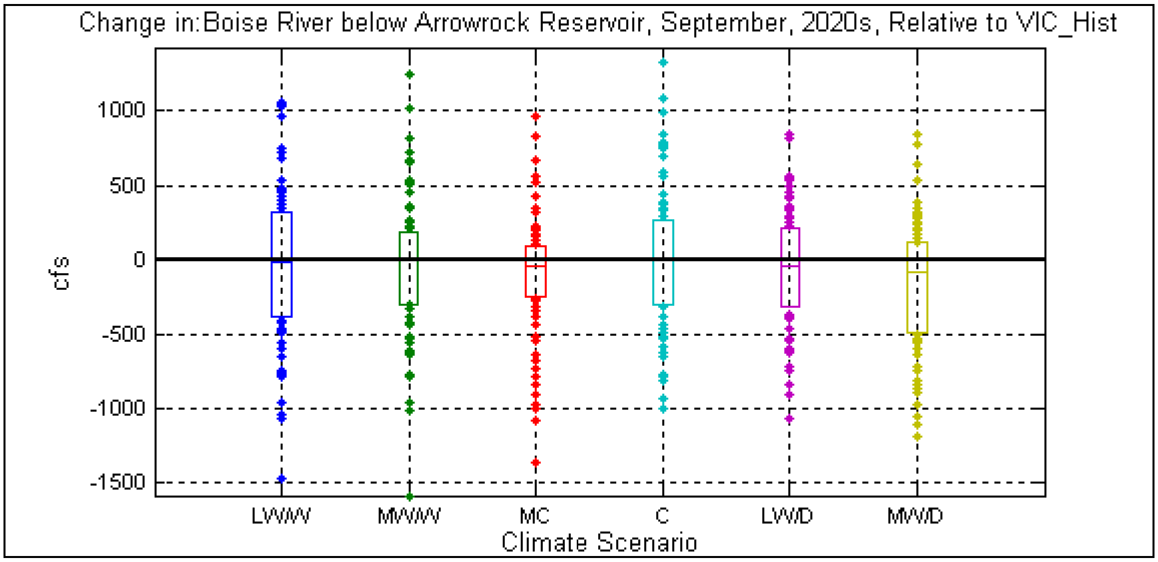


Figure 132. Change in Boise River flow below Arrowrock Reservoir in September, HD 2020 scenario, when compared to VIC simulated historical flow.

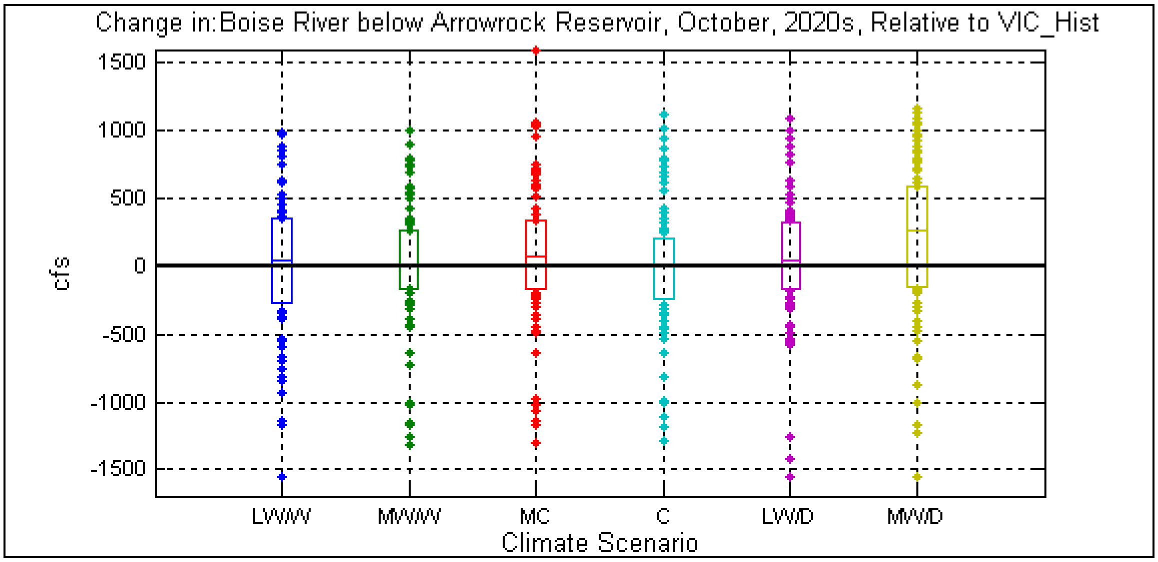


Figure 133. Change in Boise River flow below Arrowrock Reservoir in October, HD 2020 scenario, when compared to VIC simulated historical flow.

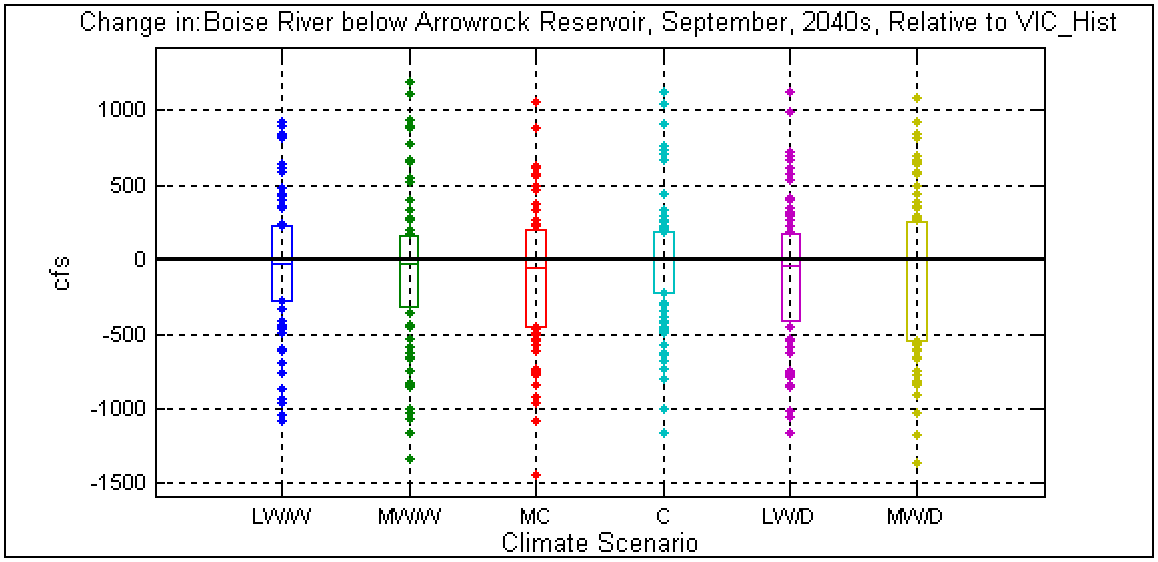


Figure 134. Change in Boise River flow below Arrowrock Reservoir in September, HD 2040 scenario, when compared to VIC simulated historical flow.

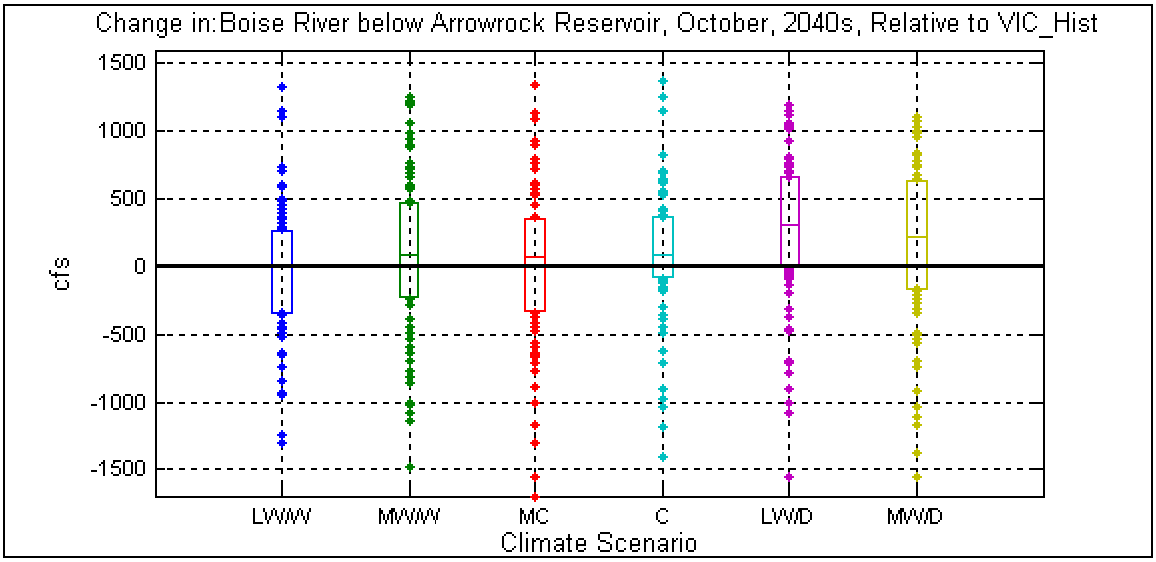


Figure 1. Change in Boise River flow below Arrowrock Reservoir in October, HD 2040 scenario, when compared to VIC simulated historical flow.

1.1.1 Summary

In all of the climate change projections in both the HD and Transient scenarios, a warmer future climate was predicted in the Snake River subbasin. Mean annual temperature increased from 0.5 and about 2° Celsius in the HD 2020 scenario and from a little more than 1 to more than 3° Celsius increase in the HD 2040 scenario.

Predicted changes in precipitation reflected either wetter or drier future conditions. The HD 2020 climates change in mean annual precipitation from historical precipitation varied between a 5 percent decrease and more than 10 percent increase in precipitation. In the HD 2040 climates, the range was even larger from between a 5 percent decrease to a 15 percent increase. While the precipitation had a wide range, most of the GCMs used in the Snake River analysis tended towards wetter conditions. The choice of these 12 GCMs to represent the range of future climates over the entire Columbia River System (Part I Report, Section 4.5.1) unintentionally resulted in the selection of primarily wet climate change projections in the Snake River subbasin when compared to historical temperature and precipitation.

For the Transient scenario, temperature results were presented using the ensemble median of all six Transient climate change projections. Predicted increases in the annual mean temperature ranged from 0 to nearly 10 degrees Fahrenheit from the mid-1950s and 2099 in the Snake River subbasin were shown. As with the Deschutes River subbasin, the ensemble median for precipitation of the six transient climate projections generally remained unchanged (note this is over a 150-year period, not the short-term 30-year window in the HD climates). More information about the details of the climate projections selected and the temperature and precipitation changes can be found in the Part I Report, Section 3.4.

The potential impact of climate change on operations in the Snake River subbasin was evaluated using the Naturalized Flow Snake Planning Model (SPM) and the Modified Flow SPM. Inflow, generated by the UW CIG VIC hydrologic model, was evaluated for the 12 HD future climates using *perfect* and *imperfect* forecasting (and one simulated historical for each) and in the Transient future climates, using only *perfect* forecasting. It was initially believed that the choice of forecasting mode would affect the results, but it was not the case.

The Naturalized Flow DPM indicated that the VIC simulated flows total volume for the period of record calibrated well with the Reclamation naturalized flows. Differences on an average monthly basis between the two datasets varied between a 0.3 percent decrease in VIC simulated flows (from Reclamation naturalized values) to no more than a 1.6 percent increase (in the monthly of July). However, fluctuations in annual average volumes between VIC simulated flows and Reclamation naturalized flow were found to be higher. Annual average volumes varied between roughly 32 percent more flow in the VIC dataset to almost 40 percent less flow in 2008 (that was the largest volume change in the period of record). When viewed at a monthly average basis, most of the increased volume occurred earlier in the year while summer and fall volumes tended to be less than historical volumes.

The Modified Flow SPM was used to evaluate five metrics in the Snake River subbasin including inflow to reservoirs; storage; flow in the Snake River at several locations, including the Boise River and in the Payette River; surface water delivery; and ESA objectives for both anadromous and resident fish species. A summary of the results by metric follow:

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 or volume or both in all of the major reservoir groups. In flow volume to the reservoirs above Brownlee Reservoir increased in all of the climates from January to April or May and decreased in the summer to fall seasons. A shift of one month in the timing of the peak inflow of the wettest climate was observed in the inflow to reservoirs on the upper Snake River above Brownlee Reservoir. A similar change in volume pattern 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.

End-of-Month Storage

End-of-month storage values are presented as a cumulative value of the reservoirs 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 storage volume for the reservoirs in that system, not an individual reservoir.

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. 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. 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 is indicative of a greater need for stored water during the high demand summer season.

On the Boise River, end-of month storage volumes followed similar patterns as on the upper Snake. 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 historic. The modeled hydrology from lesser tributaries to the Snake (Owyhee, Malheur, Burnt rivers, etc) was not presented in this report, but the data suggests that runoff from these lower elevation subbasins will generally peak in March. The shift in timing of peak inflow seen at Brownlee Reservoir were 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 demonstrate the shift seen in the model output.

The timing of flow on the upper Snake River at Heise does not appear to significantly shift to earlier in the year. By the time the flow reaches Minidoka, the peak appears to shift roughly a month earlier. This location includes flow from other watersheds such as Henry’s Fork River, Blackfoot, and Willow Creek. The Snake River between Minidoka and King Hill is influenced by spring flow. The modeled hydrology illustrates that the influence of this spring flow creates a peak during the month of March. Similarly, the modeled hydrology on the Owyhee also peaks in March and when combined, inflow peak to Brownlee occurs earlier to March when compared to historical conditions.

Because the Snake River reservoirs refill 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 refill. The flood control draft of Reclamation's reservoirs is guided by dynamic flood control rule curves that look at the forecast from January through June and subtract the water that has already run off. For example, in early January, a volume is projected from January through June. In early February, the January through June volume was updated and the amount of water that ran off in January was subtracted from that total January-through-June projected volume. If runoff occurs a month or two early as a result of climate change, the flood control storage requirement automatically adjusts to require less space later in spring. This seems to accommodate early runoff without negatively effecting refill.

Flow

Several flow locations were chosen for evaluation because they are used in operational decisions or considered important in other studies on the Snake River. These sites include 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 increase above VIC simulated historical flow during the winter and spring in the HD scenarios. 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 will also likely have larger volumes of flow in the winter and spring with a shift in the timing of that peak flow. Spring returns peak in March, influencing the Snake River between King Hill and Brownlee. 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.

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. 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.

The most significant decrease was observed in the driest climates in both HD scenarios on all river systems presented. For irrigators with supplemental storage water, this study suggests that there will be a shift from using natural flow to using storage in meeting demands under the drier future conditions. 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 have not been 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.

ESA Flow Augmentation for Anadromous and ESA for Resident Fish Species

A shift in the likelihood of delivering flow augmentation water for ESA-listed salmonids was observed in both HD scenarios when compared to the VIC simulated historical deliveries. While achieving the full 487 KAF of flow augmentation may become more difficult, particularly under the HD 2040 scenario, the likelihood of providing at least 427 KAF is predicted to improve.

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 is 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 was evaluated. Palisades Reservoir's minimum flows of 900 cfs are met between October and March for all of the climate change projections. The early fall appears 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.

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 Section 4.2.2.2.1.2, forecasting quality done as part of the Snake River subbasin analysis was considered good with r^2 values above 0.8 at most forecasting locations. Even though the forecasting quality was considered good, the modeling output remained insensitive to the mode used.

5.0 UNCERTAINTIES AND LIMITATIONS

This Part II Report summarizes Reclamation reservoir operations within the Yakima River, Deschutes River, and Snake River subbasins under the RMJOC future climate and hydrology scenarios. These scenarios reflect the use of the best available datasets, data development, and data application methodologies; however, there are a number of analytical uncertainties that are not reflected in this report's assessment results. These uncertainties relate to the development of future climate and hydrology scenarios. The Part I Report (Section 6) provides discussion on several sources of uncertainty, including:

- Global climate forcing
- Global climate simulation
- Climate projection bias-correction
- Climate projection spatial downscaling
- Generating weather sequences consistent with climate projections
- Natural runoff response
- Generating water supply forecasts under future climate and runoff conditions

In addition to these sources, there are additional assumptions made for the sake of framing the operations assessment. Two key assumptions are discussed below, focusing on how assumptions limit the interpretation of these results:

- **Social Systems Response –** Social system assumptions are implicit in how water demands and operational constraints are characterized in these operational assessments (e.g., environmental instream flow targets and other values-based operational objectives). It is possible that climate change could affect social systems in a way that could affect related conditions.
    - Although effects of climate change on crop consumptive use can be estimated, this study does not attempt to quantify the climate change impacts on water demands.
    - Model applications and methodologies for characterizing climate change influences on socioeconomic, institutional, and technological factors controlling demand remain to be developed.

  - Operational constraints that depend on socioeconomic factors (e.g., change in environmental management values that determine instream flow priorities by river tributary and during which times of the year; change in recreational values that determine water levels management at system reservoirs, etc.).

- **Discretionary Operators' Response –** This study reflects a simulated operation of current rules and constraints featured in the Yakima, Deschutes, and Snake rivers simulation models. Some of the model routines are dynamic in the sense that a change in water supply results in a change in demand or flow target, but these routines are based on historical irrigation practices and do not reflect how those practices may change in the face of climate change. This study does not feature change to any discretionary rules featured in these models (e.g., how to balance storage between multiple system reservoirs to serve multiple system benefits). Just as external social systems might respond to a changing climate, it is reasonable to expect that these system operators might react in other ways to a changing climate, learning to adjust discretionary operations as climate experience evolves.

- **Yakima River Modeling Limitations**

  - The Yakima River subbasin naturalized flows could possibly be improved. The Yakima River subbasin naturalized flows were computed using the RiverWare model for the period 1981-2005. The computation is very dependent upon the diversion and return flow assumptions used in the model. The naturalized data set could possibly be improved with further calibration by adjusting the return flow parameters and unknown diversion quantities. The reaches below Parker would likely benefit the most from additional calibration efforts.

  - The period prior to 1981 did not have the necessary gage data for use in RiverWare to directly compute naturalized flows so the period from 1926-1981 was extended using a relationship (from the 1981-2005 period) between the available Hydromet unregulated flows (which were available for specific sites from 1926-2009) and the RiverWare naturalized flows. The RiverWare estimated naturalized flows for 1926-1981 could possibly be improved by filling in the necessary missing data through estimation techniques and using the RiverWare model to compute the naturalized flows.

  - The regulated flows used in the RiverWare model could be improved with a more dynamic irrigation demand curve for use in non-prorated years. This improvement could possibly be based on temperature and precipitation data in the subbasin. The irrigation demands for non-prorated years in the RiverWare model are currently static and do not fluctuate from year to year. In reality, the demands fluctuate from day to day and week to week during the irrigation season and from year to year depending on the weather and runoff forecasts. This may influence system carry-over and water supply in subsequent years.

  - In a future with climate change or even added conservation and altered irrigation practices, the assumptions in the model such as return flow parameters and diversion patterns may change. The model may not be accurately representing the future condition with the current assumptions in the model.

  - The Yakima River subbasin VIC and Climate Change flows present the same concerns as were mentioned in the development of the Snake River and Deschutes River VIC and Climate Change flows.

- **Deschutes River Modeling Limitations:**

  - The Deschutes RMJOC climate change model (also used for the 2010 Modified Flows analysis) was calibrated to represent historical inflows to Lake Billy Chinook. The calibration at Lake Billy Chinook is considered acceptable; however, flows at some upstream locations may not be considered well calibrated. Any future analysis with this model that intends to look at locations other than the inflow to Lake Billy Chinook should evaluate and possibly adjust the historical calibration at upstream locations.

  - The locations of the VIC inflow points should be selected carefully. Only one inflow point was used on the Crooked River (near the confluence with the Deschutes). Points should have been obtained near Ochoco, near Prineville, and because of the ground water influence at Opal Springs, points should be have used upstream and downstream of that location.

  - The MODSIM models of the Upper Deschutes and Crooked Rivers were developed separately by separate agencies and then combined to develop a comprehensive Deschutes Basin Planning model. Because the models were developed at different times by different individuals and agencies, three hydrologic states were created on the Upper Deschutes River and four hydrologic states were used on the Crooked River models. The models are stable with different hydrologic states on each tributary; however, the inconsistency could make it difficult to compare results between the two. The model hydrologic states should be changed to be consistent for future evaluations using this model.

  - Hydrologic states were unchanged in this study and because of that, irrigation shortages may have been underestimated. Hydrologic states are used by the MODSIM model to automatically adjust diversions based on historical demand levels during wet or dry years. In dry years, demands have historically been less and as such, were assumed to remain in that pattern for future conditions. However, depending on climate conditions in the future, farmers may change crops, irrigation seasons may shift to later in the year, or other adjustments could be made that were not reflected in this effort.
  - VIC models were poorly calibrated to Deschutes naturalized flows, so the resulting inflow hydrographs used in the Deschutes CC modeling were poor, when compared to historical hydrographs. This is partly due to the fact that the VIC hydrologic model poorly represents systems that are ground water dominated, like the Upper Deschutes River subbasin. Future work should include a more complete calibration of the inflow hydrographs for the Upper Deschutes River subbasin, which may include utilizing a hydrologic model other than VIC that better represents ground water dominated streamflow.
  - Ground water responses from irrigation practices were “hardwired” into the Deschutes Modified Flows model by calculating what the responses to irrigation would be if irrigation had started 50 years prior to 1928. This was done because responses from ground water take up to 50 years to reach equilibrium in the model. These hardwired responses were retained in the climate change modeling because irrigation practices were assumed to remain static in this study. Future analysis should include converting these hardwired numbers back to a dynamic calculated number that is adjusted with the changing irrigation demands, although there will have to be some calculation that addresses the first 50 years before the ground water responses reach equilibrium in the model.

- **Snake River Modeling Limitations:**

  - The Snake River RMJOC climate change model (also used for the 2010 Modified Flows analysis) was statistically calibrated to represent historical monthly inflows to Brownlee Reservoir. BPA and the Corps were given values for that reporting location. The calibration at Brownlee Reservoir is considered acceptable; however, flows at some upstream locations may not be considered well calibrated or representative of the hydrologic pattern. Any future analysis with this model that intends look at locations other than the inflow to Brownlee Reservoir should evaluate and possibly adjust the historical calibration at upstream locations.

- Because the climate change projections were selected at a Columbia River Basin scale, the projections used in the Snake River subbasin were inadvertently skewed to a wetter climate. In the future, additional dry climate change projections should be considered to provide a greater understanding of the potential impacts that these drier climate change projections may have on overall operations.

- In the Snake River subbasin, 28 locations were used as VIC flow input locations. This generally was acceptable, but additional care should be taken when selecting input locations in future efforts. At times, a VIC reach was too long or too short, resulting in model instability. Hydrologic input points, whether from VIC or another hydrologic model in the future, should be provided along each major tributary in a model to avoid large areas in which one flow location is supposed to be representative of several tributaries. Similarly, if inflow locations are too close together, large swings in volume in adjacent time steps will likely cause the model to crash.

- Hydrologic states were unchanged in this study and because of that, irrigation shortages may have been underestimated. Hydrologic states are used by the MODSIM model to adjust diversions automatically based on historical demand levels during wet or dry years. In dry years, demands have historically been less and as such, were assumed to remain in that pattern for future conditions. However, depending on climate conditions in the future, farmers may change crops, irrigation seasons may shift to later in the year, or other adjustments could be made that were not reflected in this effort.

6.0 LESSONS LEARNED

- Models
    - Locations of VIC calibration points need to be considered carefully. Location selection can affect the way models work, ease of maintaining mass balance, ease of calibrating efforts, checking results, etc. More VIC inflow locations would have been very helpful in this analysis.
    - VIC time series data does not necessarily match Reclamation historical time series data or patterns, particularly in the smaller, upstream subbasins. Bias correction can cause large swings in adjacent time steps, causing model instability.
- Resources
    - Funding to complete studies of this type can be extensive.
    - Staffing levels require a wide range of expertise including, but not limited to, experts in hydrology and other sciences, computer programming, computer modeling (all types), automation, and engineering.
    - High speed computers are needed to manage data and complete model simulations.
- Selection of climate projections should be considered at a subbasin scale (e.g., Snake, Deschutes, and Yakima rivers) in addition to or rather than at a larger basin scale (e.g., Columbia River Basin scale in this case).
- It may be best to use all of the 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 can continue to be improved, use of more modeling may be a better suite of results.

7.0 FUTURE STUDY POSSIBILITIES

The purpose of this study was to understand the potential impact of supply changes resulting from selected climate change scenarios may have on operations of the three participating RMJOC agencies. Because of this initial work, additional studies or areas for further examination have been identified and include (while not exhaustive):

- Demands: Some research projects are being conducted to determine how demand behavior may change with a changing climate. As flow timing, frequency, and duration patterns change (e.g., flow occurs earlier in the year, volumes increase or decrease), changes to current flood operations, diversion practices, carryover, drafting, and other factors may need to be reconsidered. Because this study was conducted to understand how the change of supply may affect operations, additional work should be completed to understand areas of demands, flood control operations, demand changes, and other variables.
- Document additional metrics in future studies that may include (among others):
    - Magnitude and duration of impacts (e.g., prorationing, missing flow augmentation, and ESA targets).
    - Frequency of spillway use.
- Operational changes (flood rule curves, operational): Reclamation does not isolate flood control rule curves from other operational curves in some locations in the Modified Flow DPM or SPM. This is because reservoir operators have at times operated below the flood control rule curves in the winter to provide winter flows or power releases. In some locations, Reclamation uses dynamic flood control curves; however, in those cases where fixed volumes of flood control space 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. Care should be taken to correctly convey the type of GCM used between studies to ensure a comprehensive understanding of the similarities and differences is achieved.
- Flow data from these studies should be combined with Global Climate 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 greater detail. This could include adding more VIC inflow location nodes in the model to improve calibration, conducting the climate flow development process with a more appropriate hydrologic model other than VIC, or coupling surface water/ground water models to improve flow results. Ground water influence below Opal Springs needs to be addressed.

- The upper Deschutes River and the middle Snake River also have a significant influence from ground water. The ground water/surface water interaction was not fully captured by this study.

- In the calibration process, UW CIG uses bias correction techniques to adjust hydrologic model output to better reflect past naturalized flows. It is unknown how bias correction affects future simulations results. It would be interesting to compare model runs characterized by excellent calibration to those that are heavily dependent on bias correction.

- Future efforts might also focus on climate change impacts on fisheries and environmental conditions, which could translate into impacts on environmental water demands seen in reservoir systems management. For example, how do hydrologic impacts (increases or decreased in flow) or temperature increase impacts translate into impacts on anadromous or resident fish species and other aquatic life? Would flow releases from reservoirs be altered or would there be a resultant preferred temperature of water during drafts?

8.0 LITERATURE CITED

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