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

Part III – Reservoir Operations Assessment: Columbia Basin Flood Control and Hydropower

Bonneville Power Administration
U.S. Department of Energy
Portland, Oregon

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

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BONNEVILLE POWER ADMINSTRATION Vision Statement

BPA will be an engine of the Northwest's economic prosperity and environmental sustainability. BPA's actions advance a Northwest power system that is a national leader in providing high reliability, low rates consistent with sound business principles, responsible environmental stewardship, and accountability to the region. We deliver on these public responsibilities through a commercially successful business. These four characteristics define our public responsibilities.

U.S. Army Corps of Engineers Northwestern Division Mission Statement

The Northwestern Division provides engineering services and stewardship of existing water resource infrastructure, conducts water resources development, military construction, environmental protection and restoration, and emergency response operations within our assigned areas of operations to serve the Army and the Nation. On order, the Northwestern Division provides Field Force Engineering services to deployed forces or other USACE elements."

Photograph on front cover: Bonneville Dam (BPA Library photo archive).

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Part III – Reservoir Operations Assessment: Columbia Basin Flood Control and Hydropower

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Abbreviations and Acronyms

AER	Actual Energy Regulation
aMW	average Megawatt
AOP	Assured Operating Plan-pertains to the implementation of the Columbia River Treaty
Apr I	First half of April, or April 1-15
Apr II	Second half of April, or April 16-30
August I	First half of August, or August 1-15
August II	Second half of August, or August 16-31
BC	British Columbia
BC Hydro	British Columbia Hydro and Power Authority
BiOp	Biological Opinion
BPA	Bonneville Power Administration
C	Central Change-refers to Hybrid Delta climate change scenario characterization
CER	Canadian Entitlement Return
cfs	cubic feet per second
CIG	Climate Impacts Group, University of Washington
Corps	US Army Corps of Engineers
CSRB	Columbia-Snake River Basin
DOP	Detailed Operating Plan pertaining to the Columbia River Treaty

DWR	Dworshak
ECC	Energy Content Curve-a power rule curve
ESA	Endangered Species Act
FCOP	Columbia River Treaty Flood Control Operating Plan
FCRC	Flood Control Refill Curve to provide 95% confidence of Refill
FELCC	Firm Energy Load Carrying Capability
ft	feet
GCL	Grand Coulee
GCM	General Circulation Model
HD	Hybrid-Delta
HydSim	Hydrologic Simulation model
IJC	International Joint Commission
IPCC AR5	Intergovernmental Panel on Climate Change Fifth Assessment Report
kaf	thousand acre-feet
kcfs	thousand cubic feet per second
LW/D	Less Warming and Drier-refers to Hybrid Delta climate change scenario characterization
LW/W	Less Warming and Drier-refers to Hybrid Delta climate change scenario characterization
LWG	Lower Granite
Maf	million acre-feet
MC	Minor change-refers to Hybrid Delta climate change scenario characterization
Mid-C	Middle Columbia River Public Utility Districts – Grant, Douglas, and Chelan
MW	Megawatt, refers to powerhouse capacity
MW/D	More Warming and Drier- refers to Hybrid Delta climate change scenario characterization
MW/W	More Warming and Drier- refers to Hybrid Delta climate change scenario characterization
NOAA	National Oceanic and Atmospheric Administration
NPRs	Non-Power Requirements
NW	Northwest
NWPP	Northwest Power Pool
NWS	National Weather Service
OY	Operating Year
PDP	Proportional Draft Point-Reservoir draft levels to meet firm loads
PNCA	Pacific Northwest Coordination Agreement
PUD	Public Utility District

Reclamation	US Bureau of Reclamation
RMJOC	River Management Joint Operating Committee
S/W	Summer/Winter ratio pertaining to runoff volumes
SOA	Supplemental Operating Agreement-Annual agreements between the U.S. and Canadian Entities
SOP	Standard Operating Procedure
SRD	Storage Reservation Diagram-Used to compute flood control curves
TDA	The Dalles
TSR	Treaty Storage Regulation-A hydroregulation that determines Canadian Treaty Projects' operations
URC	Upper Rule Curve, or flood control curve
UW CIG HB2860	University of Washington Climate Impacts Group
VarQ	Variable Discharge, pertains to flood control procedure for Libby and Hungry Horse
VDL	Variable Draft Limit-draft limits in January through March at Grand Coulee and Hungry Horse
VECC’s	Variable Energy Content Curves-power refill curves used in HydSim
VIC	Variable Infiltration Capacity- Hydrologic Model used by University of Washington

Executive Summary

The Bonneville Power Administration (BPA), U.S. Army Corps of Engineers (Corps), and Bureau of Reclamation (Reclamation) collaborated to adopt climate change and hydrology datasets for their longer-term planning activities in the Columbia-Snake River Basin (CSRB). This was coordinated through the River Management Joint Operating Committee (RMJOC), a sub-committee of the Joint Operating Committee which was established through direct funding Memorandum of Agreements between BPA, Reclamation, and the Corps. 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 Federal Columbia River Power System 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.
This report is the third of four documents to be produced in this effort titled *Climate and Hydrology Datasets for use in the RMJOC Agencies’ Longer-Term Planning Studies*:

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• Summary Report (expected Spring 2011)

Briefly stated, Part I report provides a detailed description of future climate and hydrology datasets that are meant to serve upcoming longer-term planning assessments conducted by RMJOC agencies. Part II and Part III reports are meant to complement Part I report by presenting demonstration operations analyses featuring the use of these future climate and hydrology datasets. The Summary Report will offer a non-technical description of key themes from the three technical reports along with discussions on lessons learned and potential next steps in this collaboration. On the assessments to be described in Part II and Part III reports, 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.

This Part III report contains information from the US Army Corps of Engineers (Corps) on flood control and from the Bonneville Power Administration (BPA) on power operations. Sections 1 and 2 describe general information and describe the reservoir system along the Columbia River initiating in Canada down to and including the The Dalles Dam. Sections 3 through 9 provide detailed information on the flood control analysis completed by the Corps. The remaining sections are dedicated to a discussion of the power operation analysis conducted by BPA.

Flood Control Analysis Background and Assumptions. The flood control portion of this report was prepared to develop flood control curves influenced by climate change for use in BPA's power model which will assess the impacts of climate change on the Federal Columbia River Power System. The flood control curves are upper rule curves, which provide the maximum pool levels to which projects may operate. BPA modeled the reservoir system for fish and hydropower purposes as limited by the flood control upper rule curves. From the Part I report, 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. Flood control curves were computed for a total of 34 scenarios , because the HD scenarios and historical condition were computed in both perfect and imperfect forecasting modes, and the 2000 Level in both perfect and imperfect forecasting modes were included.

However, BPA and the Corps selected just 20 scenarios to be represented in this report. The flood control analysis in this report addresses the twelve Hybrid-Delta scenarios in forecast mode (six 2020s and six 2040s), the 2000 Level scenario in imperfect forecast mode , the six Transient scenarios in perfect forecast mode, and the 2000 Level Base Case in perfect and imperfect forecast modes. . The perfect forecast scenarios assumes perfect foreknowledge of runoff volumes, and the forecast mode assumes imperfect foreknowledge of runoff volumes.

Forecast scenarios are reported because they represent a level of uncertainty inherent in actual operations. The 2000 Level scenarios are based on historic climate. The 2000 Level perfect forecast scenario is compared to the Transient Scenarios, and the 2000 Level imperfect forecast scenario is compared to the HD scenarios, also in imperfect forecast mode. The reservoir modeling period is the 70-year period 1929 to 1998.

The Transient climate scenarios are meant to be considered together as a group, or ensemble which is meant to portray an envelope of climate possibility through time (see Part I, Section 3.3.2 for more information on Transient Climate Projections). While Transient climate projections were made for the years 1951 through 2099, the 70-years of data that the flood control curves were prepared for were based on the Transient 70-year period 1999 through 2068.

Flood Control Results and Implications. The following is a summary of the results and implications for the Columbia River Flood Control system and the major Columbia River flood control projects that have variable flood control curves that are dependent upon runoff volume forecasts. See Figure 1 for a map of the NW Region showing the major hydro projects. The results and methods of calculation are detailed in Section 3 through 7. Implications of Climate Change on Flood Control Operations are in Section 8.0, and Limitations and Uncertainties are located in Section 9.0. This flood control results section only addresses the reservoir flood control operations, or the highest pool levels to which the projects may operate.

Columbia River System Flood Control. In general, the observation of the effects of climate change for the Columbia River Basin based on the The Dalles data is that runoff occurs earlier than historically shown in the 2000 Level data. A shift of the peak monthly mean volume from June to May could mean the system may need to draft earlier for flood control to capture runoff that occurs earlier. With generally less April through August runoff volume in climate change at The Dalles, overall the system would generally draft less for flood control. The Transient scenarios show that over the 70-year period, there is a decline of the Transient ensemble median April through August runoff volume of approximately 10%.

Future climate change data show generally higher monthly mean volumes during the winter

which could result in more risk for winter flood events. Winter flood control procedures may need to change to accommodate increased occurrences of rain-driven-events and rain-on-snow events for both system flood control as measured at The Dalles and local flood control downstream of headwater projects.
A re-evaluation of the local forecasts may need to be considered with notable climate change impacts on local project runoff characteristics. With current procedures, conflicts may arise between drafting earlier for spring snowmelt and the need to reduce winter flooding. This is because flood control projects draft in the period January through April to meet their April flood control requirements for spring flood protection while higher winter flows are occurring. Any consideration of an earlier draft period might also have implications on project refill and other spring-summer objectives. Any consideration of an earlier draft period might also have implications on project refill and other spring-summer objectives such as fish flow objectives.

Some projects may have operating constraints that limit reservoir draft rates due to dam safety, downstream safety or other non power operational reasons. It may be desired to limit spilling for water quality purposes and power purposes. These constraints need to be considered if there is a need to draft to their maximum evacuation point earlier in the season.

As designed, the current flood control draft procedures can adapt to manage the range of April through August climate change volumes at The Dalles since the climate change range of volumes are similar to that of the historic volumes from 1929 to 1998. However, there are a several scenarios that had one year where the April to August runoff volumes from the climate change data are greater than the maximum volume from the 2000 Level data set that should be investigated with daily modeling.

Hydrologic runoff shape was not investigated in this study and has an influence on the ability to meet flood control objectives. The evaluation of existing flood control space and procedures to meet spring flood objectives will depend on the outcome of daily modeling. However, as with the current design of system flood control procedures, a redesign of system flood control space and the distribution of that space would be determined based on a balance between system development costs and damages prevented, knowing that the flood control system cannot protect for all hydrologic events.

Levees that protect the lower Columbia River are a key component of system flood control. With the possibility of more frequent and unpredictable winter flood events where reservoirs may not be able to manage for flood damage reduction, the importance of these levees would increase. Maintenance, repair, and improvements to levees may become a higher priority.

Mica and Hugh Keenleyside Dams. Note that Hugh Keenleyside Dam and its associated reservoir – Arrow Lakes is commonly referred to as “Arrow” and will henceforth be referred to as such. A general statement on what climate change means to flood control at Mica is not readily apparent. The Hybrid-Delta scenarios show that average flood control elevations for some scenarios are higher, and some are lower than that of the 2000 Level, so what climate change means to flood control at Mica is dependent on which climate change scenario is being examined. For the Transient scenarios, over the 70-year period, the ensemble median flood control elevations increase by approximately two feet, or 197 kaf for Mica and two feet, or 230 kaf at Arrow, which is reflective of the decrease in The Dalles ensemble median runoff volume trend.

Grand Coulee Dam. A general statement on what climate change means to flood control at Grand Coulee is not readily apparent as the Hybrid-Delta climate change scenarios do not show a consistent trend. The Hybrid-Delta scenarios show that there are some scenarios resulting in flood control elevations generally higher, and some generally lower than that of the 2000 Level scenario. The Transient scenarios show that over the 70-year period, the median flood control elevations increase approximately thirteen feet (El. 1240 ft. to El. 1253 feet, or 812 kaf, which is reflective of the decrease in The Dalles ensemble median runoff volume trend.

Brownlee Reservoir. In the period January through April, on a monthly basis, climate change scenarios have significantly higher volumes (wetter) than the 2000 Level and lower volumes for May through September. The peak month occurs in March for nearly all of the climate change scenarios, as compared to May in the 2000 Level. It is possible that with earlier and higher winter inflows to both Brownlee and The Dalles, that earlier flood control drafts may be needed at Brownlee. Overall, the 2000 Level April through July runoff volume exceedance curve falls roughly in the middle of all of the other climate change scenarios, resulting in six scenarios with higher average flood control elevations and six lower than the 2000 Level. The Transient scenarios show that over the 70-year period, the ensemble median flood control elevations increase approximately thirteen feet (El. 2045 ft. to El. 2058 feet, or 145 kaf, which is reflective of the decrease in the Brownlee and The Dalles ensemble median runoff volume trends.

Libby Dam. The Hybrid-Delta scenarios are generally wetter October through May, and drier July through September. The monthly mean peak occurs in June in both the climate change and 2000 Level with a mix of peaks being higher and lower than for the 2000 Level. Nine of the twelve Hybrid-Delta climate change scenarios generally show that the April through August runoff volumes are generally wetter than the 2000 Level volumes, resulting in some six scenarios with higher average flood control elevations and six with lower than that of the 2000 Level.

Because the Hybrid-Delta climate change scenarios as a whole do not show a consistent trend with regards to flood control elevations, a general conclusion on the impact of climate change on Libby is not readily apparent. The Transient scenarios show that over the 70-year period, the ensemble median flood control elevations increase approximately eleven feet (El. 2380 to

El. 2391 feet, or 320 kaf, which is reflective of the decrease in Libby's ensemble median runoff volume trend.

Hungry Horse. During the November through May timeframe the Flathead basin above Hungry Horse is wetter in the climate change scenarios than in the 2000 Level, and drier from June through September. The peak month is May, with nearly all scenarios having a higher peak than the 2000 Level. June is generally significantly drier with climate change. In general, climate change seasonal runoff volumes for May through September are lower than the 2000 Level volumes with ten of the twelve Hybrid-Delta scenarios resulting in higher average flood control elevations for April 30. The Transient scenarios show that over the 70-year period, the ensemble median April 30 flood control elevations increase approximately sixteen feet from El. 3529 to El. 3545 feet, or 343 kaf.

Dworshak. The selected climate change projections show the Clearwater basin to be much wetter in the November through March period than for 2000 Level and drier in the May through August period. The higher and earlier winter volumes may indicate that earlier and deeper winter flood control drafts may be warranted. The peak monthly runoff occurs in May for the majority of the climate change scenarios which is also true of the Base Case 2000 Level. The climate change seasonal runoff volumes for April through July are generally lower than the 2000 Level, resulting in higher average flood control elevations for all Hybrid-Delta scenarios. The Transient scenarios show that over the 70-year period, there is a decline of April through July runoff volumes resulting in an increase in the ensemble median flood control elevations of approximately 30 feet from El. 1525 to El. 1555 feet, or 417 kaf.

Limitation and Uncertainties. Limitations and uncertainties associated with the flood control analysis are provided in Section 9.0. Assessment of flood control for this report is based only on the climate change scenarios selected for analysis. While the analysis provided in this report can show flood control impacts based on the climate change scenarios selected, other available future climate information may be yield different results, and this should be considered in future studies. The limitation of this effort with respect to flood control is that daily time-step system flood control modeling (regulations) to determine flood control refill operations that meet flow objectives at The Dalles were not undertaken due to time constraints. Therefore, we cannot analyze, from a probabilistic or risk perspective, how existing procedures meet system flood flow objectives with climate change hydrology. At the time of this analysis, an automated daily time-step flood control model was not available to develop flood control curves for as many scenarios as studied within the time-frame desired. A new tool is under development and will be available in calendar year 2011. This tool is planned to be used in future climate change studies. Daily modeling would also assist in answering the question of how climate change can affect spring refill of projects.

Uncertainties in the forecast seasonal volumes and the timing of the runoff in late spring and early summer are the major factors in being able to control flood flows to desired levels. With climate change, results suggest that forecast skill diminishes for most locations as warming causes snowpack to diminish. . .

Next Steps. The next steps in flood control analysis are discussed in more detail in Section 13.0. Climate change scenarios other than those selected for this study should be evaluated and assessed, and may be included in further analyses. See Section 3.2 of Part 1 – "*Future Climate and Hydrology Datasets*", (Reclamation 2011) for a discussion of other scenarios not selected. Methods for temporal downscaling from monthly General Circulation Modeling to daily data streamflows and bias correction methods to account for GCM and hydrologic model biases are being investigated and may be improved. Consideration of glacial snowmelt information in Canada was not available at the onset of this study and may be included in future studies.

In parallel, preparation for, and preliminary daily modeling may be performed. The purpose of the preliminary modeling is to set up tools and procedures for future modeling, and to identify areas of concern to guide future paths. If it is determined that climate change has an undesired effect on the regulated frequency of peak flows, for example, if the frequency of flows at levels that cause flood damages increase, then the next step would be to begin to think of how flood operations might need to change to reduce undesired impacts. However, this is dependent on development of regionally accepted methods and processes that create climate change daily flows and forecasts for input to reservoir models.

The Corps will incorporate risk analyses as part of a risk assessment in future flood control studies. One such study is the Columbia River Treaty 2014 Review program that is considering continuing, terminating, or modifying the Columbia River Treaty. In this program, it is planned that daily modeling would be performed with a wider range of possible climate change scenarios before concluding the impact of climate change on flood control. Evaluation of operational and structural alternatives will be included in the risk assessment.

Hydropower Operations. The following is a summary of the results of the operational impacts of climate change on the primary Federal projects (described in more detail in sections 10-14).

Arrow (Canada): In the climate change scenarios modeled in this Part, the Arrow outflows are not impacted to the same degree that the lower U.S. projects are. However, the project does reflect the general trend of higher winter flows and reduced late summer flows. The smaller degree of impact may be due to the geographical location in the northern parts of the Columbia River Basin. The northern region has a much cooler climatology and therefore less variability to temperature related impacts on precipitation and snowmelt characteristics.

Libby Dam: Libby experiences more significant changes to its Base Case operation than most any other project. This is likely due to a combination of high variability in the project natural inflows and due to the number and nature of its operating objectives. The winter elevations are higher in the climate change scenarios by roughly 10 ft. on average as the project operates more closely or more frequently to the URC. The early spring outflows from the project are also notably higher than the Base Case, to some degree because the higher elevations do not result in as much space available to capture the local basin snowmelt. In addition, Libby is modeled to operate to a coordinated Canadian operation that meets International Joint Commission (IJC) rule curves for Kootenay Lake as agreed by the U.S. and Canadian Entities. These operating provisions do not allow for adaptive management procedures that may be warranted under climate change and are under evaluation for potential climate changes.

Hungry Horse Dam: Hungry Horse, like Libby, exhibits higher elevations in the February through May period and significantly higher outflows in the April through May period. The reasons are similar to Libby – namely higher inflows in the Feb-May period with the project operating to it's URC more frequently. The project typically operates to support a downstream minimum flow of 3,500 cubic feet per second (cfs) at Columbia Falls while targeting an April 10 Upper Rule Curve (URC) elevation.

Grand Coulee Dam: Grand Coulee follows the general theme of climate change, namely higher outflows and elevations during the winter to early spring period, higher elevations during the April period and reduced outflows during the late summer.

Dworshak Dam: Dworshak experiences higher winter outflows similar to the other projects but the elevations in the Feb-May period are significantly higher than the Base Case. This is due to higher inflows and higher flood control upper rule curves. This is more pronounced in the 2040 scenarios where the elevations may be 30 to 35 ft. higher than the Base Case.

Brownlee Reservoir: Brownlee discharge in the climate change scenarios shows an increase in discharge during the January through May period, relative to the Base Case. This corresponds closely to higher inflows in the same period.

Summer BOp Flow Targets: Climate change results in a general increase to spring flows on the Lower Snake and Columbia River. The number of years the Biological Opinion (BiOp) flow targets are met in the spring for Lower Granite and McNary are not adversely impacted during this period although the BiOp flow targets during the May period are more frequently exceeded, consequently at the expense of the desirable summer flows. There is also an increase in spill during the last half in April and the month of May at many projects, in the climate change scenarios. There is one scenario in particular, the 2040 MW/W scenario, with very high precipitation and subsequent high streamflows. This scenario results in significant high flows and exceeding high spill levels at projects such as Libby and Hungry Horse. Section 13.3 provides more details regarding the summer BiOp flow impacts, on a month-by-month breakdown.

Generation Impacts: With the discussion consistently illustrating the theme of higher winter-early spring flows and reduced late summer flows, the generation profiles for the Region and the Federal system follow suit accordingly. The 2020 scenarios show an increase in winter generation to the tune of 1100-2000 average Megawatts (aMW) for the Region based on the Central water supply and MW/W water supply respectively. The summer generation impacts from climate change are reduced in the amount of 200-400 aMW for the 2020s and 650-1560 aMW for the 2040s. Section 13.5 provides more detail on the generation impacts.

Implications of Climate Change on Hydropower Operations. The climate change scenarios reflect a consistent shift of runoff to higher winter flows and lower late summer flows. The higher winter flows, when modeled under the current operating procedures and objectives, results in a combination of higher spring outflows and project elevations. The higher flows generally spill over into the spring period as the projects refill towards their June 30 fill target date.

The outflows in late summer are thereby reduced as the natural inflows are diminished with the reduced snow tables. The trends increase from the 2020s to the 2040s (note that the 2020s reflects the years 2010-2039 and the 2040s reflects the years 2030-2059). In the future, the river management procedures would likely need to be revised accordingly through a combination of deeper December reservoir drafting, (to better accommodate higher winter flows), and possibly deeper reservoir drafts in the August-September period to compensate for the reduced natural flows in the late summer.

Hydropower Limitations and Uncertainties. Limitations and uncertainties associated with the hydropower operations are provided in Section 12.2. The numerous scenarios required that some simplifications be made in the modeling processes. Because each scenario contained 70 years of modeling results, it was not feasible to hand-tune each project for each water year to obtain the most detailed and precise operation desired in every condition. However, the scenarios were all run under the same consistent processes and review level, thereby maintaining a high level of confidence that the deltas, or differences between the scenario results were a good representation of impacts resulting from the different climate projections.

Non-power or fishery objections are subject to change over time. The scenarios contained in this Report Part III all assume the current level of fishery constraints. Ideally, a range of possible fishery requirements would provide an envelope of climate projection impacts to fish requirements.

Planning studies that incorporate a long-term horizon out to 50 years could not possibly anticipate with any accuracy the possible future outlook of new energy technologies, efficiencies or energy policies. Each of these variables could have widespread impacts upon the results of these studies.

Next Steps. This study represents the first Federal agency coordinated study using the current level of climate change information and data. This study has highlighted the impacts of climate change on flood control and power generation in general and for each climate change scenario. The impacts are significant in many cases. It must be noted early that the modeling was performed to current procedures and objectives, for the most part developed under the historical streamflow sequence (generally the 70 year period 1929-1998), which was assumed to be the best representation of future conditions.

The next steps fall under two headings and they are to monitor and evaluate. The monitoring will consist of back-casting our historical record and present conditions to see if the transition towards the future climate change scenario characteristics is underway. This will help establish a timeline to apply to the evaluation and review phase of our current river management procedures, of which flood control is key.

The evaluation phase will explore alternative processes to achieve flood control objectives and other non-power objectives assuming climate change influenced hydrology. The evaluation phase will also incorporate newer climate change information as it becomes available and develop the data and tools to better facilitate climate change data. It is expected that the evolution of technology and science of climate change, namely in the NW region, will result in more confidence in the results and in planning processes that are more consistent with the nature of climate change as it is projected to unfold on the Columbia River power system.

1.0 INTRODUCTION

The Bonneville Power Administration (BPA), U.S. Army Corps of Engineers (Corps), and Bureau of Reclamation (Reclamation) collaborated to adopt climate change and hydrology datasets for their longer-term planning activities in the Columbia-Snake River Basin (CSRB). This was coordinated through the River Management Joint Operating Committee (RMJOC), a sub-committee of the Joint Operating Committee which was established through direct funding Memorandum of Agreements between BPA, Reclamation, and the Corps. 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 Federal Columbia River Power System projects.

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The Corps makes use of the water supply seasonal volumes from Part I to calculate the reservoir flood control curves. BPA uses the hydrology datasets from Part I as natural streamflows input to their HydSim model (with streamflows from the Upper Snake, Deschutes, and Yakima and the associated effects on The Dalles from Part II). Volume forecasts from Part I are also used to compute power refill curves used in the HydSim model. The flood control curves, also known as upper rule curves (URCs), establish upper limit reservoir elevations in the HydSim model where reservoirs may not be operated above these curves except under certain conditions.

Flood control curves were developed in observed and forecast mode for each of the climate change scenarios as well as for the 2000 Level data. The observed mode is where the seasonal volumes used to compute the flood control requirements is known and reflects perfect foreknowledge of flow volumes. Observed runoff volumes of the Hybrid-Delta climate change scenarios were computed by running the VIC Hydrologic model (see Part I, Section 4.0) and summing the volume of runoff that passes a given point over a given period. The forecast mode is where the seasonal volume forecast changes from month to month and reflects uncertainty. Forecast runoff volumes of the Hybrid Delta scenarios use a forecasting procedure (See Part I, Section 5.0) to provide estimates of anticipated runoff volumes. The estimates are made each month January through June. While flood control curves were computed in both the observed and forecast modes for the Hybrid-Delta scenarios, only the forecast mode flood control curves are discussed in this Part because they better represent the uncertainties associated with actual operations. Flood control curves for Transient scenarios were computed in observed mode because forecast volumes were not developed.

The Hydrologic Simulation (HydSim) modeling effort by the BPA incorporates the URCs and other inputs and assumptions into the HydSim regulation model to determine resulting operations of the reservoirs. These results will include detailed reporting on reservoir elevations, outflows, power generation and spill flow for each of the climate change scenarios. This Part compares the output variables of the climate change scenarios against each other as well as against a Base Case 2000 Level operation.

2.0 DESCRIPTION OF RESERVOIR SYSTEMS

2.1 Mainstem Columbia River Basin

The mainstem Columbia River extends over 1,000 miles from its headwaters in British Columbia to the Pacific Ocean. Major tributaries to the Columbia River include the Snake River, Kootenay River, Pend Oreille River, Spokane River, and Willamette River basins. Together the Columbia Rivers and its tributaries above the Dalles Dam comprise a drainage basin of over 259,500 square miles.

There are 31 primary power producing, federally owned dams on the Columbia River and its tributaries. There are many more dams lacking power plants but performing other important functions. These projects are currently operated for a variety of purposes including flood control, navigation, irrigation, power production, fisheries, and recreation. This multi-use vision of the Columbia River has always been a goal of the projects since their construction. Figure 1 shows the location of major projects owned and operated by the Corps and others in the Columbia River Basin.

Figure 1. Map of Major Hydro Projects in the Pacific Northwest.

There are three major dams located on the Canadian portion of the mainstem Columbia River. From upstream to downstream, these projects are Mica, Revelstoke, and Hugh Keenleyside Dams (Arrow). Mica and Arrow regulate large reservoirs and are important for both power production as well as system flood control. For modeling purposes Revelstoke Dam is considered a run-of-river project due to minimal storage. These projects, along with another Treaty project, Duncan Dam on the Duncan River in Canada, are owned by British Columbia Hydro (BC Hydro), but operation can be influenced by the Columbia River Treaty (Treaty) between the U.S. and Canada. The Treaty is an international agreement between Canada and the U.S. for the cooperative development of water resources regulation in the upper Columbia River Basin. It was signed in 1961 and implemented in 1964. Discharge from Arrow and seasonal flood control space for Mica Dam and Arrow are coordinated per the Treaty.

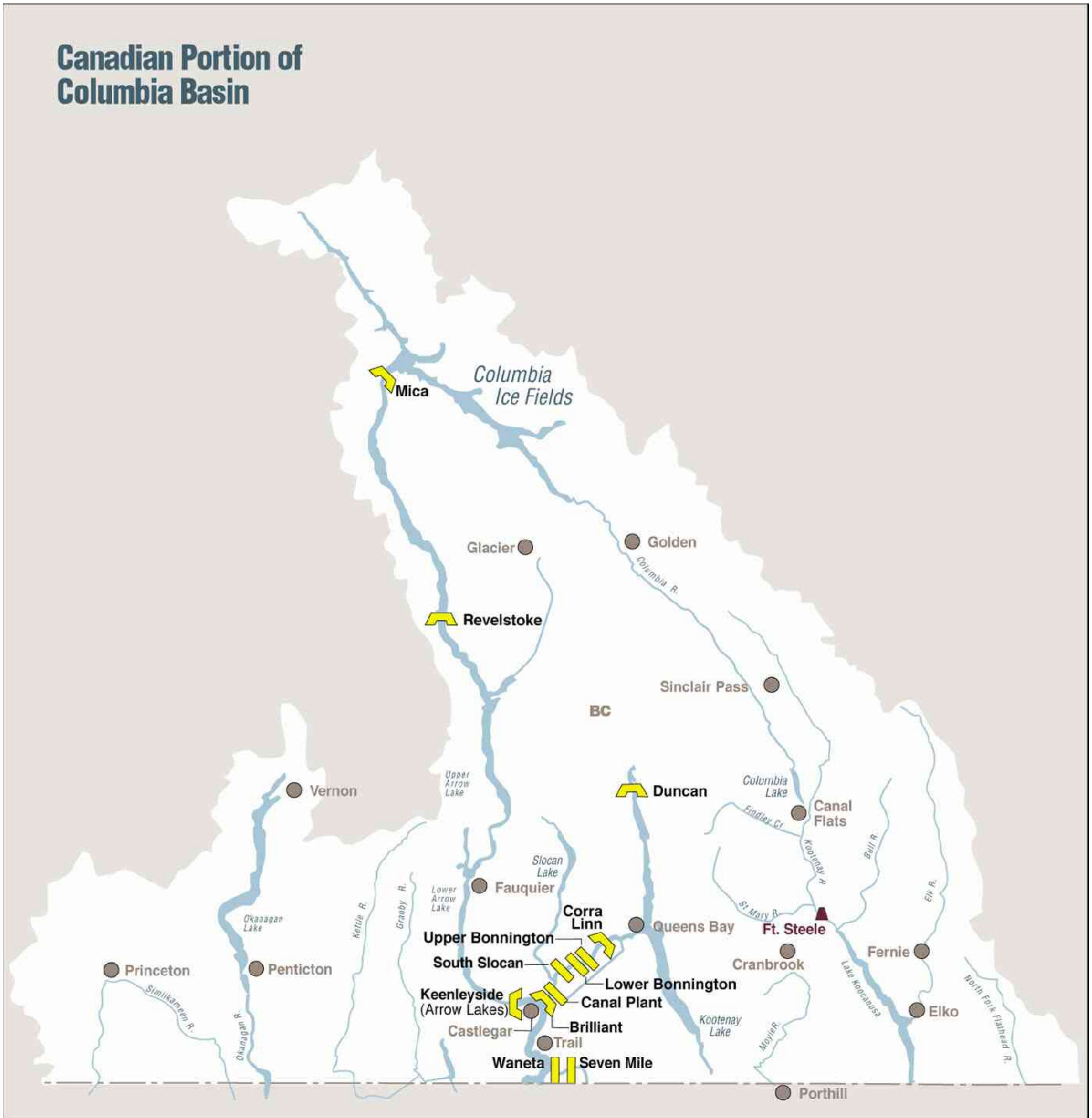

Figure 2. Canadian projects along the Columbia, Kootenay, and Pend Oreille Rivers.

The Kootenay and Pend Oreille tributaries join the Columbia River in Canada downstream from Arrow Lakes and upstream from the U.S./Canadian border at the northern extent of Lake Roosevelt, the reservoir regulated by Grand Coulee Dam. Grand Coulee Dam is operated by Reclamation for power production, flood control, irrigation, recreation, as well as fisheries and water quality concerns. The Spokane River joins the Columbia mainstem upstream from Grand Coulee Dam. Also located near Grand Coulee Dam is the John W Keys III pump generating plant that pumps water from Lake Roosevelt into Banks Lake. The water in Banks Lake is used for irrigation through the summer months. There are six pumps and six pump/generators so some of the units can also be used for generation by releasing water from Banks Lake back into Lake Roosevelt The map in Figure 3 shows the location of Grand Coulee, Banks Lake and the other Mid-Columbia projects.

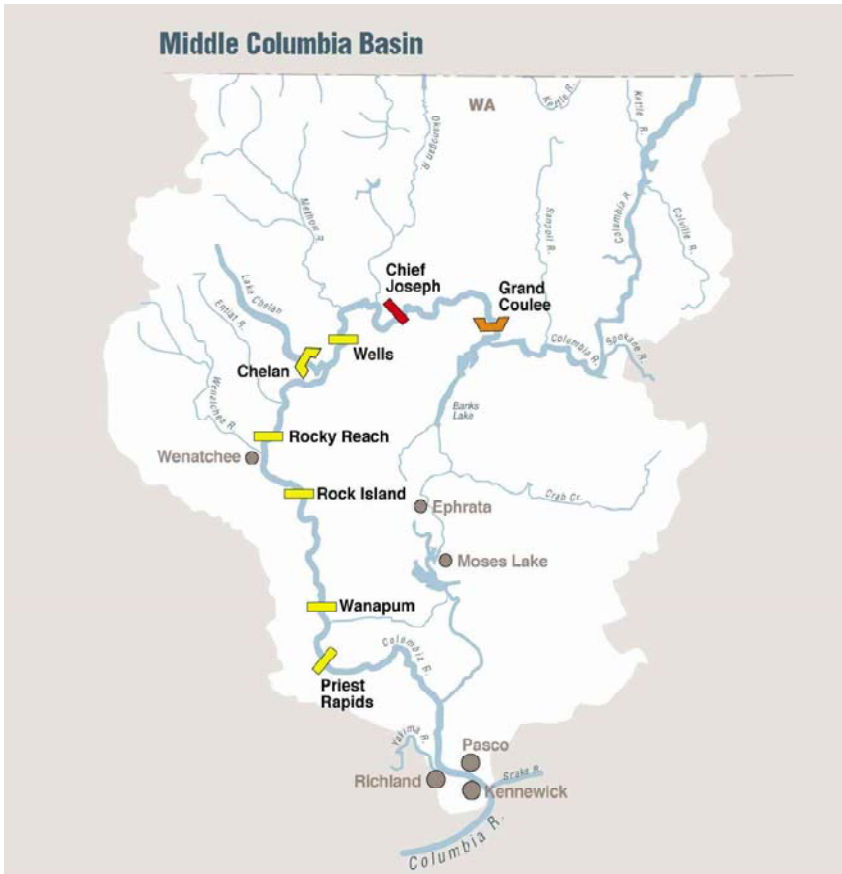

Figure 3. Mid-Columbia Projects.

Downstream from Grand Coulee dam is Chief Joseph Dam. This dam is operated by the U.S. Army Corp of Engineers (Corps). Due to minimal storage this project is considered run-of-river and not used for system flood control. Below Chief Joseph Dam is a series of non-federal dams collectively referred to as the mid-Columbia or Mid-C Projects. From upstream to downstream these projects are Wells, Rocky Reach, Rock Island, Wanapum, and Priest Rapids (Figure 3). Wells is owned and operated by Douglas County Public Utility District (PUD), Rocky Reach and Rock Island are owned and operated by Chelan County PUD, and Wanapum and Priest Rapids are owned and operated by Grant County PUD. In addition the Chelan River joins the Columbia River between Wells and Rocky Reach. This river is regulated upstream by Chelan Dam, which is owned and operated by Chelan PUD. The Mid-

C projects have relatively little storage as they are considered to be run-of-river projects. Some small seasonal regulation is typically assumed for Lake Chelan. Real time operation of the Mid-C projects is highly dependent on the outflow of Chief Joseph for daily power production and therefore coordination with BPA is important. In addition, the operation of the Mid-C projects can be influenced by the many external parties who own shares of the generation. These parties can include other regional utilities as well as power marketers.

The portion of the Columbia River just downstream of Priest Rapids dam is known as the Vernita Bar (or Hanford Reach) and provides critical spawning habitat for fall Chinook. As a result operations of Priest Rapids and the other upstream Mid-C projects can be influenced during the fall spawning period based on the guidance of fish managers. During the winter and spring months water may need to be drafted from Grand Coulee Dam to support water levels and help ensure juvenile survival. Between Priest Rapids dam and McNary dam the Snake and Yakima tributaries join the main stem of the Columbia River. The Yakima River is regulated by a series of projects operated by Reclamation. For information on this tributary please refer to Part II of this report titled *"Reservoir Operations Assessment for Reclamation Tributary Basins"*, (Reclamation 2011) This Part also includes a description of the Snake River above Brownlee Reservoir.

The remaining four mainstem projects; McNary Dam, John Day Dam, The Dalles Dam, and Bonneville Dam, are often referred to as the four lower Columbia River projects. These large projects are operated by the Corps for power production and navigation. The storage in these reservoirs is small and they are considered to be run-of-river for modeling purposes. Run-of-river projects assume no regulation, i.e., inflow is equal to outflow in all cases. However, there is a small amount of storage available in John Day reservoir for system flood control. The map in Figure 4 shows the location of these projects. Several tributaries join the Columbia River between McNary and Bonneville Dams. Some of the largest tributaries include the John Day and Deschutes Rivers. The Deschutes River is regulated upstream by both non-federal and federal projects.

Downstream from Bonneville Dam is an important spawning habitat that often influences operation of the lower Columbia River projects and sometimes the operation at Grand Coulee Dam. Tailwater levels at Bonneville Dam are maintained during the fall to ensure optimum chum spawning conditions. Through the winter and early spring it is necessary to maintain tailwater elevations below Bonneville Dam that were established the previous fall to maximize juvenile fish survival and this may require a draft at Grand Coulee Dam.

The Willamette River tributary joins the Columbia River downstream from Bonneville Dam. The Willamette River projects are operated by both private utilities as well as the Corps and Reclamation for a variety of uses that include flood control, irrigation and power production. For modeling purposes the operation of the Willamette projects does not often influence the operation of the Columbia River projects. However, in actual operations during winter flood events that occur on the western side of the Cascade Mountains it may be necessary to store water in the main stem Columbia River projects to help prevent flooding at Portland, Oregon in addition to the Willamette basin flood control storage.

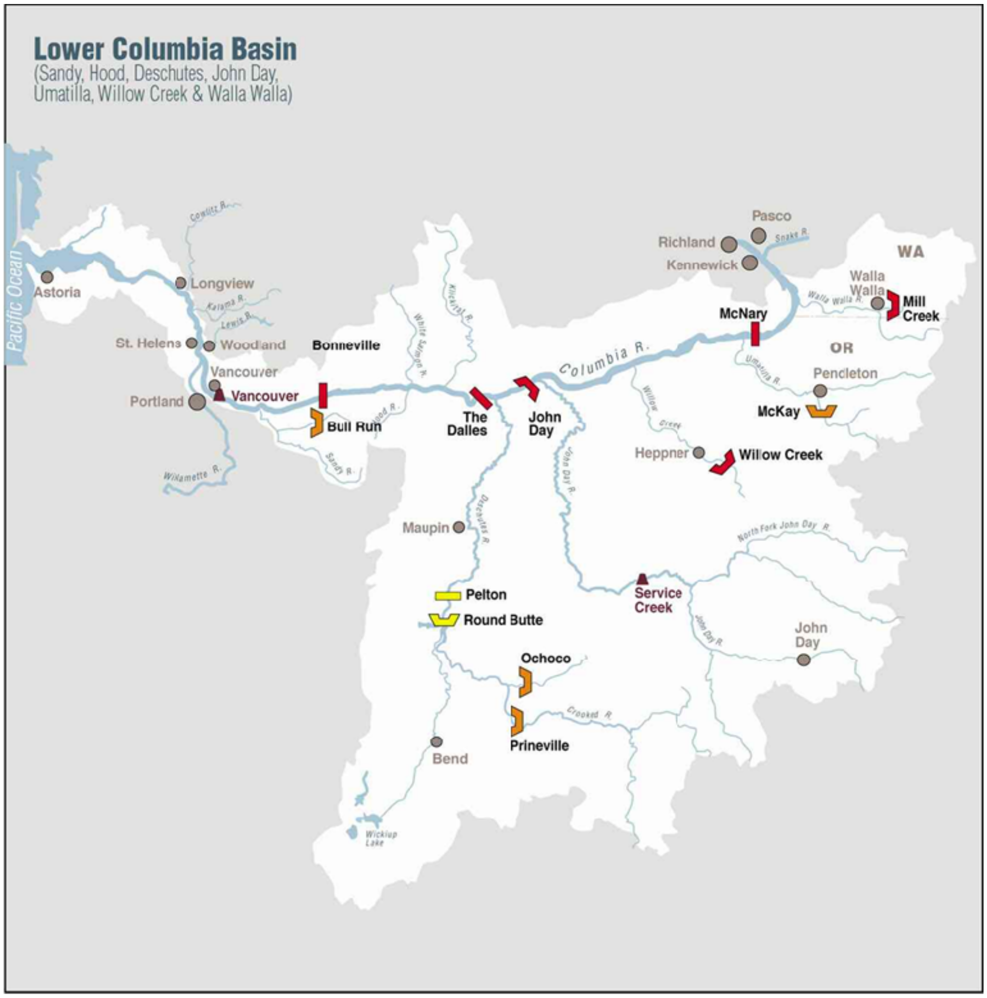

Figure 4. Lower Columbia River Projects.

2.2 Columbia River Tributaries: Kootenay, Pend Oreille and Spokane River Basins

Headwaters for the Kootenay River are located in eastern British Columbia. The river flows south into Montana before flowing northwest through the Idaho Panhandle and back into British Columbia to join the Columbia River downstream from Arrow. Lake Koocanusa is the reservoir upstream of Libby Dam. This reservoir straddles the U.S. – Canadian border. Libby

Dam is operated by the Corps and its uses include flood control, power production, fisheries, and recreation. Outflow from Libby Dam flows north through Bonners Ferry, Idaho and into Kootenay Lake in British Columbia. Kootenay Lake is also fed by the Duncan River from the north. Duncan Dam is a storage project that regulates the output of the Duncan River and produces power for BC Hydro. Duncan is also used for system flood control and operations are coordinated through the Treaty. The elevation of Kootenay Lake is maintained to a degree by Corra Linn Dam however, upstream of the dam there is a natural channel restriction which controls the elevation of Kootenay Lake and its outflow. During these times the lake is susceptible to local flooding. Downstream from Kootenay Lake is a series of five run-of-river power projects owned and operated by Canadian utility companies. Because this basin includes both U.S. and Canadian interests, operations are heavily influenced by the International Joint Commission (IJC) Order signed in 1938, that established the operating limits for Corra Linn Dam. The locations of the Kootenay projects are shown in Figure 5 and Figure 2.

Figure 5. Pend Oreille, Kootenay, and Spokane River Projects.

2.2.1 Pend Oreille Basin

The Pend Oreille Basin includes portions of northwestern Montana, southeastern British Columbia and northern Idaho. The location of U.S. and Canadian projects in the Pend Oreille basin is shown in Figure 5 and Figure 2 respectively. The Flathead River begins in northwestern Montana (Middle and South Forks) and southern BC (North Fork). Hungry Horse is the headwater project located on the South Fork Flathead River about 5 miles above the confluence with the Middle and North Fork. It is operated by the Bureau of Reclamation for power, flood control, recreation, fisheries.

Downstream from Hungry Horse the Flathead River flows into Flathead Lake, a natural lake where water levels are raised and regulated by Kerr Dam. Flathead Lake outflows can be limited due to a natural channel restriction between the dam and the lake. The maximum discharge is dependent on lake elevation. Even at full pool there are channel restrictions which could cause the lake elevation to raise during periods of high inflows resulting in local flooding around the lake. Kerr is a non-federal project owned and operated by PPL Montana and the Confederated Salish & Kootenai Tribes of the Flathead Indian NationPower.

Below Kerr Dam the Flathead River joins the Clark Fork. Three dams are located along the Clark Fork between the confluence with the Flathead River and Lake Pend Oreille. The most upstream of these projects is Thompson Falls Dam which has minimal usable storage and is considered a run-of-river project. Thompson Falls is a non-federal project owned and operated by PPL Montana. Noxon Rapids Dam is a low storage project located below Thompson Falls. Cabinet Gorge is a run-of river project located below Noxon. Both Noxon and Cabinet Gorge are non-federal projects owned and operated by Avista Energy.

Below Cabinet Gorge the Clark Fork flows in Lake Pend Oreille, another natural glacial lake. Similar to Kootenay Lake and Flathead Lake water levels in Pend Oreille are artificially maintained by Albeni Falls Dam but a natural channel restriction can limit discharge from the lake. Albeni Falls is operated by the Corps.

The Pend Oreille River flows northwest from Lake Pend Oreille through northern Idaho and northeastern Washington before joining the Columbia River just north of the U.S.US - Canadian border. Just downstream of Albeni Falls the Priest River flows in the Pend Oreille River. The Priest River is regulated upstream at Priest Lake, a small storage lake operated by the State of Idaho. There are four dams located downstream of Albeni Falls on the Pend Oreille River. All are non-federal projects with minimal storage operated for power production. Box Canyon is the most upstream of these projects and is owned and operated by Seattle City Light. The next project is Boundary which is owned and operated by Pend Oreille County PUD. The last two projects, Seven Mile and Waneta, are located in British Columbia and operated by Canadian utility companies.

2.2.2 Spokane Basin

The Spokane Basin consists of two storage projects and four run-of-river projects. All projects are non-federal. Post Falls is the most upstream project and located near the outlet of Lake Coeur D’Alene. Similar to Kootenay Lake and Flathead Lake water levels in Lake Coeur D’Alene are artificially maintained by Post Falls dam but under certain conditions outflow from the lake can be limited by natural channel restrictions. Downstream from Post Falls are four small run-of-river projects; Upper Falls, Monroe, Nine Mile, and Little Falls, and one other small storage project; Long Lake. The location of projects in the Spokane Basin is shown in Figure 5. The Spokane River flows into Lake Roosevelt.

2.3 Snake River Basin

Although there are numerous projects located in the upper portions of the Snake River Basin the majority of these projects are used for storage and irrigation and not power production. The projects located upstream from Brownlee Dam are described in Part II of this report. The lower portion of the Snake Basin includes Brownlee Dam and the Hells Canyon complex, located on the Snake River and Dworshak Dam located on the Clearwater River. Both projects are operated for system flood control as well as power production. Idaho Power Company owns and operates Brownlee Dam and the Hells Canyon Complex, the lower two (Hells Canyon and Oxbow) are run-of-river projects and do not have storage capabilities. The Corps operates Dworshak Dam. The four dams located in the lower portion of the Snake River Basin downstream from Lewiston, Idaho; Lower Granite, Lower Monumental, Little Goose, and Ice Harbor have relatively little storage and are therefore typically modeled as run-of-river.

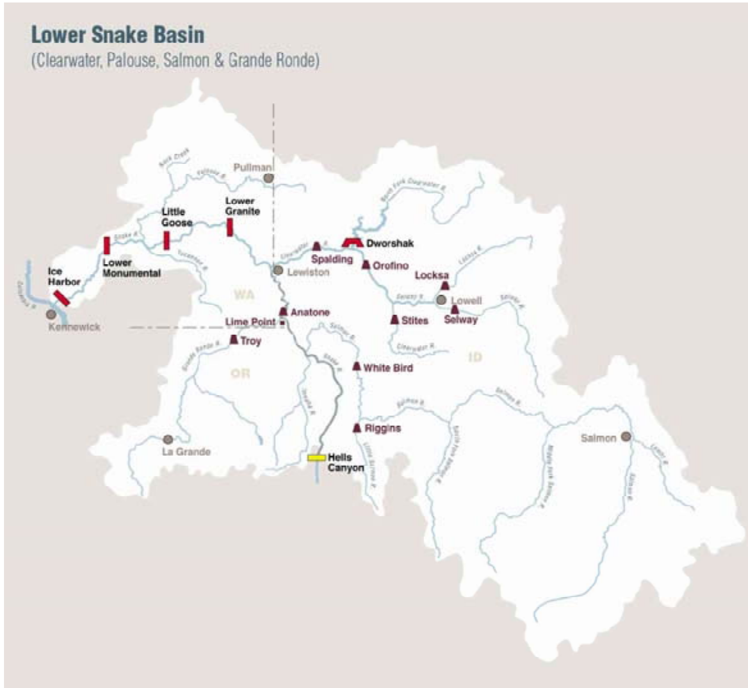

Figure 6. Lower Snake River Projects.

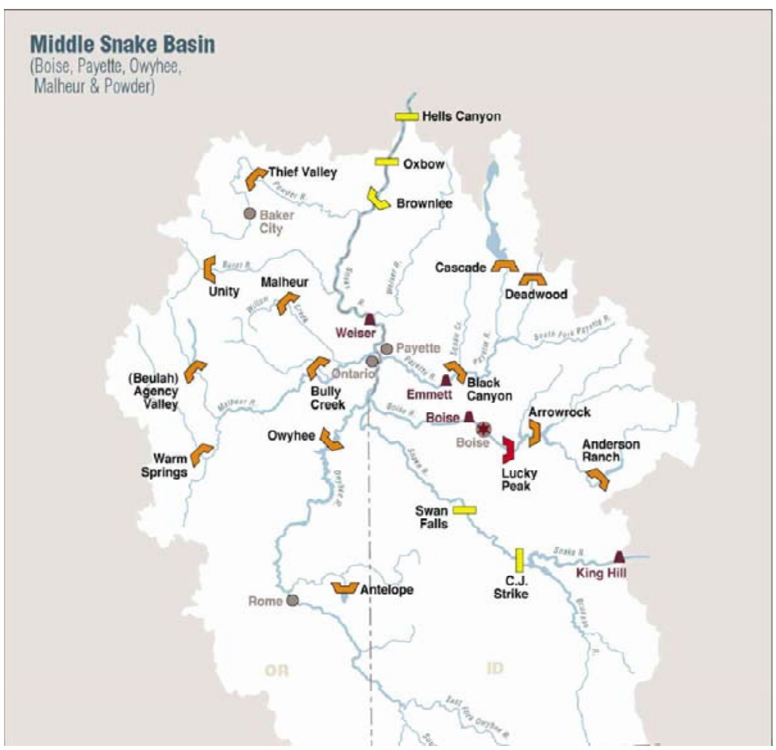

Figure 7. Middle Snake River Projects.

2.4 Non-Federal Projects

There are numerous non-federal projects located throughout the Columbia Basin. These projects are owned and operated by private utility companies. In many cases the operation of these projects is regionally coordinated under the Pacific Northwest Coordination Agreement (PNCA) to achieve the overall best coordinated operation of the Columbia River. However, projects are not required to participate in the PNCA. The largest non-participating project is Brownlee which is owned and operated by Idaho Power Company. Examples of some other large non-federal projects include Kerr, Chelan, and the mid-Columbia Projects.

3.0 DEVELOPMENT OF DATASETS

3.1 Hydrologic Input Data

A total of 34 scenarios of hydrologic data in the form of either observed or forecast runoff volumes were used from which flood control data was developed. The breakdown of the data sets are as follows:

- 2000 Level, observed
- Historic VIC, observed
- Six Hybrid-Delta centered on the 2020's, observed
- Six Hybrid-Delta centered on the 2040's, observed
- Six Transient, observed
- 2000 Level, forecast
- Historic VIC, forecast
- Six Hybrid-Delta centered on the 2020's, forecast
- Six Hybrid-Delta centered on the 2040's, forecast

Four of the 34 datasets were on based on historic climate. The 2000 Level observed data set is the set that is currently used for planning studies. The 2000 Level data set in forecast mode uses current forecast procedures to develop forecast runoff volumes. For the Historic VIC, historic climate data was input to the University of Washington Climate Impact Group's Variable Infiltration Capacity (VIC) model and to obtain the historic observed hydrological data (See Part I, Section 4.0). One set of historical VIC data was in observed mode, and one historic VIC set of runoff volumes was provided that used methodologies to forecast runoff volumes (See Part I, Section 5.0).

Twenty-four of the 34 datasets are Hybrid-Delta climate change scenarios. For information on the development of the Hybrid-Delta climate change scenarios, see Part I, Section 3.3.1:

simulated hydrology associated with these scenarios is described in Par I, Section 4.5. Runoff volumes were provided in both observed and forecast modes. For more information on the procedures used to develop forecast volumes, see Part I, Section 5.0. Six of the 34 data sets are Transient climate and hydrology scenarios (Part I, Sections 3.3.2 and 4.5). Runoff volumes for the Transient climate projections were provided only in observed mode.

The hydrologic data used to compute the flood control curves consist of seasonal volumes covering the periods of April through August, April through July, or May through September, depending upon the project. The period of record of the data provided by Reclamation was from year 1917 through 2005; however, since the reservoir modeling period is for water years 1929 through 1998, the flood control data is produced only for this period. The data used for this study is considered to be two-step bias corrected (refer to Part 1 of the report, Section 4.4, for more details) to the 2000 Level Modified flow set. Reclamation provided volumes for The Dalles and Brownlee projects that incorporate a regulation for the Upper Snake and Deschutes projects. The Reclamation provided the regulated data in June 2010 for this study.

The Hybrid-Delta scenarios are derived by imposing a step-change in climate derived from analyzing future climate conditions, on historical climates from 1916 to 2006. Historical climates of different characteristics (i.e. relatively dry, relatively wet, etc) are changed by different adjustment factors. Those scenarios derived from future climate periods 2010 – 2039 are categorized as the 2020 set, while those derived from the 2030 – 2059 periods are designated as the 2040 set.

The Transient climate projections were made for the years 1951 through 2099, the 70 years of data that the flood control curves were prepared for were based on the 70-year period 1999 through 2068 of Transient years. The Transient climate projections result from evolving climate changes gradually occurring over time (i.e. not a step-change) are reported as an ensemble of six global climate projections.

Part I contains more in-depth details on the development of both the Hybrid-Delta and Transient Scenarios. The next two subsections describe in more detail the selected Hybrid-Delta and Transient scenarios selected from the CIG HB2860 datasets that were modeled in this report.

In addition to the 26 datasets described above, two more flood control data sets were developed using the 2000 Level Modified Flow -one in observed mode, and one in forecast mode. The 2000 Level Modified Flow volumes are from the "SEASONAL VOLUMES AND STATISTICS, 1928-1999, 2000 Level Modified Streamflows Computed Seasonal Volumes 71-year Statistics, COLUMBIA RIVER BASIN", study prepared for BPA, dated May 2004. The current runoff volume forecasts consist of a forecast of seasonal volumes based on current forecast procedures when available. For years when seasonal volumes could not be produced using current forecasting procedures, Kuehl-Moffitt forecasts volumes were used. (Kuehl-Moffitt, 1968). Kuehl-Moffitt forecasts have been accepted for use in regional studies since the 1980's. Kuehl-Moffitt forecast volumes were developed for the Corps in the early 1980's with the intent to create volume forecasts similar to what the Northwest River Forecast Center would have computed back to 1928. Volumes for The Dalles and Brownlee Reservoir include regulations for the Upper Snake, Deschutes and Yakima. The criteria for the regulation of these projects is different than that for the climate change scenarios, so there are two variables changing when comparing effects of climate change on Brownlee Reservoir.

Monthly flow data was provided by BPA for certain projects for the various climate change scenarios. These monthly volumes were used to aid in determining flood control refill curves that provide a 95% confidence of refill.

The HydSim hydro-regulation studies, including the 2012 BPA Rate Case, rely on the monthly historical seventy-year stream flow data from 1929 to 1998. The HB2860 climate and hydrological dataset, produced by the University of Washington's Climate Impact Group (CIG) with collaboration with the Corps, Reclamation and BPA, is suitable for use in HydSim's seventy-year data format. The climate part of the CIG data includes effects of bias correction and spatial downscaling of a large collection of monthly global climate models over the Pacific Northwest region. The hydrological portion of the data, on the other hand, was obtained by applying the Variable Infiltration Capacity (VIC) model to a set of meteorological parameters. Details of both the climate and hydrology modeling are available in Part I of this study entitled, *"Future Climate and Hydrology Datasets"*. Eighteen climate-change scenarios covering a wide range of climate and hydrology were selected from the CIG HB2860 dataset for study in this report. Each scenario belongs to either the Hybrid-Delta (HD) type or the Transient type.

3.2 The Hybrid-Delta Scenarios

The Hybrid-Delta 2020 set and 2040 set of scenarios are listed in Tables 7 and 8 and contain names of the various Global Circulation Models and associated scenario assumptions such as the emissions, precipitation and temperature characteristics.

- Emission Paths
    - A1B – Balanced across both types (fossil and non-fossil) of resources; medium emissions; greater rate of greenhouse gas accumulation than the B1 pathway
    - B1 – Similar to above, but with more integrated resources and less emissions; emphasis on global solutions to economic, social and environmental stability

(i.e. more eco-friendly than A1B)

- Climate Change Characteristics (relative to historical climate)
  - MW – More Warming; LW – Less Warming
  - W – Wetter; D – Drier
  - MC – Minor Change; C – Central Change
- Change in Precipitation, – in inches
- Change in Temperature, – in degree Celsius

Table 7 below, lists the six scenarios chosen from the 2020 set to represent a variety of combinations of climate (LW to C to MW) and hydrological changes (D to C to W). The change in precipitation or temperature is relative to the observed values spatially averaged over the Columbia-Snake River Basin for the 1916-2006 historical period.

Table 1. 2020 Climate-Change Scenarios.

Global Circulation Model (GCM)	Emission Paths	Climate Change	Change in P (in)	Change in T (^{0}C)
ccsm3	B1	MW/D	-1.2	1.4
cgcm3.1_t47	B1	LW/W	7.9	1.1
echam5	A1B	MC	3.7	0.7
hadcm	B1	C	3.8	1.0
ipsl_cm4	A1B	MW/W	7.4	1.6
pcm1	A1B	LW/D	-1.5	1.0

Table 2. 2040 Climate-Change Scenarios

Global Circulation Model (GCM)	Emission Paths	Climate Change	Change in P (in)	Change in T (^{0}C)
cgcm3.1_t47	B1	LW/W	11.5	1.3
echam5	A1B	MC	3.7	1.5
echo_g	B1	LW/D	-7.9	1.8
hadcm	B1	C	3.7	1.7
hadgem1	A1B	MW/D	-2.5	2.8
miroc3.2	A1B	MW/W	14.2	2.7

3.2.1 Annual Volumes

Another way to analyze hydrology of the six 2020 scenarios shown in Table 7 is to compare flow volumes at The Dalles (TDA) which have often been used to represent the overall hydrological conditions of the Columbia River Basin. The bar chart below shows annual flow volumes at TDA averaged over seventy historical years (1929 – 1998) for all eighteen scenarios of the 2020 set along with the 2000L modified flow (also known as the Base Case). Note that the UW-CIG provided eighteen data sets but only six of the eighteen were modeled. It could be seen that the six chosen scenarios (blue-striped bars) listed in Table 7 encompass fairly well the full range of hydrological conditions of all 2020 scenarios – two scenarios having low volumes; two others having medium volumes and the last two having high volumes. Furthermore it could also be seen that, in general, scenarios from the 2020 set have higher flow volumes than the Base Case.

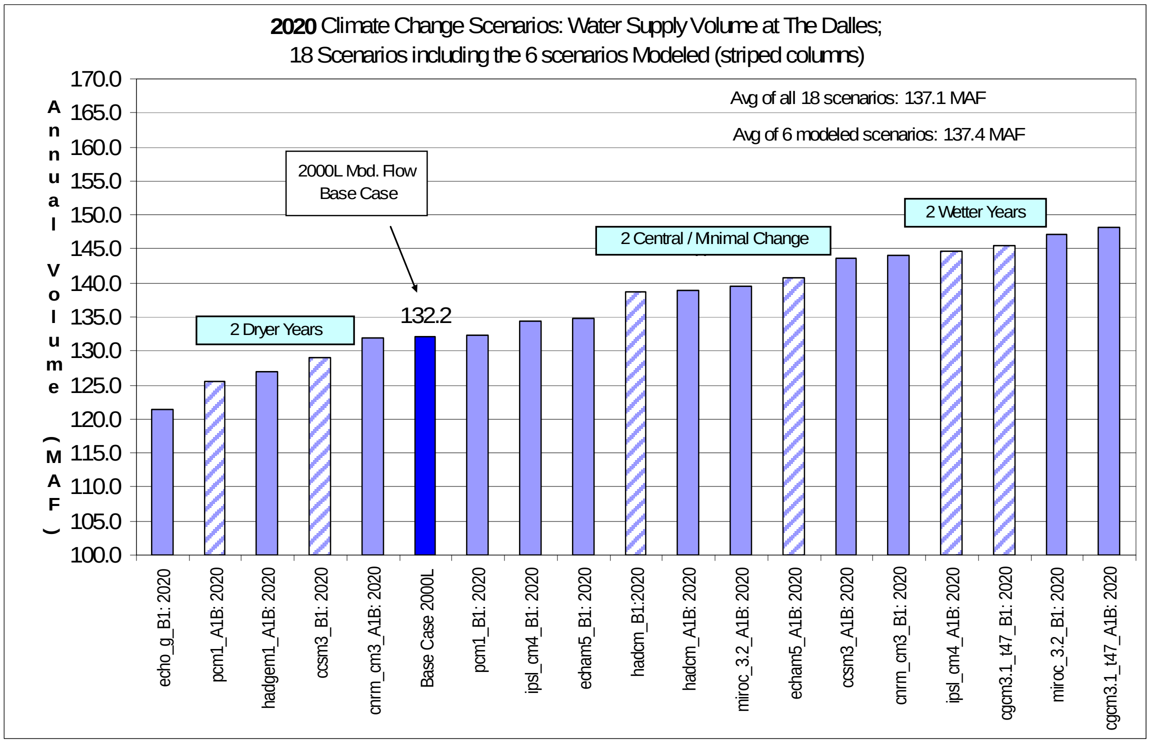

Figure 8. Annual Flow Volumes (averaged over 1929 – 1998) at TDA for 2000L Modified Flow and all 2020 Climate-Change Scenarios.

The next bar chart displays the seventy-year averaged flow volumes at TDA for the Base Case and all the 2040 set of climate-change scenarios. Similar to the 2020 set of scenarios in the previous chart, the six chosen 2040 scenarios (blue striped bars) are shown to encompass the full range of all scenarios in the 2040 set. Furthermore, scenarios in the 2040 set in general also have more flow volumes than the Base Case (dark blue bar).

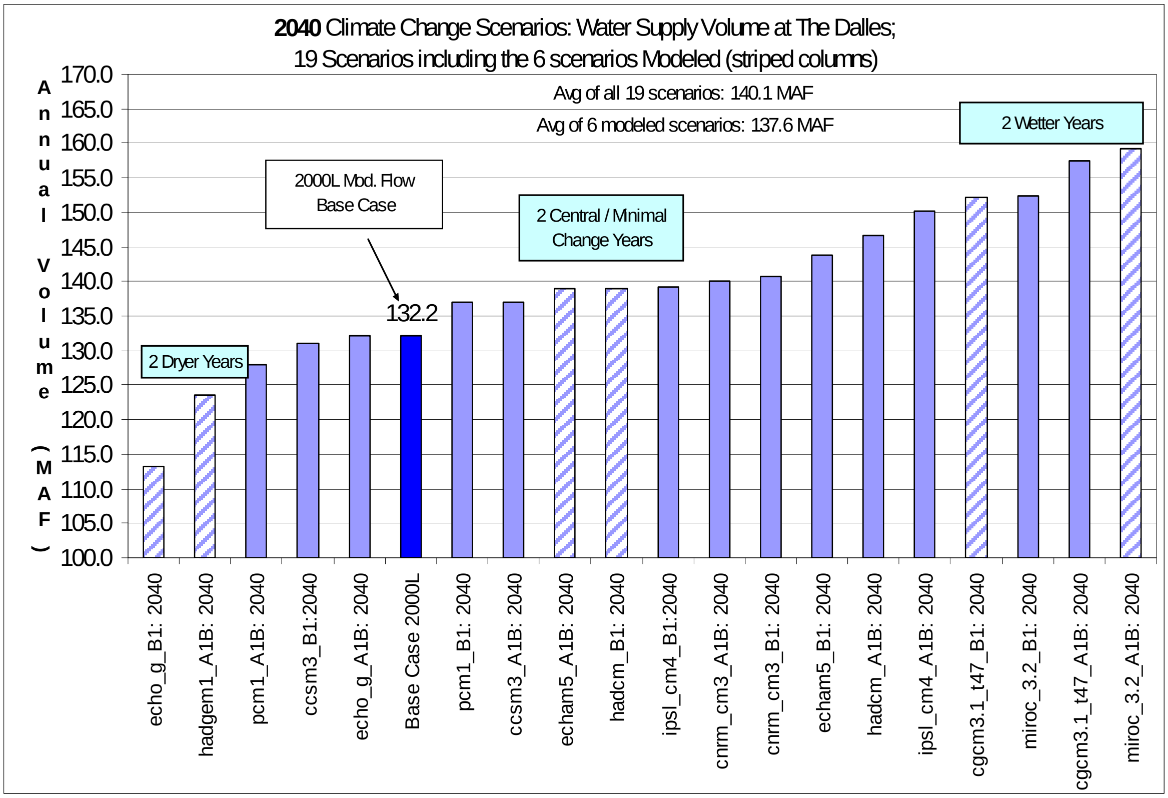

Figure 9. Annual Flow Volumes (averaged over 1929 – 1998) at TDA for 2000L Modified Flow and all 2040 Climate-Change Scenarios.

Thus far most scenarios from both the 2020 and 2040 sets show higher (seventy-year averaged) annual flows than the Base Case at TDA. Besides that characteristic, another distinctive feature of both sets of climate-change scenarios is the seasonal shift in stream flow – higher flows in winter and early spring and lower flows in late spring and summer for the Columbia River Basin. This is described in the next section.

3.2.2 Monthly Runoff

The figure below compares the seventy-year averaged stream flow at TDA for the Base Case (black solid line) and the six chosen scenarios from the 2020 set (refer to

Table 1 for the corresponding GCM names). It could be seen that nearly all scenarios have higher flows from December to May and lower flows from June to August than corresponding Base Case flows.

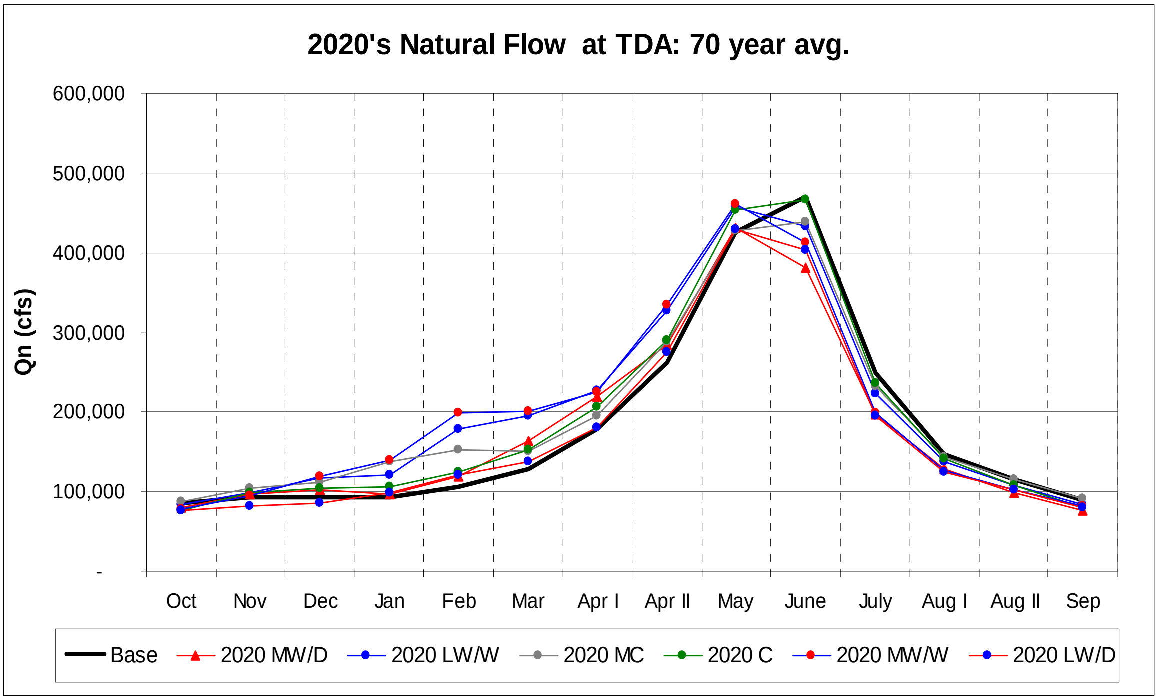

Figure 10. Monthly Seventy-year Average (1929 - 1998) Stream Flow at TDA for 2000L Modified Flows (Base) and the Six Scenarios from the 2020 Set.

The seasonal shift in stream flow from Base Case is also evident in the next figure that shows flows at TDA for the six scenarios from the 2040 set and the Base Case. All but one scenario (2040 LW/D) show higher flows from November to May and lower flows from June to August than corresponding Base flows. During the relatively high-flow winter and spring seasons (compared to Base) stream flows for the 2040 scenarios are higher than those for the 2020 scenarios, while in contrast during the relatively low-flow summer season, flows for the 2040 scenarios are lower than those for the 2020 scenarios. The more pronounced seasonal shift for the 2040 scenarios may be due to having a longer time span for climate changes to evolve.

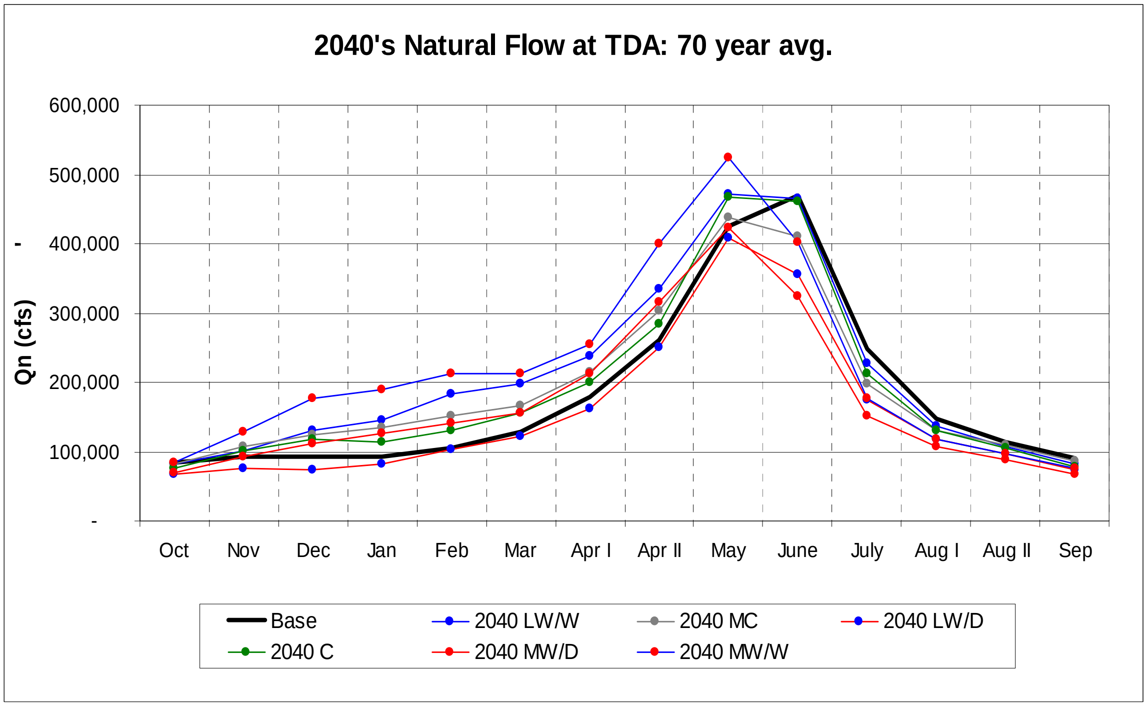

Figure 11. Monthly Seventy-year Average (1929 - 1998) Stream Flow at TDA for 2000L Modified Flows (Base Case) and the Six Scenarios from the 2040 Set.

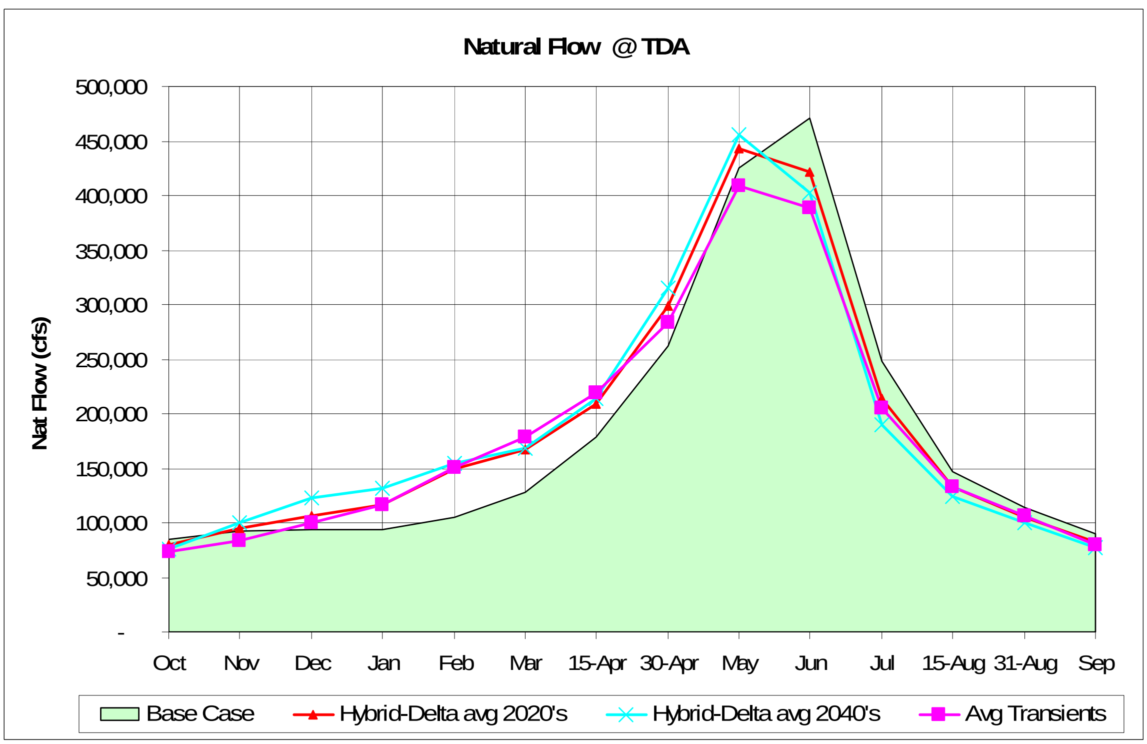

Figure 12. Natural Flows at The Dalles; Climate Change Scenario Averages.

3.2.3 Seasonal Runoff

This seasonal shift of stream flow at the Columbia River Basin (represented by flows at TDA) is a general feature of most climate change models. The shift likely results from more winter precipitation in the form of rain rather than snow leading to higher stream flows and less snow accumulation in the mountains during winter. The lower overall snowpack and higher temperature then lead to earlier and smaller runoff and thus lower flows during summer.

The bar chart below shows a different perspective on climate change induced seasonal shift in stream flows. The six 2020 scenarios (refer to Table 7 for the corresponding GCM names) are grouped in order of (seventy-year averaged) total annual flow volume at TDA - with the lowest flow at the left (2020 LW/D) to the highest flow at the right (2020 LW/W). Each scenario has seven bars displaying TDA flow volume over varying periods as percentages of the 2000L Modified Flow volume (Base Case) over the same periods:

- 1st Bar – January to March volume (winter volume)
- 2nd Bar – January to April volume (winter-to-early-spring volume)
- 3rd Bar – January to July volume (traditionally represents hydrological condition for the year)
- 4th Bar – May to July volume
- 5th Bar – April to August volume (spring-to-summer volume, currently used to establish flood control at Mica, Arrow, Brownlee, and Grand Coulee)
- 6th Bar – June to August volume (summer volume)
- 7th Bar – water year volume (overall flow volume)

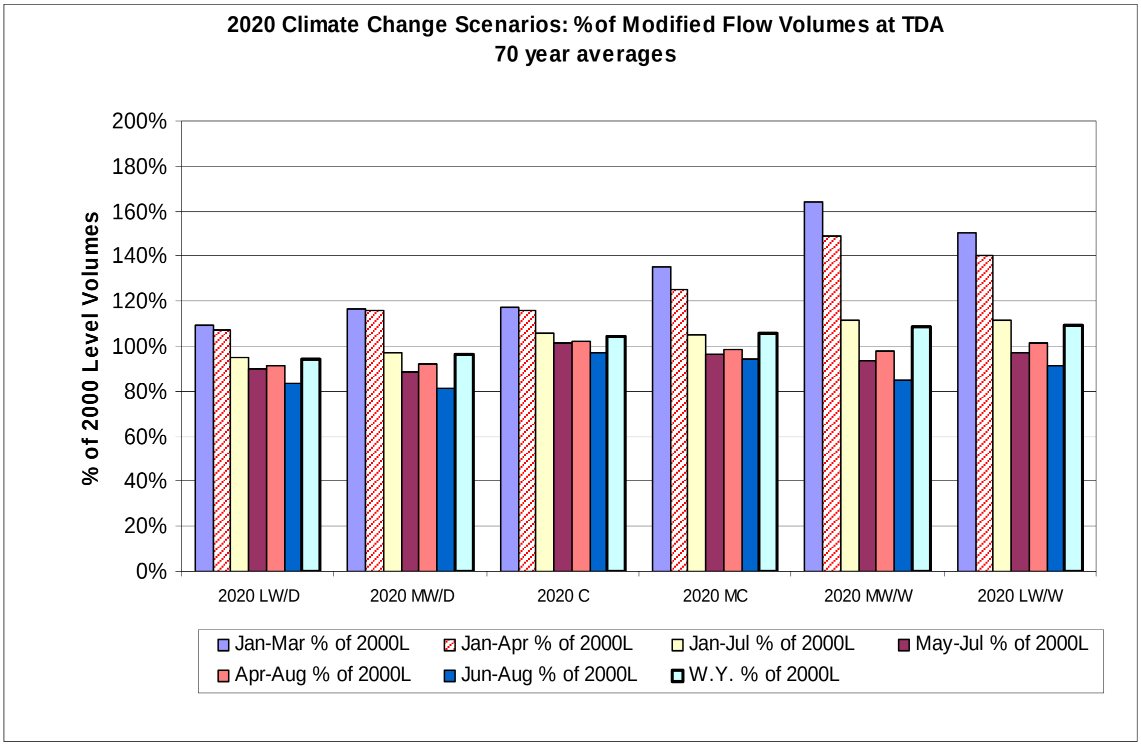

Figure 13. Six 2020 Scenarios Flow Volumes over Various Periods at TDA as Percentages of 2000L Modified Flow Volume over the Same Periods.

Looking at the first two bars, it could be seen that all the 2020 scenarios have higher winter and winter-to-early-spring volumes (greater than 100%) than the Base Case. In particular, the two wet scenarios (MW/W and LW/W) have rather high winter flows over the Base Case of more than 140%.

The third bar, traditionally used to represent hydrological condition of the Columbia River Basin, shows two relatively dry scenarios (less than 100%), two medium scenarios and two relatively wet scenarios (greater than 100%), which is consistent with the annual flow volume displayed by the last bar.

The fourth, fifth and sixth bars are the spring-to-summer and summer flow volumes typically used to determine Non-Power Requirements (NPRs) such as Bull-Trout and Salmon migration at Libby. Almost all volumes in these periods are below that of the Base Case which could require modification to operations at various projects to satisfy NPR’s under future climate change.

Finally, the seasonal shift in volume is obvious in that bars 1 and 2 are always higher than bars 4, 5 and 6 for all scenarios.

Next, a chart for the six 2040 scenarios grouped from lowest to highest annual TDA flow volume is shown below.

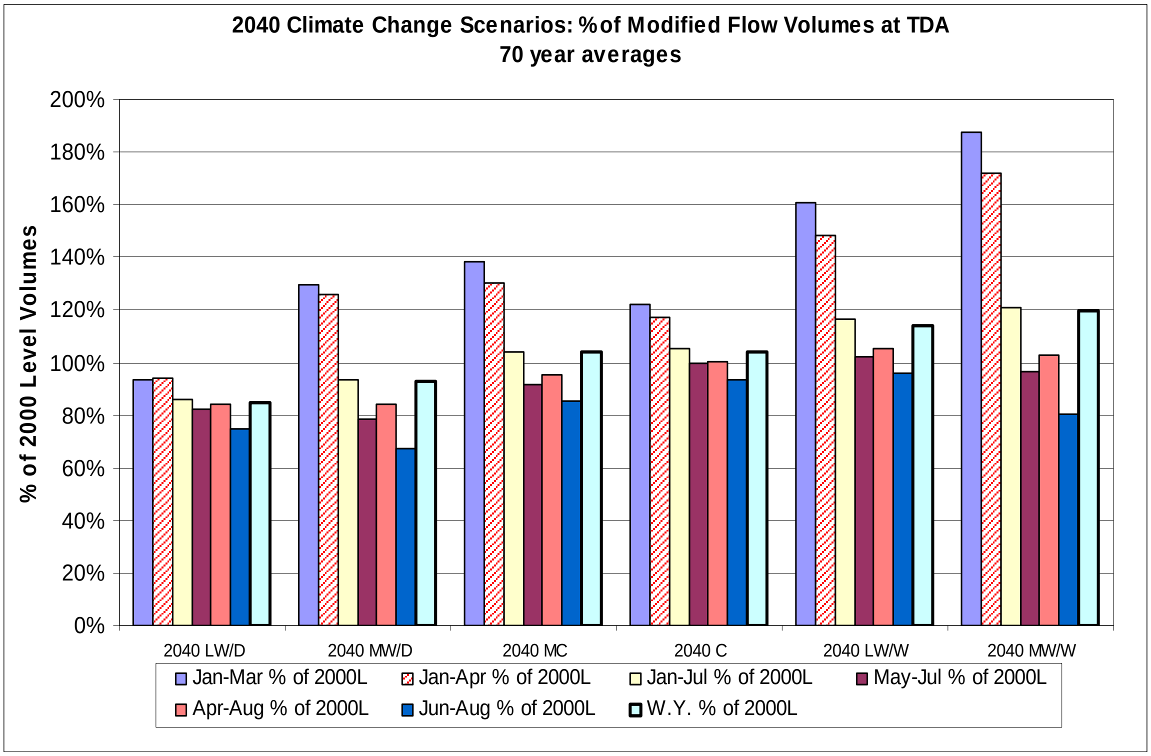

Figure 14. Six 2040 Scenarios Flow Volumes over Various Periods at TDA as Percentages of 2000L Modified Flow Volume over the Same Periods.

The 2040 set of six scenarios shows mostly similar characteristics as those of the 2020 set in that bars 1 and 2 indicate that all scenarios have higher winter and winter-to-spring volumes than Base except for the rather dry scenario (2040 LW/D). Furthermore, bars 3 and 7 again point out that the six chosen scenarios do span a wide range of volumes with two relatively dry, two medium and two relatively wet scenarios. In addition many spring-to-summer and summer volumes, represented by bars 4 to 6, are below the Base Case which also suggests operational changes at various projects to achieve NPRs. Finally, the seasonal shift in flow volume is obvious since bars 1 and 2 are higher than bars 4, 5 and 6 for all scenarios.

In addition it is also interesting to note that the dry scenario for the 2040 set is drier than the dry scenario for the 2020 set, whereas the opposite characteristic holds for the wet scenarios, as mentioned earlier.

It is clear that the 2020 and 2040 climate-change scenarios have a seasonal shift in stream flow in which higher flow occurs in the winter and spring and lower flows in late summer. Yet this seasonal shift might already have occurred gradually over the past thirty years as suggested by the next bar chart. The averaged TDA flow volumes for the three seasonal periods, which include winter-to-early-spring (January to April), May, and summer (June to August), are plotted for five temporal groups. These groups include:

1. The historic seventy-years (1929 – 1998);
2. The first fifty-one historic years (1929 – 1979);
3. The recent thirty years (1980 – 2010);
4. The average over all 2020 scenarios (near future, 2010 – 2039); and
5. The average over all 2040 scenarios (further future, 2030 – 2059).

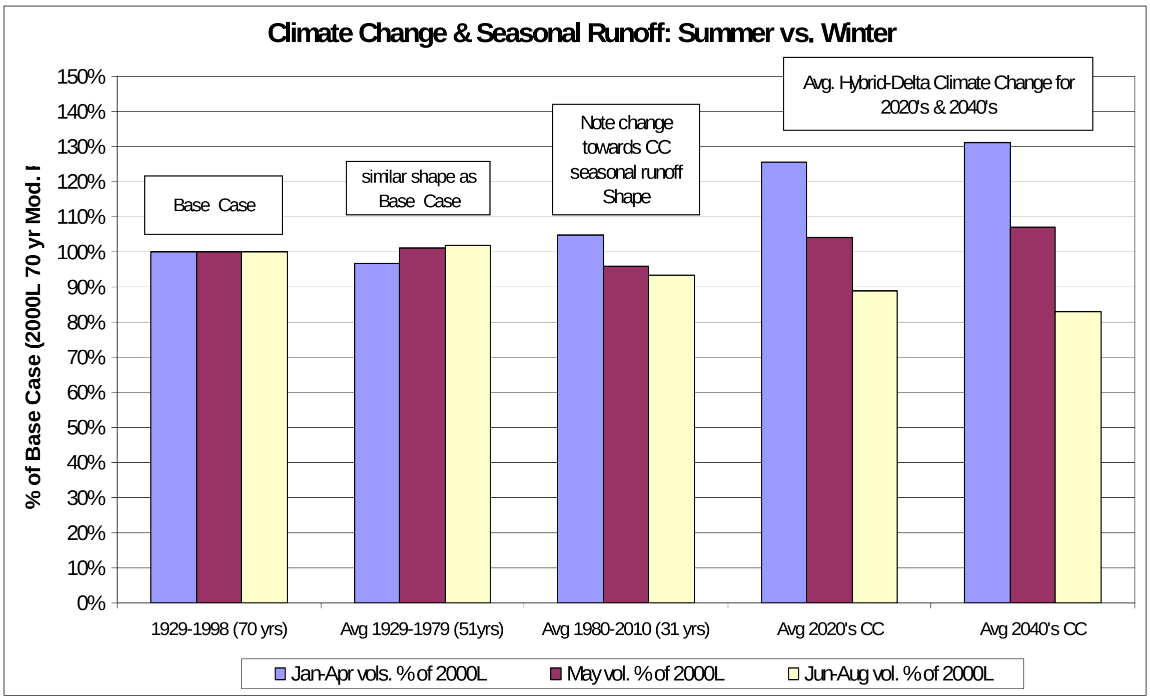

Figure 15. Summer / Winter Volumes for Historical and Future Hybrid-Delta 2020s & 2040s Scenarios.

It could be discerned that there was essentially no seasonal shift for the first fifty-one historic years (2nd group), a slight seasonal shift for the last thirty years (3rd group), a more definite shift for the 2020 scenarios (4th group) and a more dramatic shift for the 2040 scenarios (5th group).

3.2.4 Forecast and Observed Volumes

The ECC rule curve and magnitudes of many NPRs at a project depend on flow volumes over a period of time. As an example, the volume of water to be released at Libby for the sturgeon operation depends on its April to August runoff flow volumes. Given a set of stream flows for the various climate change scenarios at each project, two different sets of flow volumes could be computed from the flows: an observed volume and a forecast volume, also known as perfect and imperfect volume forecasts. Observed flow volume over a time period is obtained rather easily: multiply stream flow by the number of days in the period. On the other hand forecast volumes at each project, at or near the time periods of interest, is calculated from seasonal precipitation (October-to-date) and current snowpack within the sub-basin above the location of interest. The 2020 and 2040 Hybrid-Delta scenarios studied in this report used forecasted volumes. The observed volumes were used for the historic Base Case for the Transient scenario studies.

As a sensitivity test, the Base Case study was run using both the observed volumes and the forecasted volumes. On an average basis, the observed (perfect) volumes resulted in a slightly deeper April 30 flood control draft at Grand Coulee relative to the Base Case. However, individual water year results may vary widely. This is not without surprise knowing that forecasts are susceptible to high forecast errors. Figure 16 shows the average 70 year difference in the GCL URC between the forecasted and observed volumes.

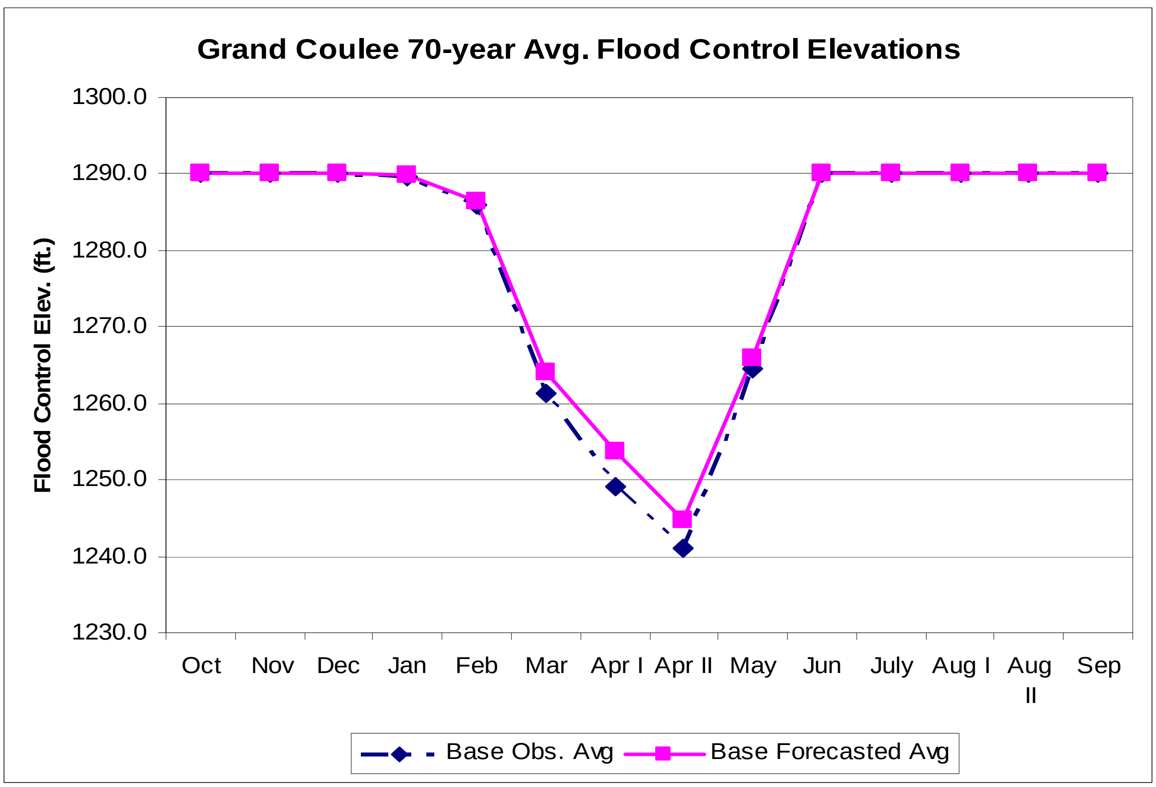

Figure 16. Grand Coulee URCs for Forecasted and Observed Volumes

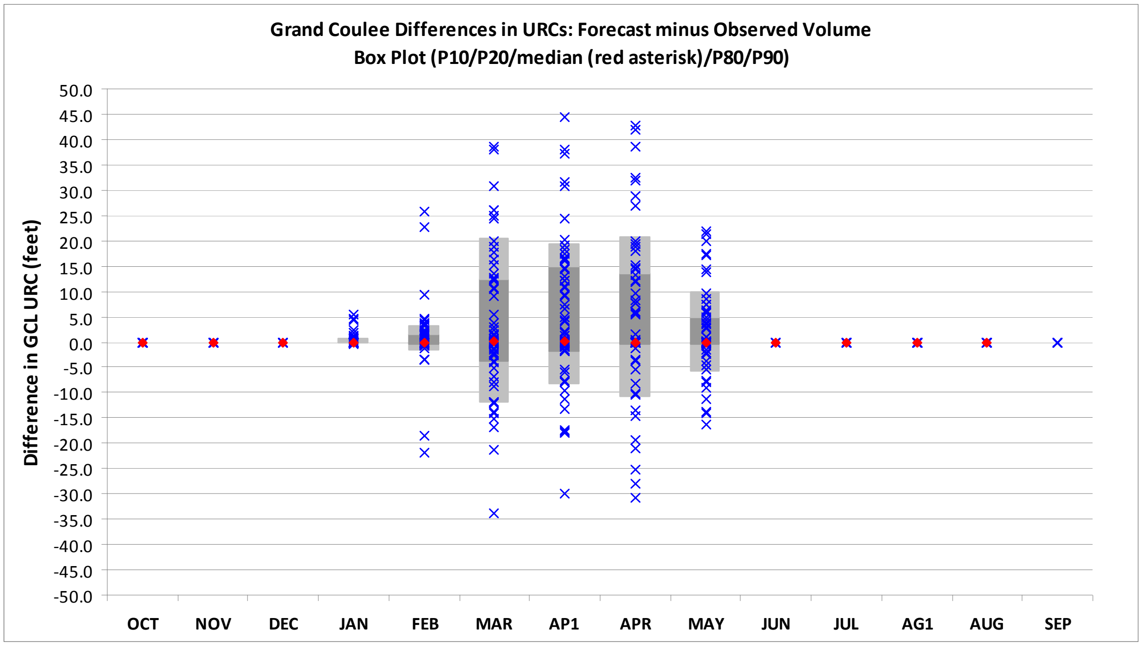

Figure 17. Grand Coulee URC Differences: Forecasted minus Observed Volumes for each of 70 years

3.3 The Transient Climate Projections

Finally, Table 3 lists the six Transient Scenarios selected for analysis in this Part. The transient scenarios are described in more detail in Section 6.1.3, as well as in Part 1of this report series in Sections 3.3.2 and 4.2.2.

Table 3. Transient Climate Projection Scenarios.

General Circulation Model (GCM)
ccsm3
cgcm3.1_t47
echo_g
hadcm
echam5
pcm1

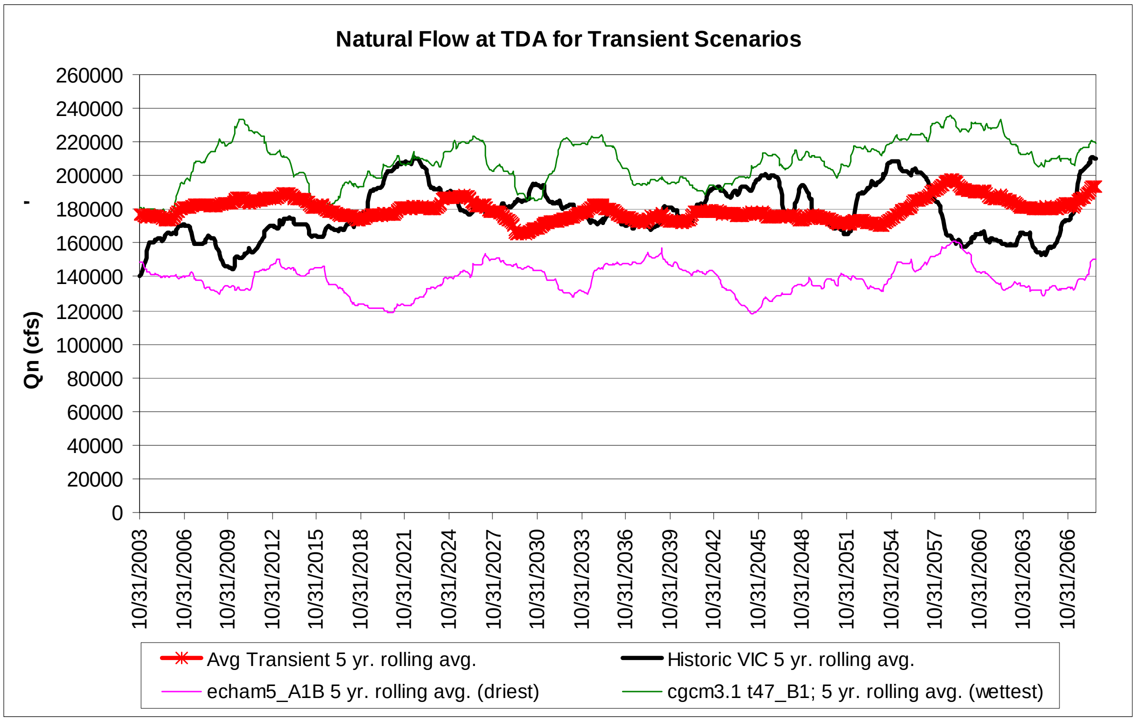

Figure 18. Natural Flows at The Dalles; 5-Yr. Rolling Average for Transient Flows.

Figure 18 plots the 5 year rolling average of the six transient scenarios and compares this streamflow average against the driest and wettest Transient scenario as well as a comparison to the historical VIC 5-year rolling average. Note that the historical VIC data set represents the 1929-1998period and is included in this graph only as a relative reference. The range of the transient flows, wettest to driest scenarios, exceeds the range in the historic flows. The driest scenario is significantly drier and the wettest scenario is significantly wetter than the historic record.

3.4 Seasonal Runoff Shift: Summer to Winter

One consistent characteristic of the climate change scenarios when compared to the 2000L Modified flows is the shifting of summer flows to the winter period. The climate change scenarios consistently reflect higher natural flows during the winter period (defined in this context as the Jan.-April period) with corresponding lower natural flows during the summer period (defined as the June-August period). The month of May serves as a sort of transition period with the climate change scenarios averaging out to be nearly the same as the Base Case flows. This shifting effect is a result of warmer winter temperatures; hence more winter rains rather than winter snow. The reduced snowpack results in lower flows in the late summer. A review of Figure 63, illustrates the natural flow shift between the summer and the winter with the month of May as the transition point. It is useful to describe these two periods in terms of a summer/winter ratio (S/W) for comparison sake. The ratio is defined as the natural flows at TDA, summed up over the summer period (June, July and August), divided by the natural flows summed up over the winter period (January, February, March and April).

Figure 19 below, charts the historical S/W ratios for volume runoff periods for the period 1929-2010. The trend line reflects a slight decline in the S/W ratio which is a climate change characteristic. Some individual years (such as 2008 and 2010) reflect a higher S/W ratio that is uncharacteristic to climate change.

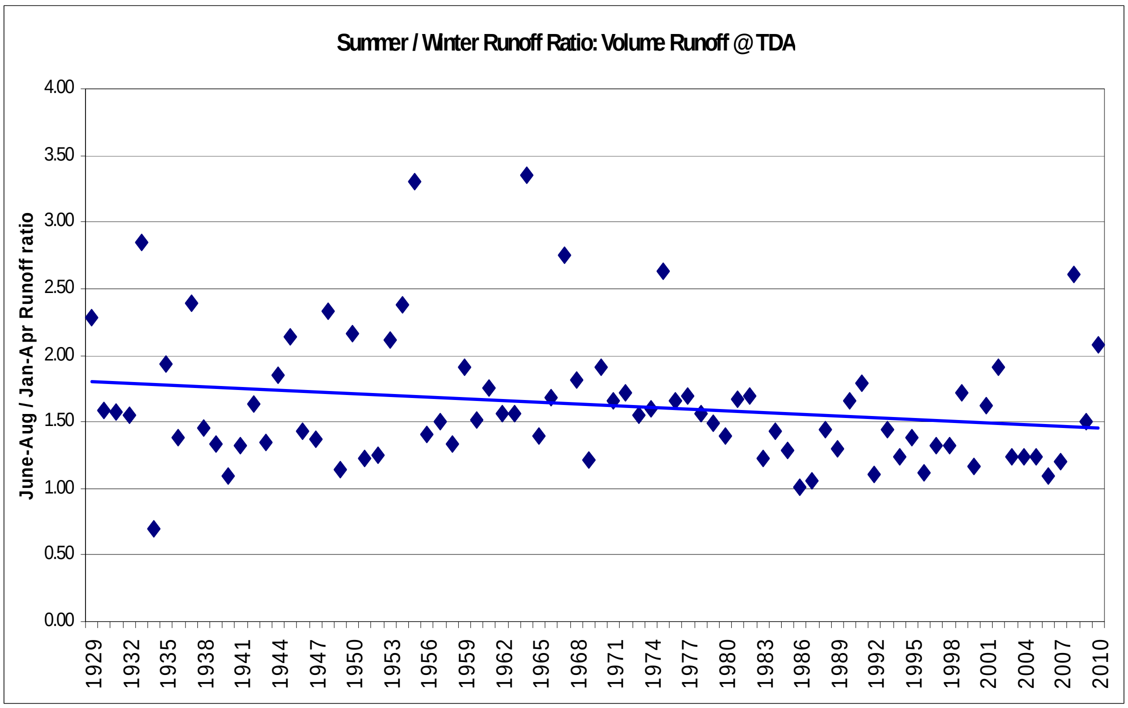

Figure 19. S/W Ratio of Runoff at TDA for the Historical period 1929-2010.

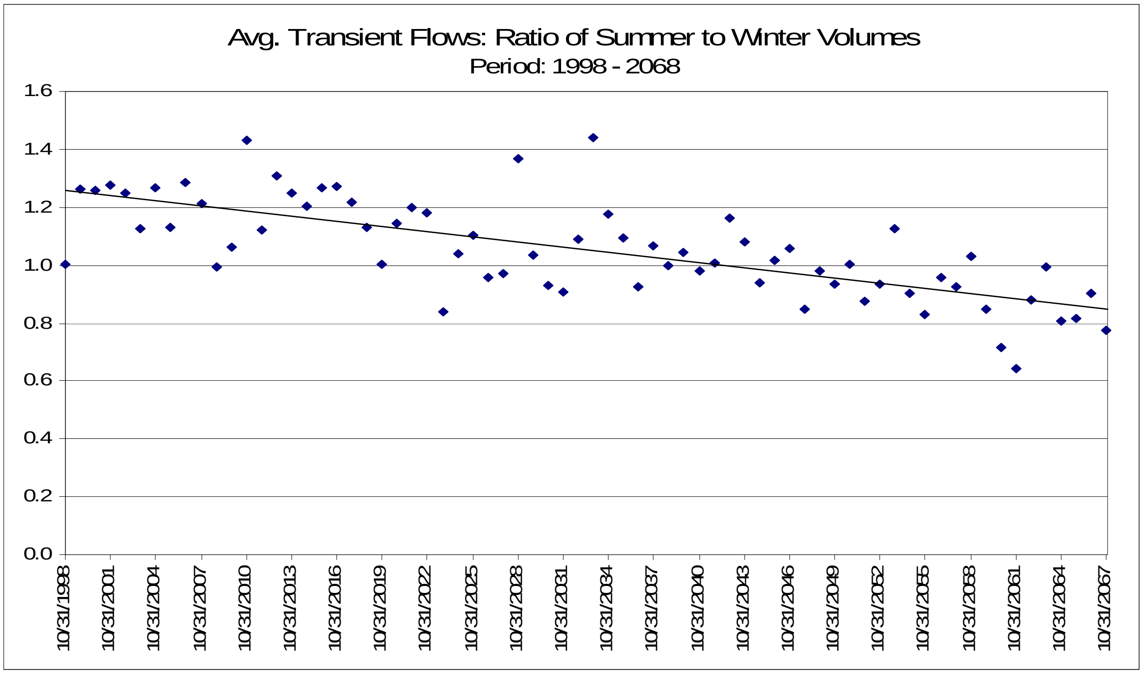

Figure 20. S/W Ratios for Transient Scenarios for the period 1999-2068.

Figure 20 above, charts the same S/W ratios for the future Transient flow scenario ensemble average. Figure 21 is a bar graph that combines the historic S/W ratios with the future climate change scenarios. Both the Hybrid-Delta and Transient scenarios are represented noting that the X-axis time scale is a proxy to represent mixed time series averages. The Transient scenarios represent a better fit for this type of time series graph since they represent a continuum change over the entire future planning horizon, as opposed to the Hybrid-Delta scenarios which are a sort of snap-shot in time to represent an average of a 30 year block. The purpose of this graph is to present a visual picture of how seasonal runoff shaping characteristics might transition from the historical to future climate change scenarios. Note from Figure 70 graph that historical decadal averages are less convincing in terms of lower S/W ratios. The 2000-2010 decade is higher than the two preceding decade averages. Longer period averages for the historical period tend to follow a more climate change like declining pattern.

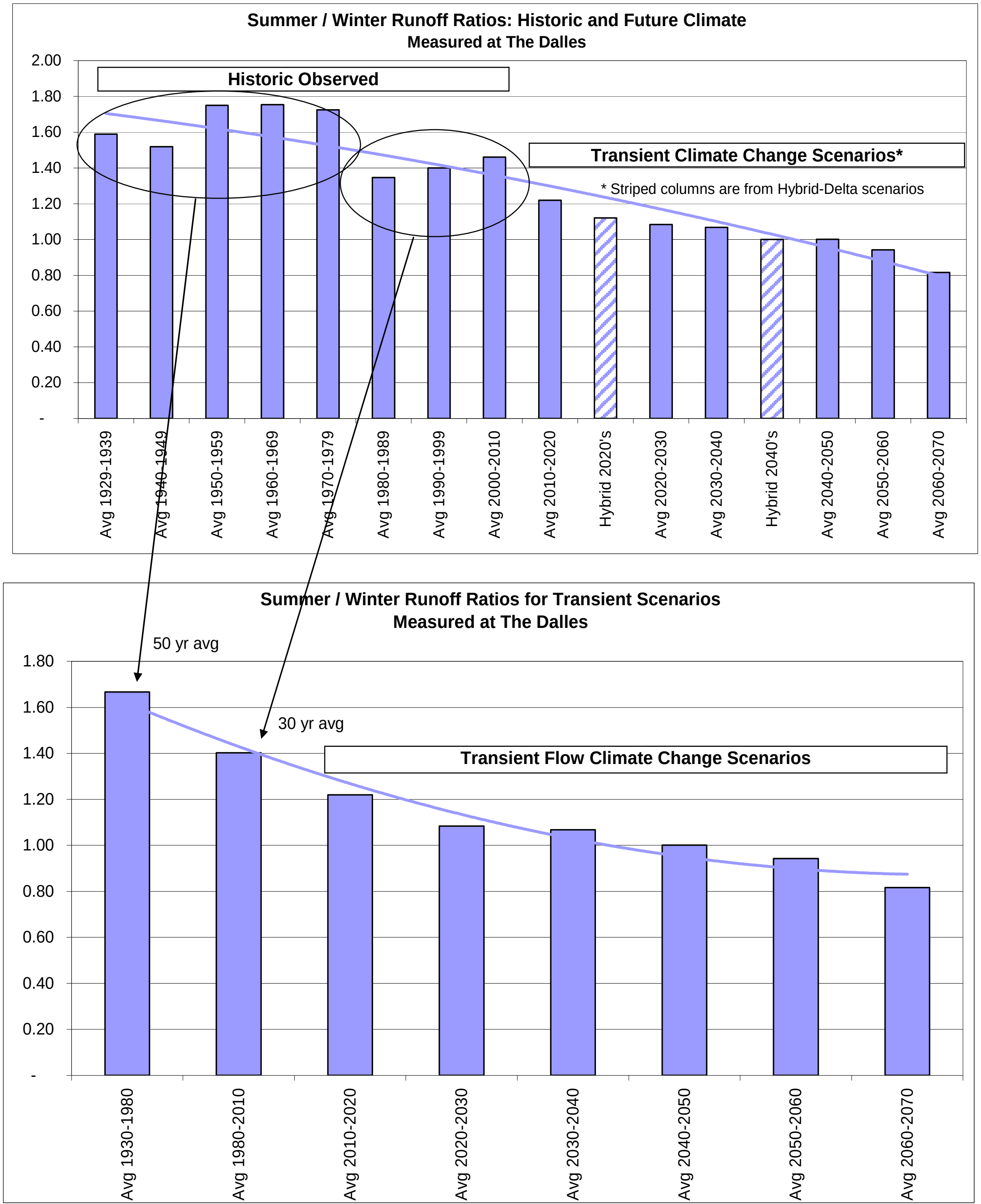

Figure 21. Period Average, S/W Ratios for Historical & Climate Change Scenarios measured at TDA

3.3 Description of AER and TSR Flood Control Datasets

Initially, two flood control data sets, a Treaty Storage Regulation (TSR) and an Actual Energy Regulation (AER) dataset were computed for each climate change scenario. Both the datasets are required for the reservoir power modeling to emulate current processes.

The TSR flood control set is used in a TSR power model run, which determines the Canadian Treaty projects' operations. The TSR power model run uses all project criteria from the current Columbia River Treaty Detailed Operating Plan (DOP) and uses only flood control and power operating criteria.

The AER set of flood control is used in an AER power model run, which uses the resulting Canadian operation from the TSR, and all U.S. projects' operating criteria including fish operations and other agreements with Canada as used in actual operations. The TSR assumes no shift of Dworshak or Brownlee flood control, and Libby uses Standard Flood Control. The AER data set assumes a shift of some flood control space from Dworshak to Grand Coulee and uses Libby Variable Flow (or VarQ) Flood Control, which is described in more detail below. Both operations are used to model actual operations. Shifting flood control space means that space that would otherwise be evacuated from Dworshak is evacuated from Grand Coulee instead.

As compared to Libby Standard Flood Control, Libby VarQ Flood Control uses higher flood control curves during the winter and provides higher reservoir releases during refill that provides flood protection while aiding in providing flow augmentation water for conservation and recovery of threatened and endangered species while maintaining system flood control. Libby VarQ flood control is not used in the TSR data sets because it is not included in the Treaty planning studies that determine Canadian Treaty operations.

Flood control space may be shifted from Dworshak to Grand Coulee generally in February through April 15th for the purpose of providing more water downstream of Dworshak in the second half of April to meet flow objectives for fish. Flood control space may be shifted from Brownlee to Grand Coulee if the Brownlee's project owner requests, but it is rarely done in actual operations and therefore is not included in this study.

The final step in computing flood control is to adjust Grand Coulee's flood control values to account for reservoirs that are drafted deeper than their flood control requirements (primarily Canadian power operations). BPA is responsible for this step. The following describes the process and the responsible agency:

1. Corps develops a TSR initial flood control set, no power drafts included in Grand

Coulee flood control computation

2. BPA Runs HydSim, with TSR flood control only, develops TSR Canadian operation

3. Corps develops an AER initial flood control set, no power drafts included in Grand Coulee flood control computation

BPA then computes URCs for use in the HydSim modeling for two purposes: building Variable Draft Limits (VDLs) for Hungry Horse and Grand Coulee, and; building URCs for Grand Coulee using the storage space in specific Columbia Basin reservoirs that were drafted deeper than the flood control requirements in the hydro-regulation studies. Variable Draft Limits are draft limits during January though March such that there is an 85% and 75% confidence that Grand Coulee and Hungry Horse, respectively, to operate to their early April flood control point as recommended for fisheries objectives. The calculations are made using the URC data files of evacuation and refill developed by the Corps for each of the climate change scenarios. The calculation of the Grand Coulee URCs follows the criteria specified in the Corps' 2003 Columbia River Treaty Flood Control Operating Plan (FCOP) and the 2010 Standard Operating Procedure (SOP) for the Computation of the Flood Control Criteria for TSR and AER Models. The steps for calculating URCs are:

1. Sets of January, February, and March URCs are calculated to develop the Hungry Horse VDLs. Calculations are made with the evacuation and refill data files supplied by the Corps and the seasonal climate change volume data. The initial AER is run with the Hungry Horse VDLs and with the URCs supplied by the Corps.

2. Results of the initial AER study are used to develop URCs for Grand Coulee that account for the additional storage space in reservoirs that were drafted deeper than the flood control requirements. Sets of January, February, and March URCs are calculated to develop the Grand Coulee VDLs. The final AER is run with new URCs and VDLs for Grand Coulee.

3. For the initial OPER run, the URCs developed in step 1 are used to update the Hungry Horse VDLs.

4. Results of the initial Operational (OPER, see section 9.2.3 for more detail) study are used to develop URCs for Grand Coulee Dam (GCL) that account for the additional storage space in reservoirs that were drafted deeper than the flood control requirements. This step accounts for any changes in reservoir storage space between the final AER run and the initial OPER run. Sets of January, February, and March URCs are calculated to update the GCL VDLs. The final OPER study is run with new URCs and VDLs for Grand Coulee.

These steps were done for each of the 28 scenarios.

See Section 10.1 for more information on the three step process for modeling the scenarios.

4.0 CLIMATE SCENARIOS NAMING CONVENTION

Table 4 shows the naming conventions used to identify the various data sets used by the Corps and BPA in the analyses, and also the file names assigned to each for data management purposes. A scenario number was assigned to each climate change scenario. An "a" following the scenario number designates that the initial flood control set is a TSR set, and a "b" designates that the initial flood control set is an AER dataset. The "fcparm" is the file containing the volume forecasts that are used to compute the flood control curves. The file names for the final output file used by HydSim is designated "bpaFCxy", where x is the scenario number and y is either "a" for TSR or "b" for AER. The quality label characterizes the Hybrid-Delta climate change scenarios (see Part I report, Section 3.3) and do not apply to the Transient climate projections. The following is the label definition:

C=Central Change

MC = Minor Change

MWD = More Warming and Drier

LWD = Less Warming and Drier

MWW = More Warming and Wetter

LWD = Less Warming and Drier

Table 4. Climate Change Data Set Names.

Scenario	Quality						a	b		File names for .srd files			Input file	Outputfile
Number	Label	Scenario Name	Data set	OBS/FCST	Category	Scenario Name	TSR/AER	fcparm	libvaq					
								file name	libsys	dwrsys	dwrlrc	dcdorg	URC	bpaFC
1		2000L	1a	Observed	Base	2000L	TSR	fcparm1	libsys1a	dwrsys1		dcdorg1	URC1a	bpaFC1a
			1b	Observed	Base	2000L	AER	fcparm1	libvaq1b	dwrsys1	dwrlrc1	dcdorg1	URC1b	bpaFC1b
2		Historic Vic	2a	Observed	Base	Historic Vic	TSR	fcparm2	libsys2a	dwrsys2		dcdorg2	URC2a	bpaFC2a
			2b	Observed	Base	Historic Vic	AER	fcparm2	libvaq2b	dwrsys2	dwrlrc2	dcdorg2	URC2b	bpaFC2b
3	MW/D	ccsm3_2020	3a	Observed	HYBRID 2020	ccsm3_2020	TSR	fcparm3	libsys3a	dwrsys3		dcdorg3	URC3a	bpaFC3a
			3b	Observed	HYBRID 2020	ccsm3_2021	AER	fcparm3	libvaq3b	dwrsys3	dwrlrc3	dcdorg3	URC3b	bpaFC3b
4	LW/W	cgcm3.1_t47_2020	4a	Observed	HYBRID 2020	cgcm3.1_t47_2020	TSR	fcparm4	libsys4a	dwrsys4		dcdorg4	URC4a	bpaFC4a
			4b	Observed	HYBRID 2020	cgcm3.1_t47_2020	AER	fcparm4	libvaq4b	dwrsys4	dwrlrc4	dcdorg4	URC4b	bpaFC4b
5	MC	echam5_2020	5a	Observed	HYBRID 2020	echam5_2020	TSR	fcparm5	libsys5a	dwrsys5		dcdorg5	URC5a	bpaFC5a
			5b	Observed	HYBRID 2020	echam5_2020	AER	fcparm5	libvaq5b	dwrsys5	dwrlrc5	dcdorg5	URC5b	bpaFC5b
6	C	hadcm_2020	6a	Observed	HYBRID 2020	hadcm_2020	TSR	fcparm6	libsys6a	dwrsys6		dcdorg6	URC6a	bpaFC6a
			6b	Observed	HYBRID 2020	hadcm_2020	AER	fcparm6	libvaq6b	dwrsys6	dwrlrc6	dcdorg6	URC6b	bpaFC6b
7	MW/W	ipsl_cm4_2020	7a	Observed	HYBRID 2020	ipsl_cm4_2020	TSR	fcparm7	libsys7a	dwrsys7		dcdorg7	URC7a	bpaFC7a
			7b	Observed	HYBRID 2020	ipsl_cm4_2020	AER	fcparm7	libvaq7b	dwrsys7	dwrlrc7	dcdorg7	URC7b	bpaFC7b
8	LW/D	pcm1_2020	8a	Observed	HYBRID 2020	pcm1_2020	TSR	fcparm8	libsys8a	dwrsys8		dcdorg8	URC8a	bpaFC8a
			8b	Observed	HYBRID 2020	pcm1_2020	AER	fcparm8	libvaq8b	dwrsys8	dwrlrc8	dcdorg8	URC8b	bpaFC8b
9	LW/W	cgcm3.1_t47_2040	9a	Observed	HYBRID 2040	cgcm3.1_t47_2040	TSR	fcparm9	libsys9a	dwrsys9		dcdorg9	URC9a	bpaFC9a
			9b	Observed	HYBRID 2040	cgcm3.1_t47_2040	AER	fcparm9	libvaq9b	dwrsys9	dwrlrc9	dcdorg9	URC9b	bpaFC9b
10	MC	echam5_2040	10a	Observed	HYBRID 2040	echam5_2040	TSR	fcparm10	libsys10a	dwrsys10		dcdorg10	URC10a	bpaFC10a
			10b	Observed	HYBRID 2040	echam5_2040	AER	fcparm10	libvaq10b	dwrsys10	dwrlrc10	dcdorg10	URC10b	bpaFC10b
11	LW/D	echog_2040	11a	Observed	HYBRID 2040	echog_2040	TSR	fcparm11	libsys11a	dwrsys11		dcdorg11	URC11a	bpaFC11a
			11b	Observed	HYBRID 2040	echog_2040	AER	fcparm11	libvaq11b	dwrsys11	dwrlrc11	dcdorg11	URC11b	bpaFC11b
12	C	hadcm_2040	12a	Observed	HYBRID 2040	hadcm_2040	TSR	fcparm12	libsys12a	dwrsys12		dcdorg12	URC12a	bpaFC12a
			12b	Observed	HYBRID 2040	hadcm_2040	AER	fcparm12	libvaq12b	dwrsys12	dwrlrc12	dcdorg12	URC12b	bpaFC12b
13	MW/D	hadgem1_2040	13a	Observed	HYBRID 2040	hadgem1_2040	TSR	fcparm13	libsys13a	dwrsys13		dcdorg13	URC13a	bpaFC13a
			13b	Observed	HYBRID 2040	hadgem1_2040	AER	fcparm13	libvaq13b	dwrsys13	dwrlrc13	dcdorg13	URC13b	bpaFC13b
14	MW/W	miroc3.2_2040	14a	Observed	HYBRID 2040	miroc3.2_2040	TSR	fcparm14	libsys14a	dwrsys14		dcdorg14	URC14a	bpaFC14a
			14b	Observed	HYBRID 2040	miroc3.2_2040	AER	fcparm14	libvaq14b	dwrsys14	dwrlrc14	dcdorg14	URC14b	bpaFC14b
15		ccsm3	15a	Observed	Transient	ccsm3	TSR	fcparm15	libsys15a	dwrsys15		dcdorg15	URC15a	bpaFC15a
			15b	Observed	Transient	ccsm3	AER	fcparm15	libvaq15b	dwrsys15	dwrlrc15	dcdorg15	URC15b	bpaFC15b
16		cgcm3.1_t47	16a	Observed	Transient	cgcm3.1_t47	TSR	fcparm16	libsys16a	dwrsys16		dcdorg16	URC16a	bpaFC16a
			16b	Observed	Transient	cgcm3.1_t47	AER	fcparm16	libvaq16b	dwrsys16	dwrlrc16	dcdorg16	URC16b	bpaFC16b
17		echo_g	17a	Observed	Transient	echo_g	TSR	fcparm17	libsys17a	dwrsys17		dcdorg17	URC17a	bpaFC17a
			17b	Observed	Transient	echo_g	AER	fcparm17	libvaq17b	dwrsys17	dwrlrc17	dcdorg17	URC17b	bpaFC17b

Scenario number	Quality Label	Scenario Name	Data set	OBS/FCST	Category	Scenario Name	TSR/AER	fcparm file name	Libvaq Libsys	DWRsys	DWRlrc	Dcdb	URC	bpaFC
18		hadcm	18a	Observed	Transient	hadcm	TSR	fcparm18	libsys18a	dwrsys18		dcdorg18	URC18a	bpaFC18a
			18b	Observed	Transient	hadcm	AER	fcparm18	libvaq18b	dwrsys18	dwrlrc18	dcdorg18	URC18b	bpaFC18b
19		echam5	19a	Observed	Transient	echam5	TSR	fcparm19	libsys19a	dwrsys19		dcdorg19	URC19a	bpaFC19a
			19b	Observed	Transient	echam5	AER	fcparm19	libvaq19b	dwrsys19	dwrlrc19	dcdorg19	URC19b	bpaFC19b
20		pcm1	20a	Observed	Transient	pcm1	TSR	fcparm20	libsys20a	dwrsys20		dcdorg20	URC20a	bpaFC20a
			20b	Observed	Transient	pcm1	AER	fcparm20	libvaq20b	dwrsys20	dwrlrc20	dcdorg20	URC20b	bpaFC20b
21		2000L	21a	Forecast	Base	2000L	TSR	fcparm21	libsys21a	dwrsys21		dcdorg21	URC21a	bpaFC21a
			21b	Forecast	Base	2000L	AER	fcparm21	libvaq21b	dwrsys21	dwrlrc21	dcdorg21	URC21b	bpaFC21b
22		Historic Vic	22a	Forecast	Base	Historic Vic	TSR	fcparm22	libsys22a	dwrsys22		dcdorg22	URC22a	bpaFC22a
			22b	Forecast	Base	Historic Vic	AER	fcparm22	libvaq22b	dwrsys22	dwrlrc22	dcdorg22	URC22b	bpaFC22b
23	MW/D	ccsm3_2020	23a	Forecast	HYBRID 2020	ccsm3_2020	TSR	fcparm23	libsys23a	dwrsys23		dcdorg23	URC23a	bpaFC23a
			23b	Forecast	HYBRID 2020	ccsm3_2021	AER	fcparm23	libvaq23b	dwrsys23	dwrlrc23	dcdorg23	URC23b	bpaFC23b
24	LW/W	cgcm3.1_t47_2020	24a	Forecast	HYBRID 2020	cgcm3.1_t47_2020	TSR	fcparm24	libsys24a	dwrsys24		dcdorg24	URC24a	bpaFC24a
			24b	Forecast	HYBRID 2020	cgcm3.1_t47_2020	AER	fcparm24	libvaq24b	dwrsys24	dwrlrc24	dcdorg24	URC24b	bpaFC24b
25	MC	echam5_2020	25a	Forecast	HYBRID 2020	echam5_2020	TSR	fcparm25	libsys25a	dwrsys25		dcdorg25	URC25a	bpaFC25a
			25b	Forecast	HYBRID 2020	echam5_2020	AER	fcparm25	libvaq25b	dwrsys25	dwrlrc25	dcdorg25	URC25b	bpaFC25b
26	C	hadcm_2020	26a	Forecast	HYBRID 2020	hadcm_2020	TSR	fcparm26	libsys26a	dwrsys26		dcdorg26	URC26a	bpaFC26a
			26b	Forecast	HYBRID 2020	hadcm_2020	AER	fcparm26	libvaq26b	dwrsys26	dwrlrc26	dcdorg26	URC26b	bpaFC26b
27	MW/W	ipsl_cm4_2020	27a	Forecast	HYBRID 2020	ipsl_cm4_2020	TSR	fcparm27	libsys27a	dwrsys27		dcdorg27	URC27a	bpaFC27a
			27b	Forecast	HYBRID 2020	ipsl_cm4_2020	AER	fcparm27	libvaq27b	dwrsys27	dwrlrc27	dcdorg27	URC27b	bpaFC27b
28	LW/D	pcm1_2020	28a	Forecast	HYBRID 2020	pcm1_2020	TSR	fcparm28	libsys28a	dwrsys28		dcdorg28	URC28a	bpaFC28a
			28b	Forecast	HYBRID 2020	pcm1_2020	AER	fcparm28	libvaq28b	dwrsys28	dwrlrc28	dcdorg28	URC28b	bpaFC28b
29	LW/W	cgcm3.1_t47_2040	29a	Forecast	HYBRID 2040	cgcm3.1_t47_2040	TSR	fcparm29	libsys29a	dwrsys29		dcdorg29	URC29a	bpaFC29a
			29b	Forecast	HYBRID 2040	cgcm3.1_t47_2040	AER	fcparm29	libvaq29b	dwrsys29	dwrlrc29	dcdorg29	URC29b	bpaFC29b
30	MC	echam5_2040	30a	Forecast	HYBRID 2040	echam5_2040	TSR	fcparm30	libsys30a	dwrsys30		dcdorg30	URC30a	bpaFC30a
			30b	Forecast	HYBRID 2040	echam5_2040	AER	fcparm30	libvaq30b	dwrsys30	dwrlrc30	dcdorg30	URC30b	bpaFC30b
31	LW/D	echog_2040	31a	Forecast	HYBRID 2040	echog_2040	TSR	fcparm31	libsys31a	dwrsys31		dcdorg31	URC31a	bpaFC31a
			31b	Forecast	HYBRID 2040	echog_2040	AER	fcparm31	libvaq31b	dwrsys31	dwrlrc31	dcdorg31	URC31b	bpaFC31b
32	C	hadcm_2040	32a	Forecast	HYBRID 2040	hadcm_2040	TSR	fcparm32	libsys32a	dwrsys32		dcdorg32	URC32a	bpaFC32a
			32b	Forecast	HYBRID 2040	hadcm_2040	AER	fcparm32	libvaq32b	dwrsys32	dwrlrc32	dcdorg32	URC32b	bpaFC32b
33	MW/D	hadgem1_2040	33a	Forecast	HYBRID 2040	hadgem1_2040	TSR	fcparm33	libsys33a	dwrsys33		dcdorg33	URC33a	bpaFC33a
			33b	Forecast	HYBRID 2040	hadgem1_2040	AER	fcparm33	libvaq33b	dwrsys33	dwrlrc33	dcdorg33	URC33b	bpaFC33b
34	MW/W	miroc3.2_2040	34a	Forecast	HYBRID 2040	miroc3.2_2040	TSR	fcparm34	libsys34a	dwrsys34		dcdorg34	URC34a	bpaFC34a
			34b	Forecast	HYBRID 2040	miroc3.2_2040	AER	fcparm34	libvaq34b	dwrsys34	dwrlrc34	dcdorg34	URC34b	bpaFC34b

5.0 DESCRIPTION OF SYSTEM FLOOD CONTROL

Flood protection in the Columbia River Basin is provided by a system of dams extending from the headwaters of the Columbia River at Mica Dam in Canada through Bonneville Dam, located about 40 miles upstream of Portland, Oregon. The system of dams includes projects in the Snake, Pend Oreille and Kootenay River basins. The basic objective for a flood regulation is to operate reservoirs to reduce to non-damaging stage levels at all potential flood damage areas in Canada and the U.S. insofar as possible, and to regulate larger floods, that cannot be controlled to non-damaging levels to the lowest possible level with the available storage space. Eight major dams work together by drafting their reservoirs through the winter then refilling by June or July capturing snow melt runoff. The eight major dams are; Mica, Arrow and Duncan in Canada owned by BC Hydro; Libby and Dworshak owned by the Corps; Hungry Horse and Grand Coulee owned by Reclamation; and Brownlee, owned by Idaho Power Company. These projects have variable flood control curves and the flood control requirement is based on the magnitude of a water supply forecast (See Section 5.4 for detailed information on flood control requirements). Controlled refill of these reservoirs provide the desired control of flow as measured at The Dalles to reduce flood damages in the Portland/Vancouver vicinity. Regulations for system flood control also provide benefits for local flood control. Other dams that contribute to system flood control, such as Kerr and Albeni Falls are not addressed in this Part because their flood control requirements are the same in every year and do not vary depending on the magnitude of the water supply forecasts.

Flood Operating Plans. The annual flood control plan for the operation of U.S. and Canadian Treaty reservoirs was predetermined in the late 1960’s and early 1970’s and has somewhat evolved over time. The current Flood Control Operating Plan (FCOP, 2003), provides the flood control guidelines for Treaty projects and was coordinated between the U.S. and Canadian Entities, signatories to the Columbia River Treaty. Flood control operations for other flood control projects are outlined in their Water Control Manuals.

System flood control objectives include the lower Columbia River as measured at The Dalles. According to the Flood Control Operating Plan, a flow of 450 kcfs at The Dalles corresponds to bank full at Vancouver, where minor damages begin. Another system objective is to refill the system of reservoirs as early as possible but not so early as to cause undesired high flows in the future. To meet system flood control needs and to refill the system of reservoirs by June or July, depending on the project, a flow to which The Dalles is to be operated is computed. This flow is called the initial controlled flow and is based on The Dalles seasonal volume forecast minus the space in reservoirs upstream, and using the curve in Chart 1 in the FCOP. This flow may be adjusted as the timing and shape of the peak flow runoff materializes to reduce flood damages and refill the reservoirs. Local Flood Control objectives include but are not limited to maximum river stages (elevations) at; Columbia Falls, downstream of Hungry Horse; Spalding, downstream of Dworshak; Kootenay Lake downstream of Duncan and Libby; Bonners Ferry, downstream of Libby; and Trail, downstream of Arrow.

5.1 Flood Control Modeling Tools.

The Corps developed and used a program called the "URC" (Upper Rule Curve) program, a program used to compute end-of-month reservoir flood control curves based on seasonal volume forecasts during the drawdown period and uses previously established estimated refill rates (space refilled in May and June) during the refill period. Inputs to the URC program are seasonal volume forecasts, project storage reservoir diagrams (SRDs), and refill percentages. Refill percentages were developed using Excel spreadsheets and are estimates of the percent of space to be refilled in May and June (see section 4.3.2 for details on refill). The outputs of the URC program are end-of-month flood control requirements in a format usable by BPA's system reservoir model HydSim.

5.2 Flood Control Assumptions

Flood control assumptions during evacuation and refill for each project are described in the following sections. Evacuation generally occurs in the October through April time frame and varies depending upon the project. Refill generally occurs in May through July.

5.2.1 Evacuation Period

For October through April, each project uses its own storage reservation diagram (SRD) that determines its flood control draft requirement for a given a runoff volume forecast. SRDs for Mica, Arrow, Duncan and Libby Standard Flood Control are referenced in the Columbia River Treaty Flood Control Operating Plan (FCOP). SRDs for all other projects along with the FCOP can be found at http://www.nwd-wc.usace.army.mil/cafe/forecast/SRD/srd.htm. The project-specific SRD and reference of its origin is provided in Table 1 below. Kerr and Albeni Falls have a fixed flood control curve that does not vary with runoff volume. One half Million-Acre-ft (0.5 Maf) is used for the end of April flood control point.

Table 5. SRD details.

Project	Source of SRD	Notes
Mica	FCOP Chart 8	Max draft 4.0 Maf
Libby	VARQ, Dec. 2003 (AER)	VarQ Flood Control
Libby	FCOP Chart 11, 1991 (TSR)	Standard Flood Control
Hungry Horse	VARQ, July 1998	
Duncan	FCOP Chart 10[1]	
Dworshak System	CRT63, Feb. 1987	
Dworshak Local	1992 Local Flood Control SRD	Shifted to Grand Coulee in AER
Arrow	FCOP Chart 5	Max draft 3.6 Maf
Grand Coulee	March 1997 SRD	
Brownlee	1998 Modified Procedure	
John Day	Apr. 1986 SRD	

[1] Duncan SRD (FCOP Chart 10) has been modified per the request by BC Hydro to delay draft from 28/29 February to 15 March.

5.2.2 Refill

Due to the large number of scenarios and limitations on time, system refill curves were not developed using a daily time-step to meet controlled flow objectives as is normally required in detailed flood control studies. In lieu of detailed regulations, default refill percentages based on previous studies are used as an acceptable proxy. Default refill percentages are the percent of refill, generally from the lowest evacuation level, to be filled at a given project in May and June. From previous daily time-step studies, refill percentages were computed from the flood regulation results for each month and each year after which the average monthly refill percent (default refill percent) was computed. The default refill percentages were used in both forecast and observed modes for all projects except for Libby and Dworshak. The default refill percentages are provided in Table 6, Project abbreviations are listed in Appendix 16.0.

Table 6. Cumulative Percent of Space to be filled by the end of the period.

Project	31-Mar	15-Apr	30-Apr	31-May	30-Jun	31-Jul	Month % is based on
Mica	0	0	0	34	86	100	31-Mar
Arrow	0	0	0	30	93	100	31-Mar
Duncan	0	0	0	34	82	100	28/29 Feb
H.Horse	0	0	0	75	100	100	30-Apr
G. Coulee	0	0	0	43	100	100	30-Apr
Brownlee	0	0	0	87	100	100	30-Apr
Dworshak[1]	FCRC	FCRC	FCRC	FCRC	FCRC	100	31-Dec
Libby[2]	0	FCRC	FCRC	FCRC (TSR) VarQ (AER)	100	100	31-Mar

[1] Compare Flood Control Refill Curve (FCRC) elevations to SRD targets for 31 March, 15 and 30 April, use the higher for each target date. The FCRC provides a 95% confidence of refill by July 31.

[2] Compare FCRC elevations to SRD targets for 15 and 30 April, use the higher for each target date

For informational purposes, Table 7 shows the flood control storage space for each of the major flood control projects, their full pool and empty pool elevations. Flood control storage volume is in thousand acre-feet (kaf).

Table 7. List of Flood Control Projects Storage and Elevation.

Project	Flood Control Storage (kaf)	Full Pool Elevation (feet)	Empty Pool Elevation (feet)
Mica	4080 (Treaty)	2470.1 (Treaty)	2319.0
Arrow	3,600	1444.0	1377.0
Duncan	1,270	1892.0	1794.0
Libby	4,980	2459.0	2287.0
Hungry Horse	2,980	3560.0	3336.0
Grand Coulee	5,185	1290.0	1208.0
Dworshak	2,016	1600.0	1445.0
Brownlee	980	2077.0	1976.0

Spreadsheet computations were used to compute Flood Control Refill Curves (FCRCs) for Dworshak, and FCRCs and VarQ outflows for Libby and are specific to the observed volumes or volume forecasts for each climate change scenario. FCRCs are lower reservoir limits that provide a 95% confidence of refill but for flood control purposes they are also used as upper limits that aid in not filling the projects too early (filling the reservoirs too early might cause future undesired spill).

Projects other than Libby and Dworshak, were drafted well below their computed FCRCs, then refilling on minimum flow (from which default refill percentages were derived). FCRCs are not a controlling factor and default refill percentages can be used. Details of computations are as follows:

Libby Standard. For Libby in the TSR, the FCRCs are computed and the lesser draft of the SRD and FCRC is used for April 15 through May. Minimum flow discharge for Libby assumed in the FCRC computation is 4 thousand cubic feet per second (kcfs). Libby Standard flood control was a procedure developed for implementation in 1991 and it drafts and refills the project for flood control by releasing a minimum flow of 4 kcfs.

Libby VarQ. For Libby in the AER, both the April 15th and April 30th flood control requirements are the lesser draft of the FCRC and SRD, whereas the May 31st flood control requirement is based on the fill amount as if Libby were regulated to the VarQ procedure starting from the Apr 30 flood control point (lesser of the FCRC and SRD). The VarQ procedure generally allows the Libby reservoir to be at a higher elevation than the Libby Standard procedure would allow and includes a procedure to compute releases during refill that are higher than the minimum flow of 4 kcfs.

The Corps computed monthly runoff volumes from monthly flows that were provided by BPA in a file named "Data for BOR f.zip", received on August 4, 2010. Split month runoff volumes were developed from the 2000 Level mean distribution of runoff volume between the first and second halves of April and from the April volumes from the data provided by BPA. Split month volumes are used because there are significant natural runoff volume differences between the first and second half of these months. The split month volumes were used to compute FCRCs, and which developed April 15th flood control curves for use in HydSim. The months of April and August are divided into two halves to better simulate the rise and fall of the natural snowpack runoff. These two months often see a significant difference in streamflows when comparing the first and second half periods.

Dworshak. The FCRCs were computed, and the lesser draft of the SRD and FCRC were used for flood control in March through June. Minimum flow for FCRC calculation is 1,600 cfs. Split month runoff volumes were developed from the 2000 Level mean distribution of runoff volume between the first and second halves of April and from the April volumes from the data provided by BPA. The split month volumes were used to compute FCRCs and which developed April 15th flood control curves for use in HydSim.

Hungry Horse VarQ— Normally, Reclamation does not start refilling Hungry Horse before 1

May, therefore refill percentages through April are zero percent. FCRCs and VarQ outflows were computed, however, the results showed low refill percentages. Because the results of the FCRC and VarQ computations were so low, the May default refill percentage of 75% was used.

Duncan—The Corps computed FCRCs and used the lesser draft of the SRD and FCRC. Minimum flow for the FCRC computation was 100 cfs. The FCRCs resulted in refill percentages that were deemed too low in May and June (average of six percent in May and 42% in June with the 2000 Level forecast scenario), so May, June and July were set to default refill percentages of 34%, 82% and 100%, respectively.

6.0 FLOOD CONTROL ANALYSIS

To analyze the effect of climate change projections on end-of-month flood control curves during the evacuation period of January through April, flood control curves for Columbia River flood control projects were computed for the six-Hybrid-Delta 2020, six-Hybrid-Delta 2040, six-Transient climate projection scenarios, and the 2000 Level scenario. The analysis for each project is provided starting with Mica in Section 6.3. Flood control curves were computed based on existing operational criteria. Comparisons of the climate change scenarios to the 2000 Level scenario were made. Figures of mean monthly volume graphs, seasonal runoff volume exceedance, flood control exceedance, and April 30th flood control elevation comparisons are provided. A summary of the effects of climate change on individual projects under current flood control operating rules is provided at the end of each project's section. Limitations and uncertainties of this analysis is discussed in Section 7.0, implication of climate change on the future flood control is discussed in Section 7.0, and the possible next steps for analysis is provided in Section 13.0.

Flood control curves during the refill period were computed based on guidance from previous studies (see Section 5.2.2). To analyze the effect of climate change on peak flows during this period, daily modeling is required (not within the scope of this effort); therefore effects on flood control during refill was not analyzed. Some information may be gleaned from monthly power studies by examining average monthly flows, such as which scenarios produce the largest monthly flow, and month in which it occurs. Future studies may include daily modeling to analyze the performance of current operational criteria on the magnitude of the peak flows during the refill period.

Flood control for the major flood control projects, Mica, Arrow, Libby, Grand Coulee, Brownlee, Libby, Hungry Horse, and Dworshak are addressed. Projects such as Kerr and Albeni Falls are not addressed in this report because their flood control requirements are the same every year and do not change with the magnitude of a runoff volume, however their requirements should be evaluated in future studies. The Dalles does not have flood control curves but its April through August runoff volumes are addressed because it is a determining factor in computing flood control requirements for Mica, Arrow, Grand Coulee, and Brownlee.

Flood control curves were developed in observed and forecast mode for each of the climate change scenarios as well as for the 2000 Level Base Case data. The observed mode is where the seasonal volumes used to compute the flood control requirements is known and reflects perfect foreknowledge. The forecast mode is where the seasonal volume forecast changes from month to month and reflects uncertainty. While flood control curves were computed in both the observed and forecast modes, only the forecast mode flood control curves are discussed in this report because they better represents the uncertainties associated with actual operations. In addition, both TSR and AER sets of flood control were computed, but only the AER sets of flood control were analyzed because they better represents actual operations (see Section 3.3 for description of AER and TSR flood control sets).

The various types of graphs used throughout the flood control section of the report are described next.

6.1 Graphs

6.1.1 Mean Monthly Volume – Hybrid-Delta

Mean monthly unregulated runoff volumes are graphed for October through September and are provided for the projects where seasonal volume forecasts are used to compute flood control curves. Separate graphs for the Hybrid-Delta 2020 and 2040 scenarios are provided and show each scenario as compared to the 2000 Level scenario. These graphs show the general characteristic of the timing and magnitude of the monthly 70-year average runoff for each scenario.

These graphs were done for the Hybrid-Delta scenarios but not for the Transient scenarios because Transient scenarios evolve over time and do not represent stationarity (where past climate is assumed static in the future), and therefore statistical analyses as used for the Hybrid-Delta scenarios would not be appropriate (see Part I, Section 3.3.2 for more information on Transient Climate Projections).

6.1.2 Seasonal Runoff Volume Exceedance – Hybrid-Delta

The observed unregulated seasonal runoff volumes of the 2000 Level and the climate change scenarios are compared by means of exceedance plots, where the y-axis is reservoir storage content in thousands of acre-feet (kaf), and the x-axis is the percent exceedance. Storage content is the volume of water in the reservoir measured from the bottom of the reservoir (not including dead storage). All of the data are based on a 70-year set of data. The following project's seasonal runoff volumes are plotted for:

- Dworshak and Brownlee: April-July
- Libby and The Dalles: April-August
- Hungry Horse: May-September

Flood control requirements at Dworshak, Libby and Hungry Horse projects are determined using the seasonal runoff volumes forecasts at their own sites whereas flood control requirements at Mica, Arrow and Grand Coulee projects are determined using the April through August forecast volume at The Dalles. For Brownlee, both The Dalles and Brownlee forecast volumes are used to determine its flood control requirements.

A percent exceedance seasonal runoff volume plot was developed by ranking all the years of seasonal runoff volume data and then assigning a percentage exceedance value to each data point. For example, an exceedance plot of the 2000 Level set of the Apr-Aug volume is done by first calculating the April – August runoff volume per year for every year from 1929 – 1998, which gives a total of 70 volume values. These 70 values are then ranked from smallest to largest in magnitude, and then a percentage exceedance is assigned to each point using the following formula:

$$E = [M/(n+1)]$$

where

E = percent of time the value is equaled or exceeded

M = the rank position of the value

n = number of values, in this case, 70

The resulting ranked data is then plotted with the Apr-Aug volume (kaf) on the y-axis, and exceedance on the x-axis. The same procedure is done for the 12 climate change sets over 70 years of Apr-Aug data.

To read the graph, for example, read a value on the x-axis, say the 10% exceedance, and locate a point on a curve corresponding to 10%. The value on the curve at that point is equaled or exceeded 10% of the time, or seven of the 70 years of values are greater than or equal to the value of that point.

These exceedance graphs were done only for the Hybrid-Delta scenarios, and not for the Transient ones, because Transient scenarios evolve over time and do not represent stationarity, and therefore statistical analyses as used for the Hybrid-Delta scenarios would not be appropriate (see Part I, Section 3.3.2 for more information on Transient Climate Projections).

6.1.3 Seasonal Runoff Volume, Ten-Year Rolling Average – Transient

The Transient scenarios represent climate that evolves over time, as compared to the Hybrid-Delta scenarios that represent a step up of future climate for a 30-year period centered on the year 2020 or 2040 and represent stationarity. Because Transient scenarios evolve over time and represent non-stationarity, statistical analyses as used for the Hybrid-Delta scenarios would not be appropriate, therefore, analysis of Transient scenarios are shown in terms of ten-year rolling averages. The Transient scenarios are viewed as equally possible scenarios and are not characterized by warmer, wetter, drier or cooler, as in the Hybrid-Delta scenarios. The Transient climate scenarios are meant to be considered together as a group, or ensemble and is meant to portray an envelope of climate possibility through time (see Part I, Section 3.3.2 for more information on Transient Climate Projections).

Graphs of the ten-year rolling average observed seasonal runoff volumes are provided for each of the six Transient scenarios and the 2000 Level scenario for the projects and periods stated in Section 6.02. The graphs also show the Transient ensemble median and its linear trend to help identify the trend moving forward in time. While Transient climate projections were made for the years 1951 through 2099, the 70-years of data that the flood control curves were prepared for were based on the 70-year period 1999 through 2068. The data on the X-axis shows the years used for modeling and is plotted with the end year of the ten-year period that the average covers. The Y-axis is the volume runoff.

6.1.4 Flood Control Storage Exceedance – Hybrid-Delta

The URC program (as described in Section 5.1) was used to calculate end-of-month flood control drafts (space requirement for flood control) based on forecast runoff volumes from the climate change and 2000 Level data sets. The flood control space requirement is the minimum space to be drafted from a full reservoir to ensure space is available near the end of April to capture spring runoff. The flood control draft is converted to reservoir storage content by subtracting the flood control draft requirement from the full reservoir content. The reservoir storage content was then ranked from highest volume (representing the lowest draft) to the lowest storage volume (representing the largest draft) for the 70-years for both 2000 Level and climate change data sets and plotted as exceedance curves. On the plots the vertical axis is the reservoir storage content in kaf, and the horizontal axis is the percent exceedance.

Figures are provided for each month January through April. Exceedance curves were developed to compare the effects of climate change projections on flood control requirements to the 2000 Level flood control requirements.

These exceedance graphs were done only for the Hybrid-Delta scenarios, and not for the Transient ones, because Transient scenarios evolve over time and do not represent stationarity, and therefore statistical analyses as used for the Hybrid-Delta scenarios would not be appropriate (see Part I, Section 3.3.2 for more information on Transient Climate Projections).

6.1.5 Flood Control April 30th Elevations Comparison – Hybrid-Delta

Box -whisker plots were created to show the April 30 flood control elevations (based on forecast data) for the Hybrid-Delta climate change scenarios alongside that of the 2000 Level scenario. These April 30th flood control elevation values are calculated from the URC program outputs using storage-elevation tables. The reason for analyzing the April 30th elevations, rather than any other month, is explained next.

Depending on the project, the timing of the maximum flood control evacuation occurs between March 15 and April 30. Projects pass inflow until refill begins, usually around the first week in May based on 2000 Level studies. However, maximum flood control drafts for the end of April are recomputed based on forecasts issued in April, therefore April 30 flood control elevations were used for this analysis. The April 30 elevation comparison plots are provided for all of the flood control projects, with two plots per project – one showing the 2020s data and the other showing the 2040s data. These box- whisker plots summarize the quartiles at the 25th percentile, 50th percentile (median), 75th percentile, minimum, average and the maximum values out of the 70 years of data. There are 17 or 18 pieces of data in each quartile.

The spacing between the different parts of the boxes in these box- whisker plots indicate the degree of spread and how the skewed the data are. The top most line of each box indicates the 75% data, which means that 75% of the data points have values lesser than or equal to that top most line value, whereas the bottom most line of the box indicates the 25% data, which means that 25% of the data points have values lesser than or equal to that value. The 50% value (median) is shown as a diamond shape with a horizontal line through it (found between the top and bottom line) and is the value at which half of the data points are above and below. The average values are shown as square shapes. Average values can be impacted by a very high or low value whereas the median is not. As an example as to how these boxes help in interpret data, if the distance between the top and median lines is greater than the distance between the median and bottom lines, it can be concluded that there is more spread in higher elevation values (between 50% - 75%) than lower elevation values(between 25%-50%). The ends of the lines, or whiskers, above the top and bottom of each box show the 0% and 100% percentiles, and provide the end points for the spread of values from 0-25% and 75%-100%.

These box-whisker plots were done for the Hybrid-Delta scenarios but not for the Transient ones because Transient scenarios evolve over time and do not represent stationarity, and therefore statistical analyses as used for the Hybrid-Delta scenarios would not be appropriate (see Part I, Section 3.3.2 for more information on Transient Climate Projections).

6.1.6 Flood Control April 30th Elevations Comparison – Transient

Graphs of the ten-year rolling average April 30th observed mode flood control elevations are provided for the six Transient scenarios and the 2000 Level scenario for each of the flood control projects. The graphs also show the Transient ensemble median and its linear trend to help identify the trend moving forward in time. The data on the X-axis shows the years used for modeling and is plotted with the end year of the ten-year period that the average covers. The Y-axis is April 30th flood control elevation.

6.2 Columbia River at The Dalles Dam

This section compares climate change scenarios to the 2000 Level scenario using the following methods and figures. For the Hybrid-Delta scenarios: observed mean monthly volumes, observed seasonal April-August runoff volume exceedance curves, and bar graph of the April-August versus March-July average runoff volumes. Comparison of the March through July runoff volumes to the currently used Apr-Aug runoff volumes is made to assess if the March through July runoff volumes might be used for calculating flood control requirements instead of the April-August due to climate change.

For the Transient scenarios: the ten-year moving average April-July runoff volume. A summary of climate change impacts to The Dalles is also provided.

6.2.1 Mean Monthly Volume – Hybrid-Delta

Figure 22 shows the observed mean monthly unregulated runoff volumes for The Dalles for each of the Hybrid-Delta 2020 and 2040 scenarios compared to the 2000 Level volumes. Beginning in November and through March or April, all but one climate change scenario had volumes greater than the 2000 Level volumes. In February, several scenarios had volumes greater than the 2000 Level. In particular, the MWW scenario has volumes about two times greater than that of the 2000 Level. The peak monthly volume was shifted from June in the 2000 Level to May in the climate change scenarios. The peaks were similar or less in the

2020 and 2040 scenarios except for three scenarios in the 2040s, where the 2040 MWW scenario had a peak of about 20% greater with smaller increases above the 2000 Level in the C and LW/W scenarios. From June through September climate change volumes are lower for all scenarios.

Higher winter volumes could mean more risk for winter flood events. A shift of peak volume from June to May could mean the system may need to draft earlier for flood control to capture runoff that occurs earlier. Higher peaks as exhibited in the 2040 scenarios may mean higher risk to spring flooding if the runoff peaks occur very quickly, and the hydrologic shape is more unpredictable than current.

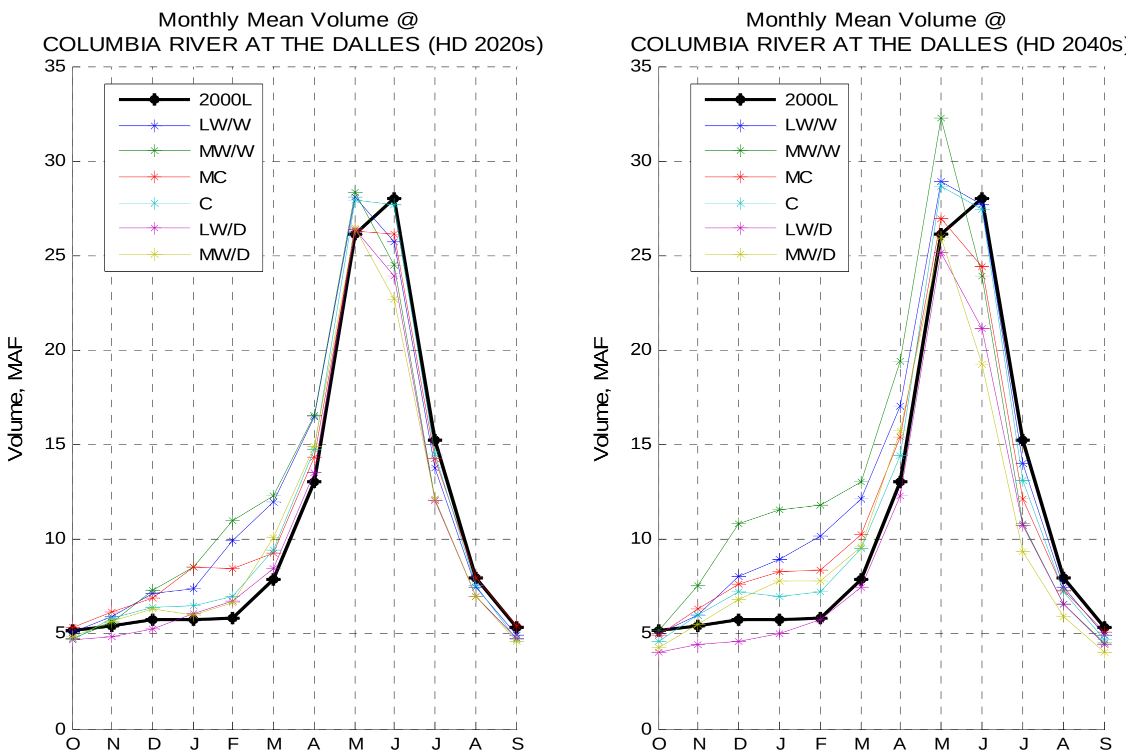

Figure 22. The Dalles Mean Monthly Volume – Hybrid-Delta.

6.2.2 Seasonal Runoff Volume Exceedance – Hybrid-Delta

Figure 23 shows the percent exceedance curve for The Dalles April through August observed volumes for the Hybrid-Delta scenarios as compared to the 2000 Level. The importance of The Dalles seasonal volume is that the flood control requirements for Mica, Arrow, and Grand Coulee are determined by The Dalles April-August runoff volume. Brownlee's flood control is determined by Brownlee's inflow forecast as well as The Dalles forecast.

Nine of the 12 Hybrid-Delta scenarios have just one year where the Apr-Aug volume is greater than the greatest volume from the 2000 Level set. This is only about one percent of all Hybrid-Delta years. The largest volume of the 2000 Level set is 132,950 kaf. The maximum volume from the 2020 and 2040 Hybrid-Delta scenarios is 151,634 kaf and 156,022 kaf respectively, which approximately 17% greater than the highest volume in the 2000 Level set. It is reasonable that this volume could occur because it is still less than that of the recent historical high 1894 event volume which was estimated at 165,000 kaf.

In general, the Hybrid-Delta scenarios volumes are generally lower than the 2000 Level. While the seasonal volumes are generally less than the 2000 Level, the impact to the projects which are dependent on The Dalles volumes (Mica, Arrow, Grand Coulee, and Brownlee) vary based on each project's storage reservation diagrams and are discussed in their respective sections. With generally less seasonal volume in climate change at The Dalles, the system would tend to draft less for flood control.

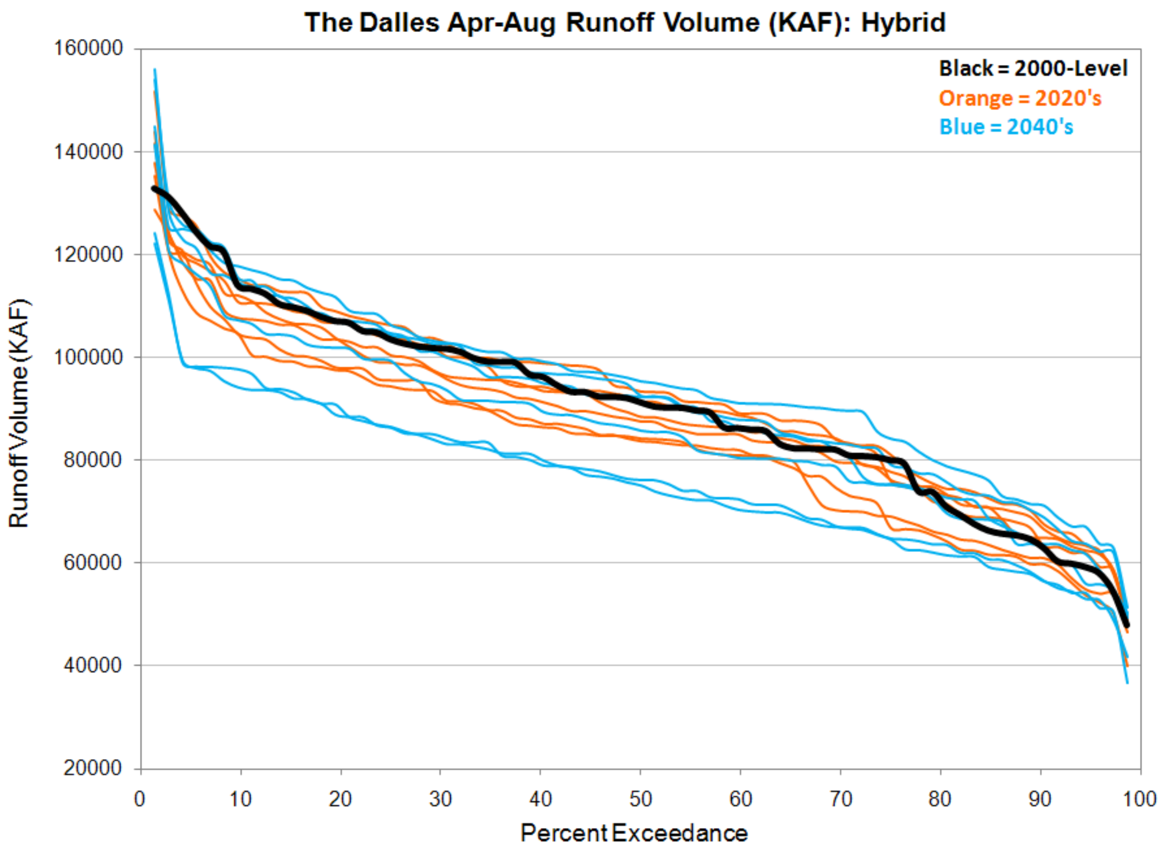

Figure 23. The Dalles Apr-Aug Runoff Volume Exceedance-Hybrid-Delta.

6.2.3 Seasonal Runoff Volume, Ten-Year Rolling Average – Transient

Figure 24 shows the ten-year rolling average April through August runoff volumes for the Transient scenarios. The median of the Transient scenarios is shown with a linear trend line of the median curve. Over the 70-year period, there is a decline of the ensemble median April through August runoff volume of approximately 10%. Impacts to flood control for Mica, Arrow, Grand Coulee, and Brownlee are discussed in their respective sections.

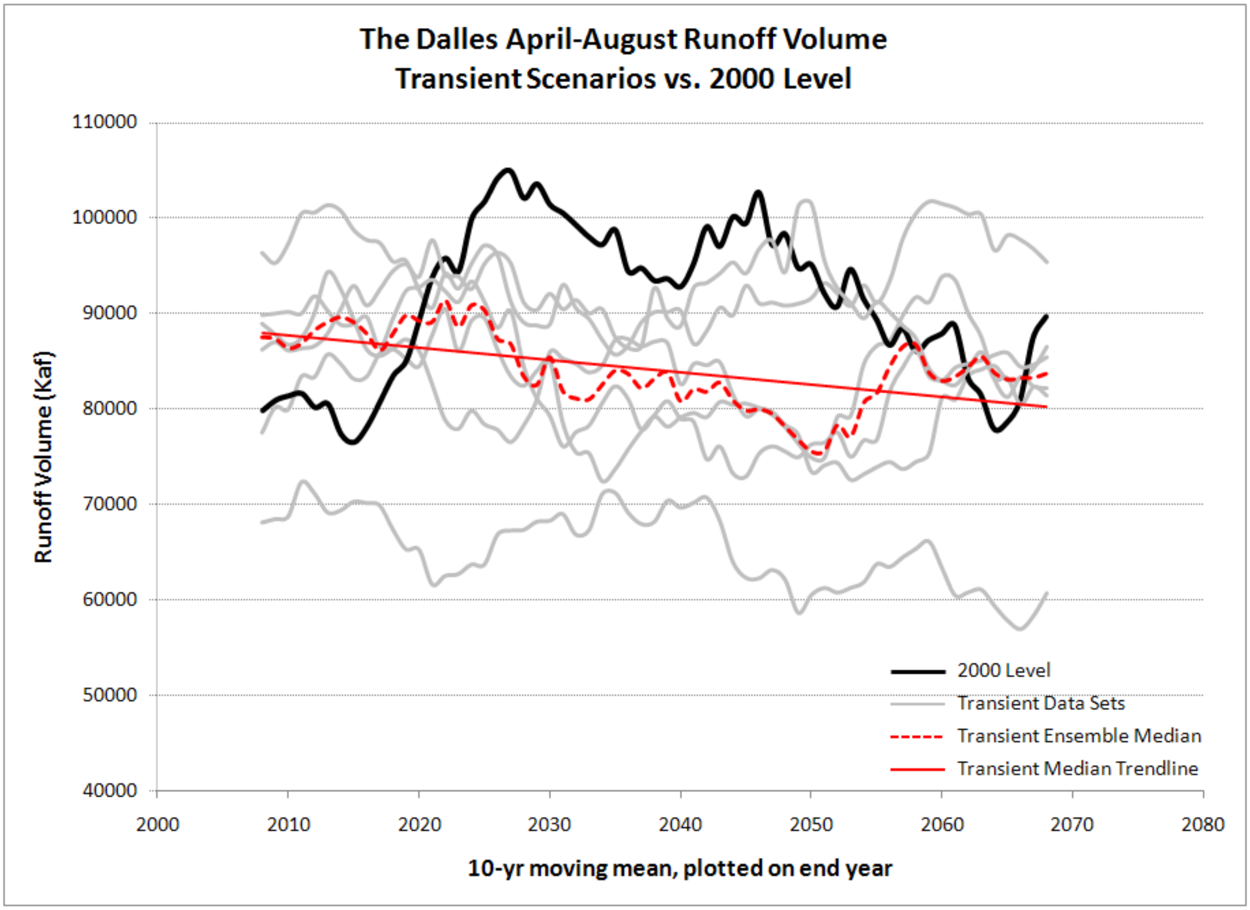

Figure 24. The Dalles Apr-Aug Runoff Volume Rolling Average – Transient.

6.2.4 Seasonal Runoff Volume Averages: Apr-Aug vs. Mar-Jul

The Dalles April through August runoff volume forecasts are used with SRDs for Mica, Arrow, Grand Coulee and Brownlee in determining the flood control requirements at these projects. The observation of the effects of climate change based on The Dalles data is that runoff occurs earlier than historically as shown in the 2000 Level data. To evaluate the earlier runoff volume, March through July runoff volumes were calculated for all the climate change scenarios as well as for the 2000 Level data to see how they differ from the April through August runoff volumes that are currently being used for calculating flood control requirements. In addition, comparing the earlier timeframe March through July runoff volumes to the currently used April through August runoff volumes was also completed to evaluate if the March through July runoff might be used for calculating flood control requirements instead of April through August period to account for the effects of climate change.

Figure 25 and Figure 26 shows the average April through August and March through July seasonal volumes at The Dalles Dam for the Hybrid-Delta 2020 and Hybrid-Delta 2040 scenarios, respectively. For the 2020 Hybrid-Delta sets, there are climate change scenarios where the April through August volume is less than that from the 2000 Level with an average of 5% less. In addition, there are two scenarios where the 2020 Hybrid-Delta sets are greater, by an average of 1.5%. In general, there is less April through August runoff volume in the climate change scenarios than in the 2000 Level.

Comparing the April through August, to the March through July volumes, the March through July volume is less than the April through August volume in the 2000 Level set, whereas in the climate change scenarios, the March through July volumes are greater. This is reflective of the higher March runoff in the climate change sets. Table 8 shows the differences and the percent differences between the two seasonal volumes. The increase in the March through July volumes may indicate that the system flood control projects may need to be at their maximum flood control drafts earlier for system flood control with climate change.

Table 8 shows the differences and the percent differences between the two seasonal volumes.

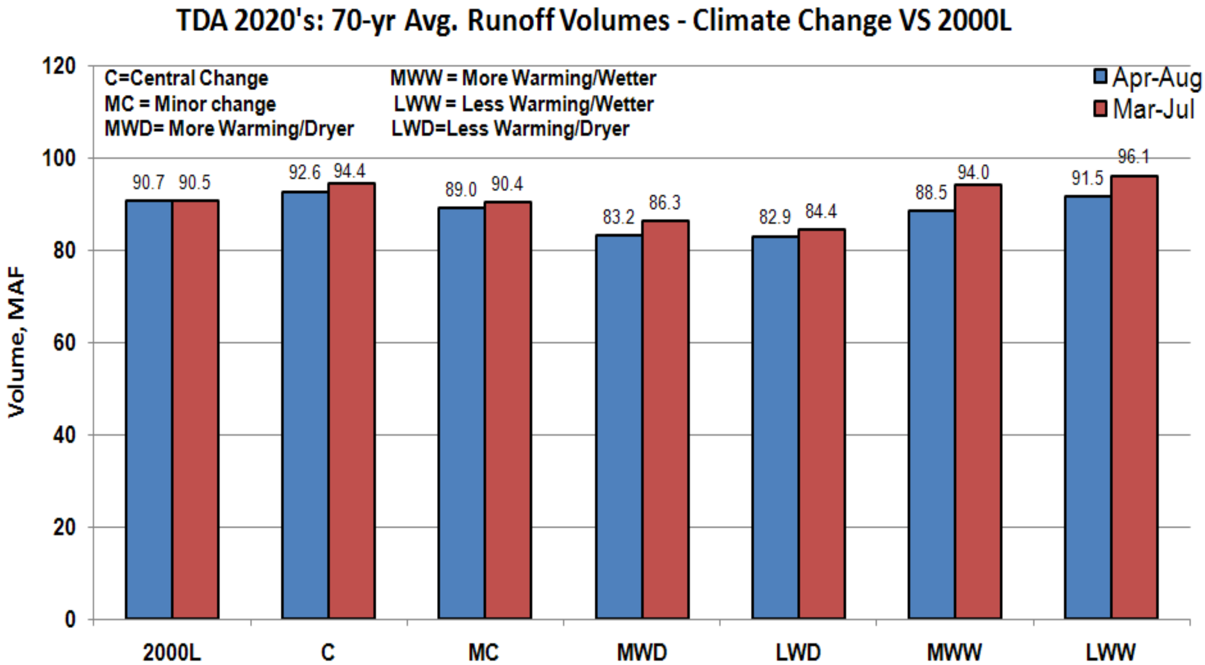

Figure 25. The Dalles Apr-Aug and Mar-Jul Runoff Volume (in kaf) – Hybrid-Delta 2020s.

Table 8. The Dalles Apr-Aug VS Mar-Jul Runoff Volume – Hybrid-Delta 2020s.

Hybrid 2020's				
Scenario	Apr-Aug (kaf)	Mar-Jul (kaf)	Mar-Jul minus Apr-Aug	Percent difference
2000L	90.7	90.5	-0.2	-0.2%
C	92.6	94.4	1.8	1.9%
MC	89	90.4	1.4	1.6%
MWD	83.2	86.3	3.1	3.7%
LWD	82.9	84.4	1.5	1.8%
MWW	88.5	94	5.5	6.2%
LWW	91.5	96.1	4.6	5.0%

As shown on Figure 26, for the 2040s there are three scenarios where the April through August volume is less than that of the 2000 Level with an average of 12.3% less, and three scenarios where it is greater, with an average of 2.5% greater.

Also as shown on Figure 26, compared to the April August volumes, the March through July volume is lower in the 2000 Level set, but higher in the climate change scenarios (similar to the 2020s). This is reflective of the higher March runoff volumes in the climate change sets.

Table 9 shows the differences and the percent differences between the two seasonal volumes. Similar to the 2020s, the increase in the March through July volumes may indicate that the system flood control projects may need to be at their maximum flood control drafts earlier for system flood control with climate change.

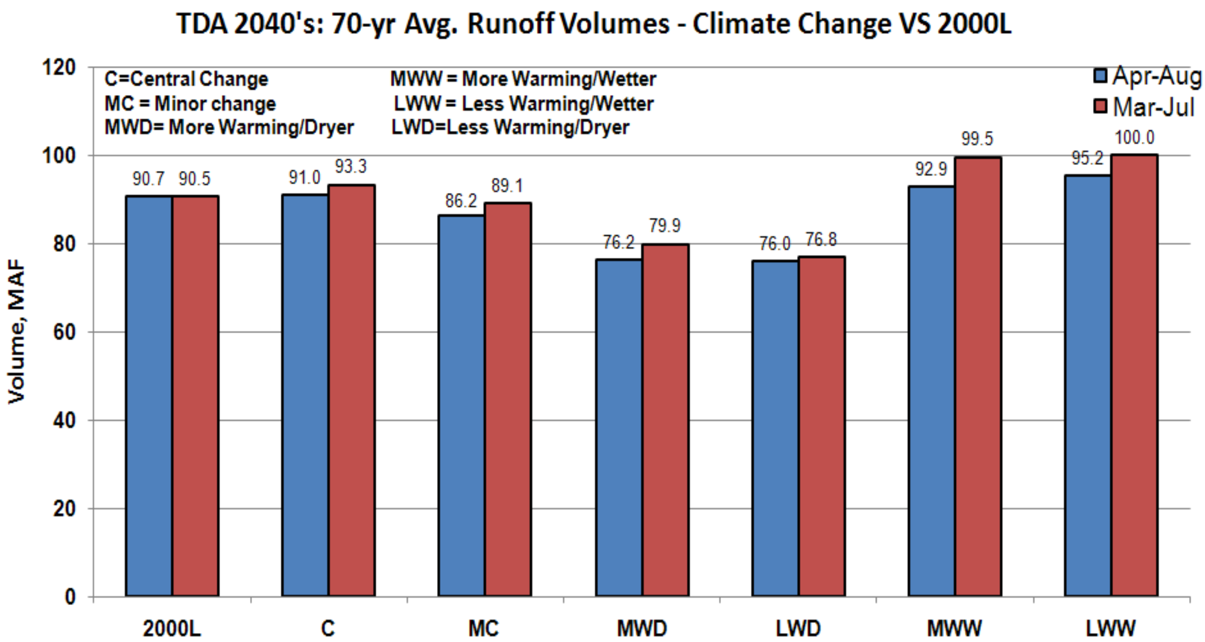

Figure 26. The Dalles Apr-Aug VS Mar-Jul Runoff Volume – Hybrid-Delta 2040s.

Table 9. The Dalles Apr-Aug VS Mar-Jul Runoff Volume – Hybrid-Delta 2040s.

Hybrid 2040's				
Scenario	Apr-Aug (kaf)	Mar-Jul (kaf)	Mar-Jul minus Apr-Aug	Percent difference
2000L	90.7	90.5	-0.2	-0.2%
C	91	93.3	2.3	2.5%
MC	86.2	89.1	2.9	3.4%
MWD	76.2	79.9	3.7	4.9%
LWD	76	76.8	0.8	1.1%
MWW	92.9	99.5	6.6	7.1%
LWW	95.2	100	4.8	5.0%

6.2.5 The Dalles Summary

Monthly average runoff volumes show higher winter volumes. Higher winter volumes could mean more risk for winter flood events. Monthly average peaks shift from June to May. A shift of peak volume from June to May could mean the system may need to draft earlier for flood control to capture runoff that occurs earlier. March through July volumes are greater than April-August volumes in the climate change scenarios but about the same in the 2000 Level data. With climate change, the increase in the March through July volumes may indicate that the system flood control projects may need to be at their maximum flood control drafts earlier for system flood control. Nearly all (99%)of the April through August seasonal runoff volumes from the climate change scenarios are less than the maximum volume from the 2000 Level data set. With generally less April through August runoff volume in climate change at The Dalles, the system would generally draft less for flood control. Higher monthly peaks as exhibited in the 2040 scenarios may mean higher risk to spring flooding if the runoff peak occurs very quickly, and if forecasting the hydrologic of the flood event is more unpredictable than in current conditions. Note that daily time step modeling is necessary to better assess peak runoff and flood risk. The Transient scenarios show that over the 70-year period, there is a decline of the ensemble median April through August runoff volume of approximately 10%.

The effects of The Dalles runoff volumes on Mica, Arrow, Grand Coulee, and Brownlee flood control requirements are addressed in the following respective sections.

6.3 Mica

Mica project is located on the Upper Columbia River in Canada. Mica's flood control curve is determined by its SRD and The Dalles April through August runoff volume. Unlike U.S. flood control projects, only a portion of the reservoir is dedicated to flood control. The total space in the reservoir is 12,000 kaf, however only 7,000 kaf is Treaty space. Under normal operations per the Columbia River Treaty (Treaty), the U.S. has rights to 7,000 kaf of reservoir space for power and 4,080 kaf for (on call) flood control space. The U.S. may request additional space, up to the full 12,000 kaf if flood control needs warrant such a request, however this was not considered in this report (a request of this type has not been used in the 40+ year life of the Treaty). For this report, the reservoir is presented in terms of Treaty space. Mica has system flood control responsibilities for the Columbia River system as measured at The Dalles and flood control at Revelstoke and at the city of Trail, (which is located downstream of Arrow, see Figure 2).

This section compares climate change scenarios to the 2000 Level scenario using the following methods and figures. For the Hybrid-Delta scenarios: forecast flood control storage exceedance curves for each month January through April, and box-whisker plots of the April 30th flood control elevations. For the Transient scenarios: the ten-year moving average of the April 30th flood control elevations. A summary of climate change impacts to Mica's flood control curve is also provided.

6.3.1 Flood Control Storage Exceedance – Hybrid-Delta

Figure 27 shows Mica's flood control storage percent exceedance graphs for each month, January through April for the Hybrid-Delta scenarios based on forecast runoff volumes at The Dalles. Based on Mica's SRD (and assuming full pool is 7,000 kaf based on the Treaty), Mica drafts to a storage content of 2,920 kaf (4,080 kaf from Treaty full pool) by the end of March when The Dalles forecast volume is greater than or equal to 80,000 kaf and drafts to a storage content of 6,610 kaf (390 kaf from full pool) in each month January through April when The Dalles volume is less than or equal to 62,000 kaf. Looking at the observed runoff volume exceedance graph for The Dalles (Figure 9), 80,000 kaf is exceeded about 70% of the time in the 2000 Level scenario (thick black line). On Figure 13, Mica flood control exceedance curve for the 2000 Level is essentially constant at 2,920 kaf of storage between the 28% and 100% exceedances in March and April. When ranking flood control curves in terms of reservoir storage in kaf from high to low, the first 20 years or (28% of the 70 years) exceeded 2,920 kaf and the remaining 50 years were at 2,920 kaf, explaining why the curve is relatively flat for percent exceedance values 28% and greater.

While The Dalles shows generally less April through August runoff volume with climate change, Mica's flood control shows some scenarios with consistently higher curves, and some scenarios with consistently lower curves than the 2000 Level because Mica's flood control varies the most when the Dalles volumes are between 62,000 and 80,000 kaf, which are considered low water years (71-yr average is 92,700 kaf). Climate change scenario curves above the 2000 Level curve reflect drier years and lesser flood control drafts, and scenarios below the 2000 Level curve reflect wetter years and deeper drafts.

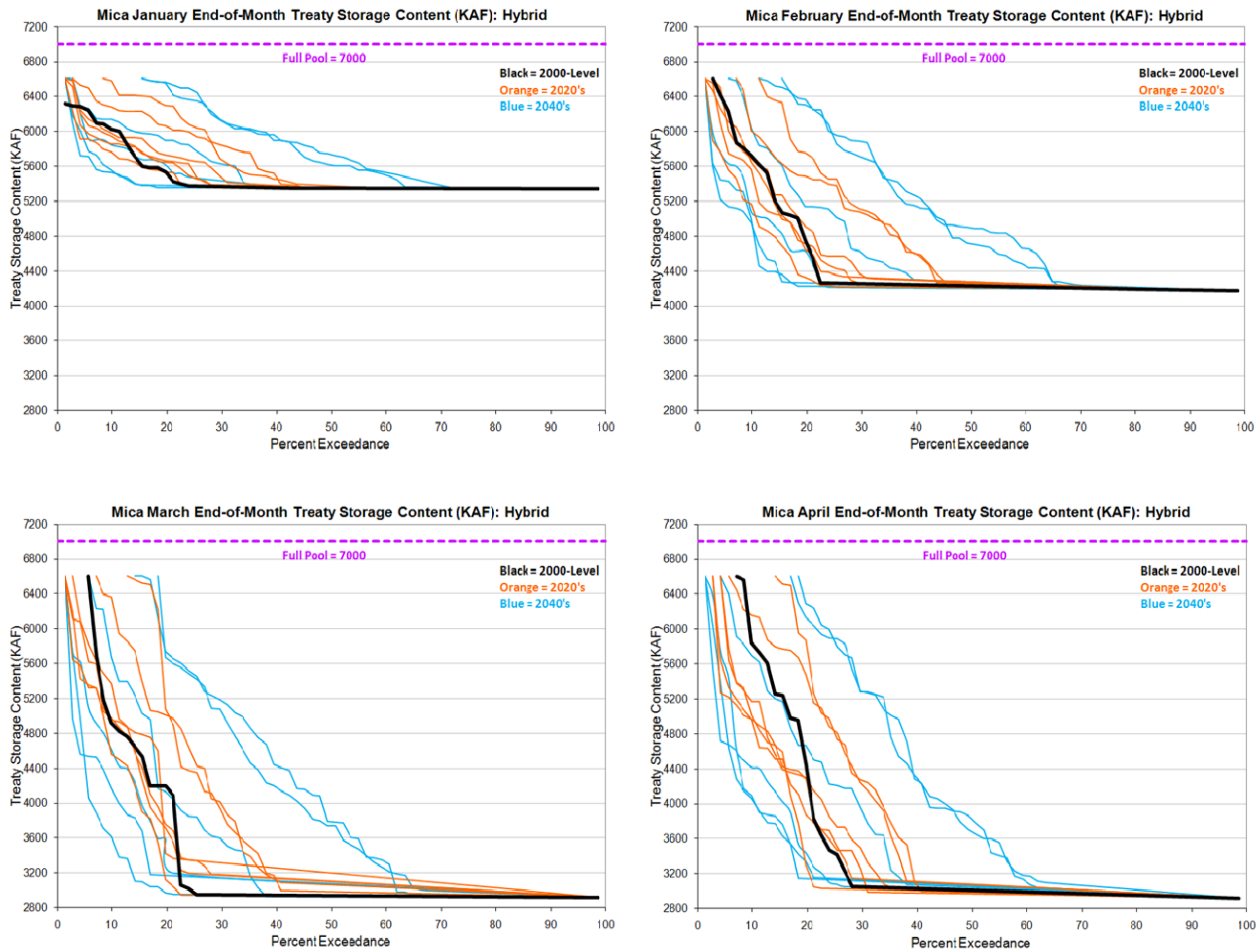

Figure 27. Mica Flood Control Storage Exceedance – Hybrid-Delta.

6.3.2 Flood Control April 30th Elevations Comparisons – Hybrid-Delta

The following two box-whisker plots show the April 30th flood control elevation comparison between the 2000 Level and the 2020 and 2040 Hybrid-Delta scenarios, respectively. In the 2020 scenarios, data is skewed toward the maximum flood control draft as in the 2000 Level. The median, 50 percentile, and minimum are the same value because Mica's lowest flood control is elevation (El.) 2428.4 ft (its maximum flood control space of 4,080 kaf, based on the 7000 kaf Treaty full) about 72% of the time. Mica's highest pool elevation is El. 2466.3 ft (minimum draft of 390 kaf) in the very lowest water years and is the same in all scenarios. There is a wider spread between the 50 and 75 percentile in the drier MWD and LWD scenarios than in the 2000 Level resulting in higher average elevations. The average elevation for the drier MWD scenario is 3.8 feet higher than that for the 2000 Level. The average elevation for the wetter LWW scenario is about 2 feet lower than that for the 2000 Level. For the LWW scenario, the reservoir is at its maximum draft at least 75% of the time which is why only the whisker between the 75 and 100 percentile shows. For the 2040 scenarios the drier MWD and LWD scenarios have a much wider spread between the 25 and 75 percentile values than the 2000 Level resulting in higher average elevations. The average elevation for these drier scenarios is about 8 feet higher than that for the 2000 Level. To put it into perspective, 8 feet is equivalent to 757 kaf, or 12,700 cubic feet per second cfs over 30 days. For the wetter C and LWW scenarios, the average elevations are about 3.5 feet lower than for the 2000 Level.

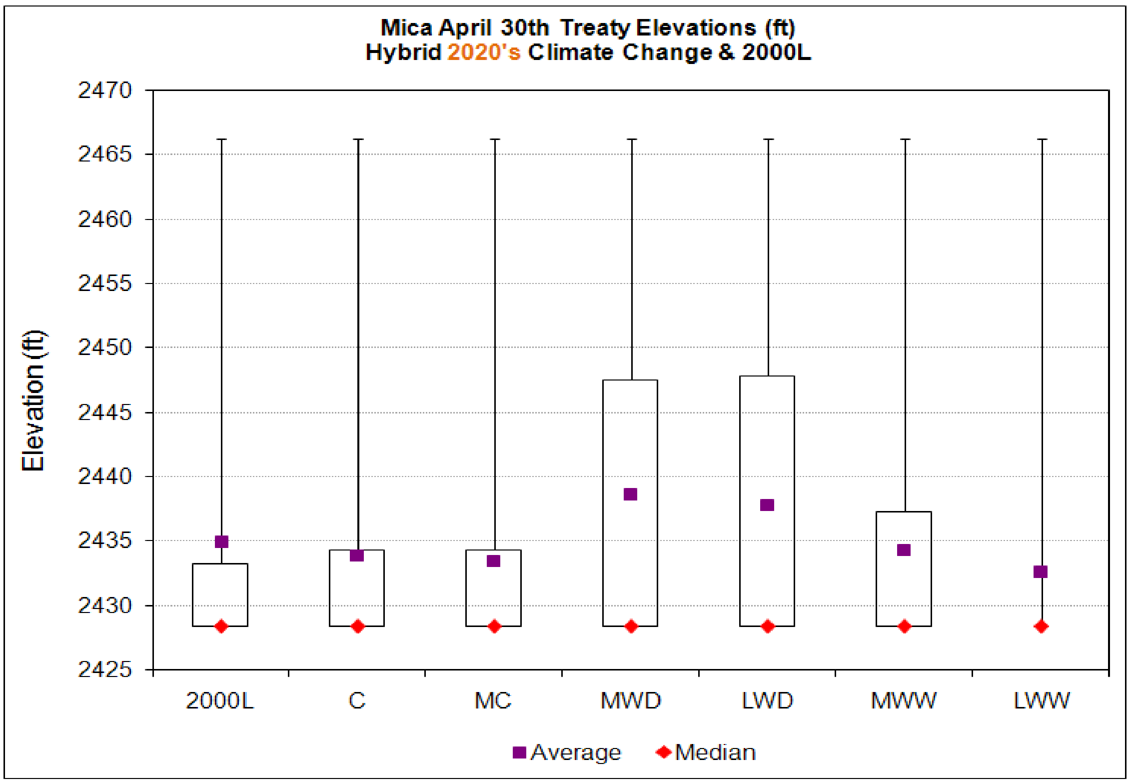

Figure 28. Mica April 30th Treaty Elevations – Hybrid-Delta 2020s.

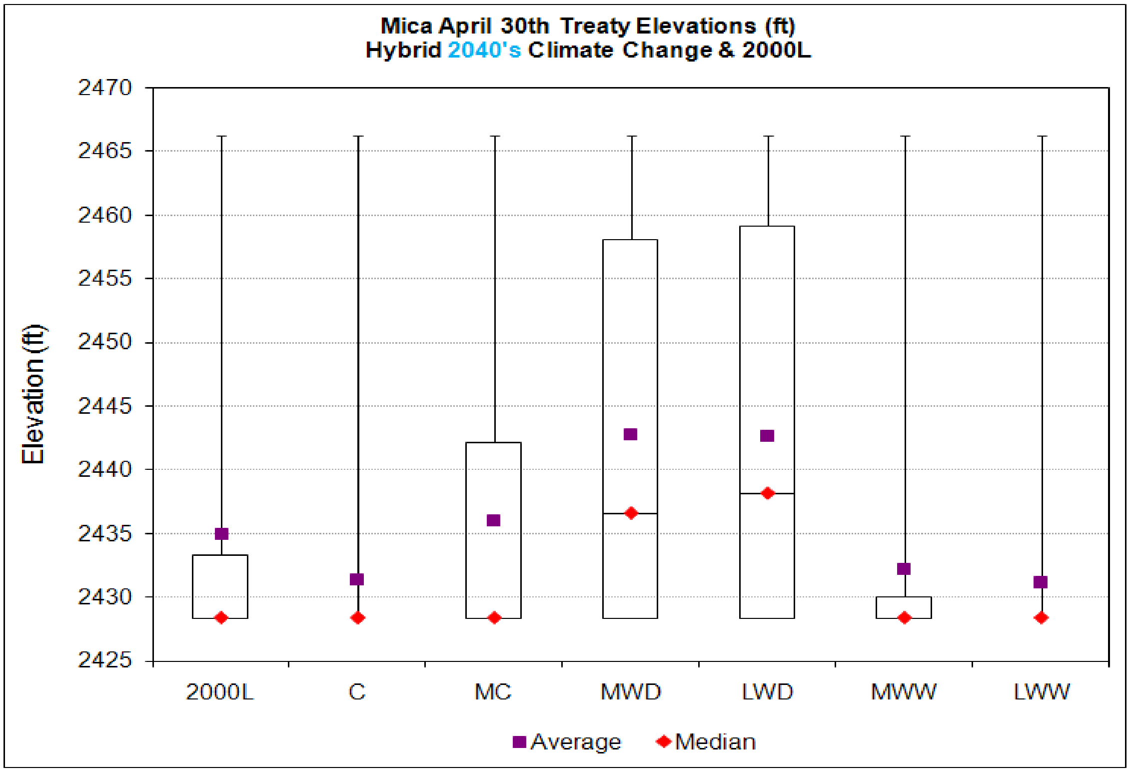

Figure 29. Mica April 30th Treaty Elevations – Hybrid-Delta 2040s.

6.3.3 Flood Control April 30th Elevations Comparisons – Transient

Figure 30 below, shows the April 30 flood control elevation comparisons between the Transient and 2000 Level scenarios, the Transient ensemble median and its linear trend line. Over the 70-year period, the ensemble median flood control elevations increase approximately two feet, or about 197 kaf, which is reflective of the decrease in The Dalles ensemble median runoff volume trend.

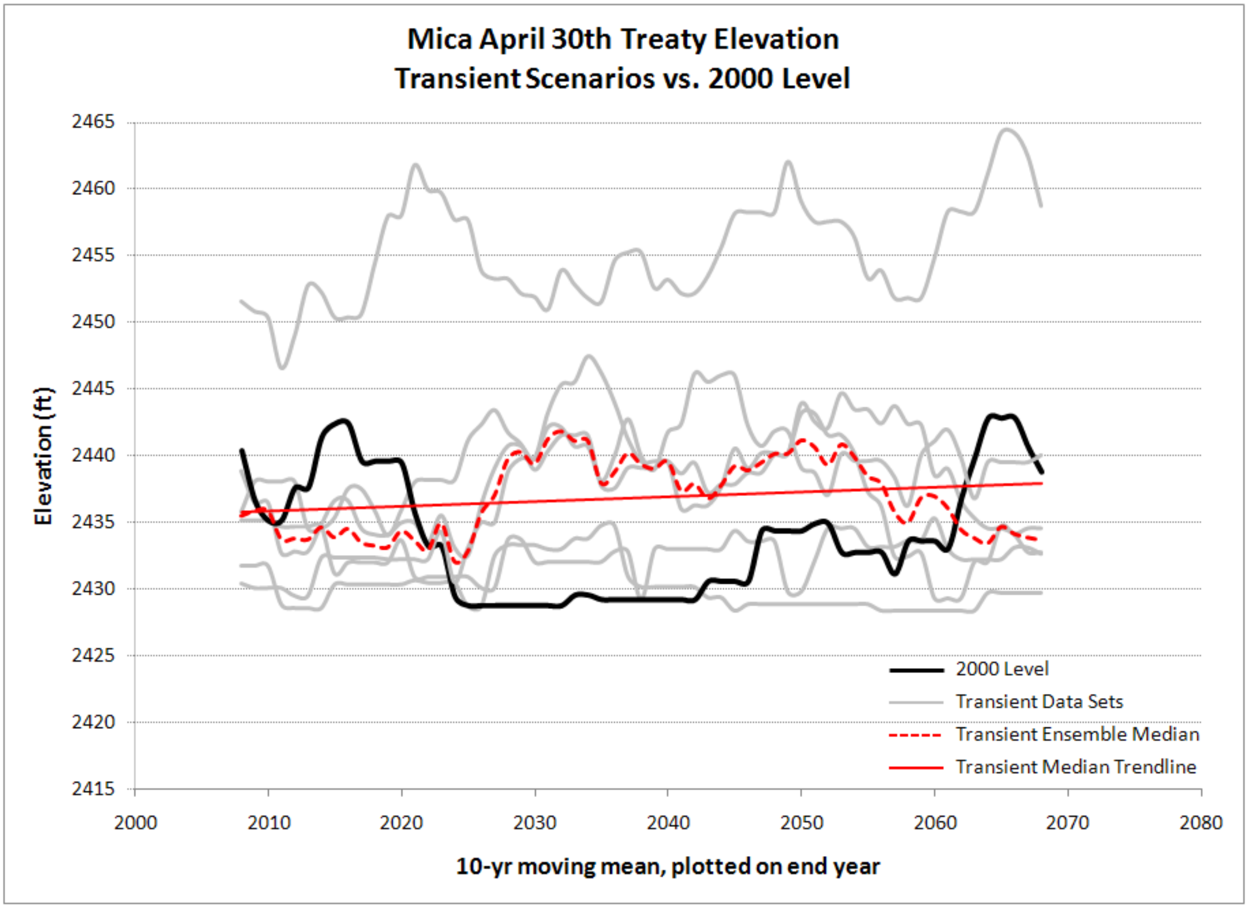

Figure 30. Mica April 30th Treaty Elevations Rolling Average – Transient.

6.3.4 Mica Summary

Mica flood control requirements are based on The Dalles runoff volume forecasts and by its SRD. A general statement on what climate change means to flood control at Mica is not readily apparent. The Hybrid-Delta scenarios show that there are some curves generally higher due to drier climate change scenarios and some curves generally lower due to wetter climate change scenarios, than that of the 2000 Level, therefore what climate change means to flood control at Mica is dependent on which climate change scenario is being examined. The average April 30th elevations are split where there are some higher and some lower than that of the 2000 Level, with the maximum differences (in average values) of eight feet higher in the driest scenario and three feet lower in the wettest scenario. Over the 70-year period, the ensemble median flood control elevation increase by approximately two feet, or about 197 kaf, which is reflective of the decrease in The Dalles ensemble median runoff volume trend.

6.4 Arrow

Arrow project (Hugh Keenleyside dam and Arrow Lakes) is located on the Upper Columbia River in Canada. As with Mica Dam, Arrow's flood control curve is determined by its SRD and The Dalles April through August runoff volume. Unlike the U.S. flood control projects addressed in this report, only a portion of the storage space in the reservoir is dedicated to flood control. The U.S. has rights to 7,100 kaf of reservoir space for power and 3,600 kaf of this is for flood control per the Treaty under normal flood control operations (the U.S. may ask for additional space up to the 7,100 kaf limit to control major floods). The total space in the reservoir is 7,100 kaf (excluding an additional 262 kaf deemed "recallable" storage). Arrow has system flood control responsibilities for the Columbia River system as measured at The Dalles as well as a local flood control components in Canada at Trail.

This section compares climate change scenarios to the 2000 Level scenario using the following methods and figures. For the Hybrid-Delta scenarios: forecast flood control storage exceedance curves for each month January through April, and box-whisker plots of the April 30th flood control elevations. For the Transient scenarios: the ten-year moving average of the April 30th flood control elevations. A summary of climate change impacts to Arrow's flood control curve is also provided.

6.4.1 Flood Control Storage Exceedance – Hybrid-Delta

Figure 17 shows Arrow's flood control storage percent exceedance graphs for each month, January through April for the Hybrid-Delta scenarios based on The Dalles forecast volumes. Based on Arrow's SRD, Arrow drafts to storage content of 3,500 kaf (3,600 kaf from full) at the end of March when The Dalles forecast volume is greater than or equal to 80,000 kaf and to a storage content of 6,390 kaf (710 kaf from full) each month, January through April when The Dalles forecast is less than 64,000 kaf. Looking at the observed runoff volume exceedance graph for The Dalles (Figure 9), 80,000 kaf is exceeded about 70% of the time in the 2000 Level scenario. On Figure 17, Arrow's flood control exceedance curve for the 2000 Level is essentially constant at 3,500 kaf of storage, between the 28% and 100% exceedances. When ranking flood control curves in terms of reservoir storage in kaf from high to low, the first 20 years or (28% of the 70 years) exceeded 3,500 kaf and the remaining 50 years were at 3,500 kaf, explaining why the curve is unchanged after 28% exceedance.

While The Dalles show generally less April through August volume with climate change, Arrow flood control shows some scenarios with consistently higher curves, and some scenarios with consistently lower curves than the 2000 Level because Arrow's flood control varies the most when the Dalles volumes are between 64,000 and 80,000 kaf, which are considered low water years (71-yr average is 92,700 kaf). Climate change scenario curves above the 2000 Level curve reflect drier years and lesser flood control drafts and scenarios below the 2000 Level curve reflect wetter years and deeper drafts.

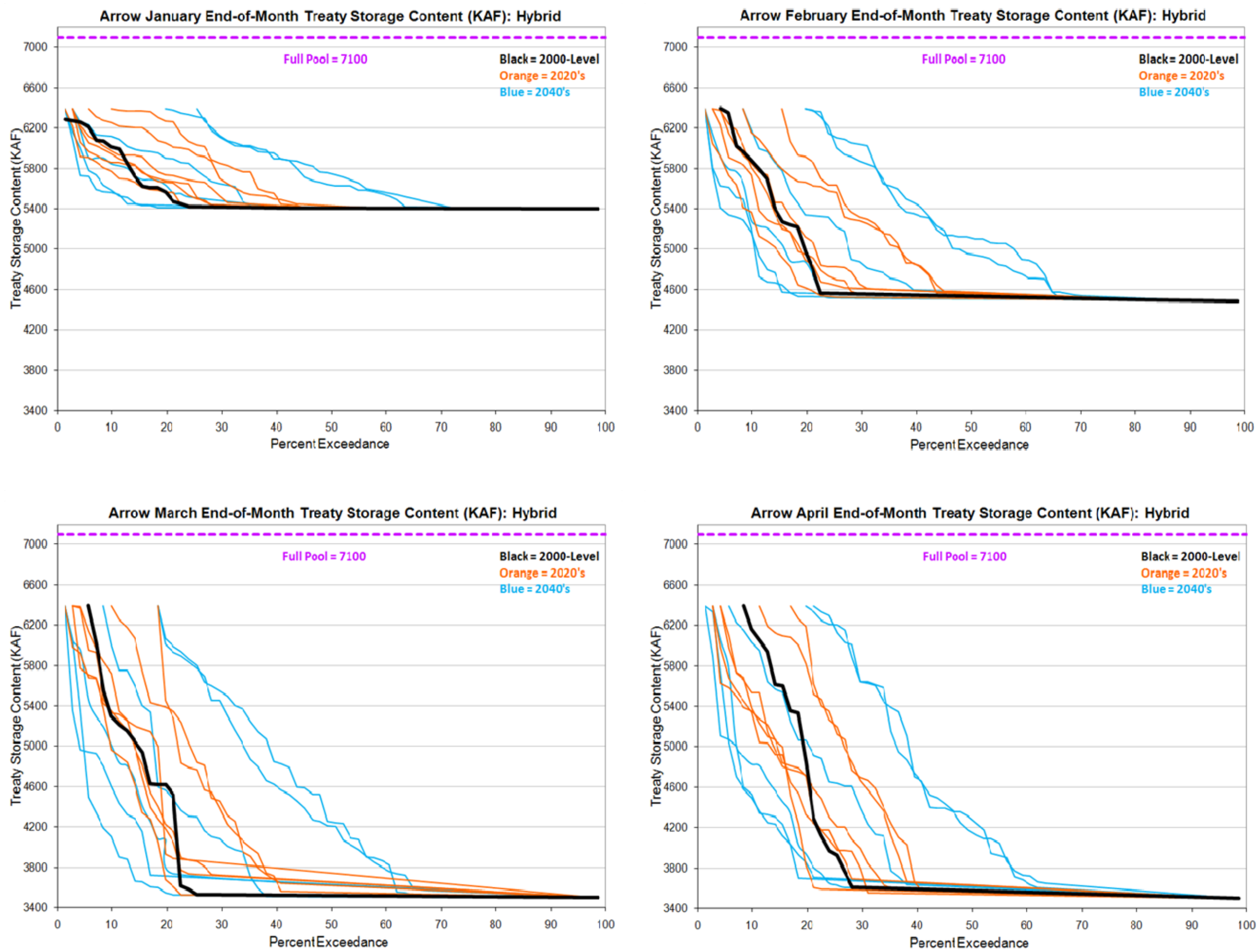

Figure 31. ARDB Flood Control Storage Exceedance – Hybrid-Delta.

6.4.2 Flood Control April 30th Elevations Comparisons – Hybrid-Delta

The following two figures show the April 30th flood control elevation comparison between the 2000 Level and the 2020 and 2040 Hybrid-Delta scenarios respectively. In the 2020 and 2040 scenarios, the median, 50 percentile, and minimum are the same value because Arrow's lowest flood control is El. 1414 ft (its maximum flood control draft of 3,600 kaf) and occurs about 72% of the time. Arrow's highest pool elevation is El. 1438.5 ft (minimum flood control draft of 710 kaf) in the very lowest water years and is the same in all scenarios. In the

2020 scenarios there is a wider spread between the 50 to 75 percentiles in the MWD and LWD (drier scenarios) than in the 2000 Level and the other climate change scenarios, resulting in higher average elevations. The average elevation in the drier MWD and LWD scenarios is about 2 feet higher than that of the 2000 Level.

Looking at the 2040s in Figure 19, the drier MWD and LWD scenarios have a much wider spread between the 25 and 75 percentiles than the 2000 Level. The MWD and LWD average elevations are about 5.5 feet higher than that of the 2000 Level. To put it in perspective, the 5.5 feet difference is equivalent to 635 kaf, or 10,700 cfs over 30 days. The wettest scenarios, C and LWW, have no spread indicating that 75% of the values were drafted at the maximum draft. The LWW scenario average elevation is about 2.5 feet lower than that of the 2000 Level scenario.

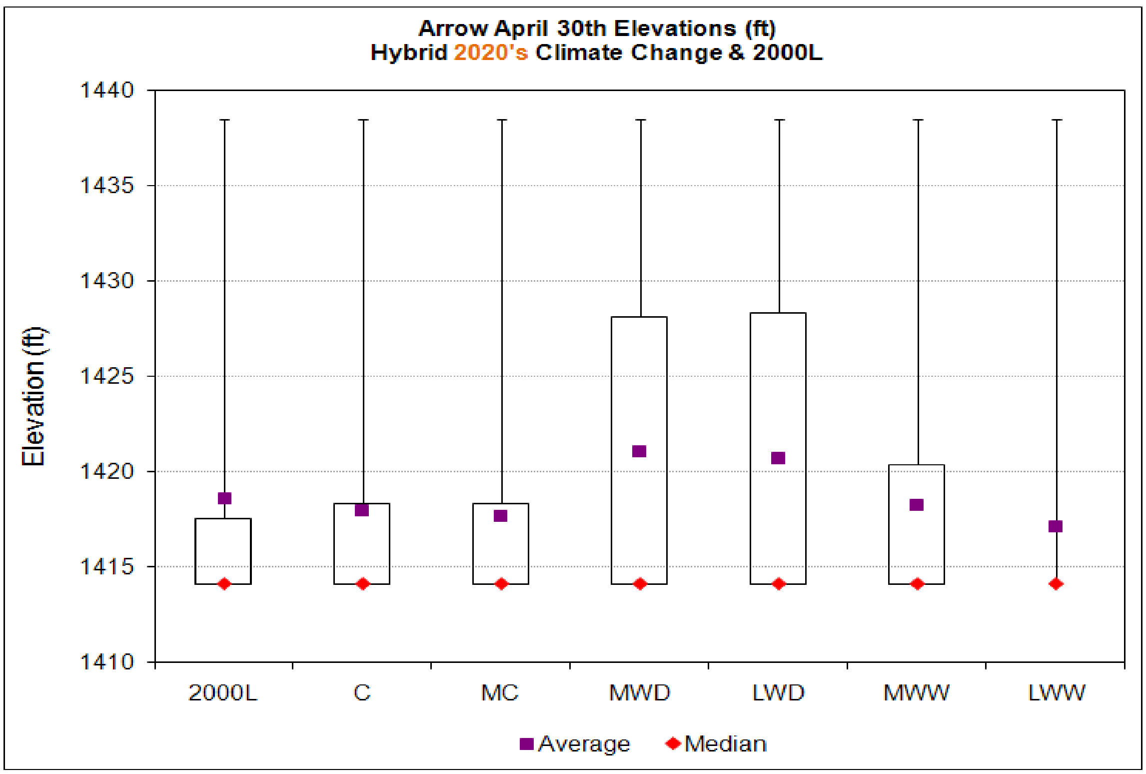

Figure 32. Arrow April 30th Elevations, 2000 Level & Climate Change Scenarios – Hybrid-Delta 2020s.

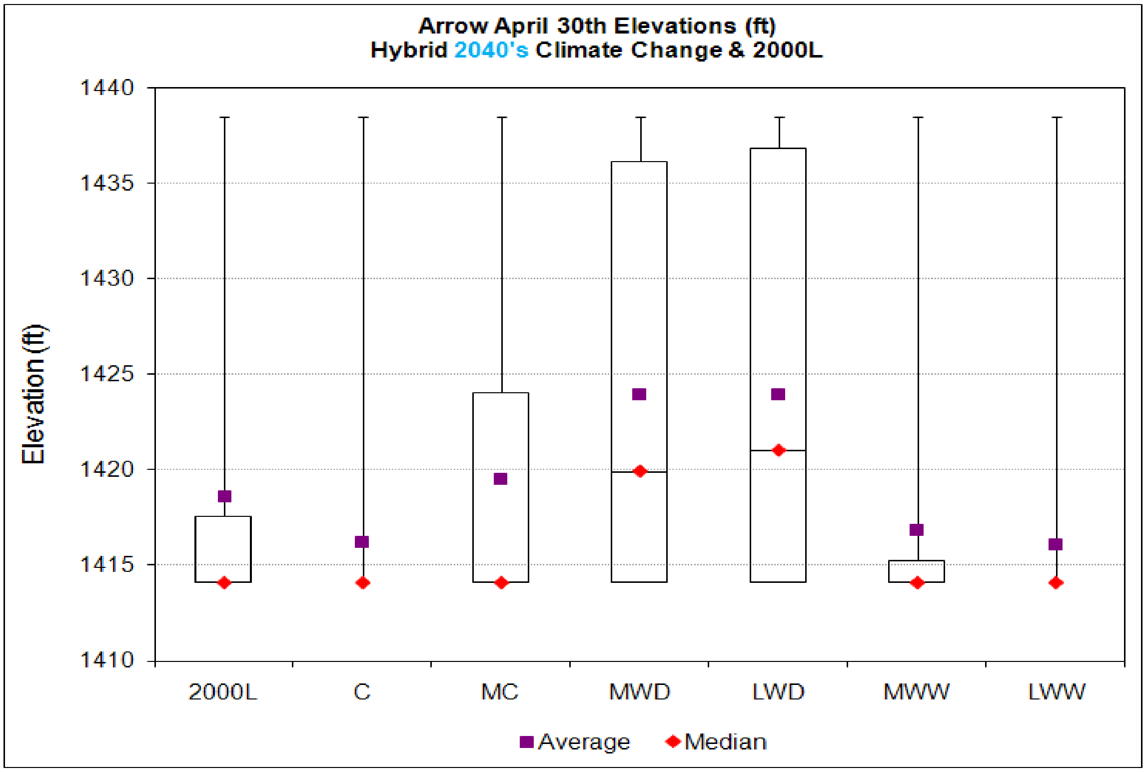

Figure 33. Arrow April 30th Elevations, 2000 Level & Climate Change Scenarios – Hybrid-Delta 2040s.

6.4.3 Flood Control April 30th Elevations Comparisons – Transient

Figure 34 shows the April 30 flood control elevation comparisons between the Transient and 2000 Level scenarios, the Transient ensemble median and its linear trend line. Over the 70-year period, the ensemble median flood control elevations increase approximately two feet, which is reflective of the decrease in The Dalles ensemble median runoff volume trend. This two feet increase of the April 30 flood control elevation, or about 230 kaf, which translates to a slight reduction in flood control space required at Arrow.

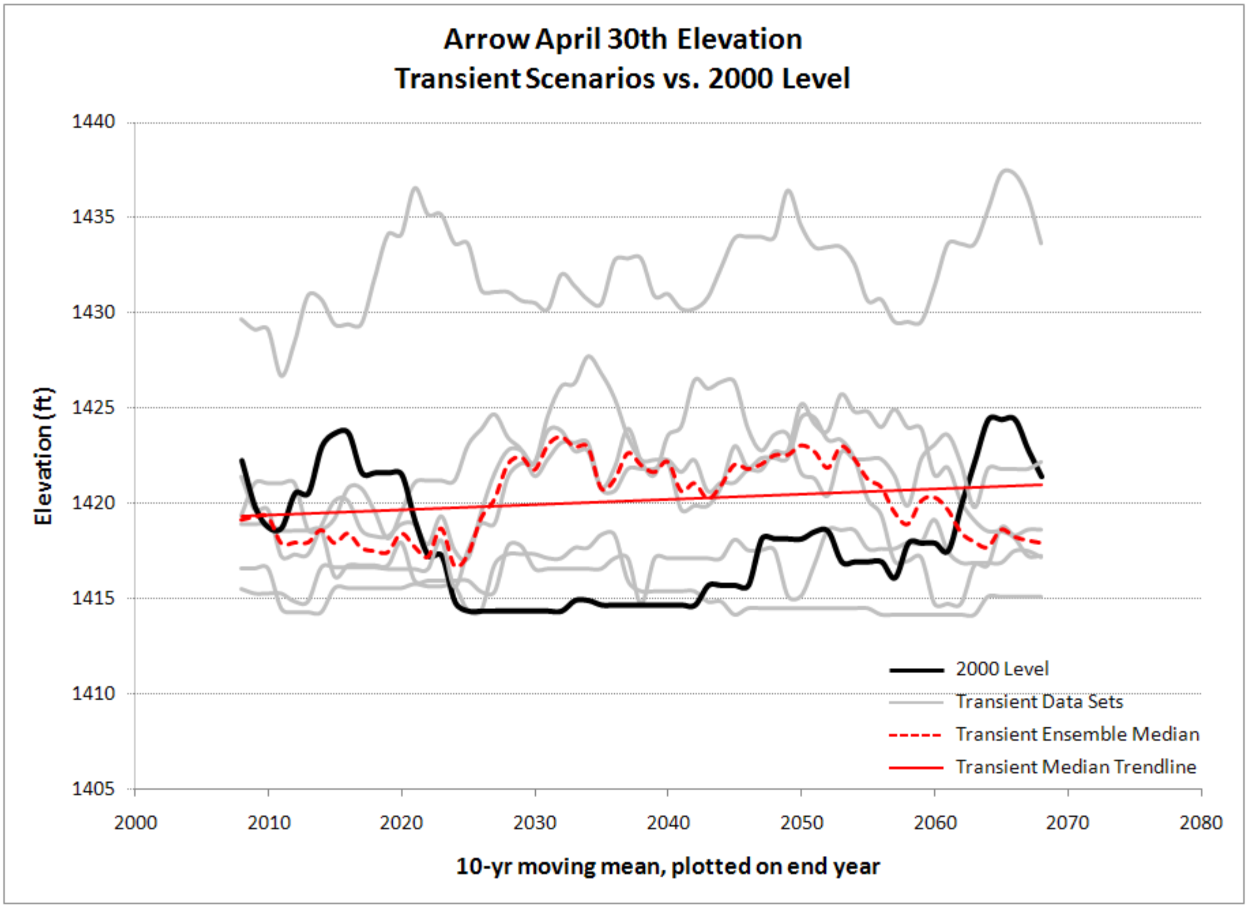

Figure 34. Arrow April 30th Elevations Rolling Average – Transient.

6.4.4 Arrow Summary

Arrow flood control requirements are based on The Dalles runoff volume forecasts. A general statement on what climate change means to flood control at Arrow is not readily apparent. The Hybrid-Delta flood control reservoir content exceedance graphs show that there are some curves generally higher, and some curves generally lower than that of the 2000 Level, so what climate change means to flood control at Arrow is dependent on which climate change scenario is being examined. The average April 30th elevations are split where there are some higher and some lower than that of the 2000 Level, with the maximum differences (in average values) of 5.5 feet higher for the drier scenario and 2.5 feet lower for the wettest scenario. The Transient scenarios show that over the 70-year period, the median flood control elevations increase approximately two feet, or 230 kaf, which is reflective of the decrease in The Dalles ensemble median runoff volume trend.

6.5 Grand Coulee

Grand Coulee project is located on the Middle Columbia River in Washington State. Grand Coulee's flood control curve is determined by its SRD and The Dalles April through August runoff volume minus the drafted flood control space in all projects upstream of The Dalles except Grand Coulee. The maximum draft for flood control space is 5,185 kaf. Grand Coulee is a major reservoir that aids in reducing flood damages for system flood control for the Columbia River, as measured at The Dalles. In addition to flood control, Grand Coulee is also a major project in operating the system for fishery objectives (BiOp, chum operations, etc.) which were assumed in these studies.

This section compares climate change scenarios to the 2000 Level scenario using the following methods and figures. For the Hybrid-Delta scenarios: forecast flood control storage exceedance curves for each month January through April, and box-whisker plots of the April 30th flood control elevations. For the Transient scenarios: the ten-year moving average of the April 30th flood control elevations. A summary of climate change impacts to Grand Coulee's flood control curve is also provided.

6.5.1 Flood Control Storage Exceedance – Hybrid-Delta

Figure 35 shows Grand Coulee's flood control storage percent exceedance graphs for each month, January through April for the Hybrid-Delta scenarios based on The Dalles forecast volumes. Based on Grand Coulee's SRD, Grand Coulee drafts in January only in very large water years, therefore there is no flood control draft requirement in most years in January. Grand Coulee drafts throughout February, March and April and may draft to empty (5,185 kaf from full) by the end of April in very large water years. Grand Coulee must draft to a storage content of 4,648 kaf (537 kaf from full) when The Dalles April through August forecast minus a correction for upstream space is 57,000 kaf.

Looking at the April end-of-month graph, generally, some of the climate change scenarios either stay above or below the 2000 Level curve. Scenarios that stay below the 2000 Level curve reflect generally wetter years causing lower pool levels overall; and those that stay above, reflect drier years allowing higher pool levels.

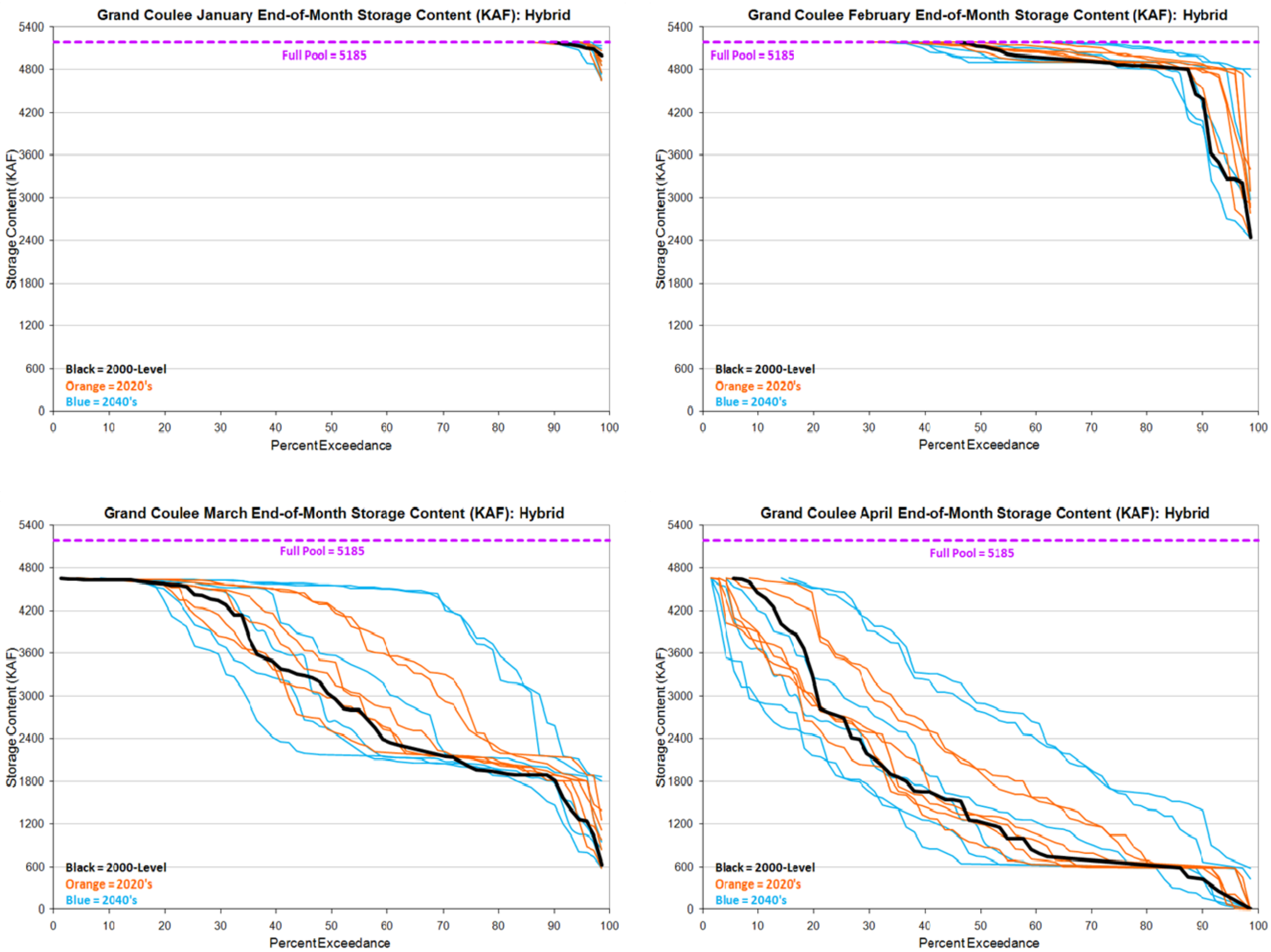

Figure 35. GCL Flood Control Storage Exceedance – Hybrid-Delta.

6.5.2 Flood Control April 30th Elevations Comparisons – Hybrid-Delta

The following two figures show the April 30th flood control elevation comparison between the 2000 Level and the 2020 and 2040 Hybrid-Delta scenarios, respectively. In the 2020 scenarios, Grand Coulee's highest pool elevation is El. 1283.3 ft and lowest pool elevation is El. 1208 ft in all scenarios. The average elevations for the drier MWD and LWD scenarios are about nine feet higher than that of the 2000 Level scenario and about two feet lower for the wetter LWW and C scenarios.

For the 2040 scenarios the drier MWD and LWD scenarios average elevations are about 20 feet higher than that of the 2000 Level, and the lowest elevations are nine to twelve feet higher than the lowest of the 2000 Level. Grand Coulee did not draft to empty in these drier scenarios. The wetter C and LWW scenarios average elevations are about seven feet lower than that of the 2000 Level scenario.

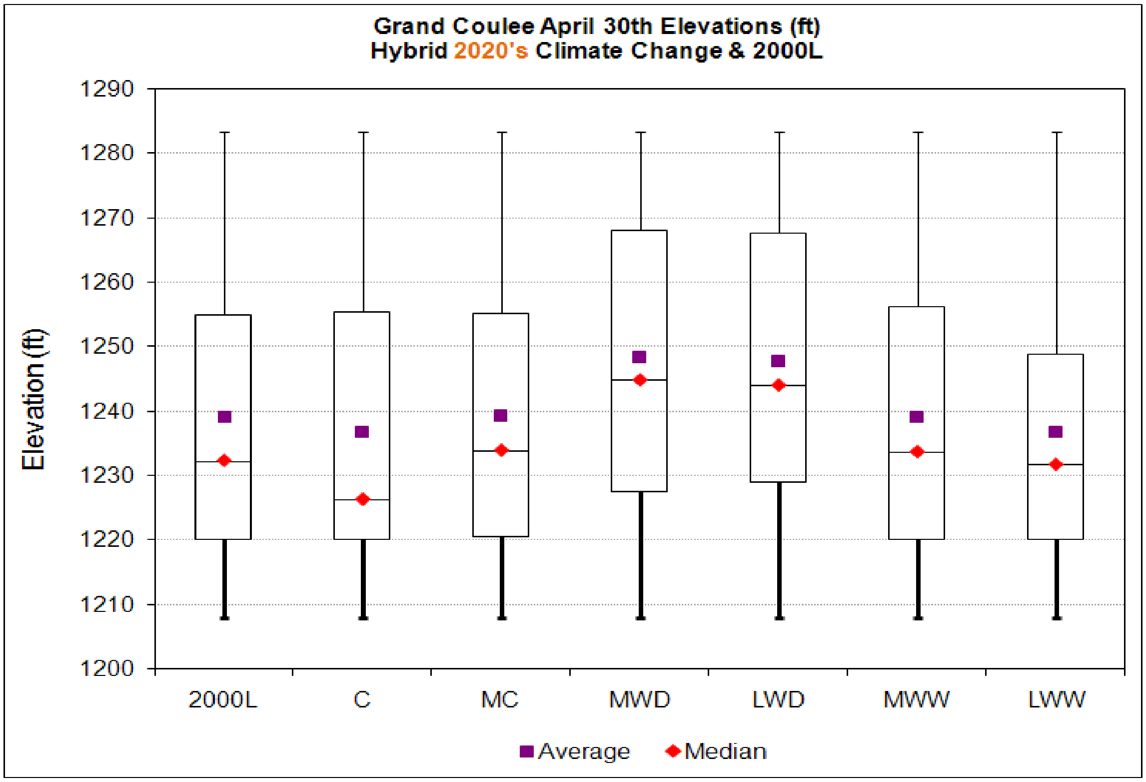

Figure 36. Grand Coulee April 30 Elevations, 2000 Level & Climate Change Scenarios–HD 2020s.

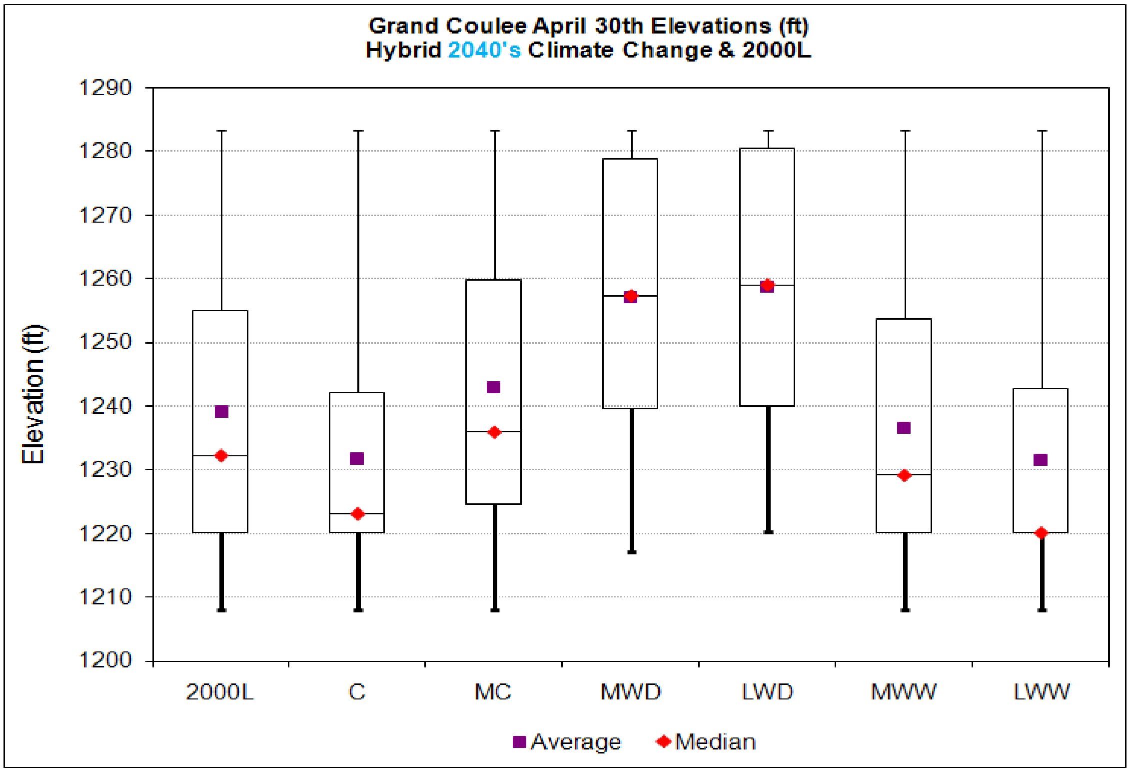

Figure 37. Grand Coulee April 30th Elevations, 2000 Level & Climate Change Scenarios–HD 2040s.

6.5.3 Flood Control April 30th Elevations Comparisons – Transient

Figure 38 shows the April 30 flood control elevation comparisons between the Transient and 2000 Level scenarios, the Transient ensemble median and its linear trend line. Over time, the ensemble median flood control elevations increase approximately thirteen feet from El. 1240 to El. 1253 feet, or about 812 kaf, which is reflective of the decrease in The Dalles ensemble median runoff volume trend.

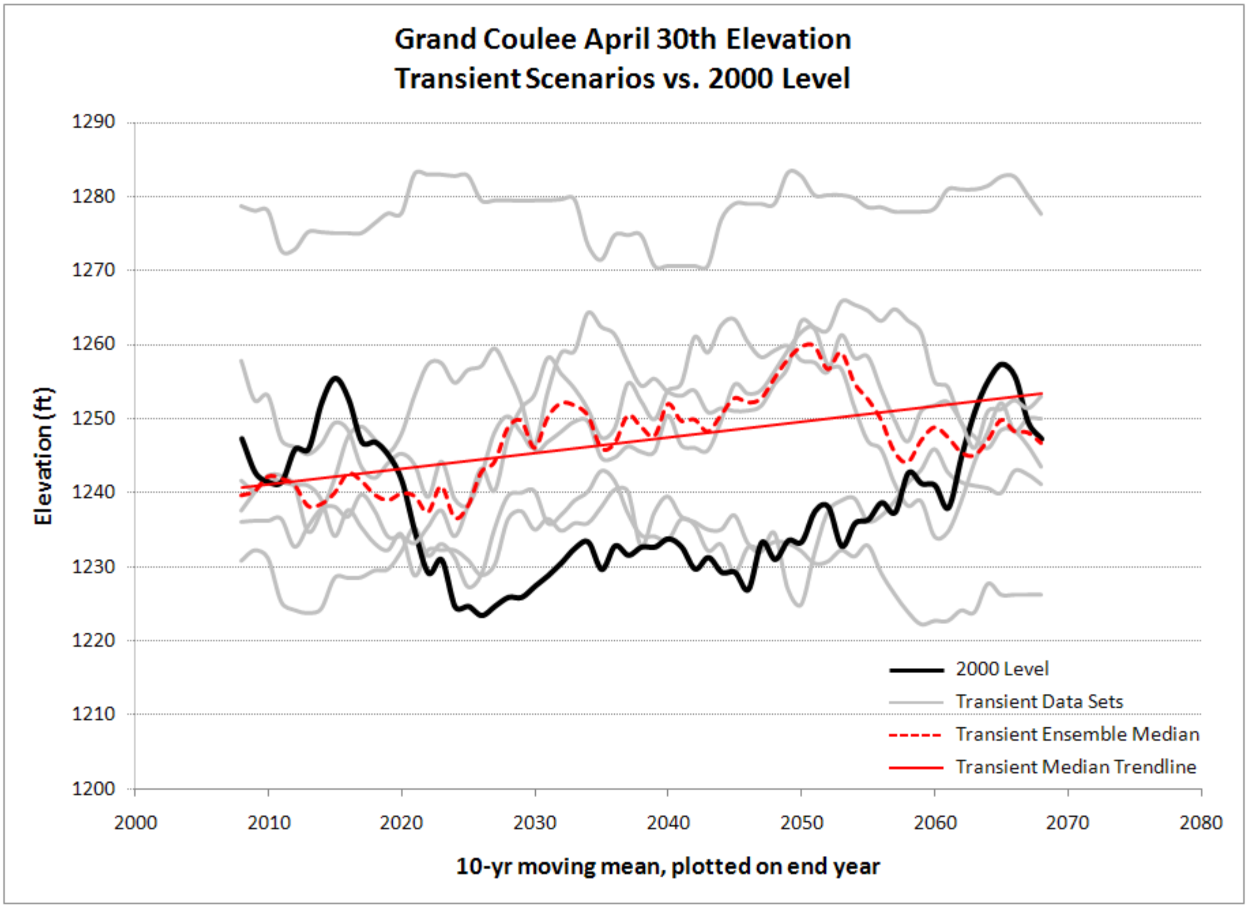

Figure 38. Grand Coulee April 30th Elevations Rolling Average – Transient.

6.5.4 Grand Coulee Summary

Grand Coulee flood control requirements are based on The Dalles runoff volume forecasts. The Hybrid-Delta scenarios show that there are some curves generally higher (drier scenarios), and some curves generally lower (wetter scenarios) than that of the 2000 Level. The average April 30th elevations are split where there are some higher and some lower than that of the 2000 Level, with the maximum differences (in average values) of 20 feet higher for the drier scenario (less flood control space required) and seven feet lower for the wettest scenario (more flood control space required). Because the climate change scenarios do not show a consistent trend, a general conclusion on the impact of climate change on Grand Coulee is not readily apparent. The Transient scenarios show that over the 70-year period, the median flood control elevations increase approximately 13 feet, about 812 kaf, which is reflective of the decrease in The Dalles ensemble median runoff volume trend.

6.6 Brownlee

Brownlee project is located on the Snake River in Idaho. Brownlee's flood control curve is determined by the April through August forecast runoff volume at The Dalles and the April through July forecast runoff at Brownlee. The maximum draft for flood control space is 980 kaf. Similar to Grand Coulee, Brownlee helps to reduce system flood damages on the Columbia River as measured at The Dalles.

This section compares climate change scenarios to the 2000 Level scenario using the following methods and figures. For the Hybrid-Delta scenarios: observed mean monthly volumes, observed seasonal Apr-Jul runoff volume exceedance curves, forecast flood control storage exceedance curves for each month January through April, and box-whisker plots of the April 30th flood control elevations. For the Transient scenarios: the ten-year moving average Apr-Jul runoff volume and the ten-year moving average of the April 30th flood control elevations. A summary of climate change impacts to Brownlee's flood control curve is also provided.

6.6.1 Mean Monthly Volume – Hybrid-Delta

Figure 39 shows the observed mean monthly regulated inflow volumes for Brownlee for each of the Hybrid-Delta 2020 and 2040 scenarios compared to the 2000 Level volumes. It should be noted that inflows to Brownlee used in these scenarios were calculated separately and shown in Part II (see Part II, Section 4.3.2 for information on the naturalized flows in the Snake River subbasin above Brownlee Reservoir). However, it has been determined that the effect of climate change is the dominating factor in the differences in curves shown in Figure 39. Beginning in January, and through April, climate change scenarios have significantly higher volumes than the 2000 Level, and lower volumes in May through September. The peak month occurs in March for nearly all of the climate change scenarios, as compared to May in the 2000 Level. Compared to the 2000 Level March peak flow, the more warming and wetter MWW peak is nearly twice as high in the 2020 Hybrid-Delta, and about 60% higher in the 2040 Hybrid-Delta. There was just one climate change scenario that had a peak in May, which is the less warm and drier LWD scenario. From June through September, climate change volumes are lower for all scenarios.

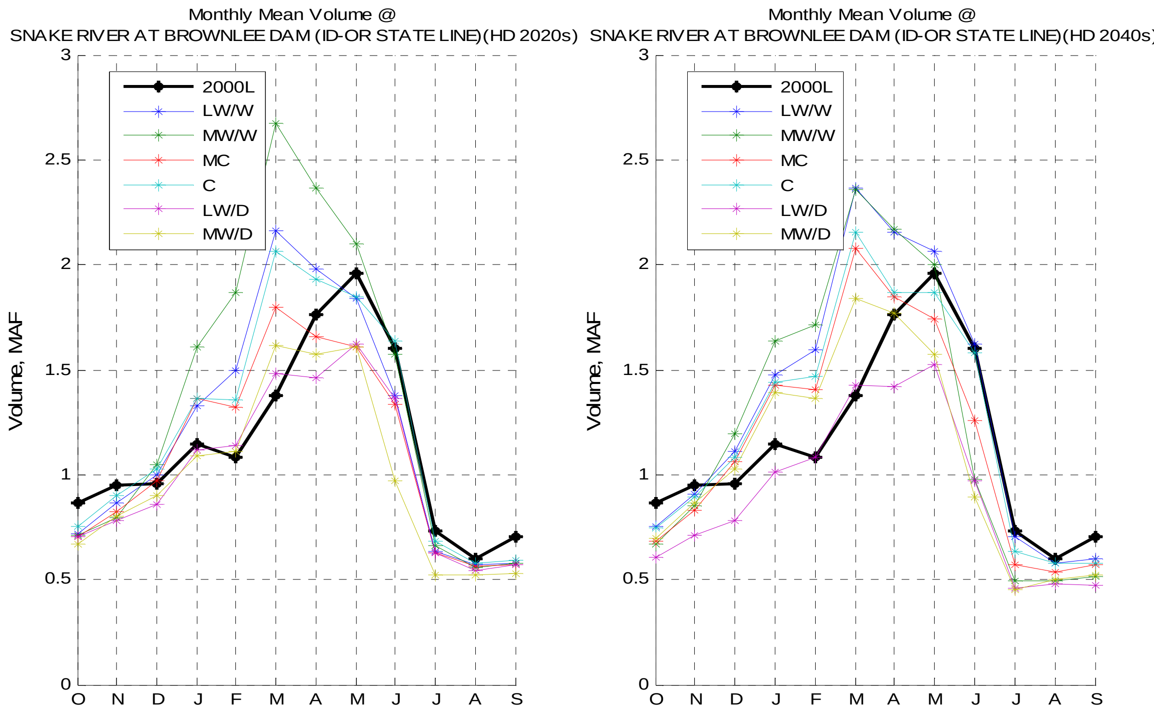

Figure 39. Brownlee Mean Monthly Volume-Hybrid-Delta.

6.6.2 Seasonal Runoff Volume Exceedance – Hybrid-Delta

Figure 40 shows the percent exceedance curve for Brownlee April through July observed volumes for the Hybrid-Delta scenarios as compared to the 2000 Level. Overall, the 2000 Level exceedance curve falls about in the middle of all of the other climate change scenarios. There are climate change scenarios that are below the 2000 Level curve throughout the full range of exceedance values, which represent dryer scenarios. Climate change scenarios above the 2000 Level curve represent wetter scenarios.

Seven of the twelve Hybrid-Delta scenarios have just one year where the Apr-Jul volume is greater than the greatest volume from the 2000 Level and one scenario had 2 years where the Apr-Jul volume was greater. The largest volume of the 2000 Level set is 12,075 kaf. The maximum volumes from the 2020 Hybrid-Delta scenarios is 13,297 kaf, and of the 2040 Hybrid-Delta scenarios is 13,470 kaf which is about 10 and 12% greater than the highest volume in the 2000 Level scenario respectively.

Figure 40 shows the percent exceedance curve for Brownlee for April through July observed volumes for the Hybrid-Delta scenarios as compared to the 2000 Level. There were three Hybrid-Delta scenarios that had one year with a greater volume than the highest volume of the 2000 Level set and one scenario with two years greater.

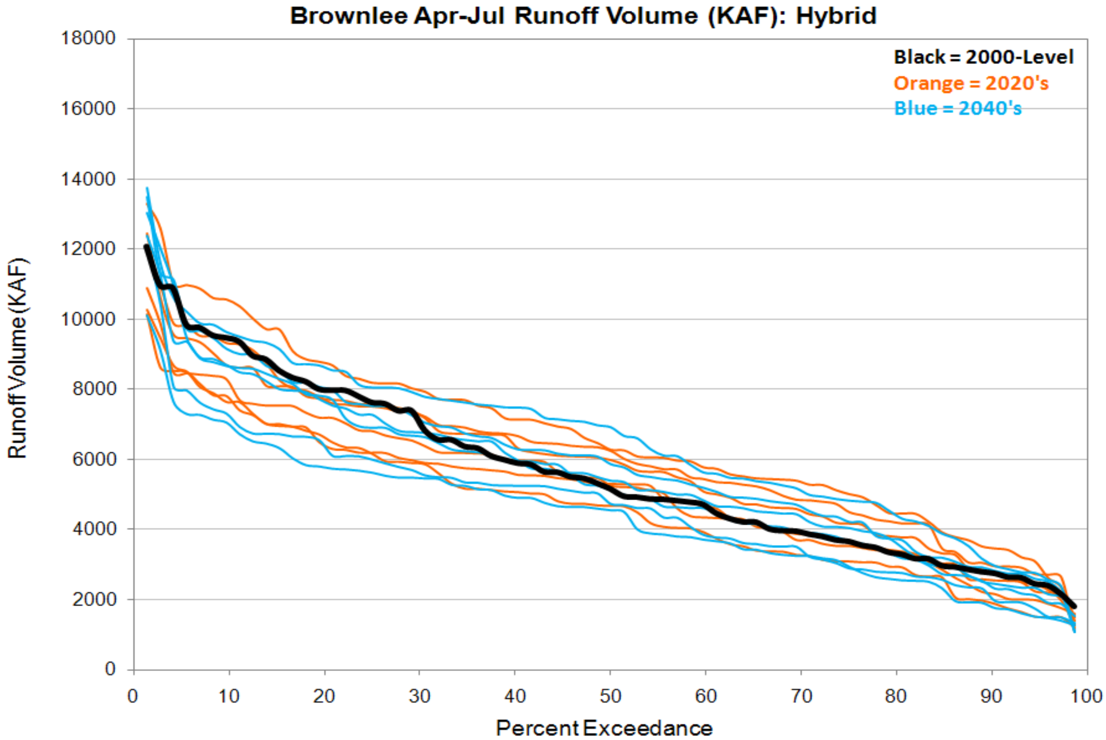

Figure 40. Brownlee Apr-Jul Runoff Volume Exceedance – Hybrid-Delta.

6.6.3 Seasonal Runoff Volume, Ten-Year Rolling Average – Transient

Figure 41 shows the ten-year rolling average April through July runoff volumes for Brownlee for the Transient scenarios. The ensemble median of the Transient scenarios is shown with a linear trend line of the median curve. Over the 70-year period, there is a decline of the ensemble median runoff volume of approximately 5%. However, there was one scenario with an extremely high volume at 17,605 kaf which is 46% greater than the 2000 Level maximum volume.

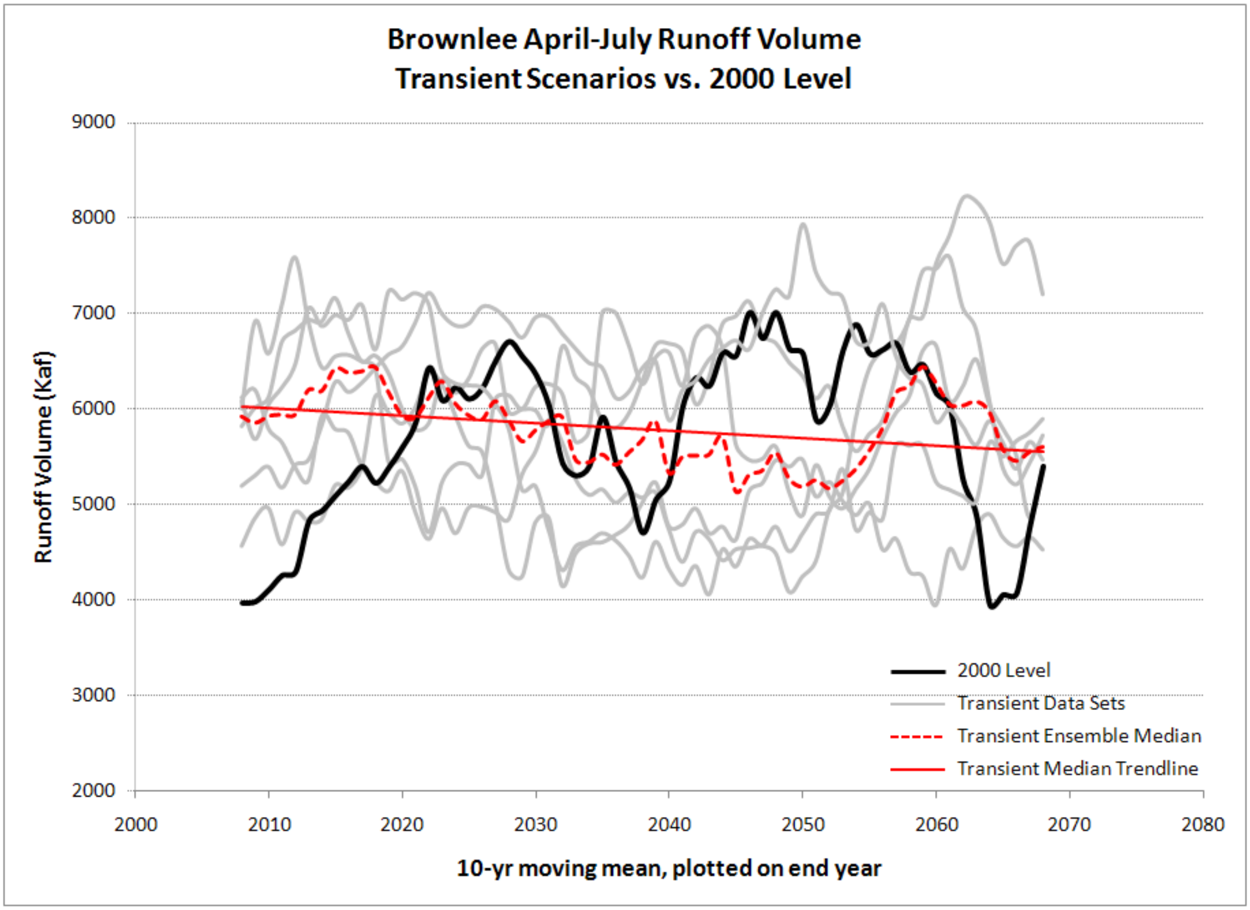

Figure 41. Brownlee Apr-Jul Runoff Volume Rolling Average – Transient.

6.6.4 Flood Control Storage Exceedance – Hybrid-Delta

Figure 42 shows Brownlee's flood control storage percent exceedance graphs for each month, February through April for the Hybrid-Delta scenarios. Brownlee does not draft for flood control in January, therefore there is no graph for that month. A three-way look-up table rather than an SRD is used to determine Brownlee's flood control draft requirement and can be found at http://www.nwd-wc.usace.army.mil/cafe/forecast/SRD/BRN1998table.pdf. Brownlee drafts throughout February, March and April and may draft to empty (980 kaf from full) by the end of April when both The Dalles April-Aug volume is greater than or equal to 115,000 kaf and Brownlee's volume forecast is greater than or equal to 6,000 kaf. For April, in years when The Dalles forecast is less than or equal to 75,000 kaf and Brownlee's forecast is less than or equal to 4,000 kaf, or when The Dalles is less than 85,000 kaf and Brownlee forecast is less than or equal to 3,000 kaf, there is no flood control draft requirement.

Looking at the April end-of-month graph, generally, the climate change scenarios either stay above or below the 2000 Level curve, except at exceedance values 90% and higher, where all of the climate change scenarios are above the 2000 Level curve. Scenarios that stay below the 2000 Level curve reflect generally wetter years and require lower pool levels overall and those that stay above the 2000 Level curve reflect drier years allowing higher pool levels. At 90% exceedance, all the climate change scenarios are above the 2000 Level curve because the combination of their The Dalles and Brownlee forecast volumes at their highest volumes are still less (drier) than that of the 2000 Level. Therefore the pool levels are higher with climate change.

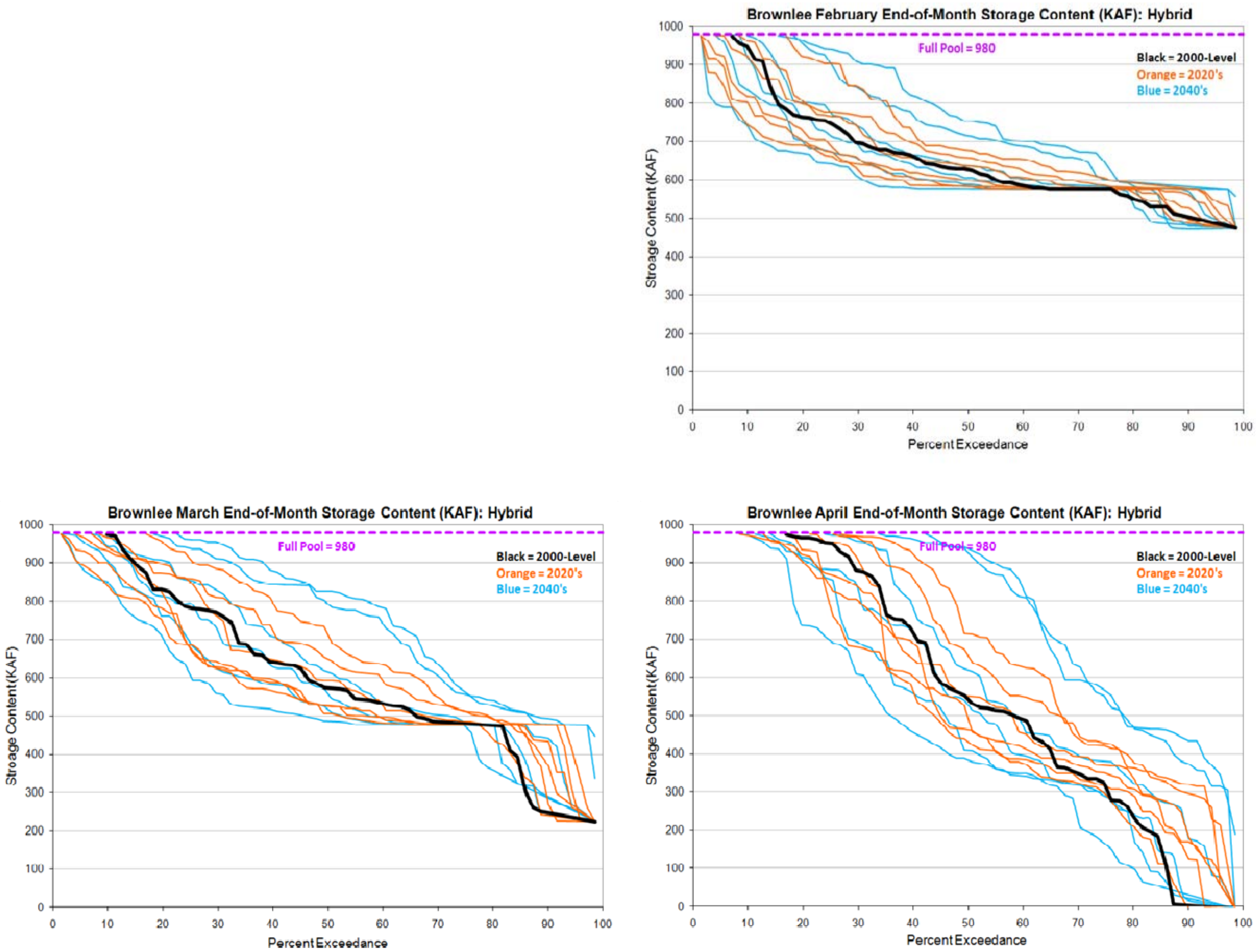

Figure 42. Brownlee Flood Control Storage Exceedance – Hybrid-Delta.

6.6.5 Flood Control April 30th Elevations Comparisons – Hybrid-Delta

The following two figures show the April 30 flood control elevation comparison between the 2000 Level and the 2020 and 2040 Hybrid-Delta scenarios respectively. In the 2020 scenarios, Brownlee's highest pool elevation is El. 2077 ft (full pool) and lowest pool elevation is El. 1975 feet in all scenarios. The average elevations for the drier MWD and LWD are about 11 to 12 feet higher than that of the 2000 Level scenario and about five feet lower for the C scenario.

In the 2040 scenarios the drier MWD and LWD scenarios average elevations are about 21 feet higher than that of the 2000 Level. In the LWD scenario in particular, the lowest elevation is 27 feet higher than the lowest of the 2000 Level. Brownlee did not draft to empty in this drier scenario. The wetter C and LWW scenarios average elevations are about 10 feet lower than that of the 2000 Level scenario.

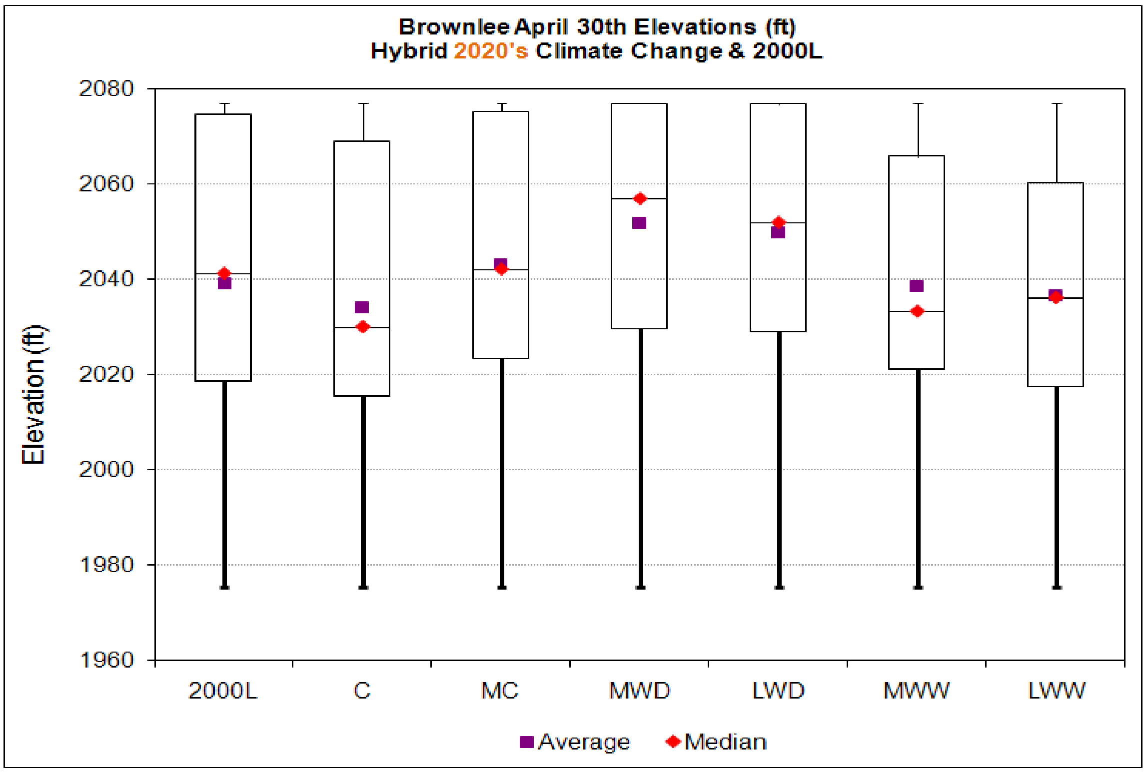

Figure 43. Brownlee April 30th Elevations, 2000 Level & Climate Change Scenarios – HD 2020s.

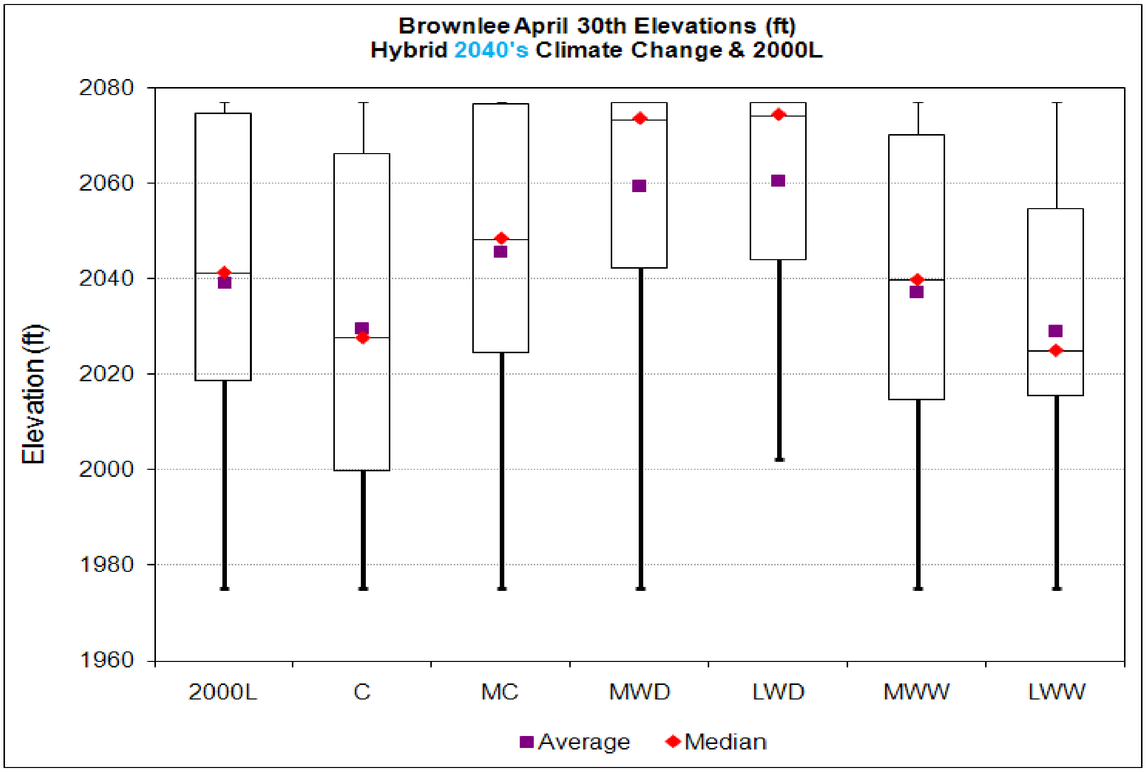

Figure 44. Brownlee April 30th Elevations, 2000 Level & Climate Change Scenarios – HD 2040s.

6.6.6 Flood Control April 30th Elevations Comparisons – Transient

Figure 45 shows the April 30 flood control elevation comparisons between the Transient and 2000 Level scenarios, the Transient ensemble median and its linear trend line. Over time, the ensemble median flood control elevations increase approximately 13 feet from El. 2045 to El. 2058 feet, or about 145 kaf, which is reflective of the decrease in the Brownlee and The Dalles ensemble median runoff volume trends.

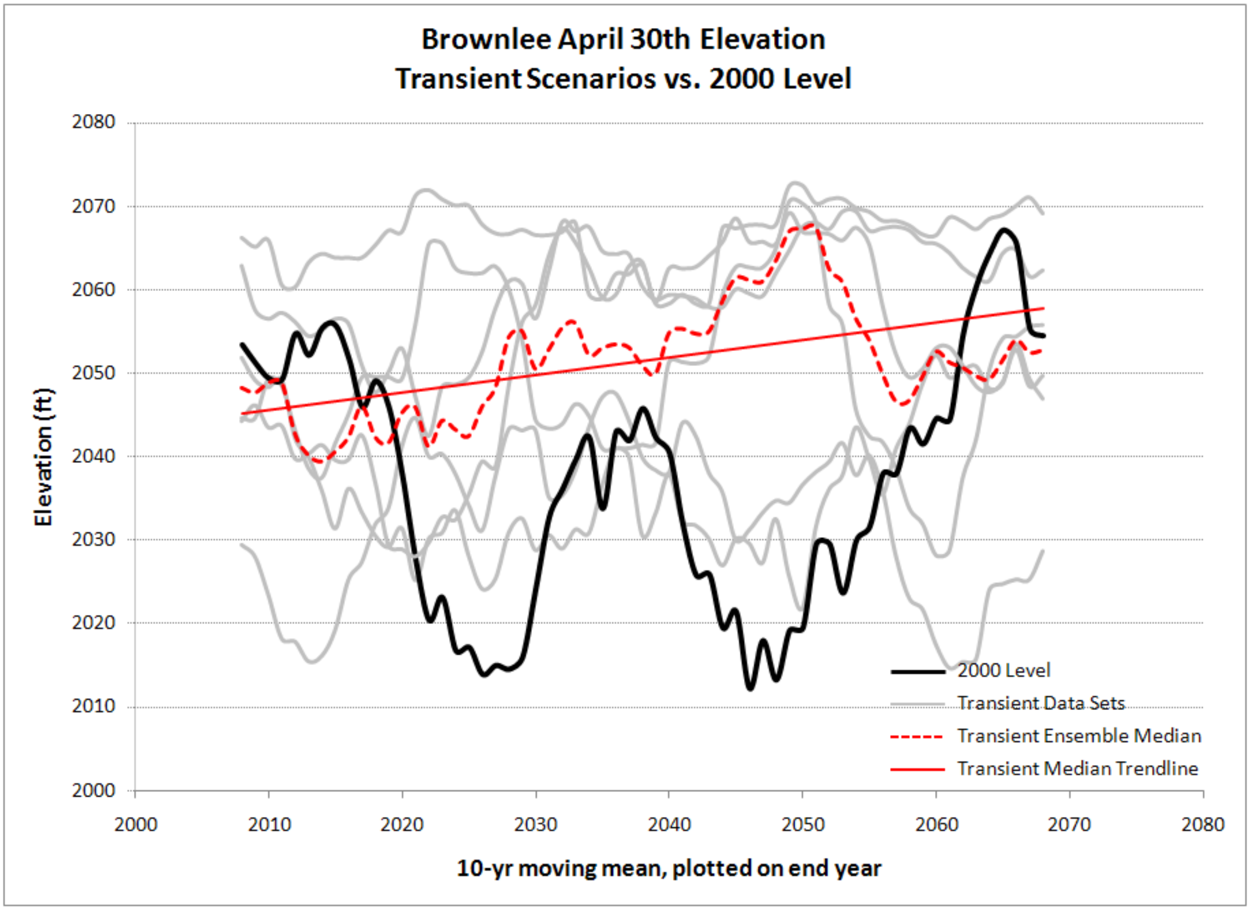

Figure 45. Brownlee April 30th Elevations Rolling Average – Transient.

6.6.7 Brownlee Summary

Beginning in January, and through April, on a monthly basis, climate change scenarios have significantly higher volumes (wetter) than the 2000 Level and lower volumes for May through September. The peak month occurs in March for nearly all of the climate change scenarios, as compared to May in the 2000 Level. It is possible that with earlier and higher winter inflows to both Brownlee and The Dalles, that earlier flood control drafts may be needed at Brownlee. Overall, the 2000 Level April through July runoff volume exceedance curve falls roughly in the middle of all of the other climate change scenarios. For the Hybrid-Delta scenarios, the flood control pool levels fall about in the middle of the various climate change scenarios, with higher pool levels in the wetter years and lower pool levels in the drier years than in the 2000 Level because the wetter years of the climate change scenarios are drier than the wetter years of the 2000 Level set and the drier years of the climate scenarios are wetter than the dry years of the 2000 Level data.

The average April 30th elevations are split where there are some higher and some lower than that of the 2000 Level, with the maximum differences (in average values) of 21 feet higher for the drier scenario and ten feet lower for the wettest scenario.

The Transient scenarios show that over the 70-year period, there is a decline of Brownlee April through July runoff volume of approximately 5%. Over time, the ensemble median flood control elevations increase approximately thirteen feet, or 145 kaf, which is reflective of the decrease in the Brownlee and The Dalles ensemble median runoff volume trends.

6.7 Libby

Libby project is located on the Kootenay River in Montana. Libby's flood control curve is determined by its flood control SRD (VarQ) and the April through August runoff volume at Libby. The maximum draft for flood control space is 4,980 kaf. Libby has system flood control responsibilities for the Columbia River system as measured at The Dalles and downstream of Libby at Bonners Ferry, Idaho.

This section compares climate change scenarios to the 2000 Level scenario using the following methods and figures. For the Hybrid-Delta scenarios: observed mean monthly volumes, observed seasonal Apr-Aug runoff volume exceedance curves, forecast flood control storage exceedance curves for each month January through April, and box-whisker plots of the April 30th flood control elevations. For the Transient scenarios: the ten-year moving average Apr-Aug runoff volume and the ten-year moving average of the April 30th flood control elevations. A summary of climate change impacts to Libby's flood control curve is also provided.

6.7.1 Mean Monthly Volume – Hybrid-Delta

Figure 46 shows the observed mean monthly regulated inflow volumes for Libby for each of the Hybrid-Delta 2020 and 2040 scenarios compared to the 2000 Level volumes. The 2020 scenarios are similar in shape and volume to the 2000 Level except there is more volume in March and less in June with climate change. The peak occurs in June in both the climate change and 2000 Level scenarios in the 2020 scenarios. The 2040 scenarios are wetter throughout October through May, and drier July through September. There is a wide variation of shape among the climate change scenarios in May and June where some of them peaked in May and some peaked in June. All climate change scenarios were higher than the 2000 Level in May, and all but one were lower in June. The more warming and wetter MWW scenario has a significantly higher volume in May of about 1,000 kaf and the peak for that scenario was in May while the 2000 Level peak occurs in June. The maximum April-August volume in the MWW scenario is 13,549 kaf compared to 9,238 kaf in the 2000 Level. The more warming and drier MWD scenario also peaked in May, and had significantly lower volume in June of approximately 600 kaf less.

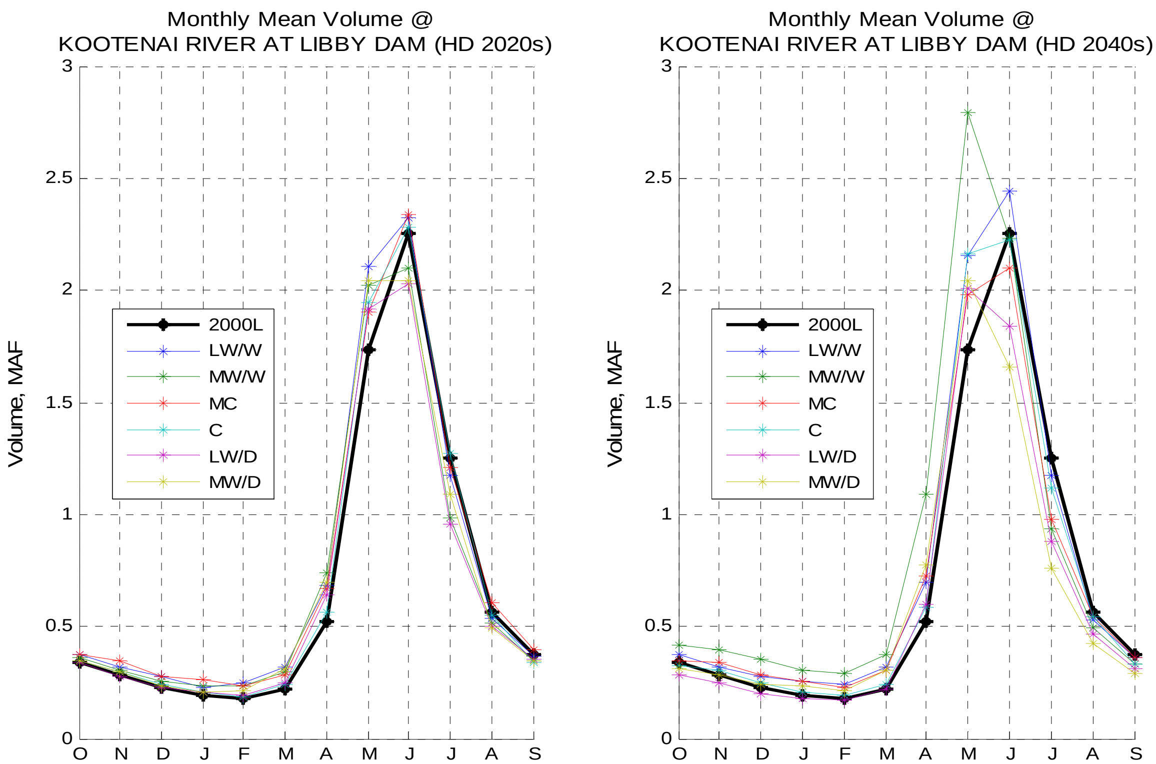

Figure 46. Libby Mean Monthly Volume – Hybrid-Delta.

6.7.2 Seasonal Runoff Volume Exceedance – Hybrid-Delta

Figure 47 shows the percent exceedance curve for Libby for April through August observed volumes for the Hybrid-Delta scenarios as compared to the 2000 Level. Overall, about nine of the twelve climate change curves are above the 2000 Level curve, meaning that generally, climate change volumes are wetter than the 2000 Level volumes. There are three climate change scenarios that are below the 2000 Level curve throughout the full range of exceedance values, which represent drier scenarios.

All of the twelve Hybrid-Delta scenarios have at least one year where the April through August volume is greater than the highest volume from the 2000 Level scenario and one Hybrid-Delta scenario had five years greater. The largest volume of the 2000 Level set is 9,238 kaf. The maximum volume from the 2020 Hybrid-Delta scenario is 10,547 kaf, and of the 2040 Hybrid-Delta scenarios is 12,715 kaf, which is about 38% greater than the highest volume in the 2000 Level set. Hybrid-Delta scenarios are wetter in the lower volume years and the mostly drier in the highest volume years.

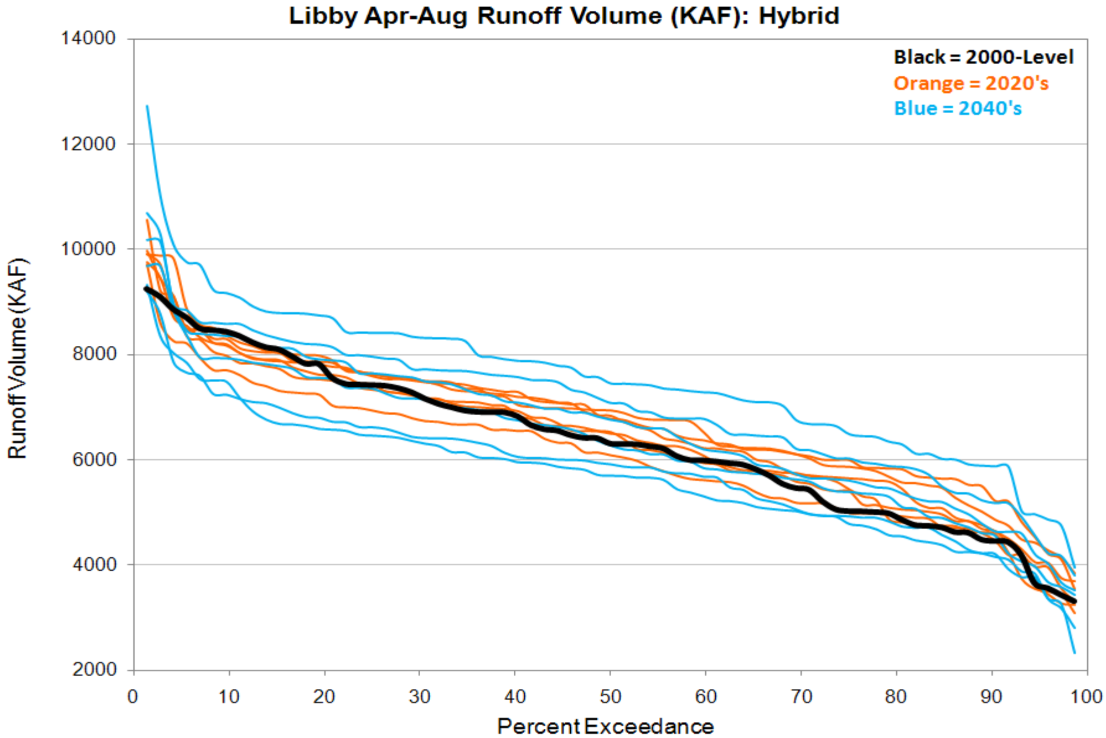

Figure 47. Libby Apr-Aug Runoff Volume Exceedance – Hybrid-Delta.

6.7.3 Seasonal Runoff Volume, Ten-Year Rolling Average – Transient

Figure 48 shows the ten-year rolling average April through August runoff volumes for Libby for the Transient scenarios. The median of the Transient scenarios is shown with a linear trend line of the median curve. Over the 70-year period, there is a decline of the ensemble median runoff volumes of approximately 5%.

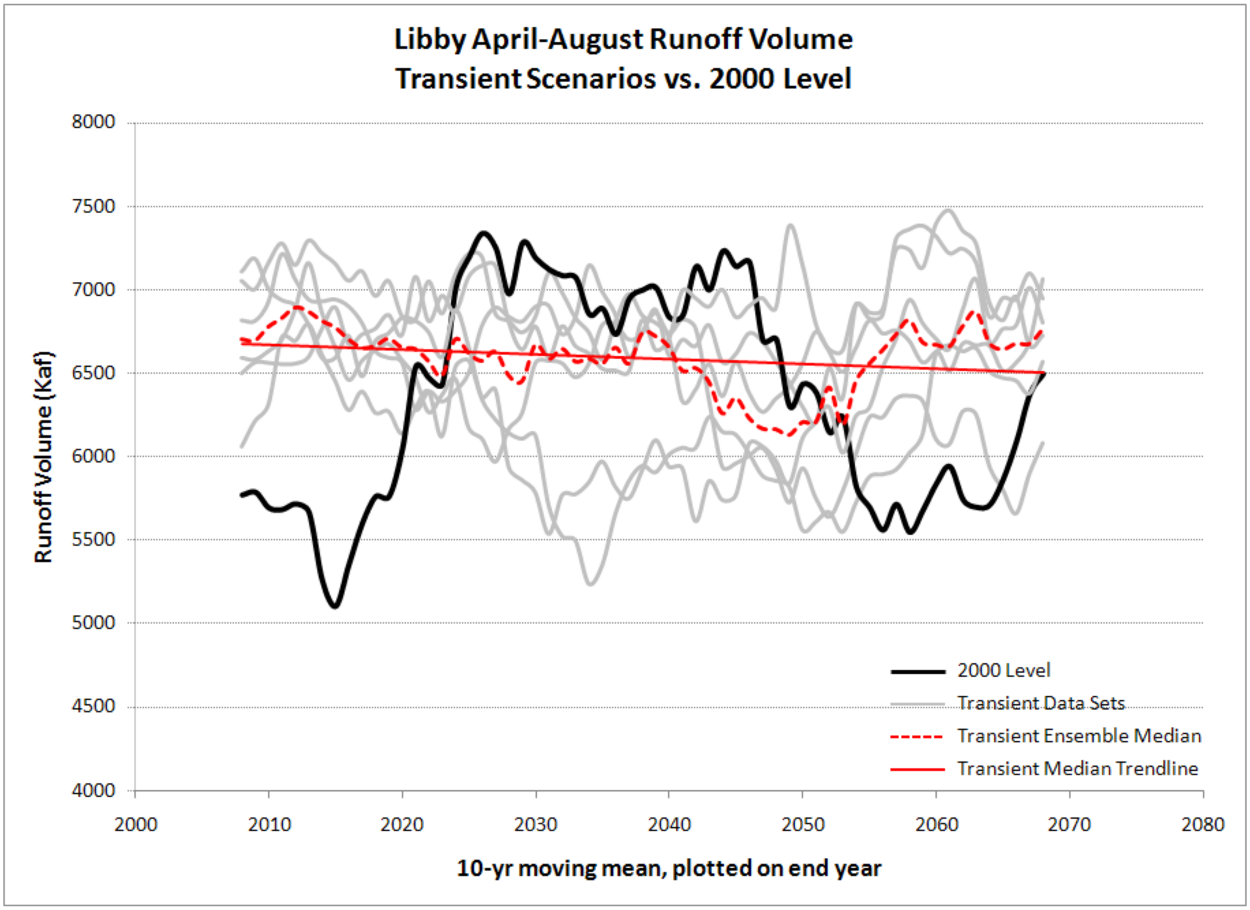

Figure 48. Libby Apr-Aug Runoff Volume Rolling Average – Transient.

6.7.4 Flood Control Storage Exceedance – Hybrid-Delta

Figure 49 shows Libby's VarQ flood control storage percent exceedance graphs for each month, January through April for the Hybrid-Delta scenarios. Libby drafts throughout January, February, March and April and may draft 4,980 kaf from full pool by the end of March and April when Libby's April through August forecast is greater than 8,000 kaf. In years when Libby's forecast is less than or equal to 4,500 kaf, Libby must draft 100 kaf from full pool by the end of April.

Looking at the April end-of-month graph, there are some climate change scenarios that stay below and above the 2000 Level curve, and some that cross the 2000 Level curve. The scenarios that stay below reflect wetter volumes, as Libby will draft deeper for wetter volumes. The scenarios that stay above the 2000 Level curve reflect drier volumes, as Libby does not have to draft as deep at the 2000 Level scenario. Instances where the climate change curves cross the 2000 Level curve reflect that in the lower water years (the left side of the graph) there is more runoff volume than in the 2000 Level, requiring deeper drafts, and in the higher water years (the right side of the graph), there is less runoff than in the 2000 Level, requiring lesser drafts.

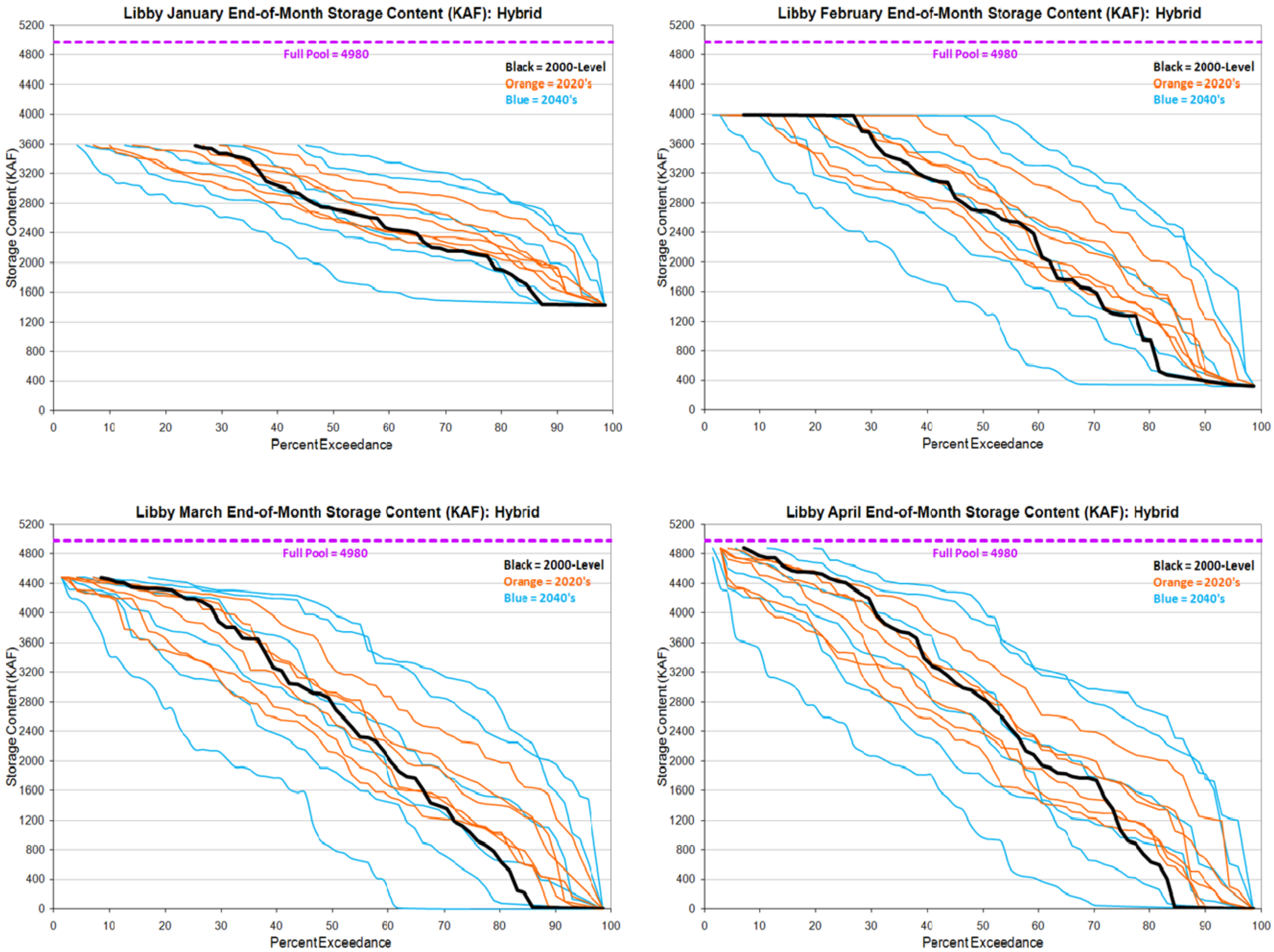

Figure 49. Libby Flood Control Storage Exceedance – Hybrid-Delta.

6.7.5 Flood Control April 30th Elevations Comparisons – Hybrid-Delta

The two figures below show the April 30th flood control elevation comparison between the 2000 Level and the 2020 and 2040 Hybrid-Delta scenarios, respectively. In all of the 2020 and 2040 scenarios, Libby's highest pool elevation is El. 2056.8 ft and lowest pool elevation is El. 2287 ft in all scenarios. For the 2020 scenarios, the average elevation for the driest LWD scenario is about 21 feet higher than that of the 2000 Level scenario and about twelve feet lower for the wet LWW scenario.

For the 2040 scenarios the driest MWD scenario average elevations are about 32 feet higher than that of the 2000 Level, and for the wet MWW scenario, the average elevation is about 44 feet lower. The MWW scenario stands out as having the lowest elevations reflecting wetter conditions compared to all other scenarios. The 2040 scenarios show a wider variation of scenarios than the 2020 scenarios.

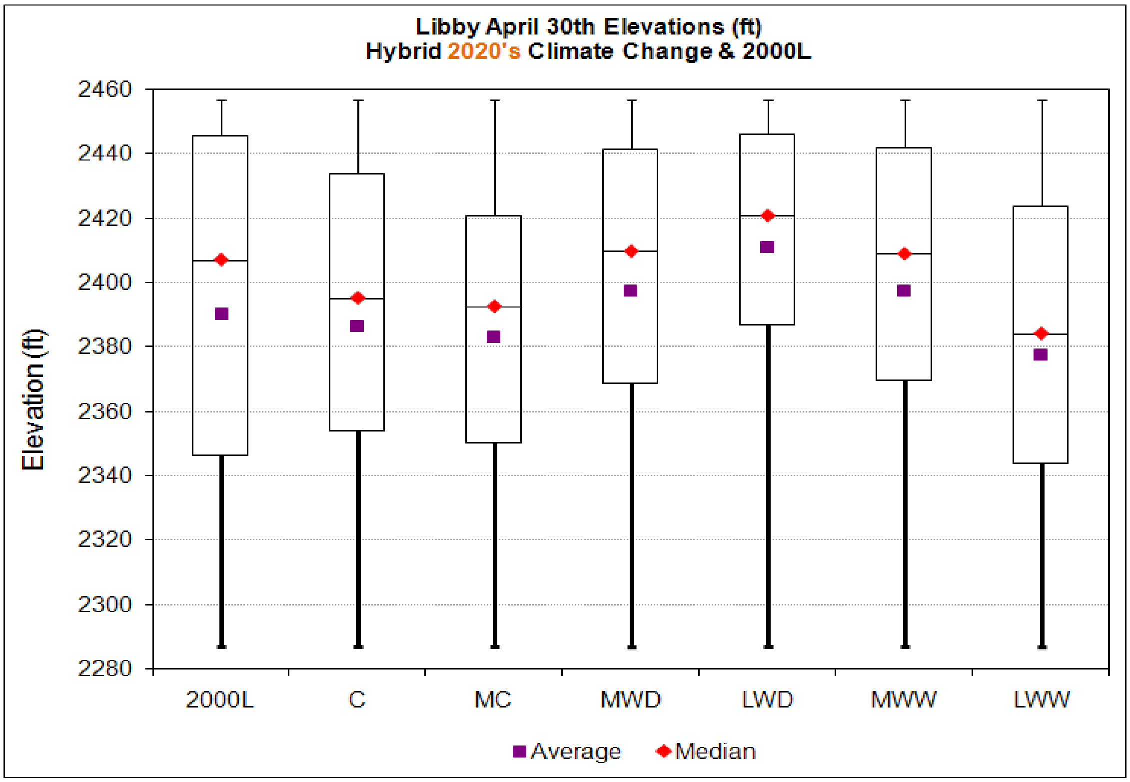

Figure 50. Libby April 30th Elevations, 2000 Level & Climate Change Scenarios – Hybrid-Delta 2020s.

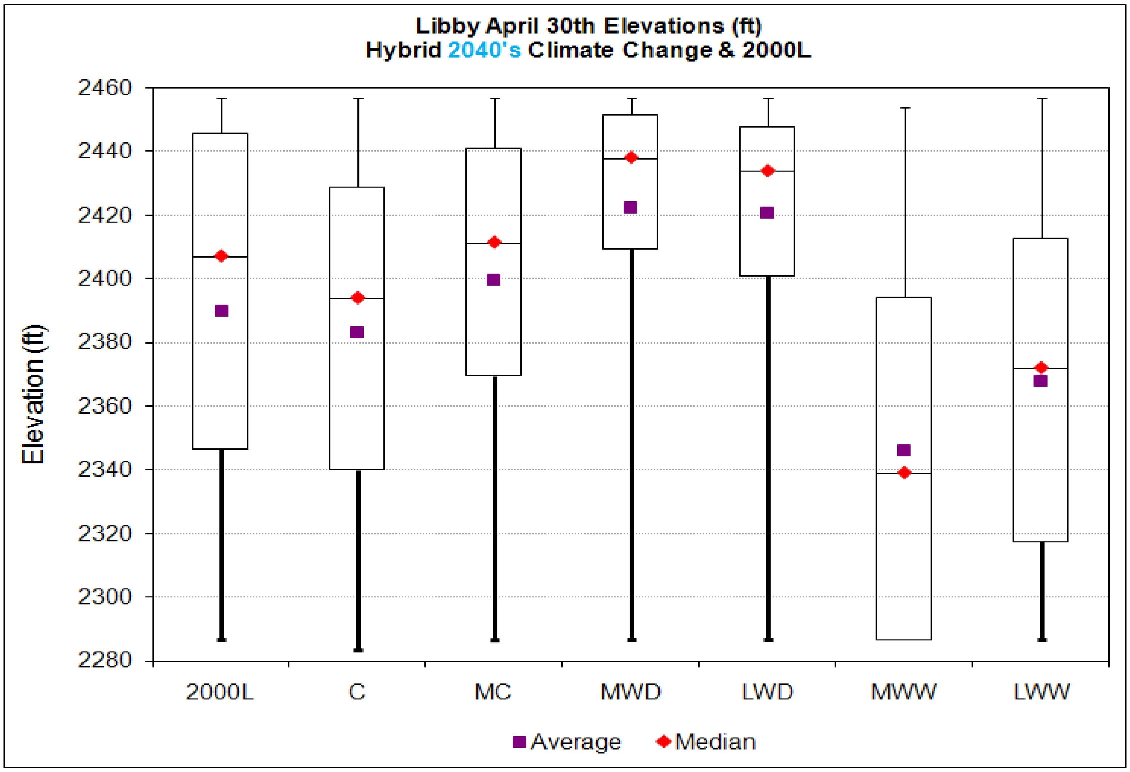

Figure 51. Libby April 30th Elevations, 2000 Level & Climate Change Scenarios – Hybrid-Delta 2040s.

6.7.6 Flood Control April 30th Elevations Comparisons – Transient

Figure 38 shows the April 30 flood control elevation comparisons between the Transient and 2000 Level scenarios, the Transient ensemble median and its linear trend line. Over time, the ensemble median flood control elevations increase approximately eleven feet from El. 2380 to El. 2391 feet, or 320 kaf, which is reflective of the decrease in Libby's ensemble median runoff volume trend.

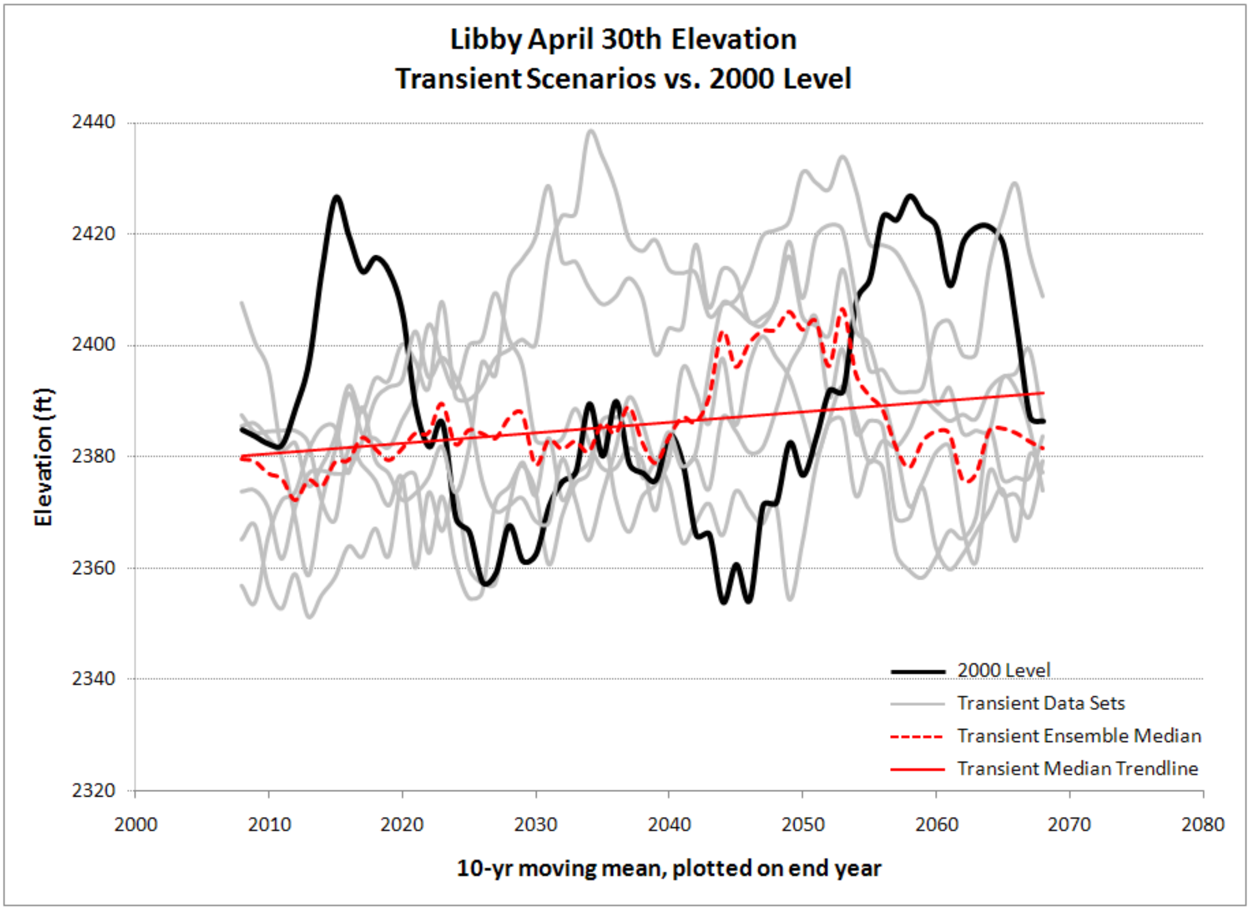

Figure 52. Libby April 30 Elevations Rolling Average – Transient.

6.7.7 Libby Summary

The Hybrid-Delta scenarios are generally wetter October through May, and drier July through September. The peak occurs in June in both the climate change and 2000 Level with a mix of peaks being higher and lower than for the 2000 Level. Nine of the twelve climate change scenarios generally show that the April through August runoff volumes are wetter than the 2000 Level volumes in the Kootenay Basin upstream of Libby. All of the Hybrid-Delta scenarios have one to five years where the highest volumes were greater than the maximum runoff volume form the 2000 Level, one of which was 38% higher. The flood control exceedance graphs show that there are deeper drafts in the lower water years (left side of the graph) and less draft in the higher water years (right side of the graph) in some of the climate change scenarios. The rest of the climate change scenarios were either drafted deeper than or drafted less than the 2000 Level over the entire range of exceedances. The average April 30th elevations are split where there are some higher and some lower than that of the 2000 Level, with the maximum differences (in average values) of 32 feet higher for the drier scenario and 44 feet lower for the wettest scenario. Because the climate change scenarios as a whole do not show a consistent trend, a general conclusion on the impact of climate change on Libby is not readily apparent.

The Transient scenarios show that over the 70-year period, there is a decline of the ensemble median April through August runoff volume of approximately 5%, and the ensemble median flood control elevations increase by approximately eleven feet, or 320 kaf, which is reflective of the decrease in Libby's ensemble median runoff volume trend.

6.8 Hungry Horse

Hungry Horse project is located on the South Fork of the Flathead River in Montana. Hungry Horse's flood control curve is determined by its flood control SRD and the May through September runoff volume at Hungry Horse. The maximum draft for flood control space is 2,982 kaf. Hungry Horse is operated for system flood control for the Columbia River system as measured at The Dalles and for local flood control downstream of Hungry Horse at Columbia Falls.

This section compares climate change scenarios to the 2000 Level scenario using the following methods and figures. For the Hybrid-Delta scenarios: observed mean monthly volumes, observed seasonal May-Sep runoff volume exceedance curves, forecast flood control storage exceedance curves for each month January through April, and box-whisker plots of the April 30th flood control elevations. For the Transient scenarios: the ten-year moving average May-Sep runoff volume and the ten-year moving average of the April 30 flood control elevations. A summary of climate change impacts to Hungry Horse's flood control curve is also provided.

6.8.1 Mean Monthly Volume – Hybrid-Delta

Figure 53 shows the observed mean monthly regulated inflow volumes for Hungry Horse for each of the Hybrid-Delta 2020 and 2040 scenarios compared to the 2000 Level volumes. The 2020 scenarios are similar in shape to the 2000 Level except climate change is wetter in November through May and generally drier in June through September. In the 2020 scenarios, during the late fall and winter, there is nearly twice as much volume in the 2020s. In the 2040s, the increase in volume during this period is even more pronounced. The peak month remains as May, and the climate change peaks are greater than that of the 2000 Level, by up to about 15% in the 2040 scenario. In the more warm and drier MWD scenario, the June volume is about half of that for the 2000 Level.

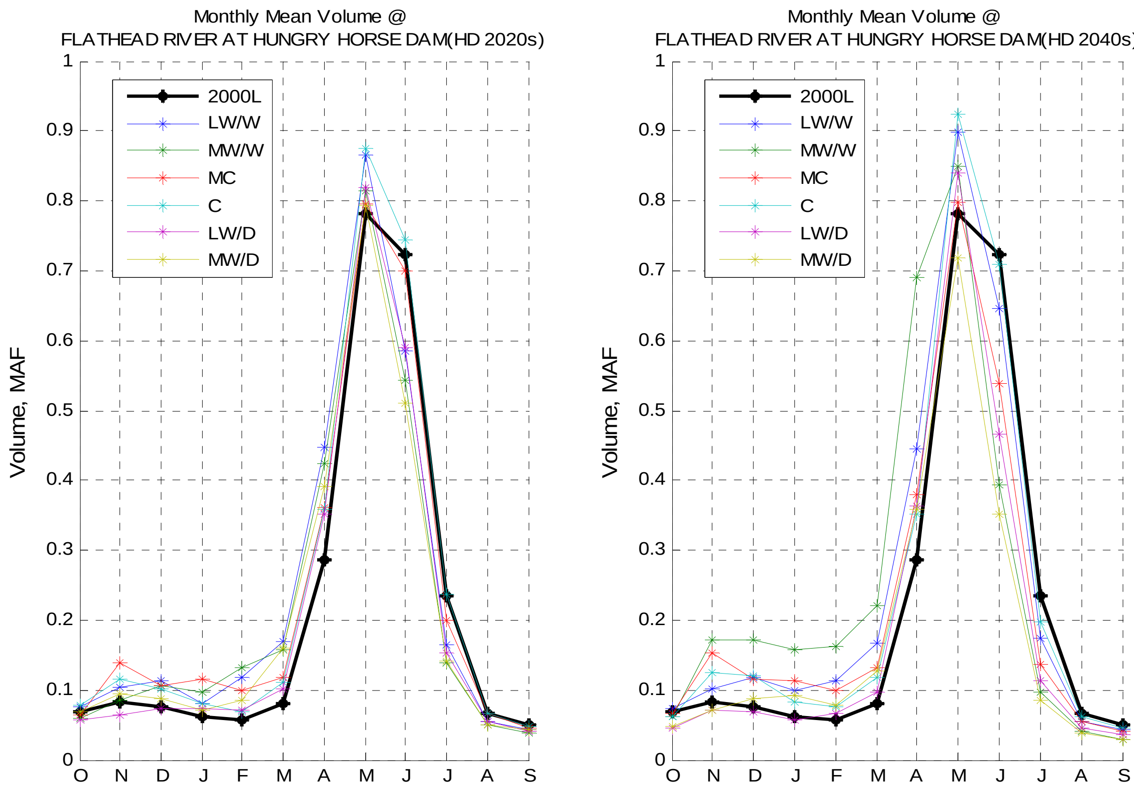

Figure 53. Hungry Horse Mean Monthly Volume – Hybrid-Delta.

6.8.2 Seasonal Runoff Volume Exceedance – Hybrid-Delta

Figure 54 shows the percent exceedance curve for Hungry Horse for May through September observed volumes for the Hybrid-Delta scenarios as compared to the 2000 Level. Overall, about ten of the twelve climate change curves are below the 2000 Level curve, meaning that generally, climate change volumes are lower than the 2000 Level volumes. However, in the 2020s, four of the six scenarios had one to three years where the runoff volumes are higher than the maximum volume of the 2000 Level. The maximum runoff volume from the 2000 Level scenario is 2,943 kaf. The highest runoff volume of the 2020s is 3,599 kaf. In the 2040s two of the six scenarios had runoff volumes higher, with the maximum of 3,955 kaf which is an increase of 34% over the maximum of the 2000 Level.

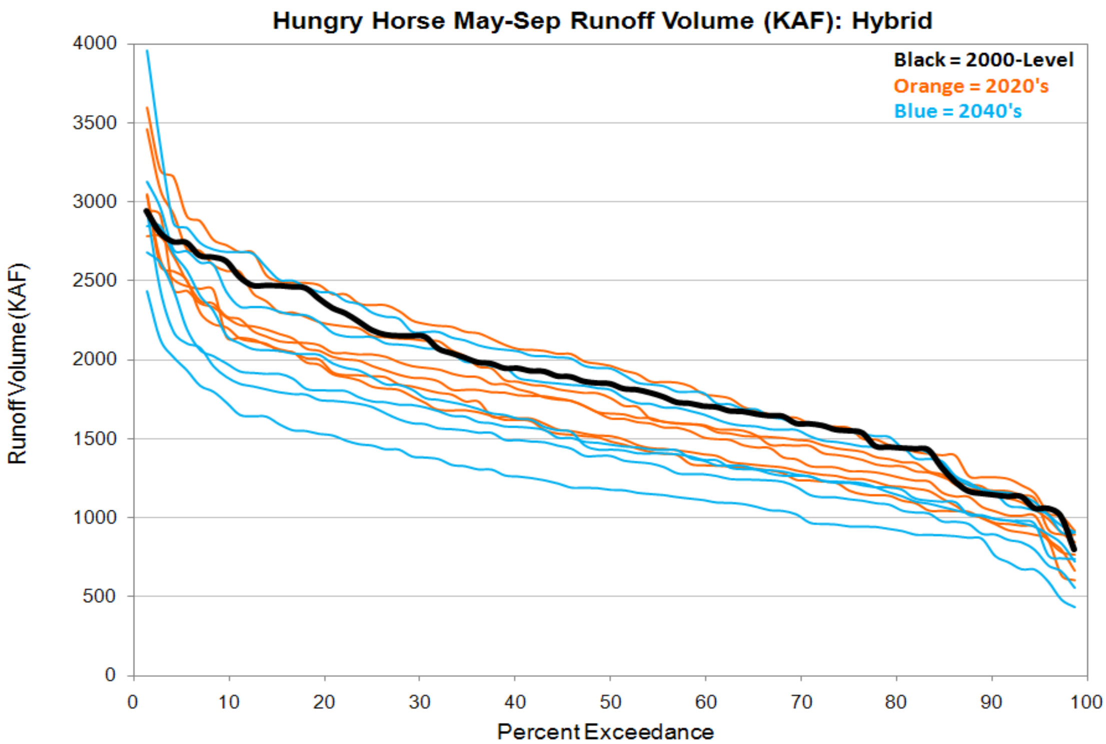

Figure 54. Hungry Horse May-Sep Runoff Volume Exceedance – Hybrid-Delta.

6.8.3 Seasonal Runoff Volume, Ten-Year Rolling Average – Transient

Figure 55 shows the ten-year rolling average May through September runoff volumes for Hungry Horse for the Transient scenarios. The ensemble median of the Transient scenarios is shown with a linear trend line of the median curve. Over the 70-year period, the ensemble median shows there is a decline of runoff volume of approximately 16%.

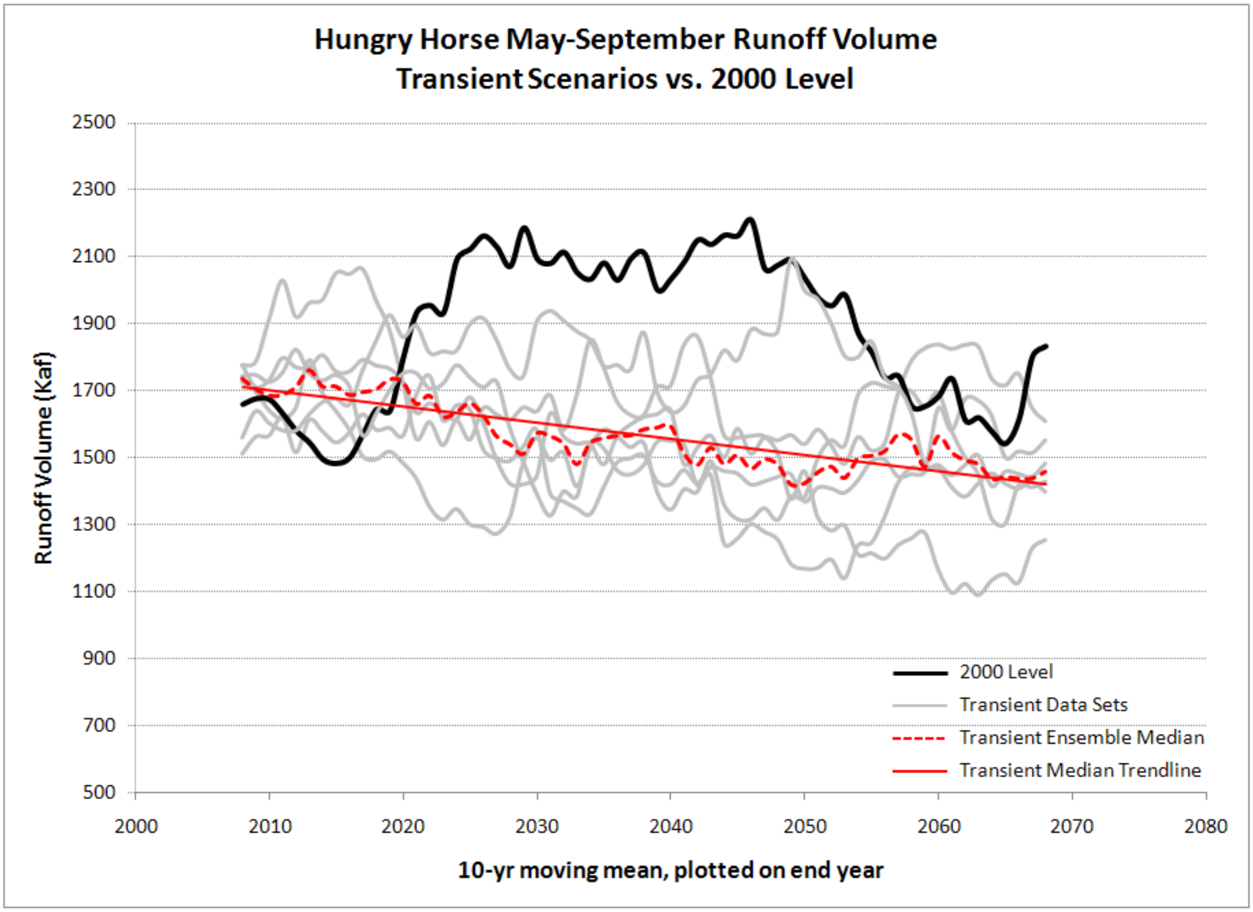

Figure 55. Hungry Horse May-Sep Runoff Volume Rolling Average – Transient.

6.8.4 Flood Control Storage Exceedance – Hybrid-Delta

Figure 56 shows Hungry Horse's flood control storage percent exceedance graphs for each month, January through April for the Hybrid-Delta scenarios. Hungry Horse drafts throughout January, February, March and April and may draft to empty (2,982 kaf draft from full) by the end of April when Hungry Horse's May through September forecast is greater than 3,680 kaf. In years when Hungry Horse's forecast is less than or equal to 1,000 kaf, there is no flood control draft requirement and Hungry Horse reservoir may be full the end of April.

Looking at the April end-of-month graph, generally, all but two of the climate change scenarios are above the 2000 Level curve except near the 100% exceedance on the right side of the graph. The curves above the 2000 Level line reflect that the climate change scenarios are drier than the 2000 Level and therefore do not need to draft as deeply. Near the 100% exceedance, some of the climate change curves fall below the 2000 Level curve. This is due to the volumes that are higher than the maximum volume of the 2000 Level that causes deeper flood control drafts. The maximum volume of the 2000 Level does not cause Hungry Horse to draft to empty.

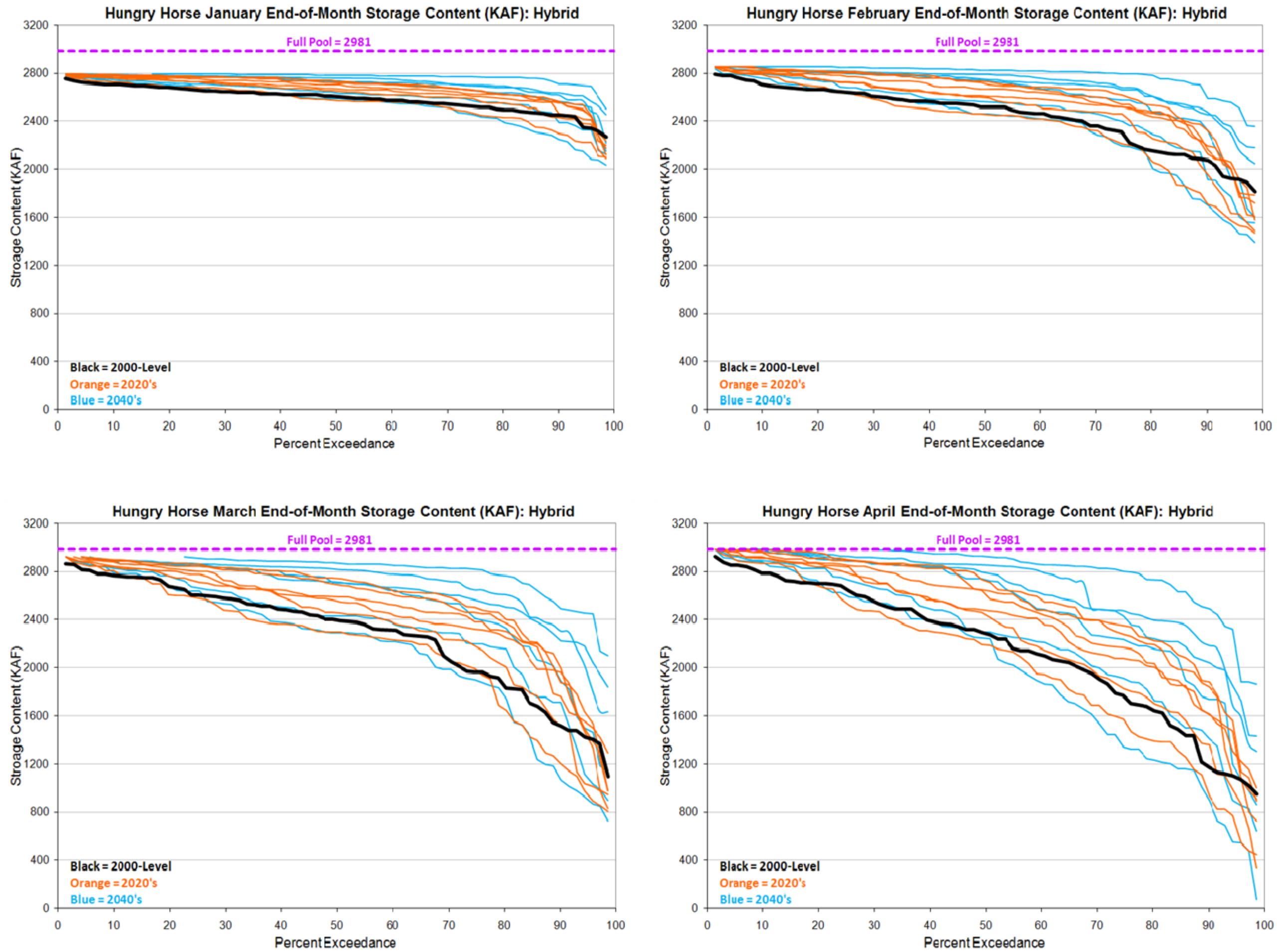

Figure 56. Hungry Horse Flood Control Storage Exceedance – Hybrid-Delta.

6.8.5 Flood Control April 30th Elevations Comparisons – Hybrid-Delta

The following two figures show the April 30th flood control elevation comparison between the 2000 Level and the 2020 and 2040 Hybrid-Delta scenarios, respectively. In the 2020 scenarios, the 25 to 75 percentile data are skewed toward the higher elevation, as in the 2000 Level. All of the scenarios have a wider overall distribution of elevations than the 2000 Level. The average elevation of the drier MWD scenario is about 20 feet higher than that of the 2000 Level. The average elevation of the wet C scenario is about eight feet lower than that of the 2000 Level. The highest elevation of the 2000 Level is 3557.6 ft while all of the

2020 scenarios are at the highest pool elevation of 3560 ft (full pool). The lowest pool elevation of the 2000 Level is El. 3447.1 while the lowest pool for the MC scenario is about 61 feet lower.

For the 2040 scenarios the driest MWD scenario average elevations are about 33 feet higher than that of the 2000 Level, and for the wet C scenario, the average elevation is about twelve feet lower. The 2040 scenarios show higher elevations reflecting generally drier conditions than the 2020 scenarios.

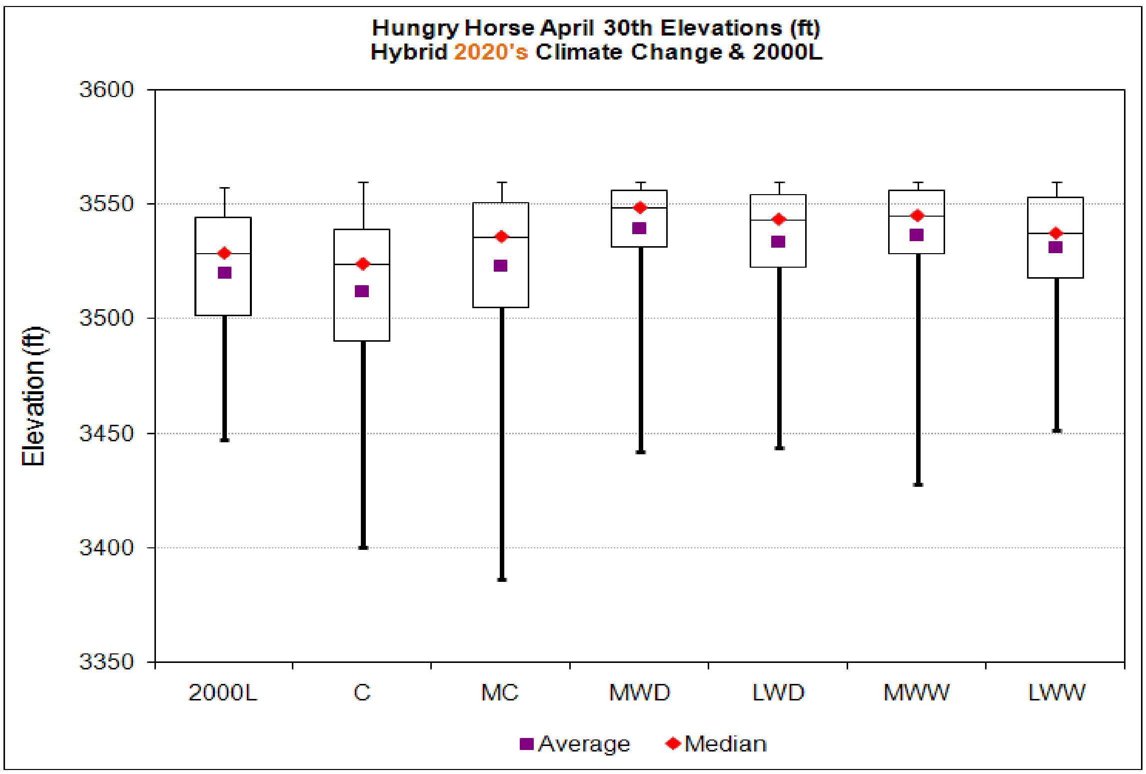

Figure 57. Hungry Horse April 30 Elevations, 2000 Level & Climate Change Scenarios–HD 2020s.

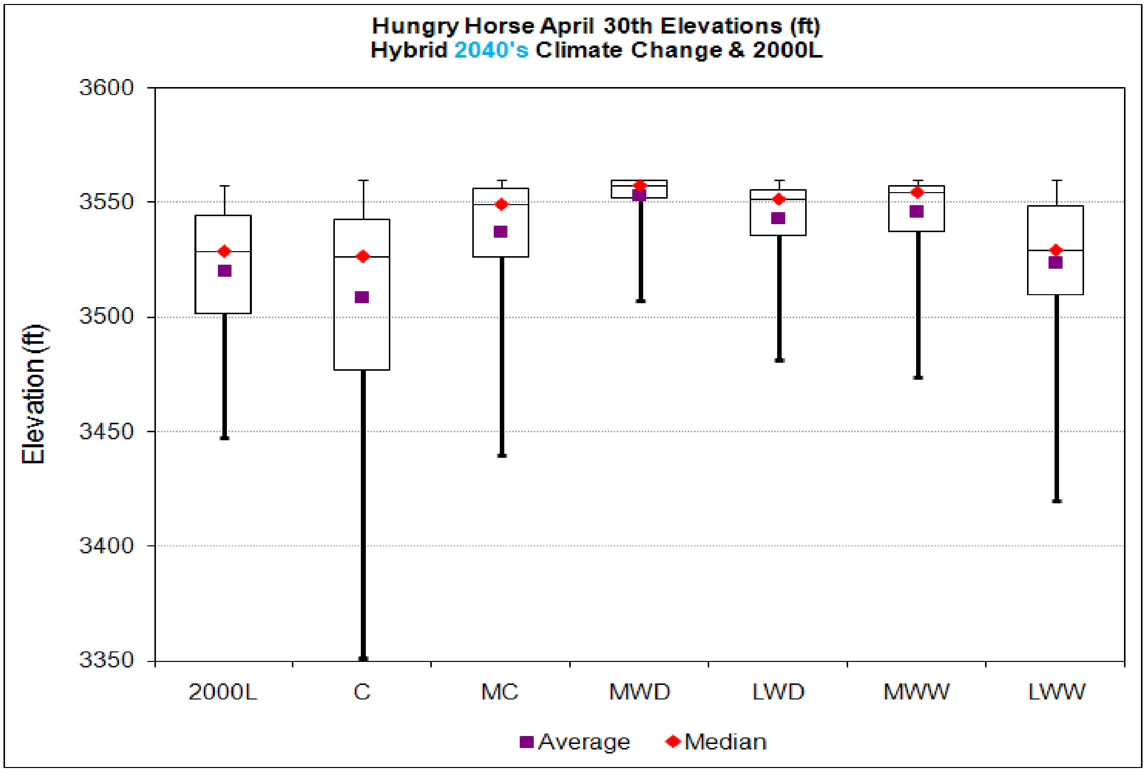

Figure 58. Hungry Horse April 30th Elevations, 2000 Level & Climate Change Scenarios – HD 2040s.

6.8.6 Flood Control April 30th Elevations Comparisons – Transient

Figure 59 shows the April 30 flood control elevation comparisons between the Transient and 2000 Level scenarios, the Transient ensemble median and its linear trend line. Over time, the median flood control elevations increase approximately sixteen feet from El. 3529 to El. 3545 feet, or about 343 kaf, which is reflective of the decrease in Hungry Horse's ensemble median runoff volume trend.

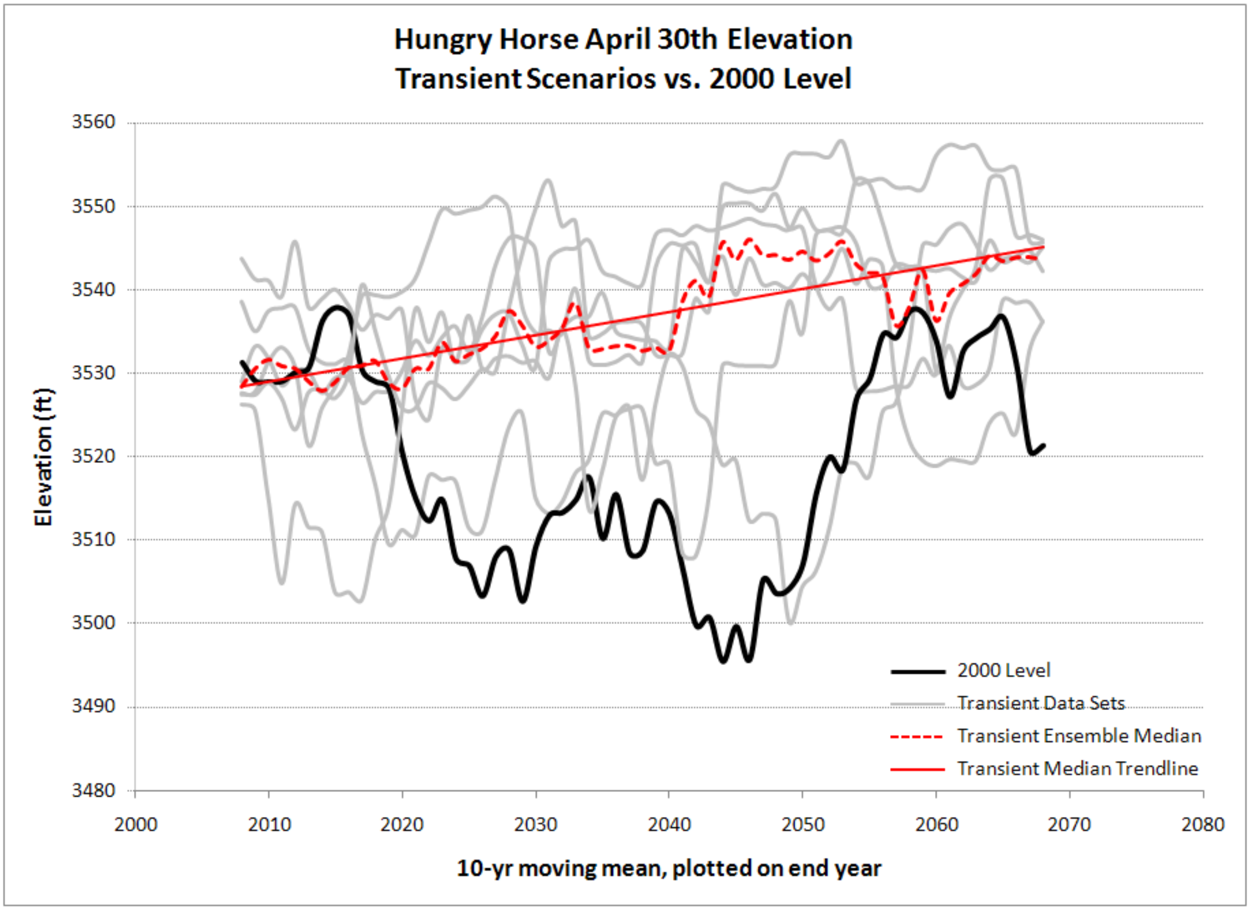

Figure 59. Hungry Horse April 30 Elevations Rolling Average – Transient.

6.8.7 Hungry Horse Summary

During the November through May timeframe the Flathead basin above Hungry Horse is wetter in the climate change scenarios than in the 2000 Level, and drier from June through September. The peak month remains in May, with the climate change peaks being greater than that of the 2000 Level by up to about 15% in the 2040 scenario. June is generally significantly drier with climate change. In general, climate change seasonal runoff volumes for May through September are lower than the 2000 Level volumes, however, over half of all the climate change scenarios have one to three years where the highest volumes are greater than the maximum runoff volume of the 2000 Level . Flood control exceedance curves reflect drier runoff volumes therefore the exceedance curves are higher throughout nearly the entire range of exceedances except near the 100% exceedance. This is due to the volumes that are higher than the maximum volume of the 2000 Level that causes deeper flood control drafts.

The average April 30th elevations are split where there are some higher and some lower than that of the 2000 Level, with the maximum differences (in average values) of 33 feet higher for the drier scenario and 12 feet lower for the wettest scenario. Generally, Hungry Horse flood control is higher due to lower seasonal volumes with climate change.

The Transient scenarios show that over the 70-year period, there is a decline of median ensemble May through September runoff volume of approximately 16%, and the ensemble median flood control elevations increase approximately sixteen feet, or about 343 kaf, which is reflective of the decrease in Hungry Horse's median runoff volume trend.

6.9 Dworshak

Dworshak project is located on the North Fork of the Clearwater River in Idaho. Dworshak's flood control curve is determined by its flood control SRD and the April through July runoff volume at Dworshak. The maximum draft for flood control space is 2,016 kaf. Dworshak has system flood control responsibilities for the Columbia River system as measured at The Dalles and downstream at Spalding.

This section compares climate change scenarios to the 2000 Level scenario using the following methods and figures. For the Hybrid-Delta scenarios: observed mean monthly volumes, observed seasonal Apr-Jul runoff volume exceedance curves, forecast flood control storage exceedance curves for each month January through April, and box-whisker plots of the April 30th flood control elevations. For the Transient scenarios: the ten-year moving average Apr-Jul runoff volume and the ten-year moving average of the April 30th flood control elevations. A summary of climate change impacts to Dworshak's flood control curve is also provided.

6.9.1 Mean Monthly Volume – Hybrid-Delta

Figure 60 shows the observed mean monthly unregulated runoff volumes for Dworshak for each of the Hybrid-Delta 2020 and 2040 scenarios compared to the 2000 Level volumes. Beginning in October and through April, climate change scenario volumes are significantly greater than the 2000 Level volumes. In February, one Hybrid-Delta 2020 scenario has about three times the 2000 Level volume. In the Hybrid-Delta 2040 scenario, in December, one of the scenarios shows the December volume to be about 3.5 times the 2000 Level volume. From May through September, climate change volumes are lower. All but three of the Hybrid-Delta scenarios show the peak monthly volume occurring in May, as in the 2000 Level scenario. The higher and earlier winter volumes may indicate that earlier and deeper winter flood control drafts may be warranted.

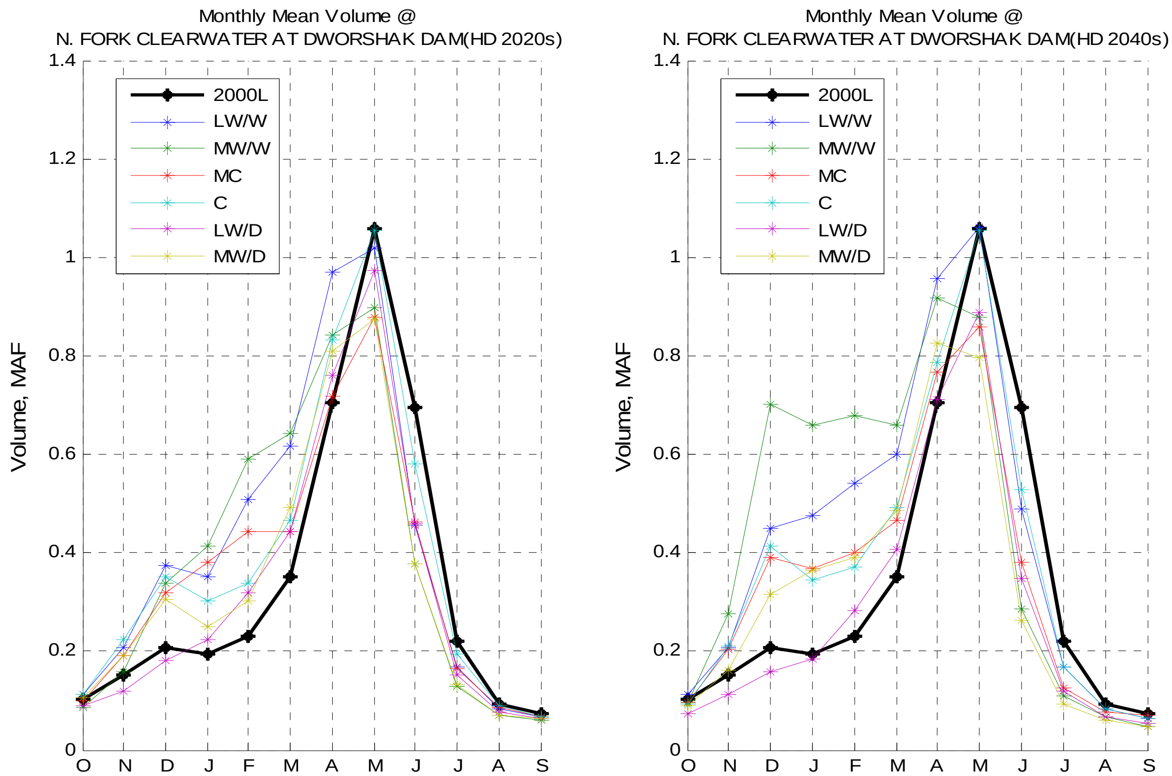

Figure 60. Dworshak Mean Monthly Volume – Hybrid-Delta.

6.9.2 Seasonal Runoff Volume Exceedance – Hybrid-Delta

Figure 61 shows the comparison of observed April-July runoff volume exceedance curves for Dworshak for Hybrid-Delta 2020 and 2040 scenarios. The April-July runoff volume is input to the determination of Dworshak's flood control curves. Figure 47 shows that for all climate change scenarios, the April-July volume at 50% exceedance is less than the 2000L. This indicates that in general, the future climate projections in the Clearwater Basin are dryer than the last 70 years as represented by the 2000 Level volumes. However, as can be seen on the left side of the graph, in the very wettest years in seven of the twelve scenarios, the climate change volumes show higher volumes than the 2000 Level scenario. The highest volume of the 2000 Level is 4,775 kaf and the highest volume of the climate change scenarios is 6,120 kaf (2040 C scenario), about a 28% difference from the 2000 Level.

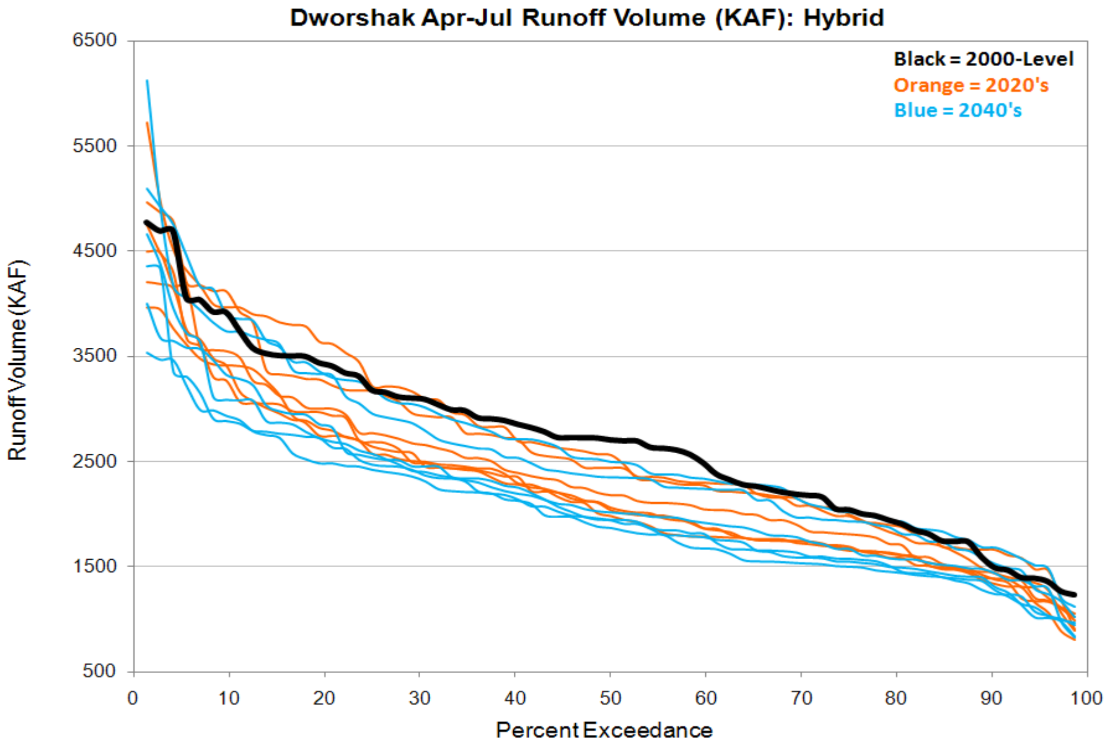

Figure 61. Dworshak Apr-Jul Runoff Volume Exceedance – Hybrid-Delta.

6.9.3 Seasonal Runoff Volume, Ten-Year Rolling Average – Transient

Figure 62 shows the ten-year rolling average April through July runoff volumes for Dworshak for the Transient scenarios. The ensemble median curve of the Transient scenarios is shown with a linear trend line of the median curve. Over the 70-year period, there is a decline of runoff volumes of approximately 14%.

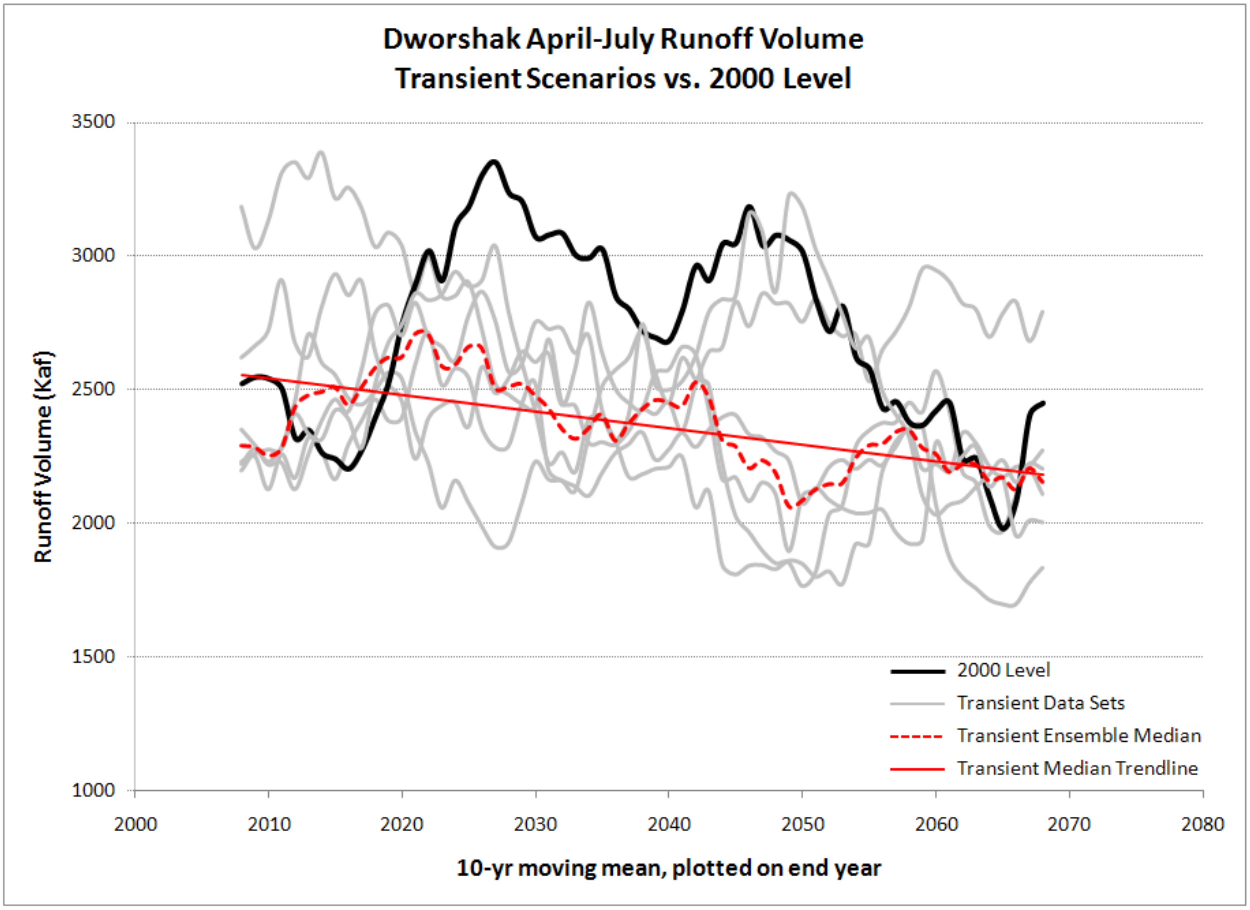

Figure 62. Dworshak Apr-Jul Runoff Volume Rolling Average – Transient.

6.9.4 Flood Control Storage Exceedance – Hybrid-Delta

Since all the flood control graphs discussed in this report are based on the AER data set, the Flood Control Exceedance graphs reflect a shift of flood control space from Dworshak to Grand Coulee.

Figure 63 shows the Dworshak forecast flood control storage exceedance curves for each month, January through April. Flood control curves draft progressively deeper from January through April as a result of the SRD which has the maximum draft on 30 April in the higher water years. The exceedance curves show that nearly all climate change scenarios require less flood control drafts (allow higher reservoir elevations) as compared to the 2000 Level for each month, January through April. Looking at the graph for April, which is the date of maximum evacuation from the storage reservation diagram, in the years with the highest April-Jul runoff volumes represented by the right hand side of the graph, the reservoir flood control contents may be much higher than that for the 2000 Level.

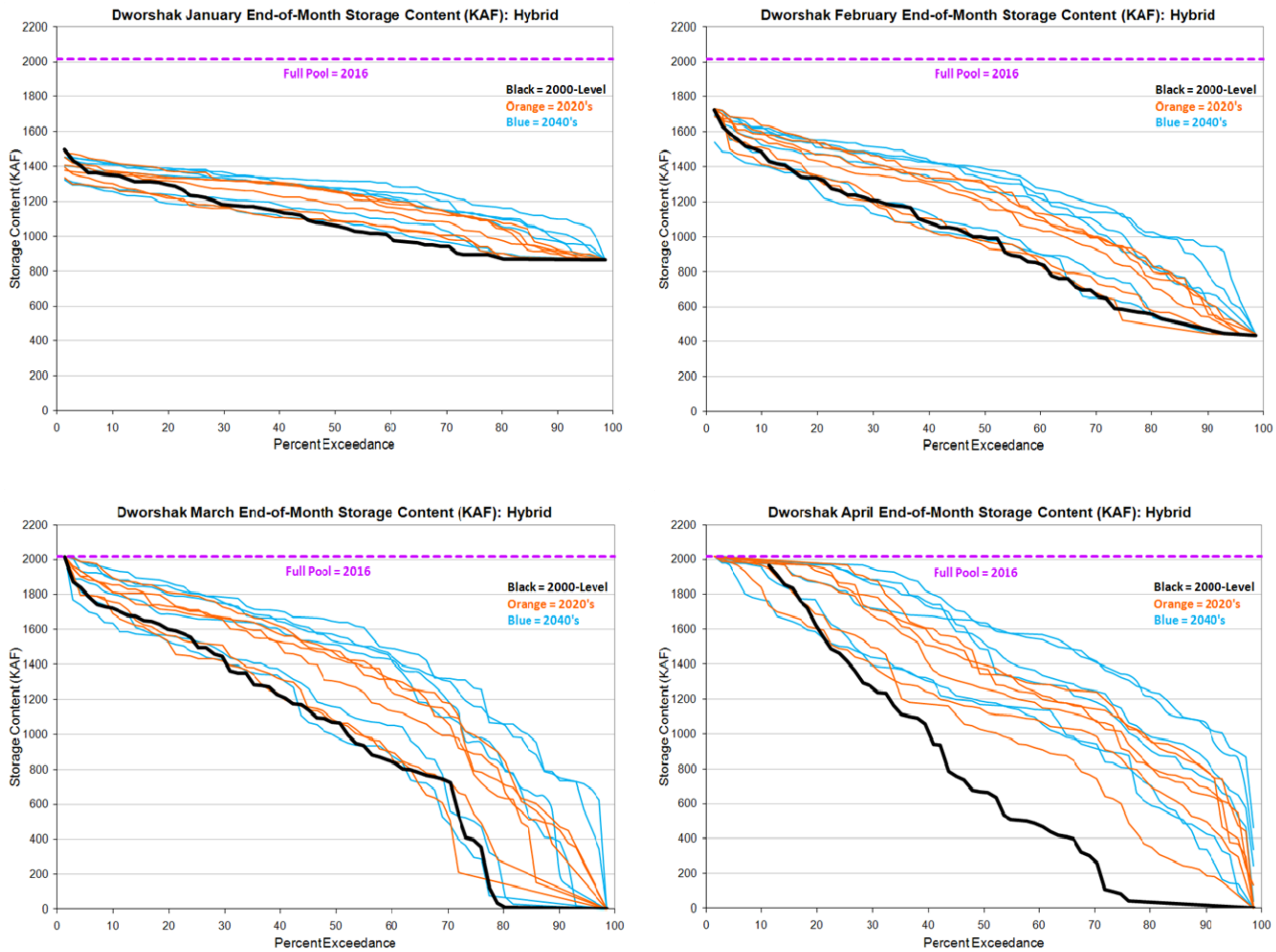

Figure 63. Dworshak Flood Control Storage Exceedance – Hybrid-Delta.

6.9.5 Flood Control April 30th Elevations Comparisons – Hybrid-Delta

The following two figures show the April 30th flood control elevation comparison between the 2000 Level and the 2020 and 2040 Hybrid-Delta scenarios, respectively. All of the 2020 and 2040 scenarios show the distribution skewed toward higher elevations than the 2000 Level, reflecting dryer conditions. In the 2000 Level, Dworshak's highest pool elevation is El. 1597.4 ft whereas it is full at El. 1600 ft in all of the 2020 and 2040 scenarios. None of the climate change scenarios have an average lower than the 2000 Level. In the 2020 scenarios, the average elevation of the driest MWD scenario is about 47 feet higher than that of the 2000 Level.

For the 2040 scenarios the driest MWD scenario average elevation is about 60 feet higher than that of the 2000 Level. The lowest elevation of the MWD scenario is 48 feet higher than that of the 2000 Level, which drafted empty.

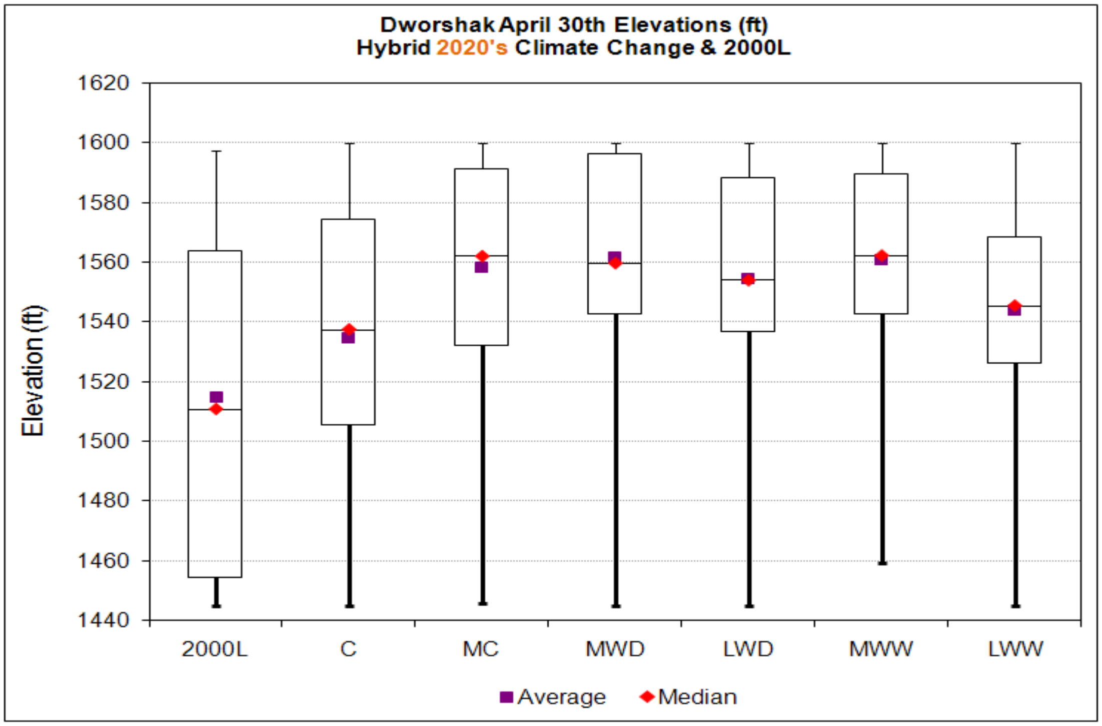

Figure 64. Dworshak April 30 Elevations, 2000 Level & Climate Change Scenarios – HD 2020s.

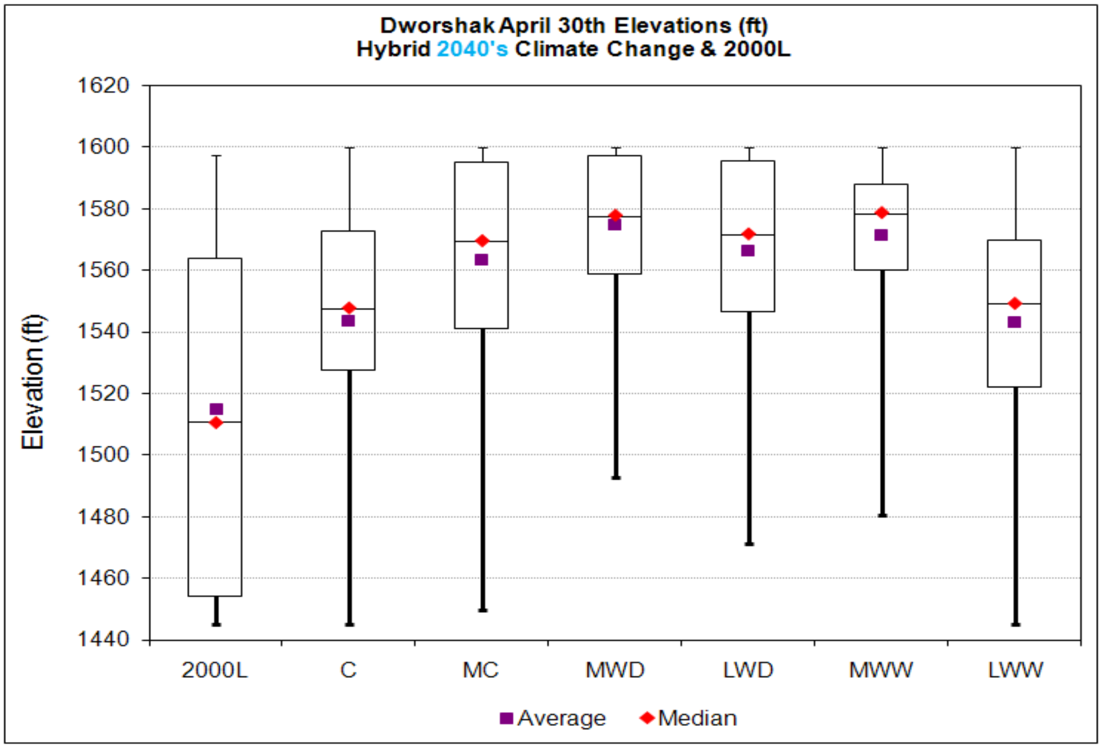

Figure 65. Dworshak April 30 Elevations, 2000 Level & Climate Change Scenarios – HD 2040s.

6.9.6 Flood Control April 30th Elevations Comparisons – Transient

Figure 66 shows the April 30 flood control elevation comparisons between the Transient and 2000 Level scenarios, the Transient ensemble median and its linear trend line. Over time, the median flood control elevations increase approximately thirty feet from El. 1525 to El. 1555 feet, or about 417 kaf, which is reflective of the decrease in Dworshak's ensemble median runoff volume trend.

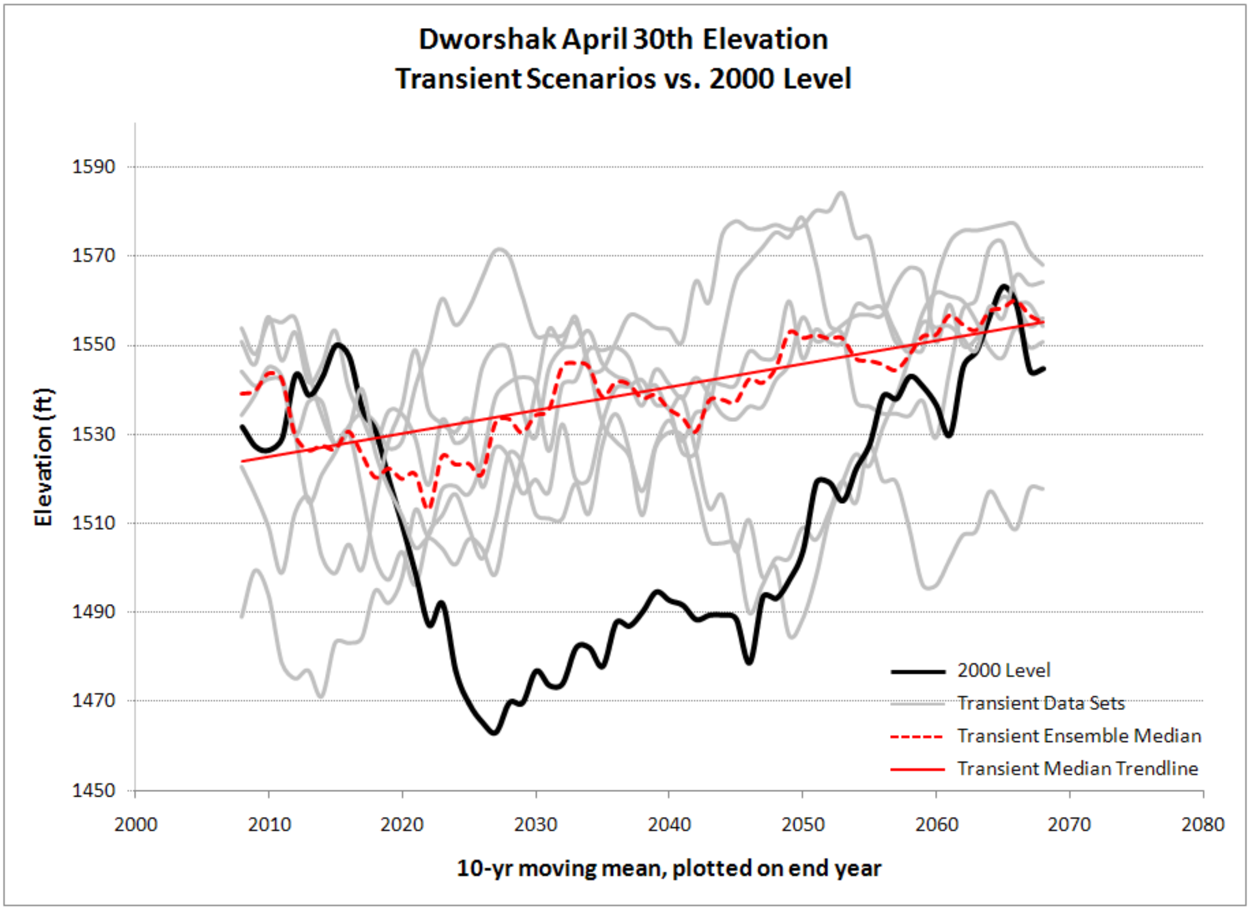

Figure 66. Dworshak 30 Elevations Rolling Average – Transient.

6.9.7 Dworshak Summary

Climate change projections used in this study show the Clearwater basin to be much wetter in the November through March period than for 2000 Level and drier in the May through August period. The higher and earlier winter volumes may indicate that earlier and deeper winter flood control drafts may be warranted. The peak monthly runoff occurs in May for the majority of the climate change scenarios and for the 2000 Level. The April-July seasonal volumes are drier in the climate change scenarios than in the 2000 Level scenario which generally results in higher reservoir levels. In many of the Hybrid-Delta scenarios, there is one year from each scenario where the runoff volume is higher than the highest of the 2000 Level set.

The average April 30th elevations are always higher in the climate change scenarios than in the 2000 level. The maximum difference (in average values) is 60 feet higher for the driest scenario. Generally, Dworshak flood control elevations are higher than the 2000 Level scenario due to generally lower seasonal volumes.

The Transient scenarios show that over the 70-year period, there is a decline of April through July runoff volumes of approximately 14%, and the ensemble median flood control elevations increase approximately thirty feet, or about 417 kaf, which is reflective of the decrease in Dworshak's ensemble median runoff volume trend.

7.0 IMPLICATIONS OF CLIMATE CHANGE ON FLOOD CONTROL OPERATIONS

The following paragraphs address the possible implications of climate change to flood control.

Are existing space and procedures adequate? The basic objective for flood regulations is to operate reservoirs to reduce to non-damaging levels the stages at all potential flood damage areas or to the lowest possible level with the available storage space. As designed, the current draft procedures can adapt to manage the range of Apr-Aug climate change volumes at The Dalles because the climate change range of volumes are similar to that of the historic volumes from 1929-1998. However, the current system flood control space and the distribution of that space were determined based on a balance between system development costs and damages prevented, knowing that the flood control system cannot protect for all hydrologic events.

Space required for flood control is based on the amount of snowpack, rainfall during the refill season, and shape and timing of the runoff. At The Dalles, ninety-nine percent of the observed April-August runoff volumes from the climate change data are less than the maximum volume from the 2000 Level data set. While the climate change runoff volumes are within the range of the 2000 Level data, an analysis using daily modeling is needed to evaluate the effect of the timing and shape of the peak of the climate change projections to assess how existing procedures and maximum flood space perform with climate change flows as compared to the 2000 Level flows.

In years when regulated flows are expected to exceed a certain threshold, there is additional space in Canadian Treaty reservoirs available for a fee. Impacts to Canadian projects with climate change are planned to be studied under the Columbia River Treaty 2014 Review program that is considering continuing, terminating, or modifying the Columbia River Treaty. In Columbia River Treaty 2014 program, it is planned that daily modeling would be performed with a wider range of possible climate change scenarios before concluding the impact of climate change on flood control space needs.

Drafting Earlier to Capture Earlier Spring Snowmelt. For system flood control, the shift of average monthly peak flow timing from June to May, and the increase of March through July compared to the April through August runoff volumes (current forecast period) at The Dalles indicate that earlier maximum drafts of flood control projects may be needed. For example, currently, Grand Coulee evacuates the reservoir beginning in January, February or March to its maximum draft by April 30. With the shift in peak flow timing and increase in

March through July runoff, Grand Coulee may need to begin drafting in December to reach a maximum draft by the end of March (subject to the maximum daily draft rate).

Winter Flood Control. Winter flood control is needed for rain-driven-events and rain-on-snow events. For example, for Dworshak, climate change projections show that project inflows in late fall and early winter events are much higher than in the 2000 Level scenario. The current winter flood control draft is 700 kaf draft in December. Because climate change projected flows are higher and may be occurring earlier beginning in about November, drafts for winter events may need to occur earlier, say October, and draft deeper to accommodate the increased inflows in November and thereafter.

Conflicts between Winter and Spring flood control. Conflicts between drafting earlier for spring snowmelt and reducing winter flooding may increase. While projects are drafting to meet their April flood control requirements, high winter rain events may occur at the same time. Earlier maximum drafts may require drafting at a steeper rate or beginning the draft earlier. However, drafting at a steeper rate for spring flood needs along with higher winter and early spring unregulated flows could increase winter and early spring flooding.

Project Operational Constraints. Some projects may have operating constraints that limit reservoir draft rates due to dam safety, downstream safety or other non- power operational reasons. It may be desired to limit spilling for water quality purposes and power purposes. These constraints need to be considered if there is a need to draft to the maximum evacuation point earlier.

Evaluation of very high events. Most of the climate change scenario data sets contained higher forecasted spring runoff volumes than the maximum runoff volume from the 2000 Level. These highest runoff volume years should be further evaluated to determine the possible risks to flood control.

Snow vs. rain-driven. The Columbia River flood control system is primarily snow driven. Climate change projections show that the basin may be tending toward more rain-driven flood events. More attention is needed regarding impacts from high winter flow events. Given that winter flood events are less predictable than snowmelt driven events, and may tend to occur more often with climate change, changes in flood operating criteria may be needed, such as deeper minimum winter drafts that are constant every year. During the refill season there may be more rain events. These rain events that may cause high flows, especially when coupled with snowmelt, may make spring inflows more unpredictable than if it were snowmelt dominated. Communications and coordination between forecasting and operating agencies during actual operations during the winter and spring may need to increase.

Basin differences. Individual basins respond differently to climate change projections, so a comprehensive analysis meeting basin by basin needs and then incorporating into system considerations is needed. With substantially higher winter flows, further investigation into effects to local flooding is needed.

Effect of Transient Scenarios. Looking at the Transient ensemble scenarios, there was a definite trend in that all median seasonal volume forecasts decrease over time resulting in a trend for the median flood control elevations to increase.

Effect on Levees. Levees that protect the lower Columbia River are a key component of system flood control. With the possibility of more frequent and unpredictable winter flood events where reservoirs may not be able to manage for flood damage reduction, the importance of these levees would increase. Maintenance, repair, and improvements to levees may become a higher priority.

8.0 LIMITATIONS AND UNCERTAINTIES FOR FLOOD CONTROL OPERATIONS

Preparation of flood control curves for this study provides end-of-month flood control requirements during evacuation and estimates of flood control requirements during refill. This section describes limitations and uncertainties in this effort in preparing flood control requirements.

Assessment of flood control for this report is based only on the 20 climate change scenarios selected for analysis. Other scenarios (a total of 34 climate change projections were obtained) not used in this analysis should be considered when attempting to project what climate change means for flood control.

The limitation of this effort with respect to flood control is that the flow objectives at The Dalles should be evaluated using a daily time step system flood control model to determine flood control refill operations. This was not undertaken in this study due to time constraints and uncertainty in the quality of the existing flow data. Therefore, we cannot analyze, from a probabilistic or risk perspective, how adequate existing procedures are at meeting system flood flow objectives with climate change hydrology at this time. To be able to analyze how existing flood control procedures perform using climate change hydrology, flood regulation studies using daily streamflows would be required. Using our current models, regulations are performed one year at a time, results are examined, and the regulation is adjusted as needed to meet the flood flow objective at The Dalles. This method is time consuming and labor intensive and was therefore not used in this study. A new tool is being developed to automate the process, and is planned to be used in future climate change studies.

Another objective for the Columbia River system is to refill the projects so that stored water can be used to augment flows for fish and for power generation in the summer, fall, and early winter. Daily modeling would assist in answering the question of how climate change can effect refill.

Uncertainties in the forecast seasonal volumes and the timing of the runoff in late spring and early summer are the major factors in being able to control flood flows to desired levels. With climate change, results suggest that forecast skill diminishes for most locations as warming causes snowpack to diminish.

9.0 HYDSIM – HYDRO REGULATION MODEL

The Hydro Simulator Program (HydSim) is a monthly hydro-regulation model that simulates the operation of seventy hydro-projects (depending on particular studies) in the Pacific Northwest under specific stream flow conditions and operating requirements. The model is used to determine the hydro-system's energy capability, along with each project's outflow and ending storage contents. HydSim is a deterministic model, not an optimizer (e.g. of power generation).

The HydSim model simulates one period (month) at a time, not using any forwarding-looking process. April and August are split into two half-periods because these months have significant natural flow differences between their first and second halves.

The model is typically run using historical stream flow for water year sequences 1929 through 1998. HydSim could also be run using stream flow traces generated by the Ensemble Stream-flow Predictor (ESP) model. The ESP model applies historical 1949 through 2003 weather patterns to current snowpack and soil conditions to create a forecasted set of stream flows.

HydSim could be run in a continuous mode where at the beginning of each operational year (first half of August), each project's initial storage contents match its ending storage contents of the previous water year (previous July). Alternatively, the model could be run in a refill mode where each project's storage content is initialized to the same value at the beginning of all water years. Typically, mid-term studies (three to eighteen months out) are run in refill mode, while long-term studies (more than eighteen months out) are run in continuous mode.

The projects modeled in HydSim could be classified as either storage or run-of-river projects, described briefly below:

- Storage reservoirs regulate inflows to adjust the river's natural flow pattern to reshape water on a seasonal basis to conform more closely to water uses. Storage projects capture spring and summer snowpack runoff for late summer and autumn release when natural stream flows are low.

- Run-of-river projects have limited storage capability and pass inflow on a day-average basis. They were developed for navigation and hydro-power generation.

For each period, the model reads input files containing unregulated natural stream flow, power load (demand) forecasts, power resources such as wind generation, thermal plants and hydro-independent projects (smaller projects not regulated by Hydsim), operating rule curves and operating requirements (see the next section for more details). Subtracting wind, thermal and hydro-independent resources from the total load yields a reduced load referred to as the

”residual hydro load” which is one of the objectives HydSim operates the hydro system to meet.

Starting typically at the first period of August with a set of prescribed initial storage contents, HydSim regulates each project to draft, or fill, proportionally to meet the residual hydro load beginning with upstream projects and working downstream while simultaneously checking that outflow and content requirements are met. If there are conflicting requirements while attempting to meet load and operating objectives, the model follows a priority list of constraints to determine the final operation for each project.

HydSim is used to model a variety of mid and long-term planning some of which include fish operations, load and resource studies, inventory projections and outage planning. The next section contains some details of HydSim modeling.

9.1 Model Description and Rule Curves

HydSim regulates the operation of each project according to a set of rule curves, which are mainly determined by stream flows, flood control, loads, project physical limitations and non-power requirements such as minimum outflow and elevations for fish operations, and minimum elevation for recreation.

As an example of how HydSim regulates a storage project, Libby dam will be presented in the following narrative. For simplicity, changes in Libby reservoir elevation over a historical year are presented as examples on how various requirements and objectives lead to rule curves that determine project operations.

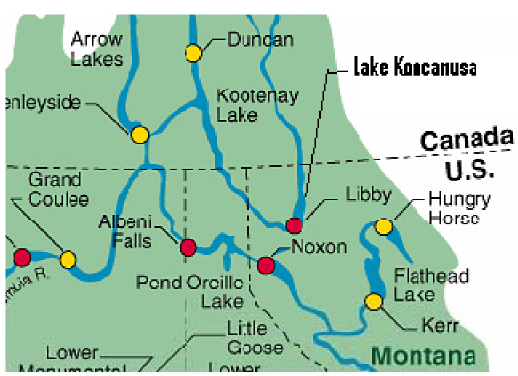

Figure 67. Libby Dam and Lake Koocanusa.

Libby Dam is located on the Kootenai River in northwestern Montana, about 40 miles south of the Canadian border. Most of the 8,985 square mile drainage basin above the dam lies in

British Columbia, Canada. The dam has about 5.0 million acre-feet of active storage in Lake Koocanusa and is operated for the multiple, and often conflicting, objectives of hydropower production, storage space for both local and Columbia River System flood control, water quality and quantity targets for fishery concerns, and local recreation. Some of the Libby project characteristics are: normal full pool elevation at 2,459 feet, normal minimum pool elevation at 2,287 feet, minimum outflow at 4,000 cubic feet per second, and maximum outflow restricted by a daily limit on the change in the tailwater, the height of water above sea level as it leaves the dam. The reservoir also has five turbine generator units in a powerhouse with a total of 525 megawatts (MW) of capacity.

Located east of the Cascades Mountain Range, Libby is influenced by a seasonal weather pattern where most of the precipitation occurs during winter months. During that time, snow accumulates and water is held in natural storage until temperature rises, causing spring stream flow runoff. Stream flows begin to rise in mid-April, reaching a peak flow during May or early June. Occasionally rainfall adds to the flow. Rain and snowmelt over the low-lying portions of the basin in the winter can also raise stream flows and cause flooding.

9.1.1 Energy Content Curve (ECC)

Given forecasted stream flows at Libby, HydSim computes the Energy Content Curve (ECC) (see the HydSim Manual for more details). The ECC is a lower limit on a project's storage content whose objective is to have a high probability of achieving full storage content at the end of the operating year, which is July. As an example the ECC for Libby using the 1937 historical stream flows is shown below.

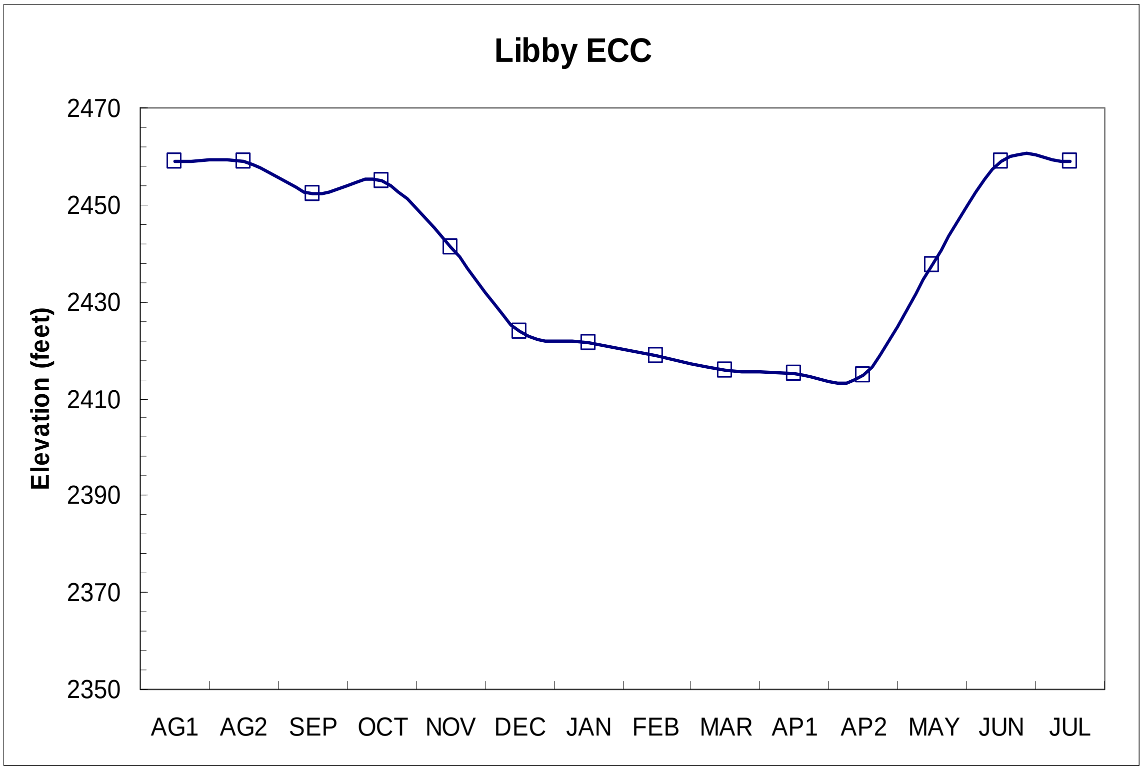

Figure 68. Libby ECC for the 1937 water-year historic stream flow.

Notice that indeed at the end of July, the water elevation behind Libby Dam is at a maximum elevation of 2,459 ft. Since the ECCs intention is to have Libby full again by the next July, and with the anticipated snowpack accumulation during winter and eventual snowmelt in spring for the upcoming operating year, the reservoir must be drafted (water released from the reservoir) down sufficiently around spring to have enough space to hold the anticipated snowmelt runoff. Hence the drawdown begins October and continues until the reservoir reaches a minimum in the second period of April, when snowmelt runoff typically begins. From that point onward Libby starts to refill until it reaches the maximum pool elevation in July.

9.1.2 Upper Rule Curve (URC)

HydSim would operate Libby to the ECC if full storage by July were the only objective. However, the project will operate to the flood control curve if it is lower than the ECC. The flood control curve, also referred to as the Upper Rule Curve (URC), assures that a reservoir is drafted to ensure space is available to capture snowmelt that would otherwise be passed downstream causing potential flooding. The 1937 Libby URC is shown below.

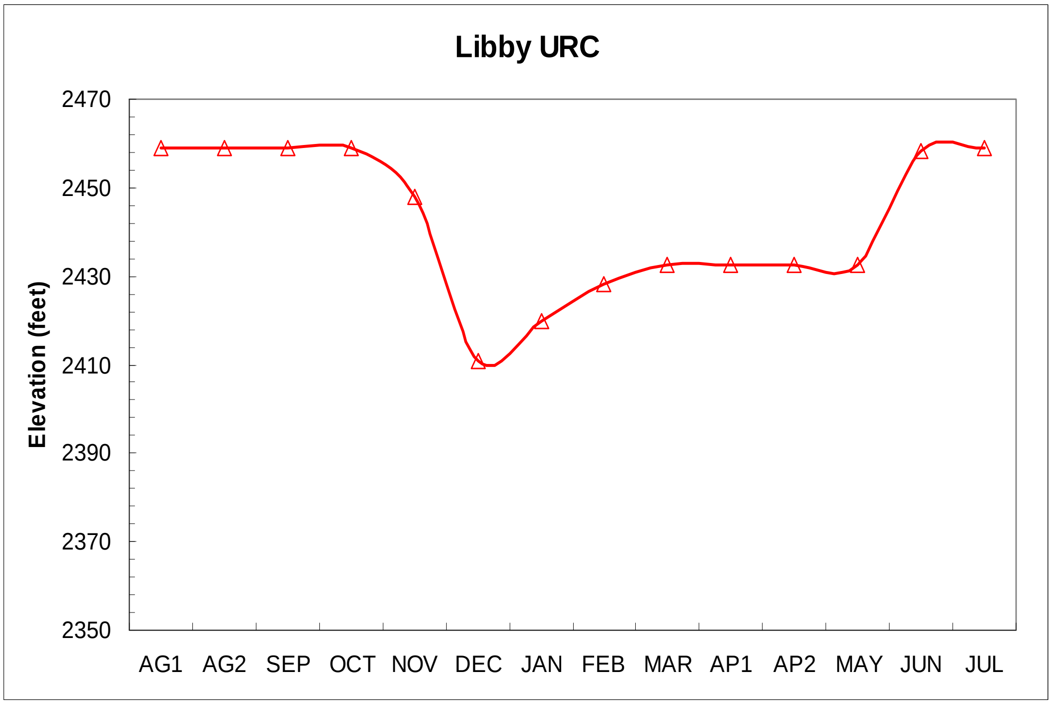

Figure 69. Libby URC for the 1937 water-year historic stream flow.

Both the ECC and URC for Libby are plotted for comparison below.

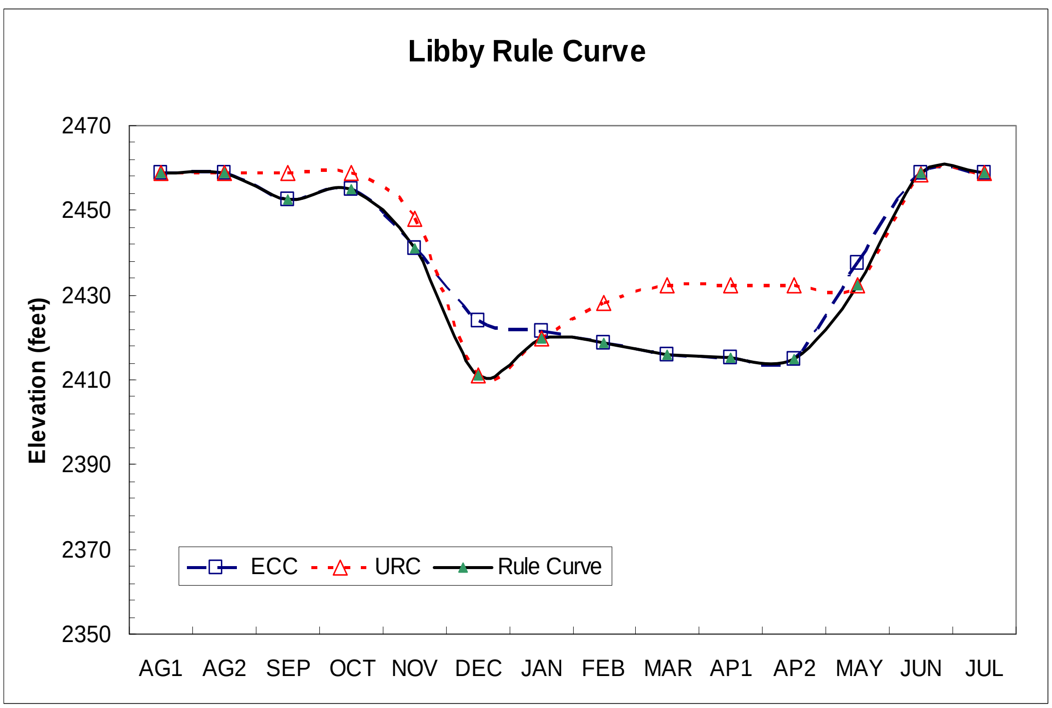

Figure 70. Comparison between Libby ECC, URC and Operating Rule Curve.

As seen in the plot, for December, January and May the ECC (blue dashed curve) is higher than the URC (red dotted curve) during the same time, leaving Libby potentially not having enough storage for forecasted runoff. Hence for those months, HydSim would draft Libby deeper than the ECC, down to the URC level, to have potentially enough storage for runoff. Libby then will operate to the resulting rule curve (black solid curve) if flood control and July refill were the only objectives (note that Libby often operates to minimum flows or URC during this period). As part of the normal project operation, water flows through Libby's turbine generators and produces power.

9.1.3 Proportional Draft Points (PDPs) to Meet Load

One planning principle that was adopted by the region during the 1960s era of the PNCA, was the ability of the region to meet power loads by coordinating reservoir draft in an equitable and efficient manner. Proportionally drafting projects was this mechanism. The early planners and authors of this principle had no inkling of the non-power fishery and Endangered Species Act (ESA) requirements that would come to bear on the region in the coming decades. As a consequence, proportional draft logic does remain in the planning process and in the HydSim model logic, but its influence on modeling outcomes has been minimized to a degree. Other modeling requirements that reflect more current objectives often overwrite the projects operations resulting from the PDP logic. This short description and example of PDP logic described below (using Libby as an example), applies primarily to the first or second step of the three step modeling process (See section 10.2 for a more complete description).

In an average water year with enough runoff, Libby could generate enough power to meet its share of the Residual Hydro-Load, defined as the Firm Energy Load Carrying Capability (FELCC) as it operates for flood control and refill. But in a low water year such as 1937, HydSim would operate the reservoir to release more water through turbines to generate the additional power to meet load, thus drafting the reservoir lower (than the flood-control and refill rule curve) in a proportional manner with the other storage projects. The plot below compares the flood-control and refill rule curve (black) that could not meet load and the lower rule curve (blue) that could. By drafting much deeper than the flood-control and refill curve to meet load, HydSim could not operate Libby back to full storage content in July.

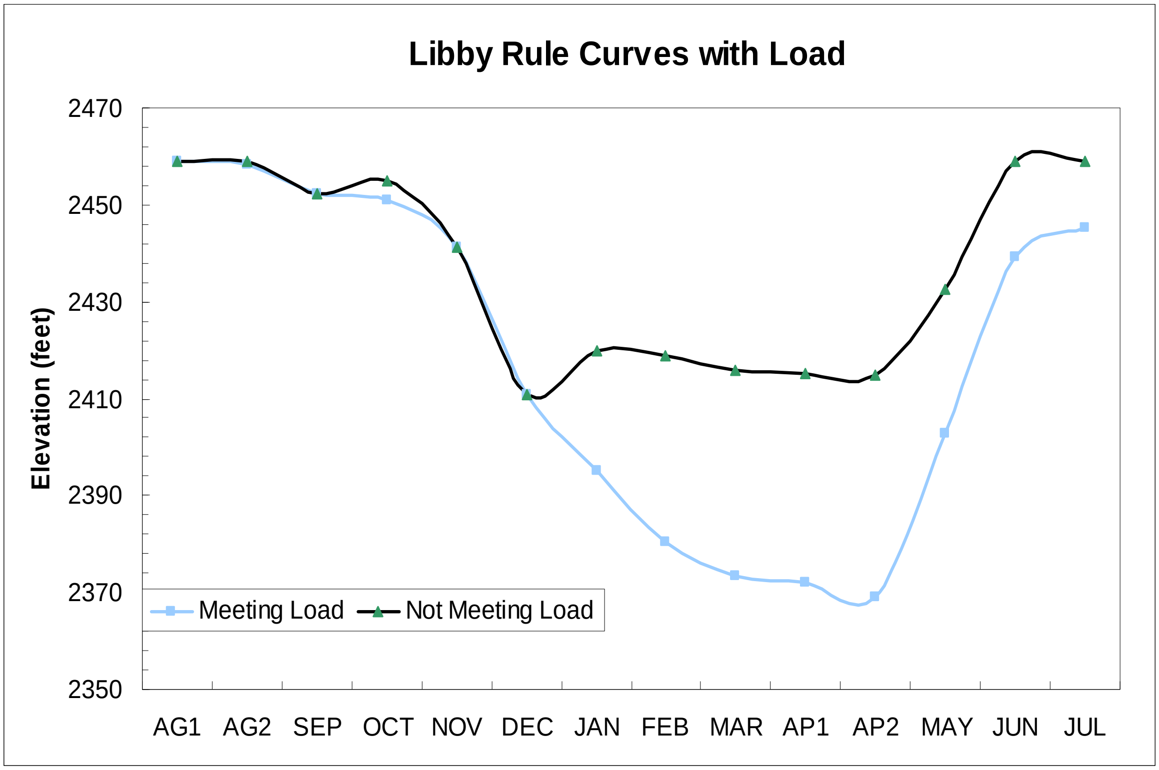

Figure 71. Libby Operating Rule Curve for FELCC Loads

9.1.4 Non-Power Requirements (NPRs)

However, for other studies such as Actual Energy Regulation (AER), HydSim in addition, takes into account non-power requirements (NPRs) such as minimum outflow at certain projects for fish operation, or minimum elevation at other projects for recreation. For example, among the many NPRs at Libby are the specified outflows for sturgeon from May to June, and for salmon and bull trout from July to September. To have the amount of water available for these NPRs from late spring to the end of summer, the reservoir elevation must be kept as high as possible from fall to spring, which means keeping the elevation close to URC, the flood-control curve. Because the NPRs have higher priority than meeting load, HydSim would modify the load-meeting rule curve (blue) to the NPR-meeting rule curve (green) to operate Libby, shown in the plot below.

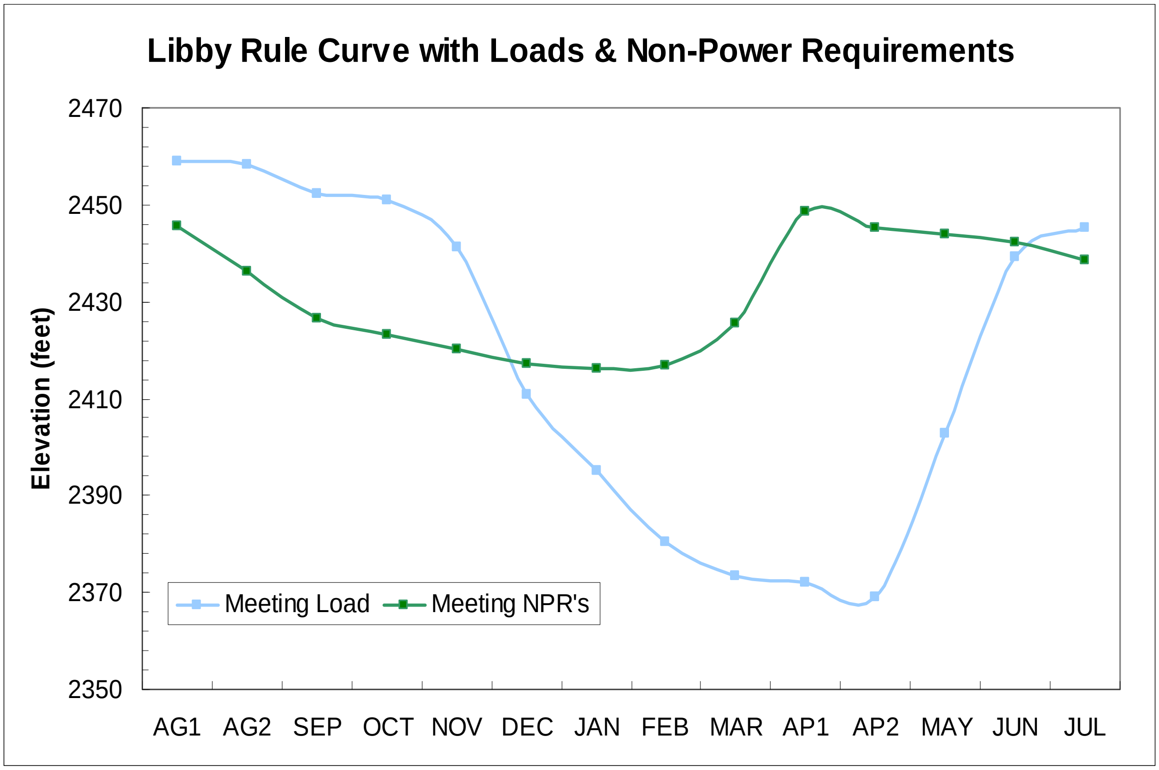

Figure 72. Libby Rule Curve for FELCC and NPRs

Finally, the green curve in the figure above is the operating rule curve for Libby for the historical 1937 operating year. This rule curve operates the reservoir for flood control, to satisfy NPRs and to meet load whenever possible. However, because of the low water condition, it is not possible to refill Libby by July. The U.S. storage projects generally target refilling their reservoirs by July 1.

9.2 Running the HydSim Model – A Three-Step Modeling Process

The climate-change studies in this Part were based on adopting the version of the Hydsim model and data that was used for the 2012 BPA Rate Case analysis, which among other functions, calculates hydro power generation subject to project characteristics, meeting loads and NPRs. An existing study that was run for the 2012 Rate Case analysis was adopted as the Base Case study to which each of the climate change scenarios could be compared. The study was modified to some degree to reduce the complexity of the study and to better accommodate the many climate change scenarios that would be modeled in a similar manner. This Base Case study, as well as all the climate change scenario studies, consisted of running

HydSim in three different modes or steps: the Treaty Storage Regulation (TSR), Actual Energy Regulation (AER) and Operation (OPER). Each of these three steps is described briefly below.

9.2.1 TSR Step

The first model run is the TSR that conforms to the Columbia River Treaty with Canada as defined in the Detailed Operating Plan (DOP) for each year. Studies in this report follow the DOP10. The TSR regulates the seventy or so hydro-projects to meet flood control and load without imposing any NPRs except NPR's for the lower Snake River projects are included.. When the TSR is completed, operations of the main Canadian projects which are Mica, Duncan and Arrow, are then fixed as input into the AER Step. The TSR step is most influenced by PDP logic to meet power loads.

9.2.2 AER Step

The AER model is run next (Mica, Duncan and Arrow operations are fixed from the TSR. Fixed, meaning resulting month end elevations in the TSR are input directly into the AER for the remaining US federal and non-federal projects according to the Pacific Northwest Coordination Agreement (PNCA Operating Year 2010) operating criteria. The US projects are regulated to meet the NPRs specified in the PNCA in addition to load (if possible) and flood control. The NPR's include fish operations, wildlife protection and recreation at various projects. The completed AER then fixes operations of the non-federal projects.

9.2.3 OPER Step

Finally the OPER step is performed (now with the three Canadian and the US non-federal projects fixed) to regulate the US federal projects to meet NPRs that are closer to actual operations than those specified in the PNCA. As an example, the Chum Salmon operation at Bonneville from November to March, PNCA requires a fixed 125 kcfs flow, while actual chum operation defines a variable flow that depends on Bonneville's tailwater elevation. Further complications also arise from Supplemental Operating Agreements (SOAs) with Canada that modify the operations of the three Canadian projects from those specified in the TSR.

In summary, the HydSim model regulates (i) the Canadian projects according to the Columbia River Treaty mainly to meet load, (ii) the US non-federal projects to meet load, if possible, and the PNCA NPRs, and (iii) the US federal projects to meet load, if possible, and a set of more realistic NPRs. All projects are always operated to maintain elevations below the flood control upper rule curves, as a priority.

10.0 OTHER INPUTS INTO HYDSIM

Along with future stream flows from the climate-change scenarios (Section 3.0), HydSim also uses projected power loads and resource data, the details of which are discussed in this section.

10.1 Loads

The power load assumptions used in modeling the climate change scenarios are broken down into three study period horizons. The Base Case scenarios are assuming load levels for OY 2012. The 2020 Hybrid-Delta scenarios are based on load projections for OY 2020 and the 2040 Hybrid-Delta and the transient flow scenarios are both based on load assumptions for OY 2040. All load assumptions were determined by BPA's, Regional Coordination Section with input from BPA's Load Forecasting Group. The loads were broken down into two headings, Federal and Regional (Coordinated System).

The HydSim modeling process utilizes the concept of "residual hydro" loads. The determination of surplus and deficit energy projections for both the Federal and Regional System is based on the following formula:

Generation - Loads = Surplus (or deficit)

Because the HydSim model regulates hydro projects only, other resources such as nuclear, thermal, contract imports, wind, some small hydro projects and hydro independent projects are taken into account by means of off-setting the sum of these resources against the total loads. These resources are broken down into seven headings; non-Federal CER (Canadian entitlement return), renewables, cogeneration, imports, intra-regional transfers in, large thermal and non-utility generation. The remaining load product is referred to as "residual hydro" load because the total load has been reduced to a smaller residual load after netting out the non-modeled resources. For the Federal residual load, the load components fall into three main headings; Federal firm obligations, exports and Intra-regional transfers out.

The surplus / deficit formula then becomes:

Generation (HydSim hydro projects) + Other Generation (not modeled in HydSim; e.g. thermals, nuclear, wind, etc.) – Total Load requirements = Surplus / Deficit

It is generally desirable to utilize existing load forecasts when running special HydSim studies, for two reasons; 1) Time saved in not having to perform new load forecasts and 2) Consistency with other studies that share some commonality in input assumptions. Load data is stored in a BPA data model referred to as LARIS. The source load forecast files used in the climate change studies were taken from the following:

- Base Case (OY 2012): LARIS Study 66 used in 2010 Rate Case
- 2020 Hybrid-Delta scenarios: LARIS Study 67 for OY 2020 (2010 White Book)
- 2040 Hybrid-Delta scenarios: LARIS Study 67 for OY 2040 (2010 White Book)
- Transient scenarios: LARIS Study 67 for OY 2040 (2010 White Book)

10.1.1 Federal Loads

The forecasted Federal residual hydro loads were adjusted for the hydro independents and temperature adjustments. Figure 73 displays the average adjusted loads for the six climate change studies performed using both the 2020 and 2040 Hybrid-Delta flow scenarios. These averages are compared to the Base Case loads assumed for OY 2012.

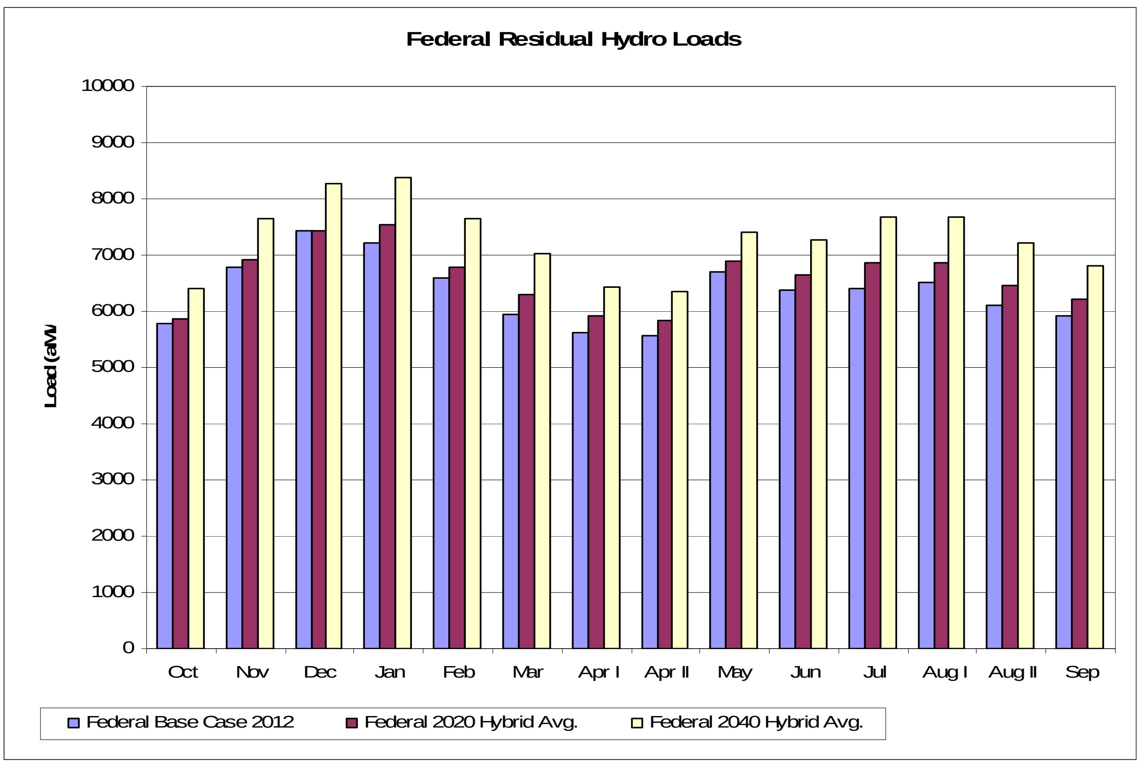

Figure 73. Federal Residual Hydro Loads.

10.1.2 Regional Loads

The forecasted Regional residual hydro loads were adjusted for the hydro independents and temperature adjustments. Figure 74 displays the average adjusted loads for the six climate change studies performed for both the 2020 and 2040 Hybrid-Delta flow scenarios. These averages are compared to the Base Case loads assumed in study 21 for OY 2012. The load forecasts for the 2040 scenarios reflect a significant increase.

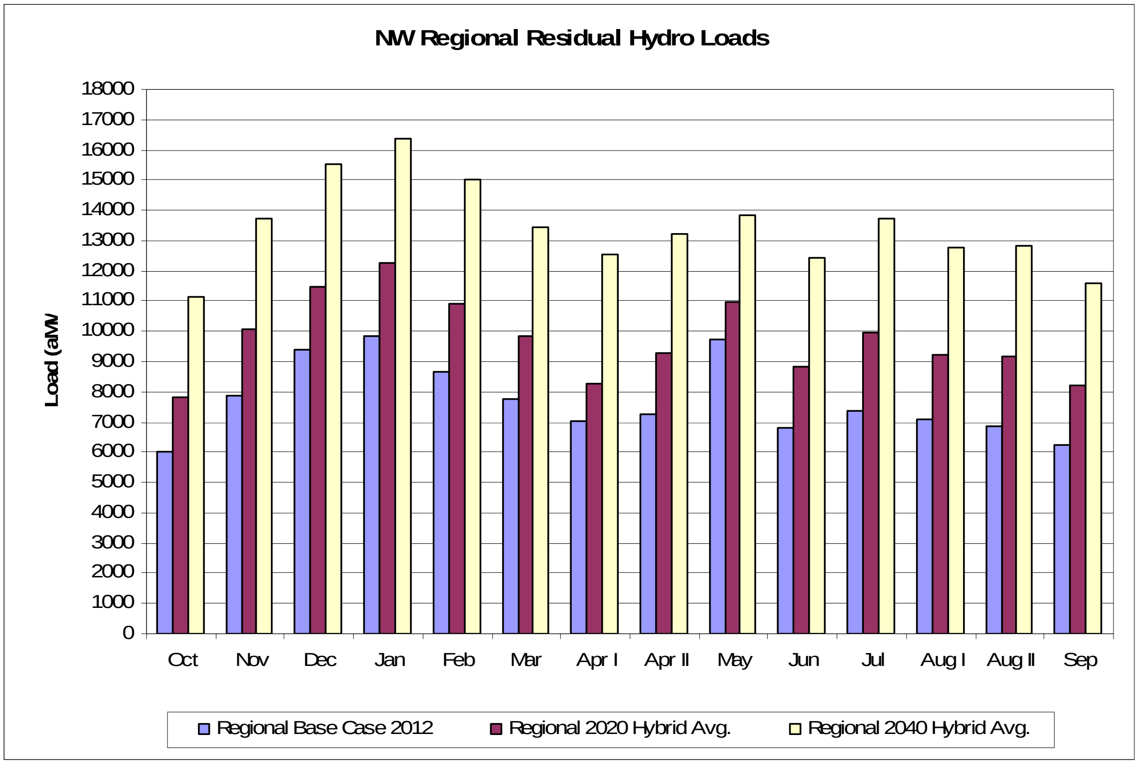

Figure 74. Regional Residual Hydro Loads.

10.2 Temperature Adjustments

Temperature departures from normal influence the load demand. Higher temperatures in the summer will result in higher air conditioning loads. Colder temperatures in the winter will result in high heating loads during the winter season, or conversely, warmer temperatures in the winter will reduce the heating load. Because all of the GCMs agree that climate change will result in increased temperatures in the NW region, it was desired to determine an estimate of the load fluctuations resulting directly from the temperatures associated with each climate scenario. BPA's Load Forecasting and Analysis Section, computed the load adjustments associated with the climate change scenario temperature departures from normal.

Load adjustments were made relative to temperature departures from normal. The “normals” were defined as the 30-year (1970-2000) normal temperatures for the three load centers; Portland, Seattle and Spokane as recorded by the National Weather Service (NWS).

The six scenario average load adjustments for the 2020s and 2040s, based on temperature changes are as follows:

Regional load adjustments for the 2020 Hybrid-Delta scenarios ranged from a high of 224 aMW in July (air conditioning load increases due to warming) to a low of -687 aMW in December (warming, hence heating load decrease). The Federal load adjustments were a high of 166 aMW in July and a low of -237 aMW in December.

Regional load adjustments for the 2040 Hybrid-Delta scenarios ranged from a high of 423 aMW in July (load increase) to a low of -846 aMW in December (load reduction). The Federal load adjustments for the 2040s ranged from a high of 412 aMW in July to a low of -291 aMW in December.

The Transient Flow scenarios were similar to the 2040 Hybrid-Delta load adjustments but to a slightly lesser degree. The results of these load adjustments are provided in Section 11.0.

10.3 Plant Availabilities

Generating projects will in most cases have some turbines that are undergoing maintenance or otherwise unavailable for producing power. It would be therefore be too optimistic to assume that the 100% of the project is available to produce power during every period. The Hydsim model uses the concept of “plant availabilities” to represent a plant factor in terms of percentage of full power generating capacity. The plant availabilities used in the climate change HydSim studies are based on the OY 2012 Rate Case study where the Canadian and U.S. non-federal monthly project availabilities are obtained from the PNCA data submittal on February 1, 2009. The availabilities are expressed in percentages representing of turbine capacity available for generation after accounting for maintenance. For examples, all the Canadian projects are assumed to be 100% available, whereas plant availability at Wells Dam (below Grand Coulee Dam) is less than 100% and listed in table below.

Table 10. Wells Monthly Availability

PROJ	JUL	AG1	AG2	SEP	OCT	NOV	DEC	JAN	FEB	MAR	AP1	AP2	MAY	JUN
Wells	92	92	92	85	85	92	95	93	90	88	92	92	92	92

On the other hand, the US federal project availabilities are calculated from actual monthly project power output averaged from 2001 to 2009. As an example, the Grand Coulee Dam

(GCL) availability is listed in the table below.

Table 11. Grand Coulee Monthly Availability

PROJ	JUL	AG1	AG2	SEP	OCT	NOV	DEC	JAN	FEB	MAR	AP1	AP2	MAY	JUN
GCL	72	71	71	67	67	71	74	76	75	70	72	72	72	72

The monthly availabilities are applied for all seventy years in the HydSim studies.

10.4 Project Objectives

A brief summary of specific project objectives is described below.

Mica, Duncan and Arrow

These three Canadian projects are operating in accordance to the 70-year DOP10 and PNCA OY10. This is a Treaty Storage Regulation (TSR) run to joint Canadian and U.S. objectives including the storage of up to 1 million-acre-feet (Maf) in Arrow to be released to enhance the outmigration of juvenile salmon.

Libby

Libby is operated to minimum flows or flood control during the Jan-April period to increase its ability to reach its URC target on April 10. During the spring-summer period, Libby is operated for flood control, Sturgeon and Bull Trout flow objectives, IJC compliance and BiOp draft targets. During the fall, Libby drafts slightly to reach its variable flood control elevation at the end of December (generally elevation 2411.0 feet unless dry water supply is forecasted for the upcoming April through August period).

Hungry Horse

Similarly to Libby, Hungry Horse is operated in Jan-April to meet a minimum flow at Columbia Falls (typically 3,500 cfs) or flood control,) as it targets its April 10 URC elevation. During the spring-summer period, Hungry Horse attempts to refill to full elevation by June 30 (elev. 3560.0 feet.) while maintaining flood control objectives. The project then drafts to either elevation 3540.0 feet (low water) or 3550.0 feet by Sept. 30, depending on the April through August water supply. During the fall, the project operates to maintain a minimum flow of 3,500 cfs at Columbia Falls while staying below its December 31 URC elevation of approximately 3549 feet.

Grand Coulee

Grand Coulee operates between its variable draft limit and URC during the January through April period, as it targets its April 10 URC elevation. During this period it is also operating to support Chum Salmon below Bonneville Dam and minimum flows at Priest Rapids in support of Fall Chinook spawning at Vernita Bar. During the spring, Grand Coulee continues to operate for flood control, provide minimum Steelhead flows of approximately 135 kcfs below Priest Rapids and provide the BiOp minimum flow objectives at McNary. Grand Coulee attempts to refill by June 30 to maximize summer releases for the juvenile Salmon outmigration as it attempts to support the McNary Dam summer BiOp flow targets. The project drafts to elevation 1278-1280 feet on August 31, then operates to meet load and support Chum Salmon spawning efforts below Bonneville Dam, while drafting no deeper than elevation 1270 feet in December. Banks Lake is also actively pumping water from above Grand Coulee into Banks Lake to support Central Washington irrigation efforts. This operation runs from early spring to late summer.

Dworshak

Dworshak generally operates to meet Snake River fishery objectives during the summer. The project typically runs on minimum flow or flood control flows during the Jan-April period to increase the likelihood of hitting its April 10 URC target. During the spring-summer period, the project operates to flood control as it fills towards full (elevation 1600 feet) on June 30. The project then drafts to elevation 1535 feet at the end of August and then elev. 1520 feet at the end of September to increase Snake River flows for outmigration of juvenile Salmon and to release cooler water into the Snake River for additional fish survival measures.

Lower Columbia and Snake River projects

The four Lower Snake projects; Lower Granite, Little Goose, Lower Monumental and Ice Harbor and the four Lower Columbia River projects, McNary, John Day, The Dalles and Bonneville, all operate to spring and summer spill operations as defined in the Corps 2010 Water Management Plan.

11.0 MODELING RESULTS

The results of the climate change scenarios are described in this section and generally shown with respect to the Base Case study.

11.1 Summary Approach

The general approach to assessing the impacts of climate change on the Columbia River Hydro system is to first establish a Base Case study – meaning a study that regulates the hydro projects under current objectives, streamflows, loads, and modeling procedures. Secondly, this Base Case study is rerun after replacing the current assumed variables with the new climate change assumed variables. The differences between these two studies would then be attributed to climate change conditions. The Base Case study was based on a current hydro regulation with modeling input assumptions for the operating year 2012. The climate change scenarios introduce two variables that are expected to change with global warming. These two variables are the streamflows and loads. Streamflows are influenced by precipitation (rain and snow), among other considerations, and both streamflows and loads are influenced by temperatures. The streamflows (water supply) for each climate change scenario are described in more detail in Part 1, Section 4.0. The load adjustments resulting from future climate temperature changes are described in Section 10.2 of this Part.

Because loads are projected to increase in time due to population load growth and increasing temperatures, the future climate change periods described under the headings, 2020s (2010-2039), 2040s (2030-2059) and Transient flow period (1999-2068) also include project load growth values for these periods.

11.2 Project Operations

11.2.1 Arrow

Operation of the Canadian projects is heavily influenced by the Assured Operating Plan (AOP) and the DOP. These plans are part of the Treaty between the United States and Canada and help to coordinate operation of the Columbia River. The 70-year average discharge of each 2020 and 2040 Hybrid-Delta scenario are shown in the two figures below along with the Base Case study. The dry scenarios (LW/D and MW/D), result in lower outflows during the fall and winter. The medium and wetter scenarios result in higher discharges from Arrow in this same period. This trend increases between the 2020 and 2040 Hybrid-Delta studies.

Discharge during the April through June period is constrained by a trout spawning operation at Arrow and variability between studies is relatively low for the Base Case and 2020 Hybrid-Delta studies. However, the 2040 Hybrid-Delta studies begin to trend toward higher discharge relative to the Base Case during this time. The scenario with the highest flows during this period is the more warm and wet scenario (MW/W). During the summer months flows tend to be near to above the Base Case during July and then near to below the Base Case during August and September. This trend increases between the 2020 and 2040 Hybrid-Delta studies.

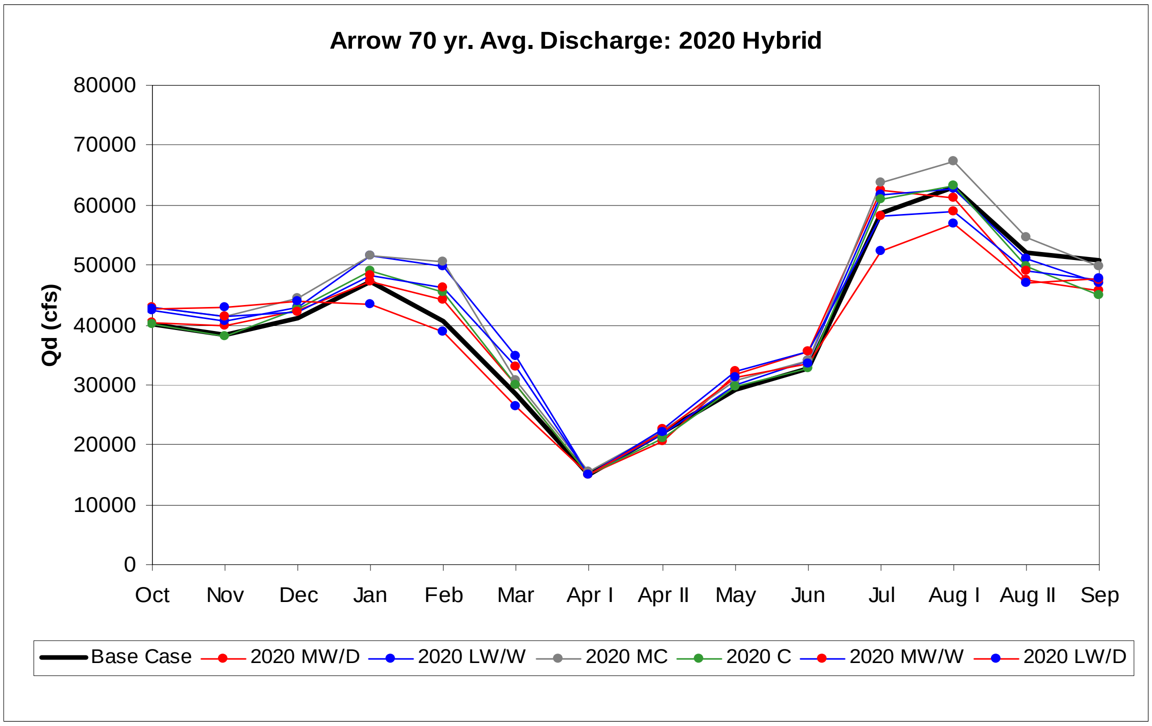

Figure 75. Arrow Discharge: 2020 Hybrid-Delta.

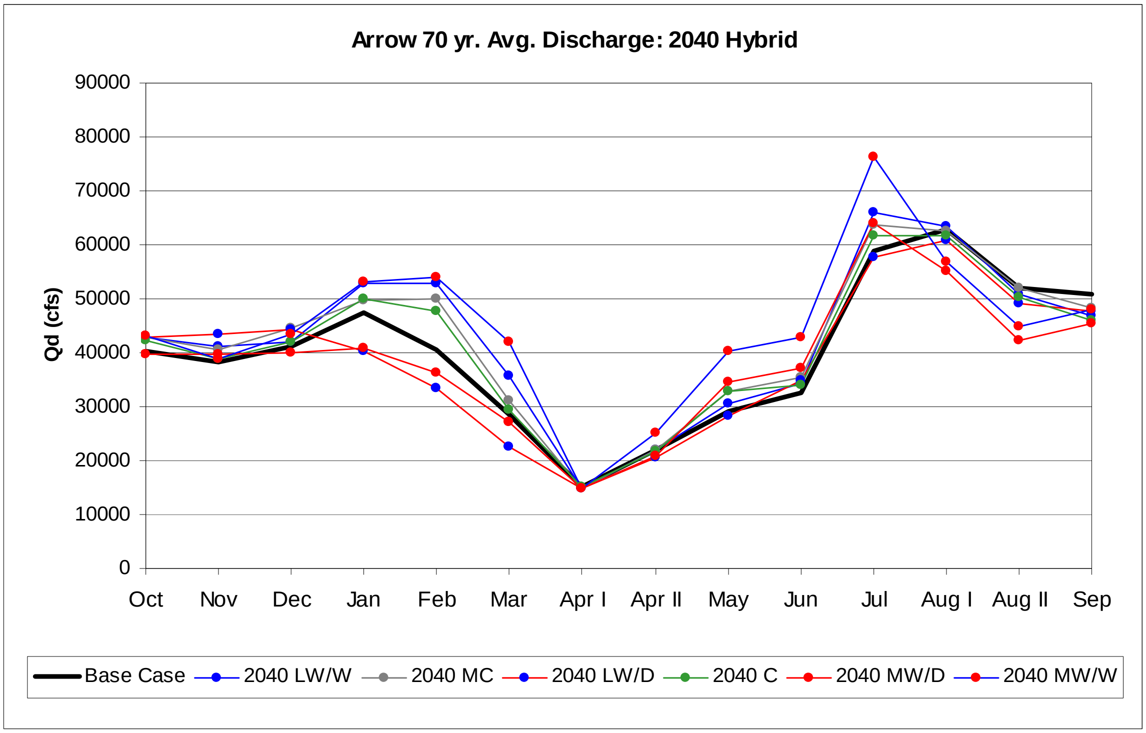

Figure 76. Arrow Discharge: 2040 Hybrid-Delta.

The 70-year average period elevations of each 2020 and 2040 Hybrid-Delta scenario are shown in Figure 77 and Figure 78 along with the Base Case scenario. During the October through January period the elevation of all scenarios with the exception of the drier scenarios (MW/D and LW/D) tend to be near, to above the average Base Case elevations. This trend changes during the period February through April when the medium and wetter scenarios tend to draft deeper than the Base Case study. During the summer months the drier and warmer years tend to have lower average Arrow elevation relative to the Base Case. These trends become more apparent between the 2020 and 2040 Hybrid-Delta studies.

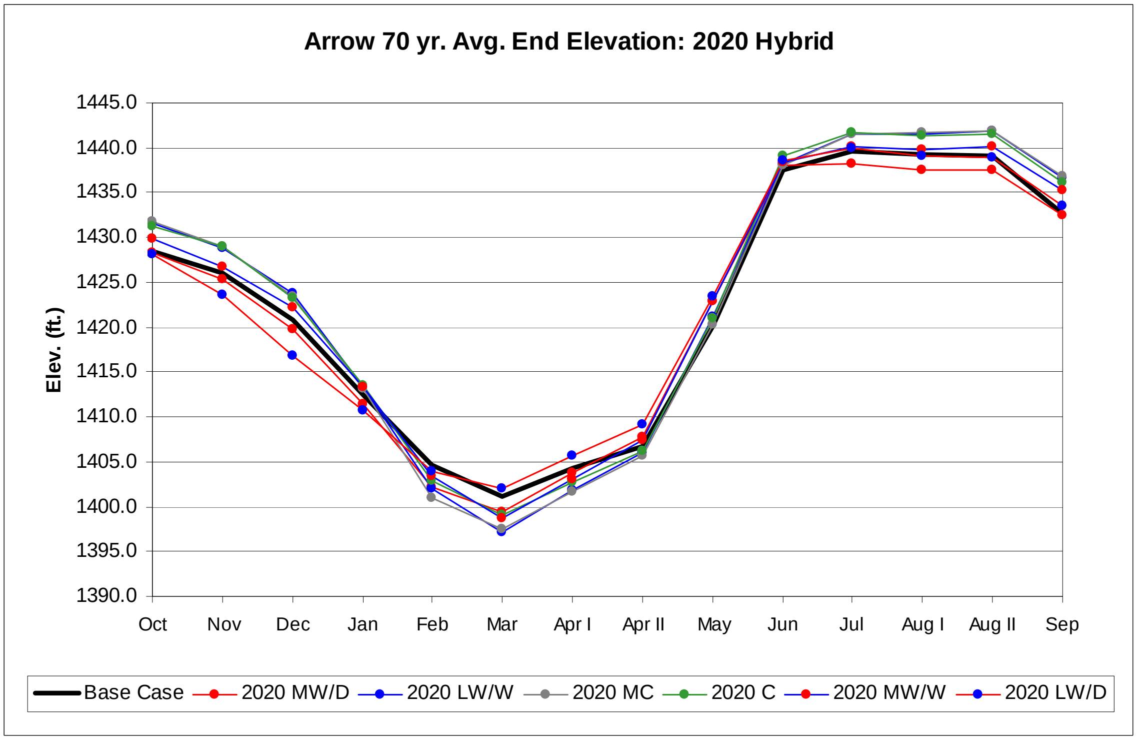

Figure 77. Arrow End Elevations: 2020s Hybrid-Delta.

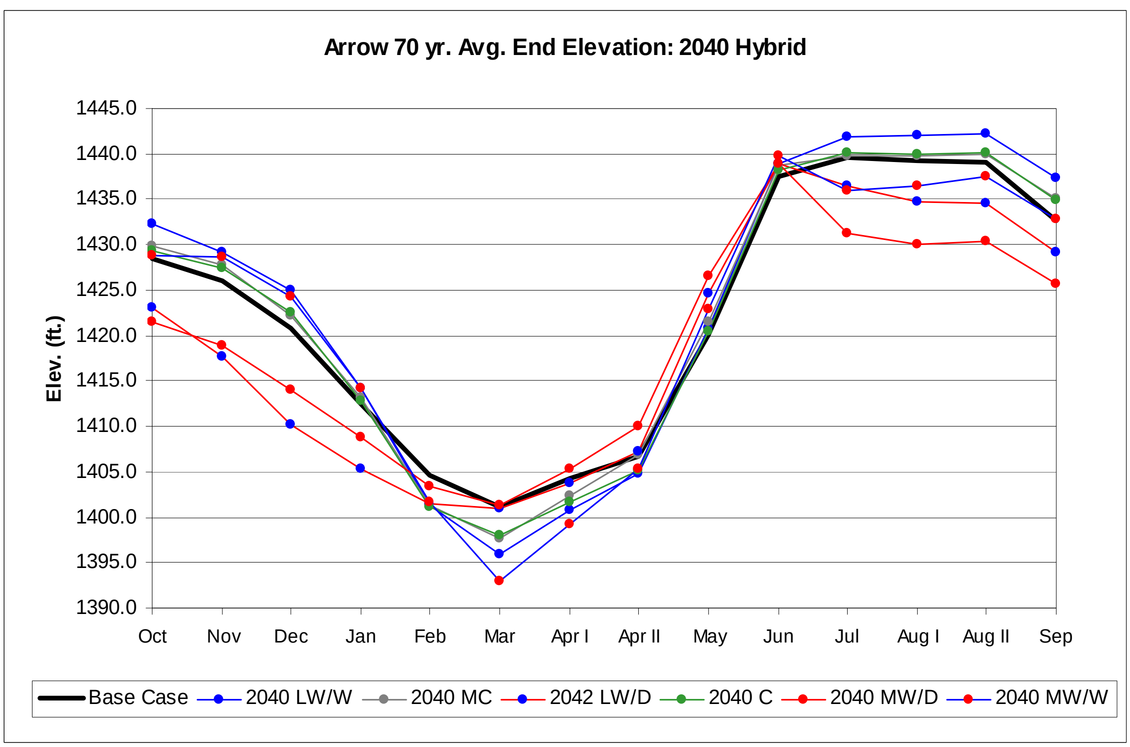

Figure 78. Arrow End Elevation: 2040s Hybrid-Delta.

11.2.2 Libby

A comparison of the average Libby discharge between the Base Case study, 2020 Hybrid-Delta and 2040 Hybrid-Delta studies, are shown in Figure 79. One obvious trend in this figure is the increase in discharge among the various climate change scenarios during the periods April 16 through June 30 when compared to the Base Case. There is also a slightly reduced average discharge in the climate change scenarios relative to the Base Case during the July 1 through August 15 periods.

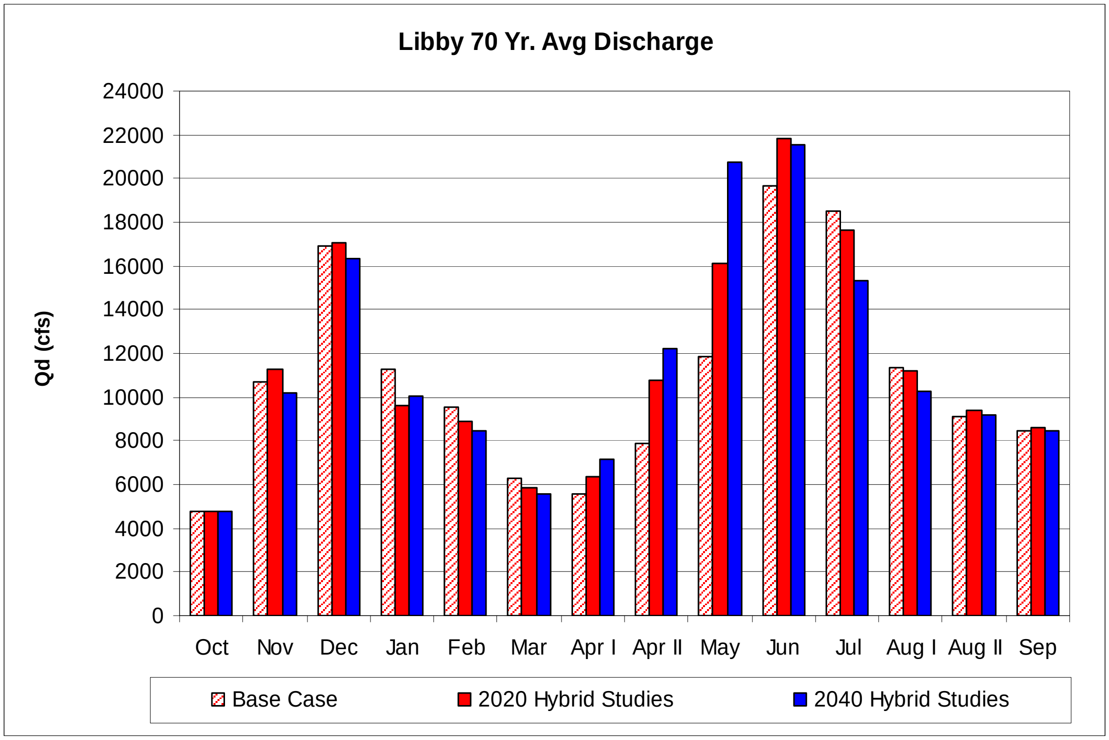

Figure 79. Libby Average Monthly Discharge for Base Case and Climate Change Scenarios.

The average period Libby reservoir end elevations for the Base Case, 2020 Hybrid-Delta and 2040 Hybrid-Delta studies are shown in Figure 80. Elevations during the summer and fall are similar among all climate change scenarios. However, during the January through April flood control drawdown period and the May refill period, average reservoir elevations are much higher in the climate change scenarios. Several variables can influence the reduced drawdown at Libby; among them are water supply forecasts, timing and shape of the spring freshet, and limited discharge downstream at Kootenay Lake due to a channel restriction. A discussion of channel restricted flow and trapped storage at Libby and how it impacts reservoir operations is provided in a later section.

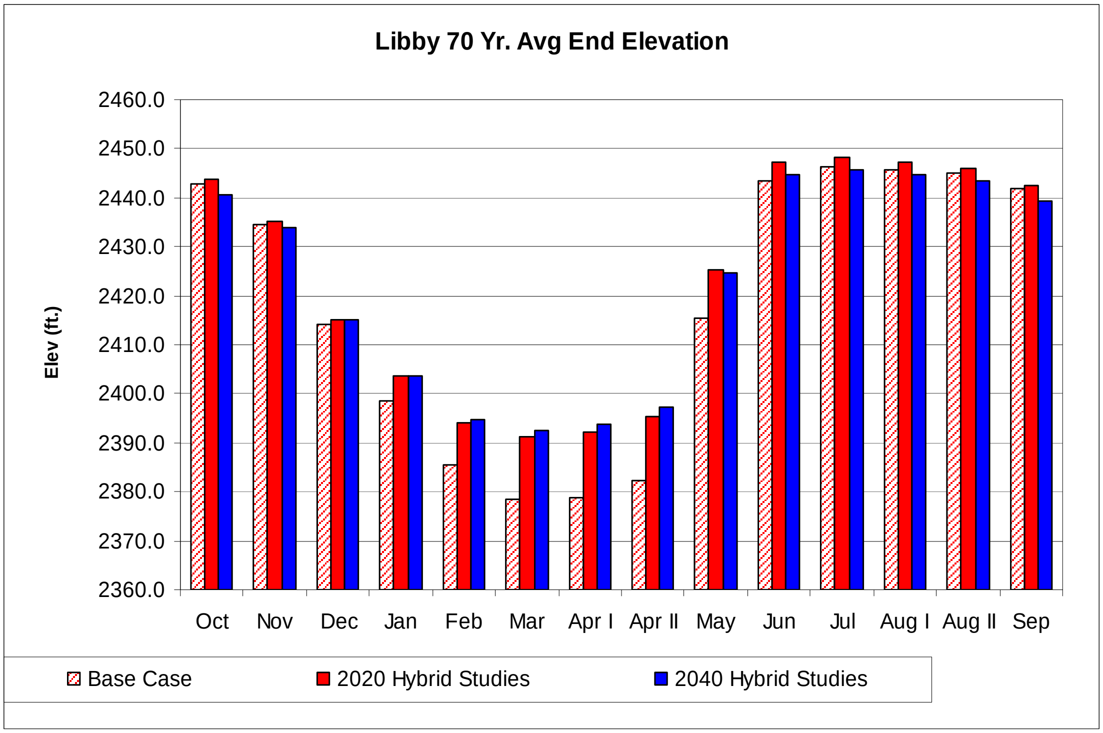

Figure 80. Libby Average End Elevation for Base Case and Climate Change Scenarios.

Figure 81 and Figure 82 provide a more in-depth comparison of discharge and reservoir elevation between 2020 Hybrid-Delta climate change scenarios and the Base Case scenario. These figures show the 70-year average by model period. Relative to the Base Case scenario the 2020 Hybrid-Delta scenarios tend to have lower discharge in January and February and higher discharge April through June. Discharge during July is consistently lower in the climate change studies relative to the Base Case. The higher winter and early spring reservoir elevation is likely resulting in the reduced winter discharge while the combination of reduced flood control space and an earlier and possibly faster spring freshet may be the main drivers for the higher spring discharge. The inflows into Libby are also a key driver in determining the project discharge (Figure 46). The lower July discharge may also be caused by an earlier runoff.

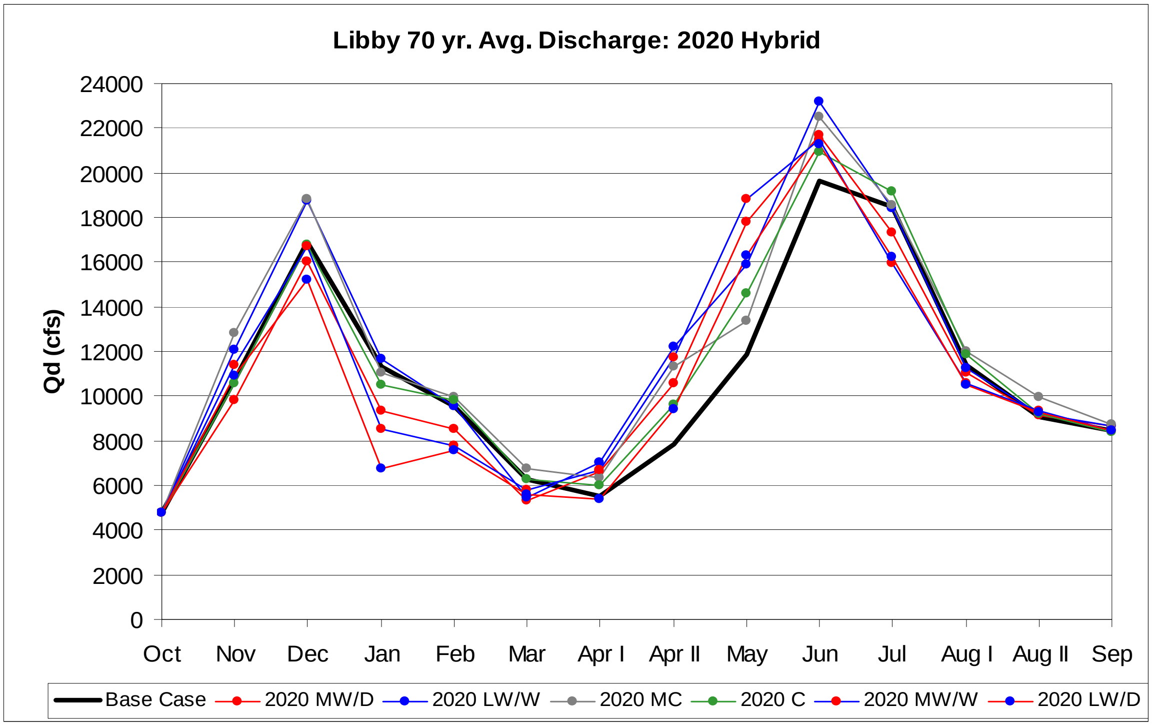

Figure 81. Libby Discharge: 2020s HD.

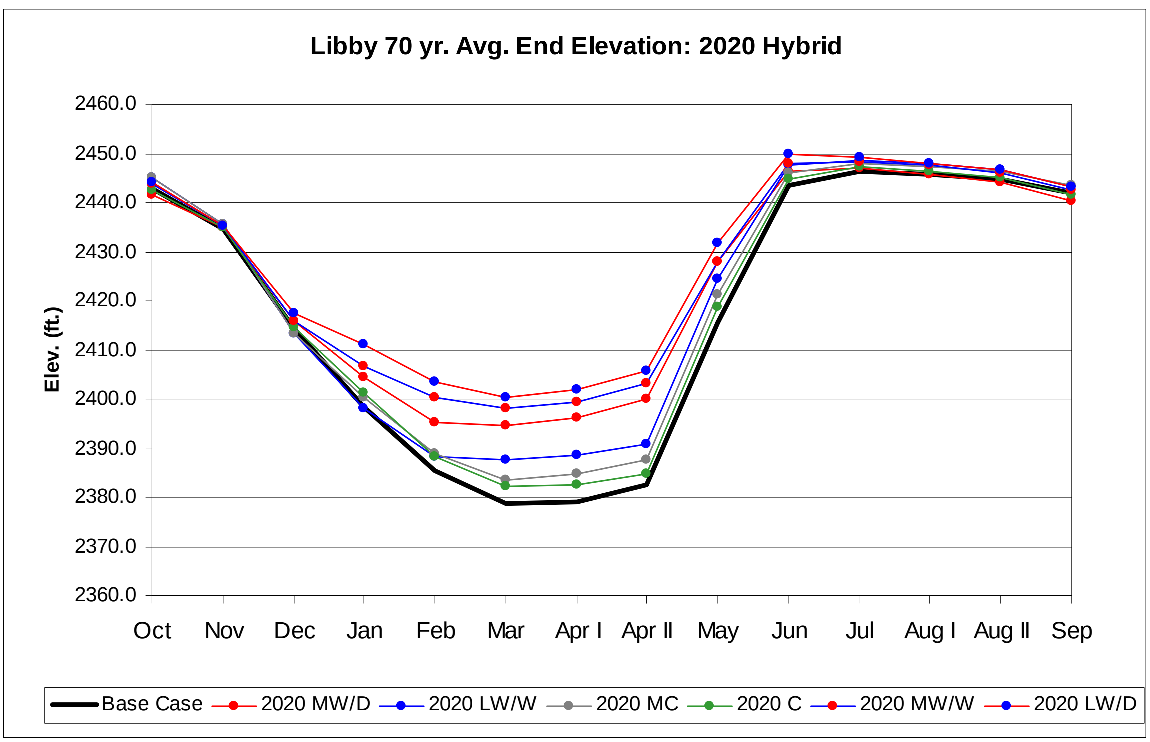

Figure 82. Libby End Elevations: 2020s HD.

Figure 83 and Figure 84 provide a comparison of discharge and reservoir elevation between the 2040 Hybrid-Delta climate change scenarios and the Base Case scenario. Compared to the 2020 Hybrid-Delta scenarios the Libby discharge is no longer below the Base Case for all scenarios during January and February. However, the trend of higher spring discharge and lower discharge in summer is more pronounced. The comparison of elevation indicates the wetter scenarios (LW/W, MW/W) and the central scenario (C) tend to have elevations comparable or lower than the Base Case during portions of the winter drawdown. Among the 2040 Hybrid-Delta studies the MW/W scenario stands out due to very high discharge during April and May. The reason for these flows is that many years in this study were prevented from reaching the required flood control elevations due to downstream flow limitations at the channel restriction at Kootenay Lake.

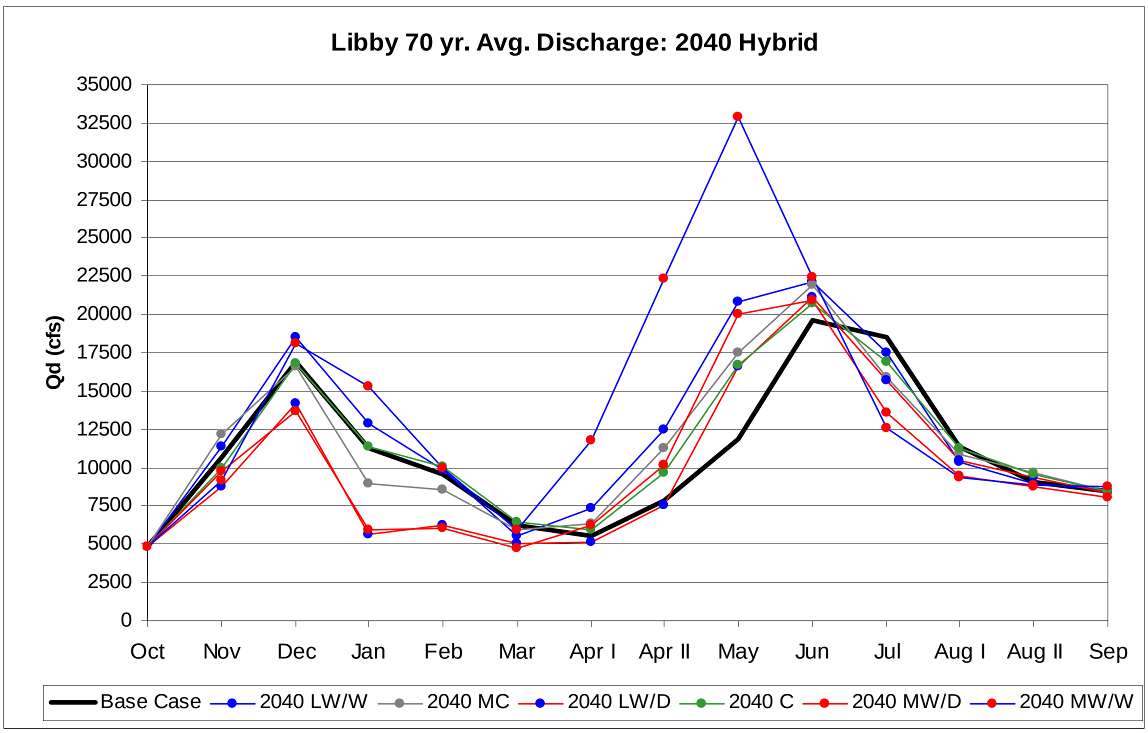

Figure 83. Libby Discharge: 2040s HD.

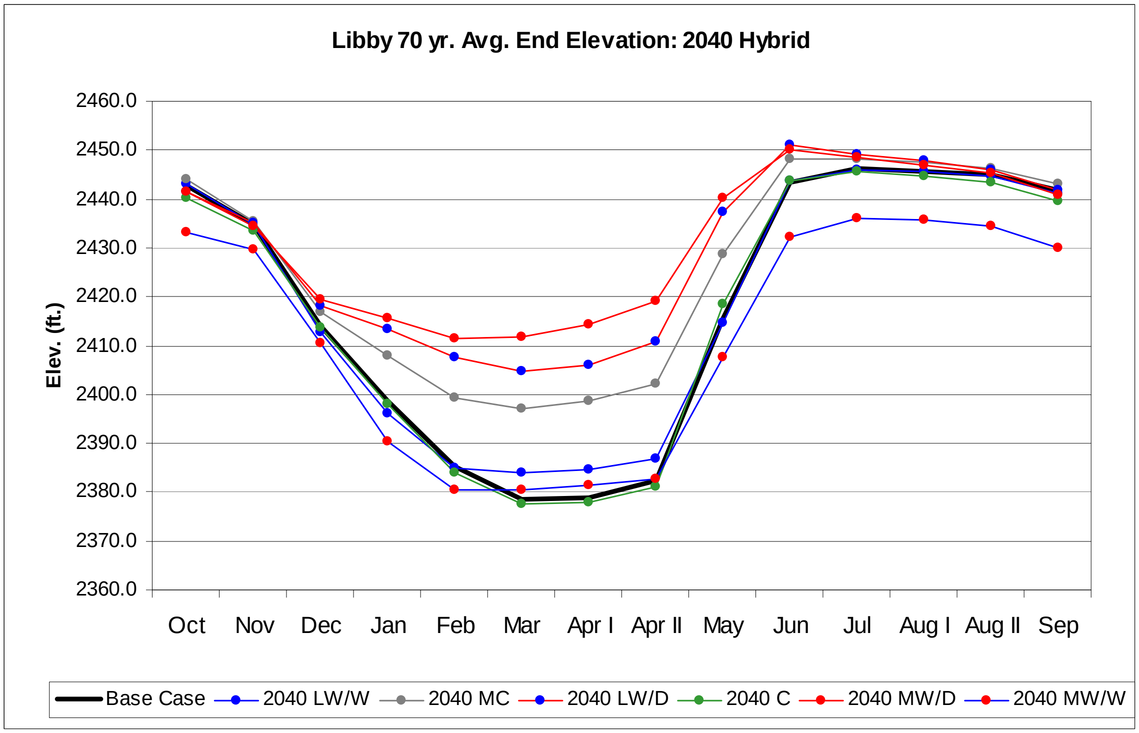

Figure 84. Libby End Elevations: 2040s HD.

The magnitude of the spring discharge in the 2040 MW/W Hybrid-Delta scenario may lead to the conclusion that the reservoir should have been drafted deeper before the spring runoff. However, without consideration of the channel restriction at Kootenay Lake the discharge and elevation results presented in Figure 83 and Figure 84 may be misleading as the resulting reservoir elevation is not always an accurate indication of the computed flood control space. Our current modeling assumption is that Libby reservoir is allowed to be above flood control elevation if Kootenay Lake discharge is at the maximum channel flow restriction or if Libby needs to back off from its required flood control draft to not exceed the winter Kootenay Lake IJC rule curve. The model does not allow the elevation at Kootenay Lake tocan increase to accommodate the higher flows necessary for Libby to reach flood control. These assumptions are based on current agreed modeling criteria between Canada and the U.S. The average trapped storage in Libby Reservoir above flood control for the 2020 and 2040 Hybrid-Delta studies are presented in Figure 85 and Figure 86.

In both the 2020 and 2040 Hybrid-Delta studies the drier climate scenarios (LW/D and MW/D) tend to have trapped storage that is similar or slightly increased relative to the Base Case while the wetter scenarios (LW/W and MW/W) show an increase in trapped storage. Between the 2020 and 2040 Hybrid-Delta studies the amount of trapped storage in the wet scenarios increases significantly while the trapped storage associated with the drier scenarios decreases.

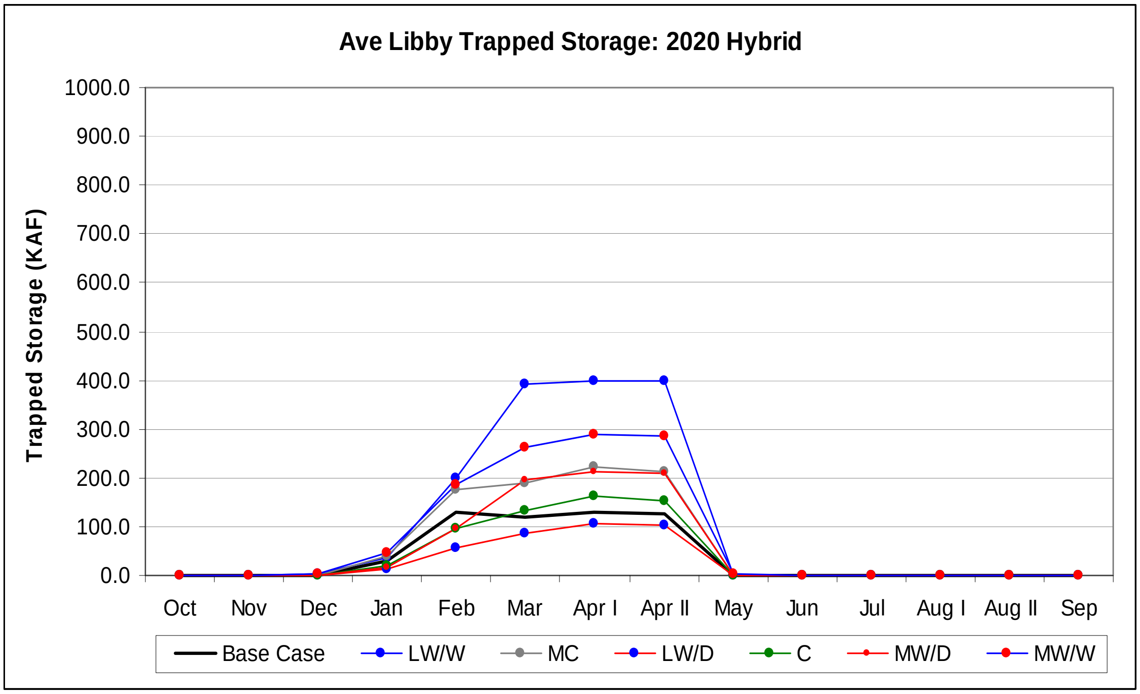

Figure 85. Average Storage trapped in Libby above required flood control due to channel restriction at Kootenay Lake in the 2020 Hybrid-Delta scenarios.

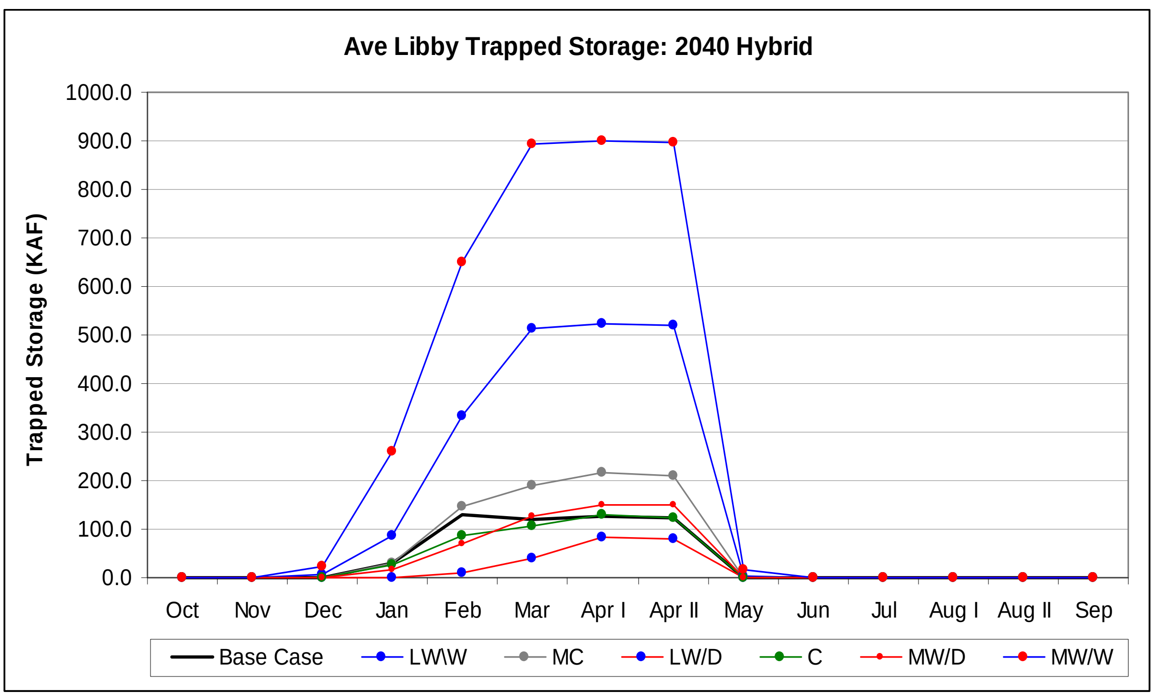

Figure 86. Average Storage trapped in Libby above required flood control due to channel restriction at Kootenay Lake in the 2040 Hybrid-Delta scenarios.

The trapped storage in Libby reservoir in the 2040 MW/W scenario and the high spring discharge is likely the result of higher winter inflows and the desire to maintain winter flows below the IJC rule curves. These factors contribute to inadequate drawdown of Libby reservoir and therefore subsequent higher spring flows. A more in-depth comparison of the regulated outflow and natural inflow into Libby is provided in the box and whisker diagrams shown in Figure 87 and Figure 90 respectively. Another interesting observation is that after the freshet the average discharge and average reservoir elevation in the 2040 MW/W scenario drop below the Base Case through the summer due to lower inflows. This suggests that a climate scenario similar to the 2040 MW/W may require modifications to the Libby drawdown and flood control procedures, updating the international coordinated operations of Libby and Kootenay Lake to allow for higher winter discharge, and a modification of the Libby refill procedure to prevent high discharge during the spring runoff and adequate outflows during the summer months. The following four graphs plot the inflows and regulated outflows for Libby for the 2040 MW/W scenario. Note that the vertical scale capping out at 90,000 cfs is maintained throughout each graph to give the reader a consistent frame of reference in comparing flows.

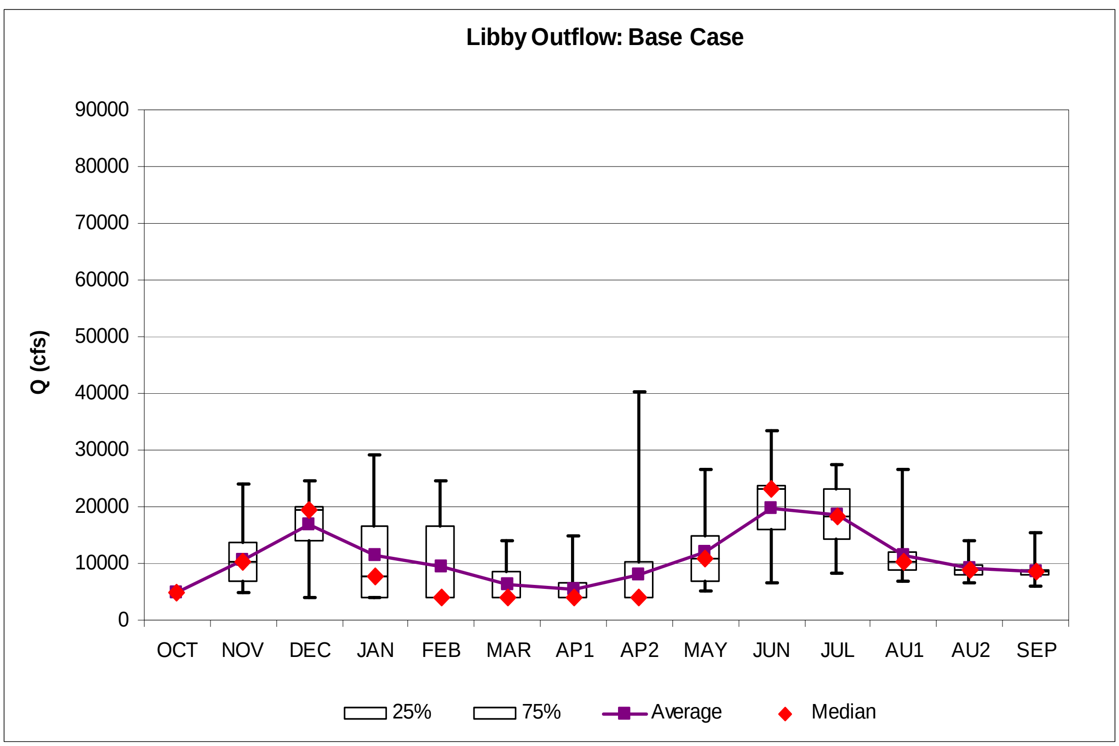

Figure 87. Libby Base Case 70 year discharge distribution.

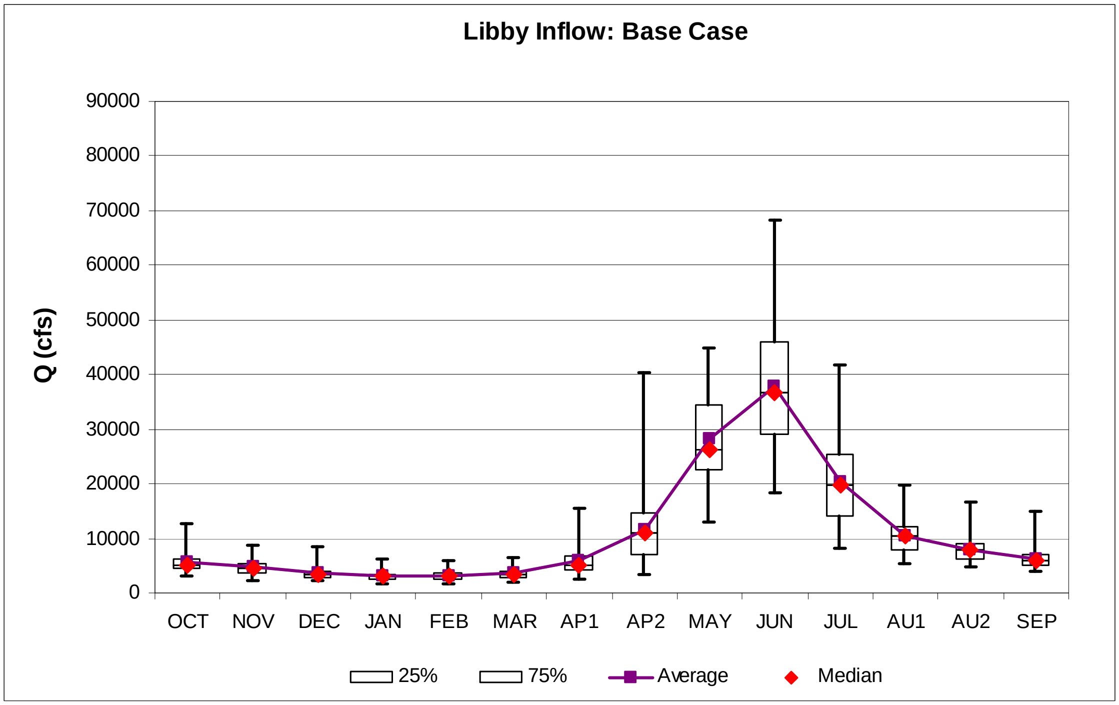

Figure 88. Libby Base Case 70 year natural inflow distribution.

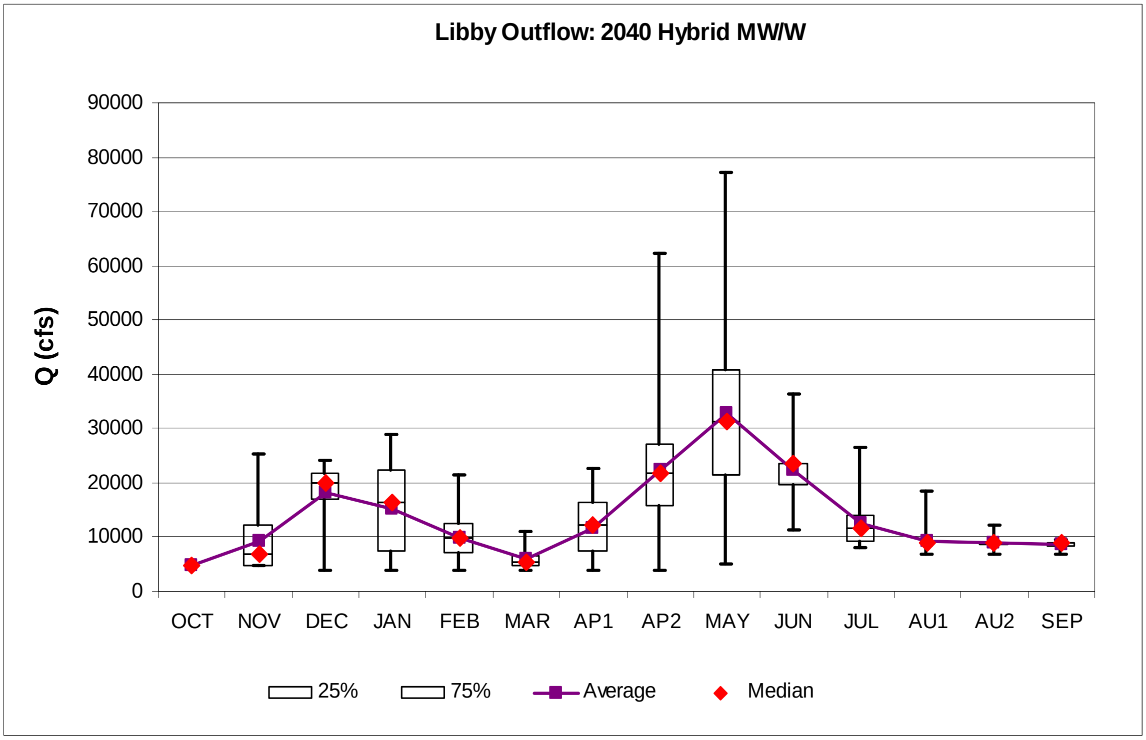

Figure 89. Libby 70 year outflow distribution for 2040 Hybrid-Delta MW/W study.

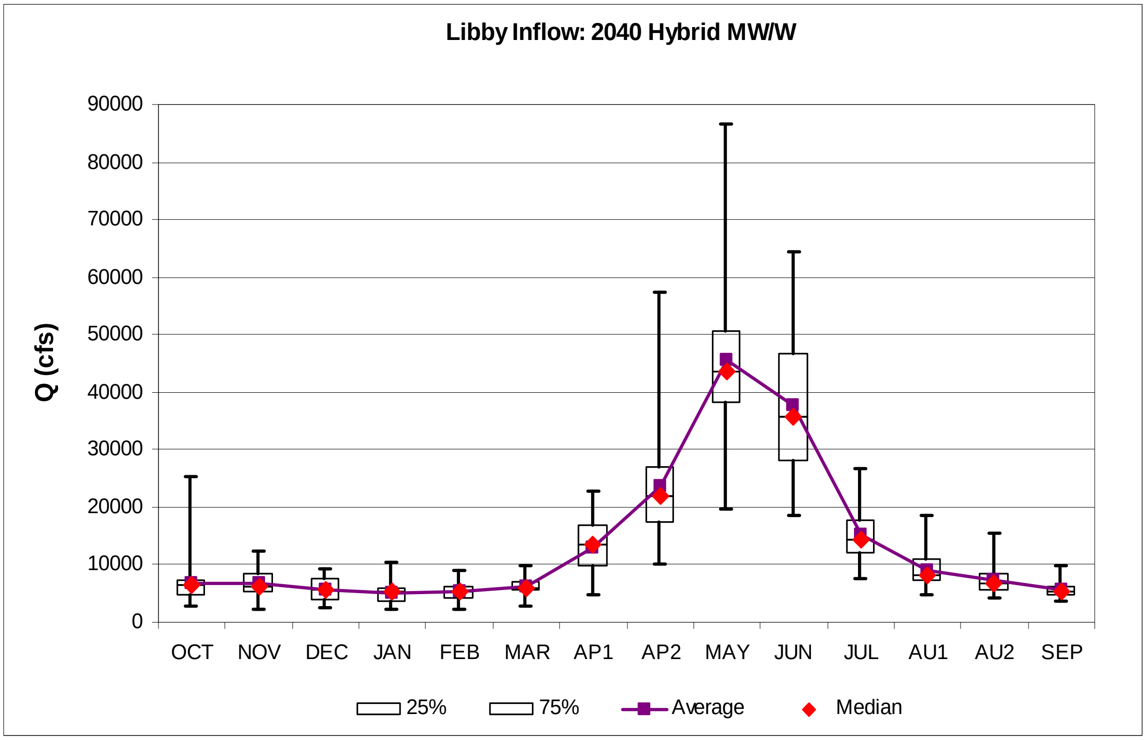

Figure 90. Libby 70 year natural inflow distribution for 2040 Hybrid-Delta MW/W study.

11.2.3 Hungry Horse

The figures and discussion for Hungry Horse in Section 6.8 indicate that the climate change scenarios tend toward lower inflow volume in the May to September period. Because this forecast period is used to determine the flood control requirements at Hungry Horse, the climate change scenarios tend to result in higher winter reservoir elevations with less draft for flood control. This trend is stronger in the 2040 Hybrid-Delta scenarios than the 2020 Hybrid-Delta scenarios. However, just because the May to September period has lower average inflow volumes doesn't necessarily indicate that the overall spring runoff peak is lower or the need for flood control space is reduced, as space requirements also depend on the shape and timing of the runoff.

A comparison of the period average inflow for the climate change scenarios and the Base Case is provided in Figure 91. This figure indicates that inflow in the climate change scenarios increases relative to the Base Case November through May with more significant increases occurring in March and April. Also the climate change scenarios result in less inflow into the reservoir June through October with the biggest reduction occurring in June. The reduced inflow in the May through September period results in higher winter flood control reservoir elevations. This reduced flood control draft results in lower discharge during the winter.

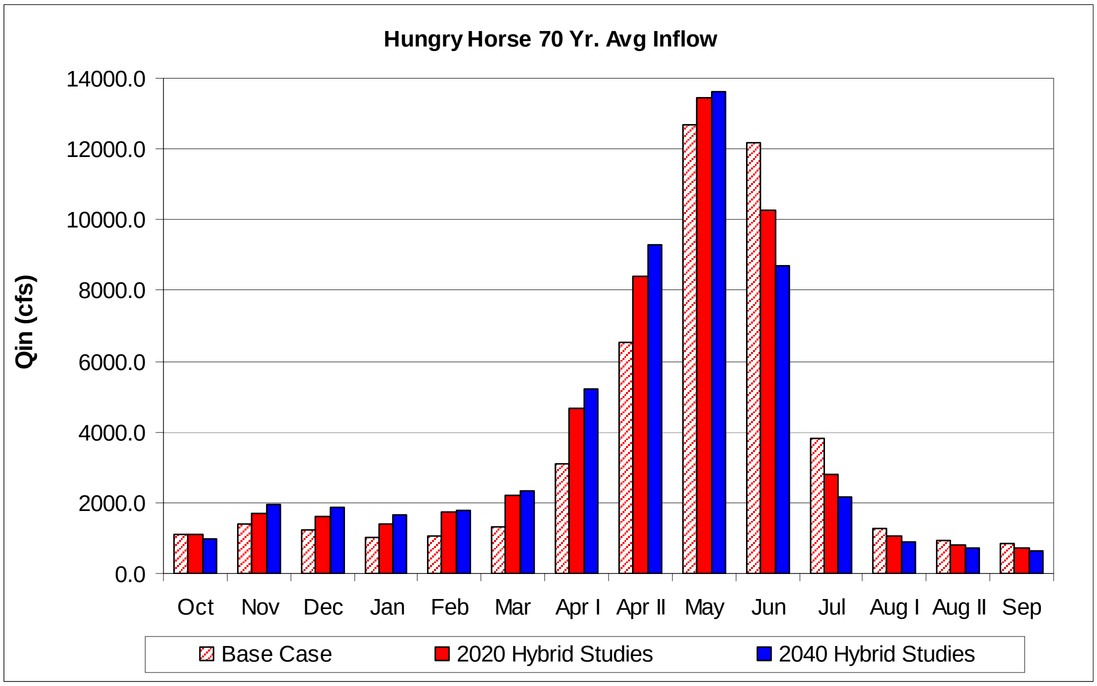

Figure 91. Hungry Horse Avg. Mo. Inflow for Base Case and Climate Change Scenarios.

Figure 92 and Figure 93 show the reduced flood control evacuation and the slightly lower winter discharge in the climate change scenarios. One impact of a reduced flood control draft and an early runoff is that discharge can be very high in April and May when the freshet begins. The summer elevation is very similar in the Base Case and climate change scenarios but the lower inflow in the climate change scenarios results in slightly lower discharge.

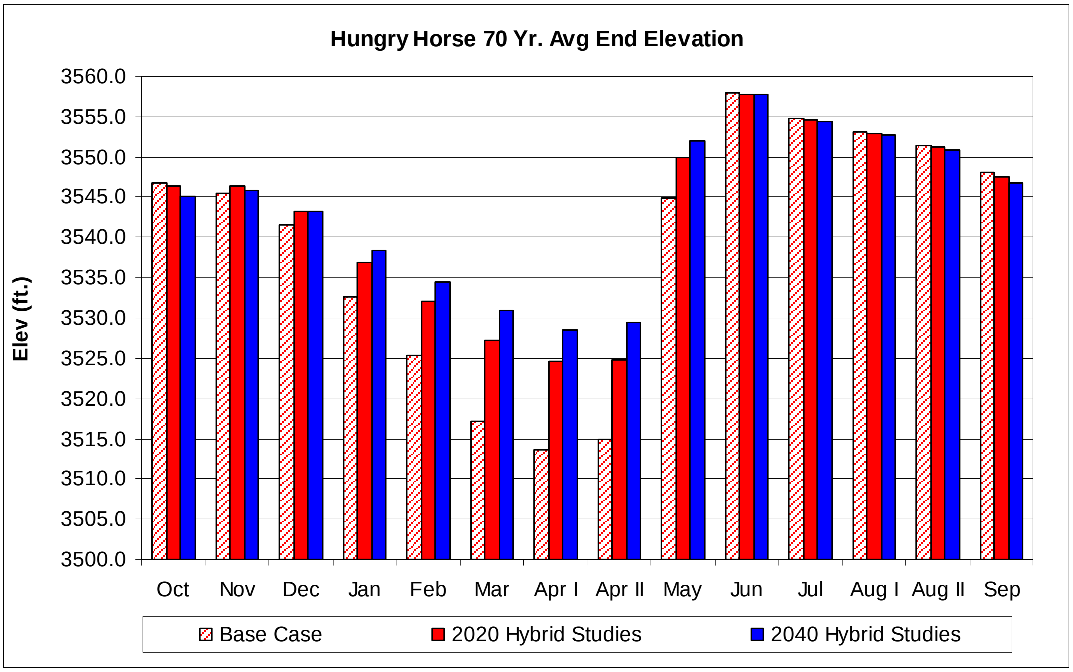

Figure 92. Hungry Horse Average End Elevation for Base Case and Climate Change Scenarios.

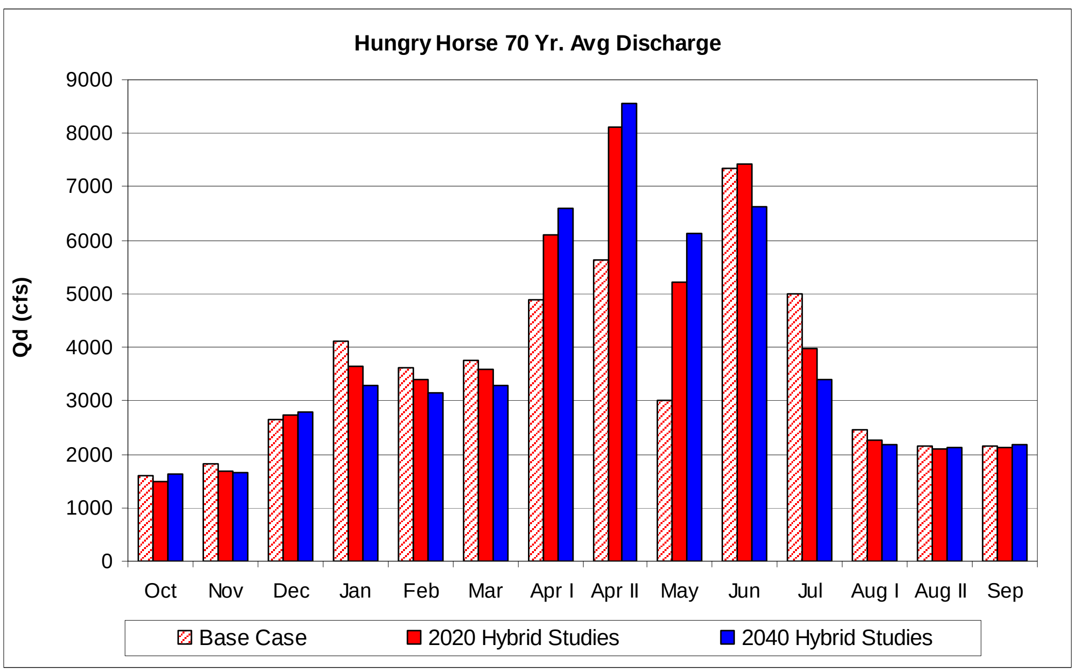

Figure 93. Hungry Horse Avg. Mo. Discharge for Base Case and Climate Change Scenarios.

Figure 94 and Figure 95 provide a more detailed comparison of period ending elevation and period average discharge in the 2020 Hybrid-Delta climate change scenario and the Base Case scenario. With the exception of 2020 C projection, each climate change scenario drafts less during the winter resulting in less winter discharge and more spring discharge. Discharge in the summer is then typically lower. Figure 96 and Figure 97 provides a more detailed comparison of period ending elevation and period average discharge between the 2040 Hybrid-Delta scenarios and the Base Case. These scenarios show the same overall patterns observed in the 2020 Hybrid-Delta studies.

One difference between the 2020 and 2040 Hybrid-Delta studies is the magnitude of the spring discharge in the MW/W scenario. This high outflow in the second half of April is due to drafting to reach the flood control at the same time high inflows are occurring. High flows in May in the Base Case are a result of filling the project to the May flood control curve while releasing higher inflows. The amount of flood control draft can accommodate the runoff volume; however, the drawdown procedures are not adapted to the earlier runoff.

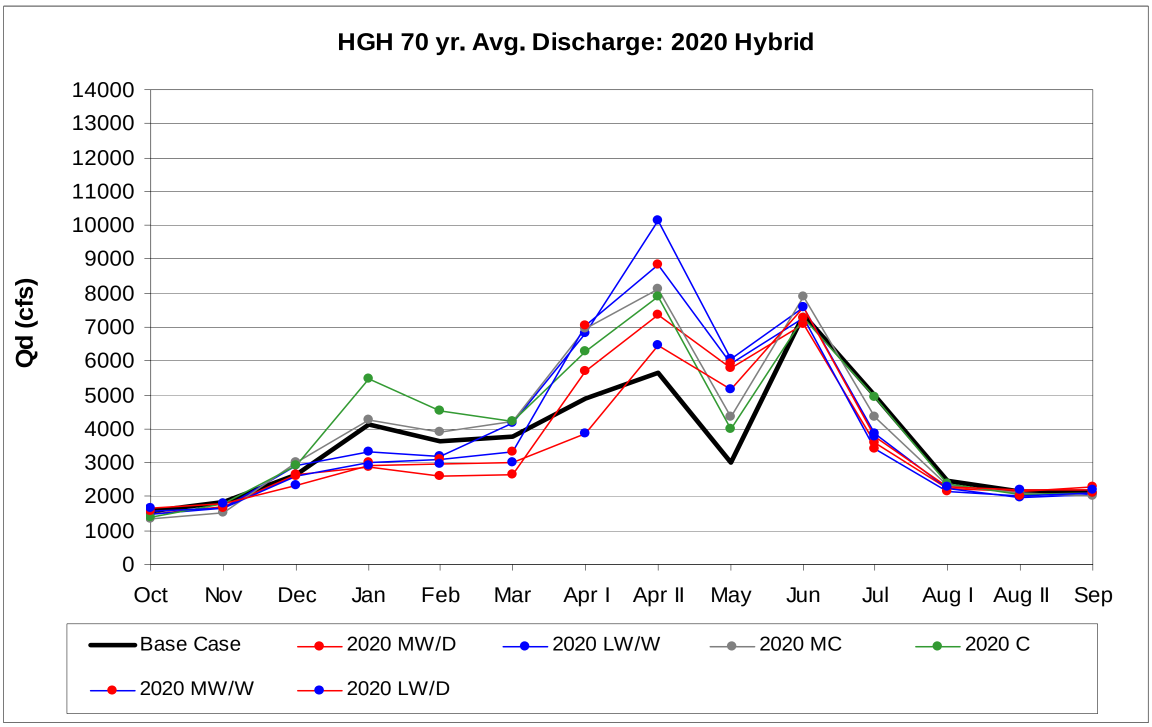

Figure 94. Hungry Horse Discharge: 2020s Hybrid-Delta.

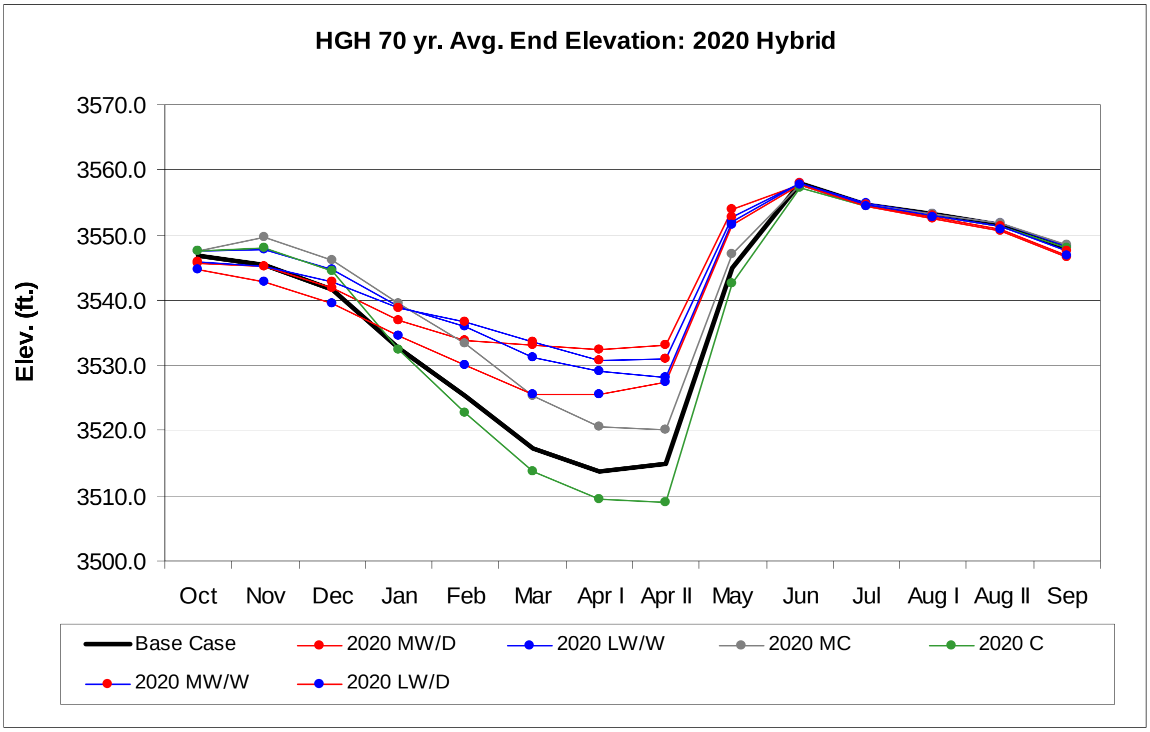

Figure 95. Hungry Horse End Elevations: 2020s HD.

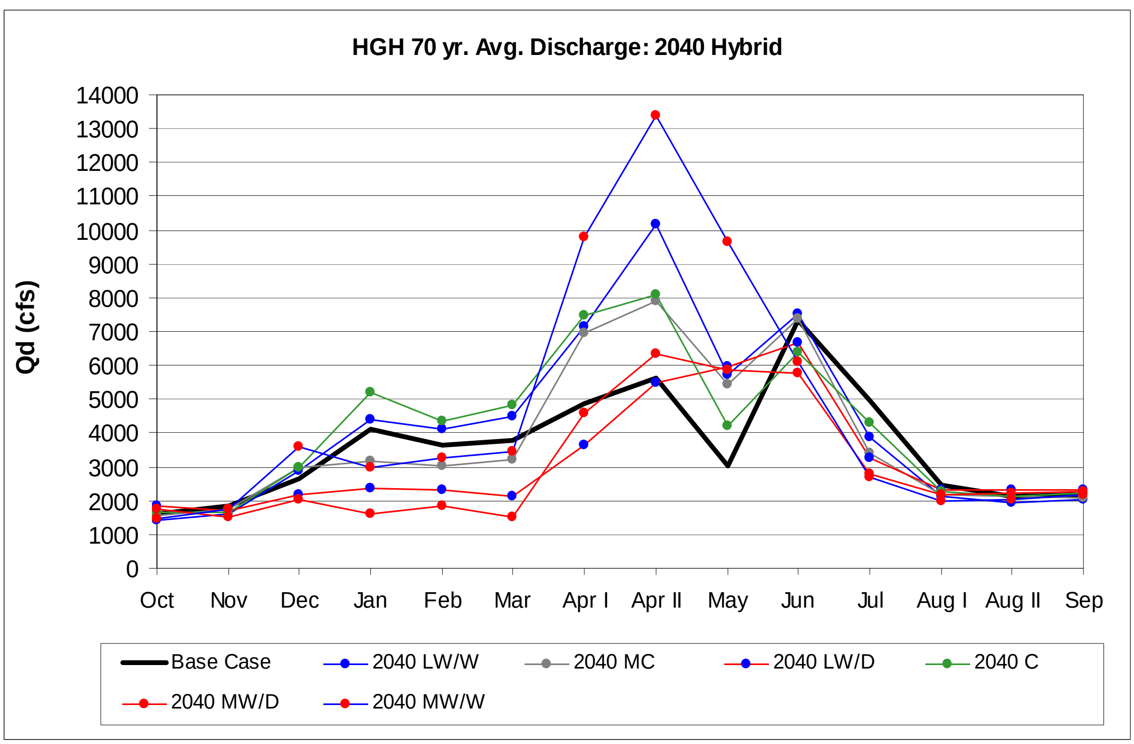

Figure 96. Hungry Horse Discharge: 2040s Hybrid-Delta.

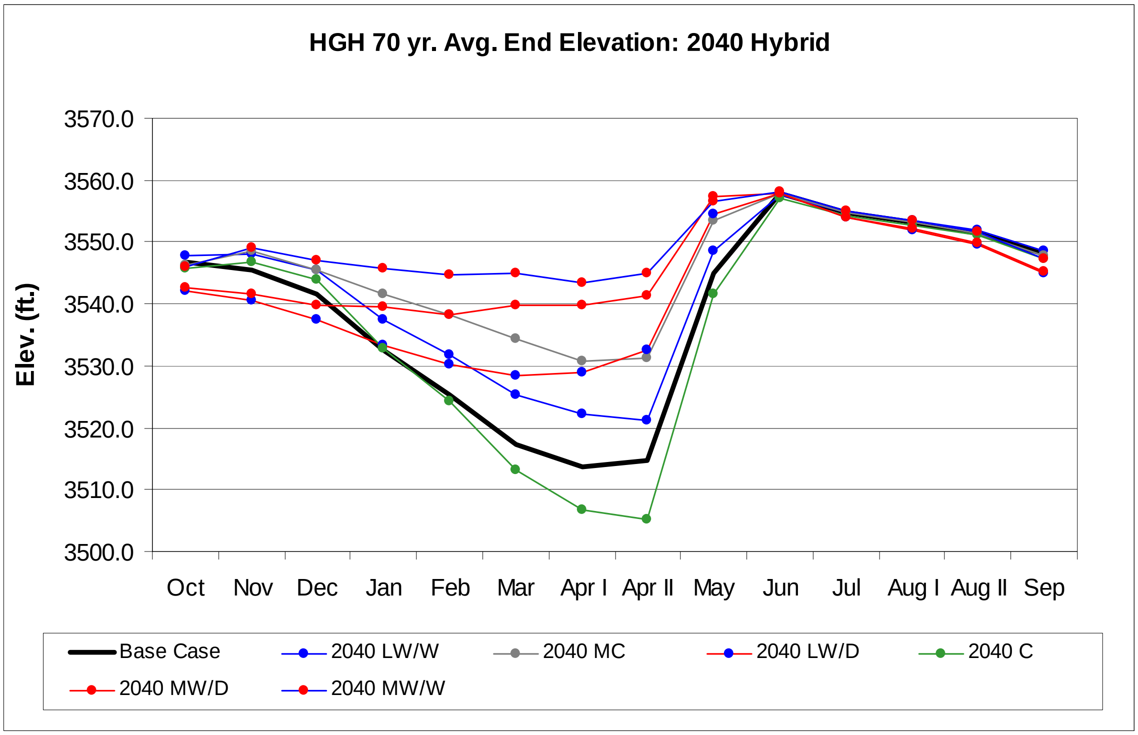

Figure 97. Hungry Horse End Elevations: 2040s HD.

Downstream from Hungry Horse the HydSim model contains a maximum channel flow constraint of 52,000 cfs applicable at all reservoir elevations. During the April II period, 20% of all years are running to this channel restriction in the 2040 MW/W scenario. The Base Case contains no years bound by this constraint. Discharge from Kerr and Albeni Falls is limited by a channel restriction that is dependent on reservoir elevation. Kerr typically operates at this maximum channel flow during the first half of April so Table 12 doesn't show much difference between the Base Case and the 2040 Hybrid-Delta MW/W scenario. However, downstream at Albeni Falls, an increase in the percentage of years where discharge is limited by channel restriction during the spring runoff period in the 2040 MW/W. From an operational perspective these years are problematic. Unless the runoff can be adequately anticipated enabling drafting below the flood control elevations, the ability to control the project elevations are limited and local flooding problems may arise.

The natural channel flow restrictions at Kerr and Albeni Falls may limit the ability of these reservoirs to draft to their respective target elevations in the early spring. Daily time step-models would better assess this implication. This problem is amplified in climate change scenarios such as 2040 MW/W where flood control space is inadequate to effectively regulate the spring runoff. Table 12 compares the percentage of water years running at a channel flow restriction in the Base Case and the 2040 Hybrid-Delta MW/W climate scenarios. The bold text indicates greater than 5% of water years limited by channel restriction flow. This data highlights an operational problem that may arise due to an earlier runoff.

Table 12. Comparison of the % of water years on channel restricted flow in the Pend Oreille Basin.

Location	Climate Scenario	Oct	Nov	Dec	Jan	Feb	Mar	Apr I	Apr II	May	Jun	Jul	Aug I	Aug II	Sep
Hungry Horse	**Base Case**	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	2040 MW/W	0%	0%	0%	0%	0%	0%	4%	**20%**	0%	0%	0%	0%	0%	0%
Kerr	**Base Case**	0%	0%	0%	0%	0%	1%	**100%**	**91%**	**24%**	0%	0%	0%	0%	0%
	2040 MW/W	0%	0%	0%	**6%**	3%	1%	**100%**	**80%**	**57%**	0%	0%	0%	0%	0%
Albeni Falls	**Base Case**	0%	0%	4%	3%	1%	3%	**40%**	**20%**	**21%**	**19%**	0%	0%	0%	0%
	2040 MW/W	0%	3%	**40%**	**36%**	**43%**	**37%**	**89%**	**76%**	**56%**	1%	0%	0%	0%	0%

11.2.4 Grand Coulee

Figure 96 shows the Grand Coulee Dam (GCL) 70-year averaged monthly discharge for the Base Case (red striped bar), the 2020 scenarios (averaged over all six 2020 scenarios – red bar) and the 2040 scenarios (averaged over all six 2040 scenarios – blue bar). Grand Coulee monthly discharges follow a similar pattern as the monthly natural stream flow at TDA discussed previously in Section 3.2.2. Relative to the Base Case, higher natural inflows during the winter to spring period results in higher discharges during this period at Grand Coulee. Consequently, lower natural flows during the summer and fall periods results in lower discharge at Grand Coulee relative to the Base Case during this same period.

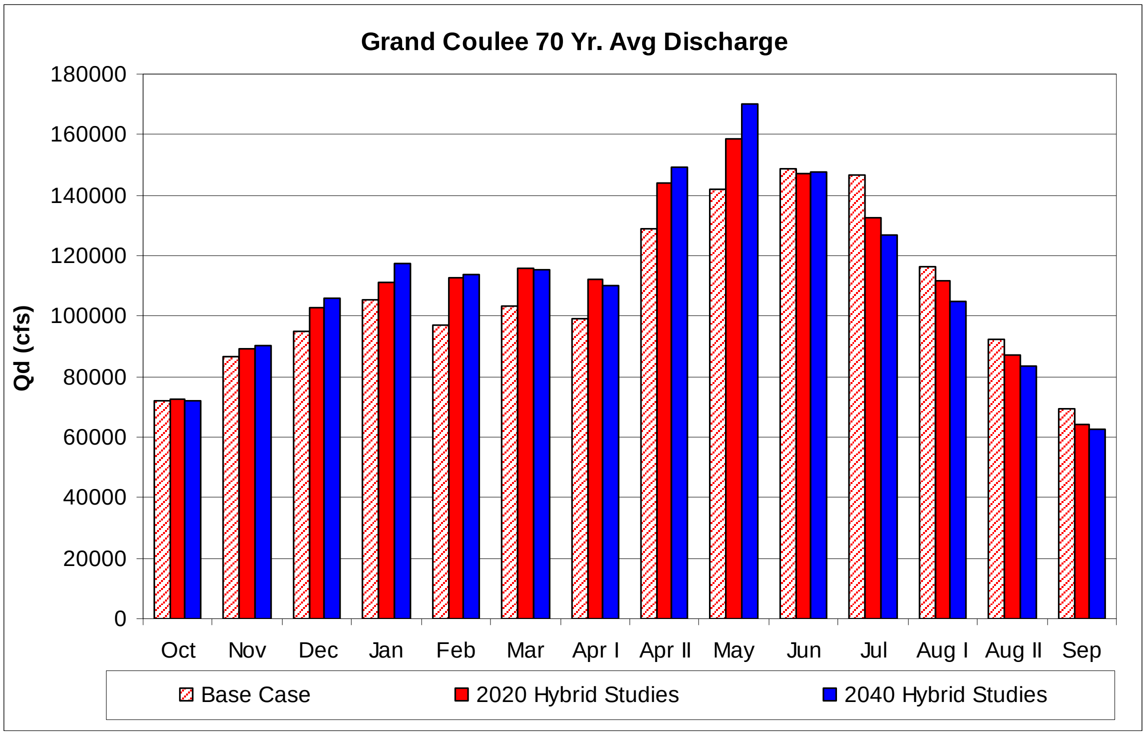

Figure 98. Grand Coulee Average Monthly Discharge for Base Case and Climate Change Scenarios.

The monthly average discharges at Grand Coulee for the 2020 and 2040 Hybrid-Delta scenarios are shown in Figure 98, above. These discharges correspond to the 70-year average monthly end elevations illustrated in Figure 99. The chart includes the Base Case, the 2020 scenarios and the 2040 scenarios.

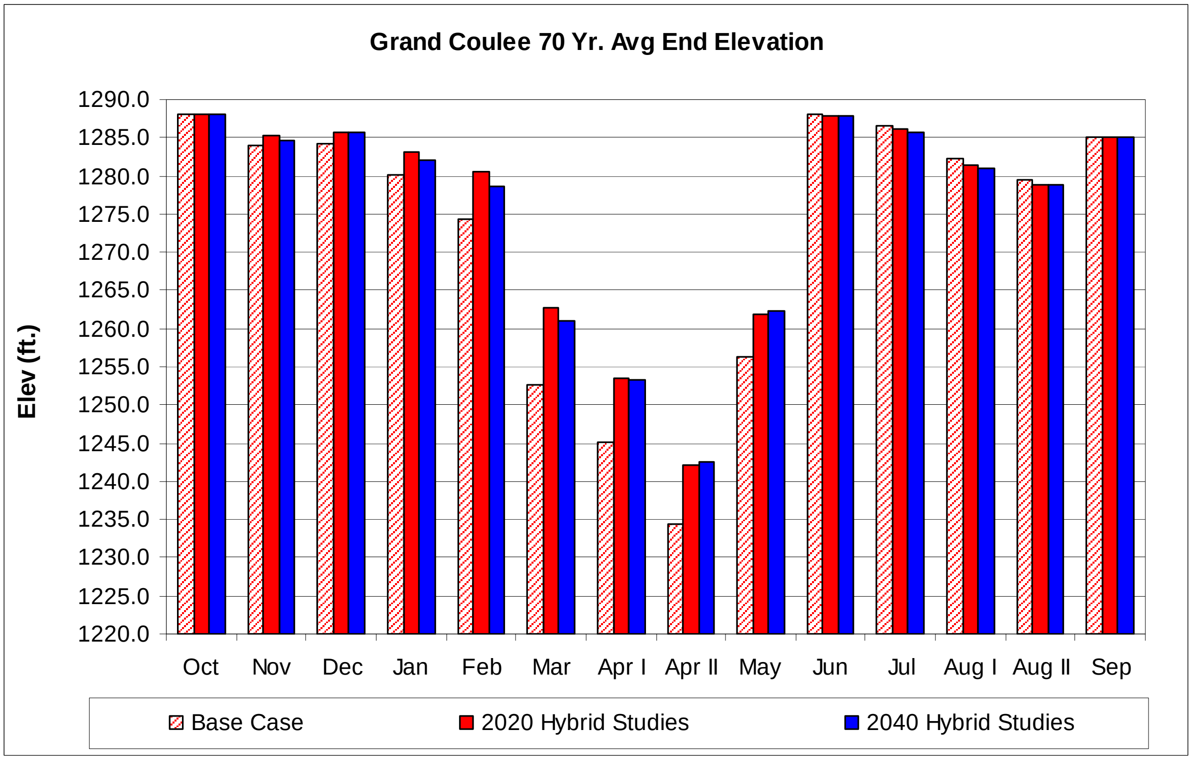

Figure 99. Grand Coulee Average End Elevation for Base Case and Climate Change Scenarios.

From June to the beginning of October, Grand Coulee operates to a range of target elevations from 1278 feet to 1288 feet, which can be seen in Figure 98. Elevations for the climate change scenarios are nearly the same as those for the Base Case. Because climate change scenarios have less stream flow relative to the Base Case for these months, the project discharges less water in the climate change scenarios, as seen in Figure 98.

From November to June, along with satisfying other requirements, the Grand Coulee end elevation is generally dependent on the URCs. The June 30 ending elevation targets the maximum elevation, achieved by the Base Case and all climate change scenarios.

Figure 98 shows the 70- average monthly Grand Coulee discharges for the Base Case and the six Hybrid-Delta 2020 scenarios separately. It could be seen that the overall shape of the discharge retains the same general seasonal characteristics as that in Figure 98. Relative to the Base Case, all but one of the 2020 scenarios has more discharge from November to May (due to higher inflows) and less discharge from June to September (due to lower inflows). The earlier shift in seasonal shape for climate change scenarios is due to seasonal stream flow pattern and Grand Coulee operations discussed earlier in this section. The driest scenario, 2020 LW/D, has 1.5 inches less annual precipitation (at The Dalles) than the Base Case (

Table 1), which leads to less stream flow overall and hence less discharge for most periods. In general, for each period those scenarios having more stream flow (as seen in natural flows at TDA in Figure 10) tend to have higher Grand Coulee discharges.

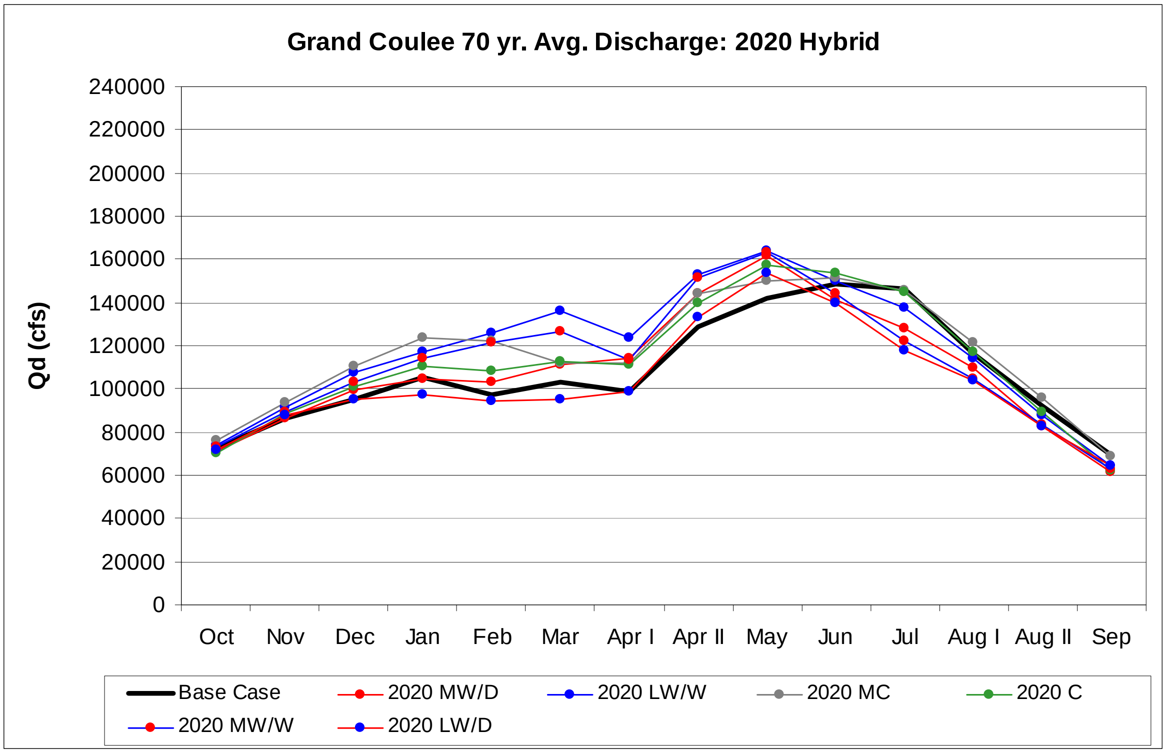

Figure 100. Grand Coulee Discharge: 2020s Hybrid-Delta.

Similarly, the 70-year average monthly Grand Coulee discharges for the Base Case and the six Hybrid-Delta 2040 scenarios are shown in Figure 99. The seasonal discharge patterns cover a larger range of values than those shown in Figure 98 due to the 2040 scenarios having a wider range of precipitation and warming changes relative to the 2020 scenarios (see Table 1 and Table 2). Seasonal differences between Base Case and climate change scenarios are due to stream flow and its influence on Grand Coulee operations already discussed earlier. At each period, those scenarios with higher inflow (Figure 11) tend to have higher discharges.

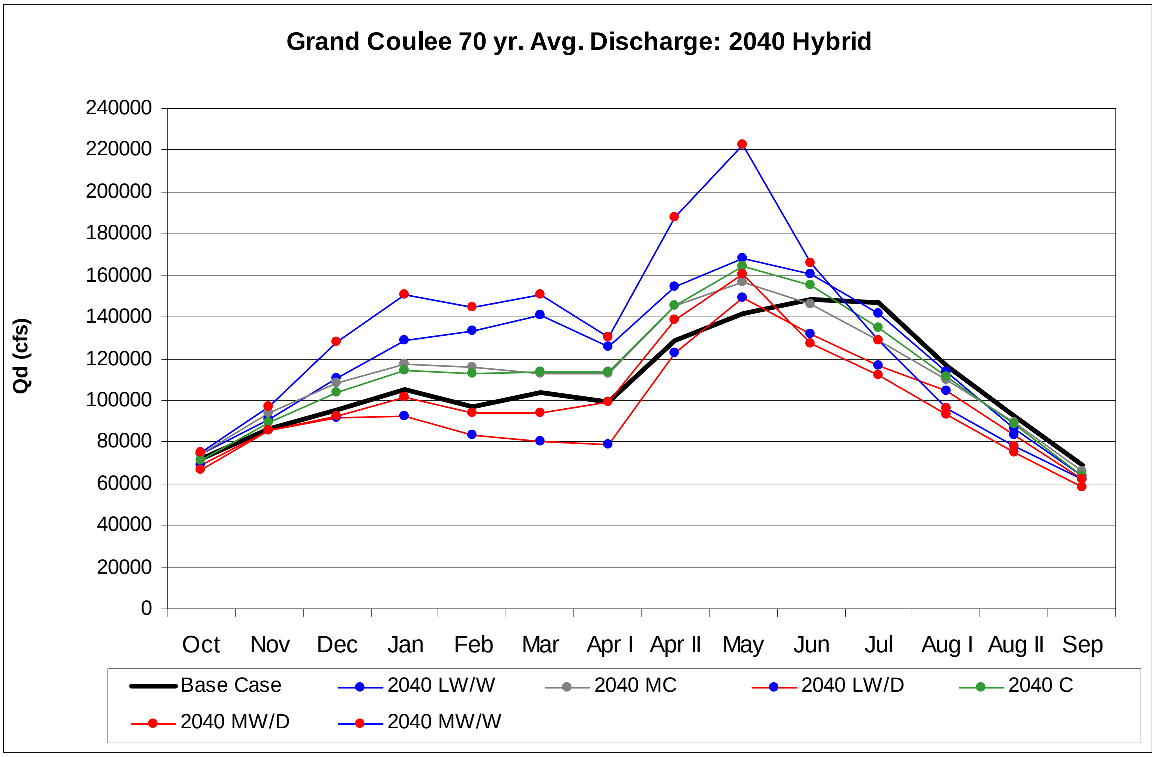

Figure 101. Grand Coulee Discharge: 2040s Hybrid-Delta.

Next, Figure 102 shows the 70-year average Grand Coulee monthly end elevations for the Base Case and the six Hybrid-Delta 2020 scenarios. As mentioned earlier, from June to October when Grand Coulee operates to a set of target elevations, elevations for all scenarios are close to each other. Then from November to April, Grand Coulee is drafted to satisfy URC and NPR (e.g. chum flow at Bonneville and minimum flow requirements below Priest Rapids) which results in a project minimum elevation in April. Although the URC at Grand Coulee is determined by the April-to-August flow volume at TDA and available storage at several upstream projects (e.g., Mica, Duncan, Arrow, Hungry Horse, etc), it can be seen that in general those with more April through August TDA flow volumes are drafted deeper. Lastly, from May to June, Grand Coulee discharges boosted by the peak season of snowpack runoff, serve to meet help downstream fish objectives and refill Grand Coulee elevation toward its targeted maximum elevation in June for all cases.

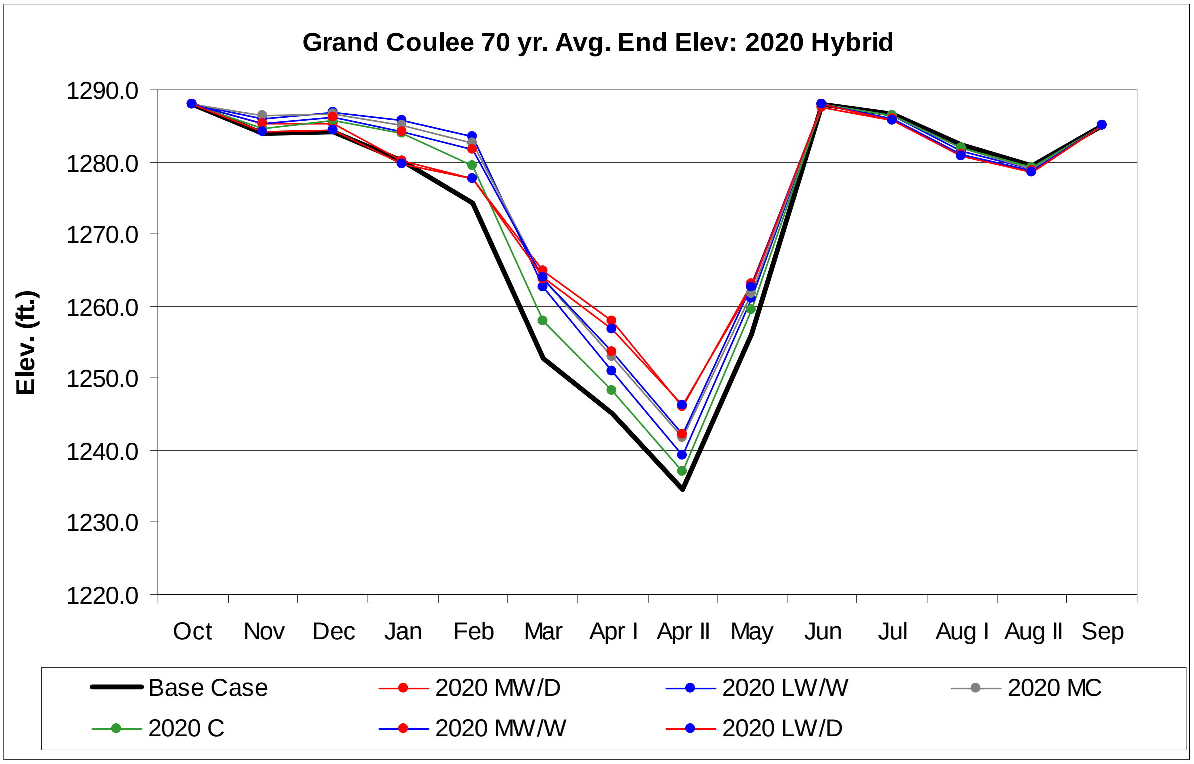

Figure 102. Grand Coulee End Elevations: 2020s HD.

Finally, the 70-year average Grand Coulee monthly end elevations for the Base Case and the six Hybrid-Delta 2040 scenarios are plotted in Figure 101. Similar to the Hybrid-Delta 2020 scenarios shown in Figure 100, from June to October all elevations are close to each other when Grand Coulee operates to a set of target elevations. Furthermore from November to April, those scenarios having a higher April through August TDA volume, tend to be drafted deeper for flood control. The exception is Hybrid-Delta 2040 LW/D, the driest scenario, which has 7.9 inches less precipitation than the Base Case (Table 8). Even though the Hybrid-Delta 2040 LW/D has the lowest overall stream flow, having to satisfy the NPR of chum flow at Bonneville forces a deeper draft than the Base Case from November to February.

Grand Coulee drum gates require periodic maintenance during the April through May period. This maintenance requires the reservoir to be below elevation 1255 feet, which is frequently achieved through flood control draft. The climate change scenarios may result in increased force drafts to perform the drum gate maintenance since the climate change scenarios result in higher April through May elevations at Grand Coulee relative to the Base Case.

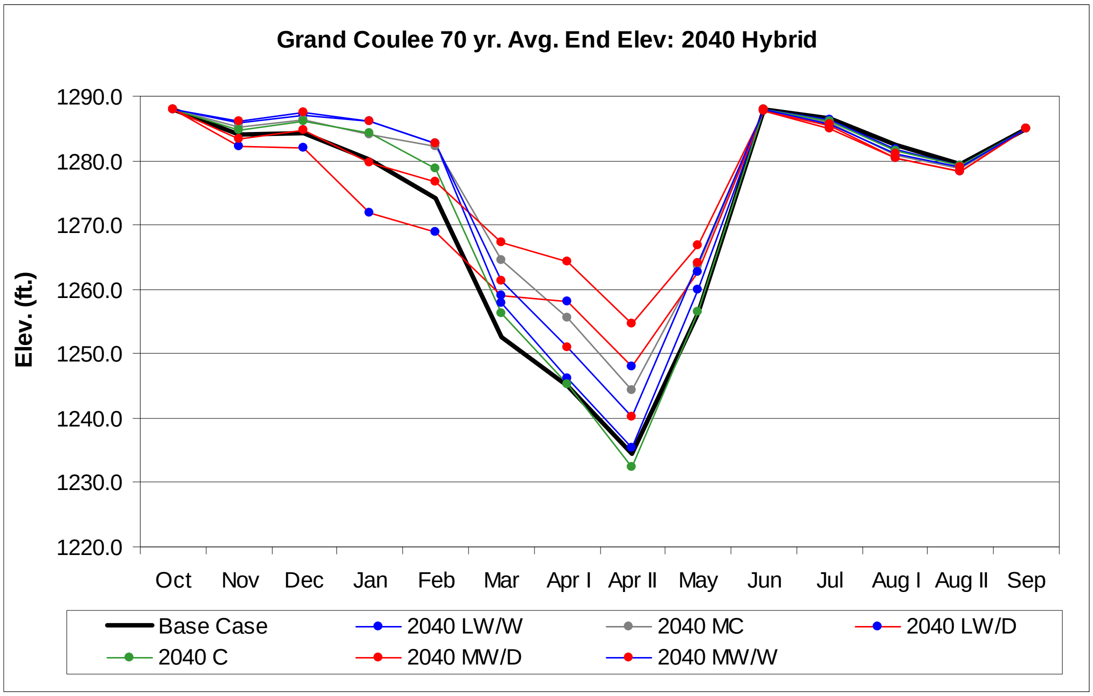

Figure 103. Grand Coulee End Elevations: 2040s HD.

Figure 104 below, shows the five year rolling average for Grand Coulee for the Transient scenarios. Note the high variability of the outflows between the driest and wettest scenarios.

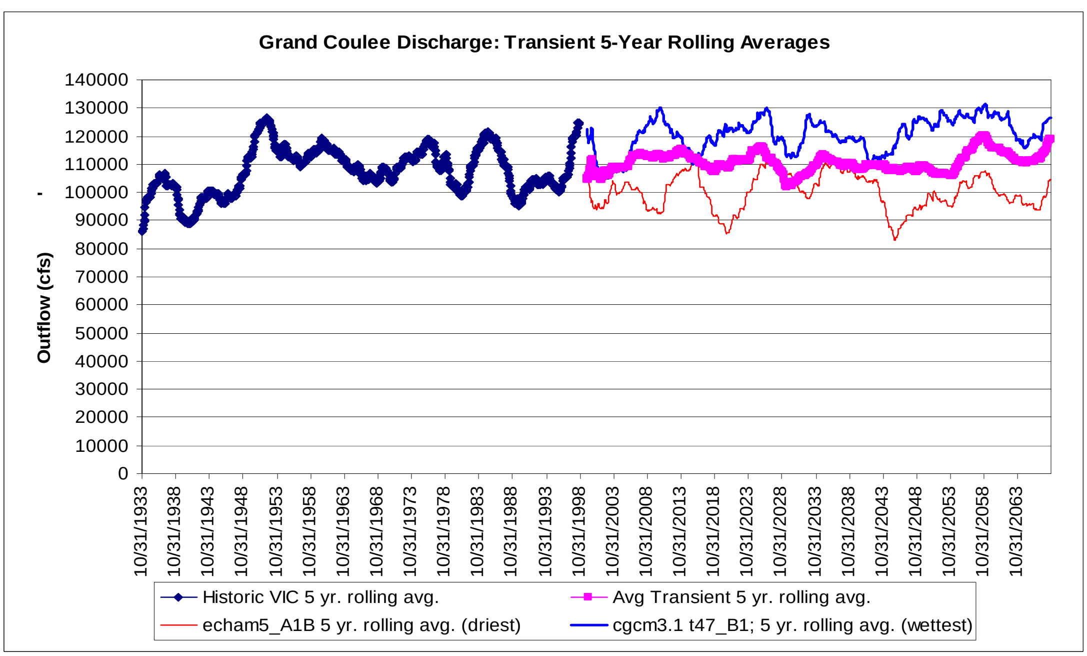

Figure 104. Coulee 5-Yr. Rolling Average Discharge for Historic and Transient Scenarios.

11.2.5 Dworshak

Dworshak (DWR) is located in the Clearwater Basin in Idaho, on the eastside of the Cascades, further south and lower in elevation than the upper Columbia River Basin. Hence the climate and hydrology at Dworshak are slightly different than those on the main stem of the Columbia discussed earlier in this report. Figures 103 and 104 charts show the DWR 70-year average monthly discharge and elevations respectively for the Base Case (red striped bar), the Hybrid-Delta 2020 scenarios (averaged over all six 2020 scenarios – red bar) and the Hybrid-Delta 2040 scenarios (averaged over all six 2040 scenarios – blue bar).

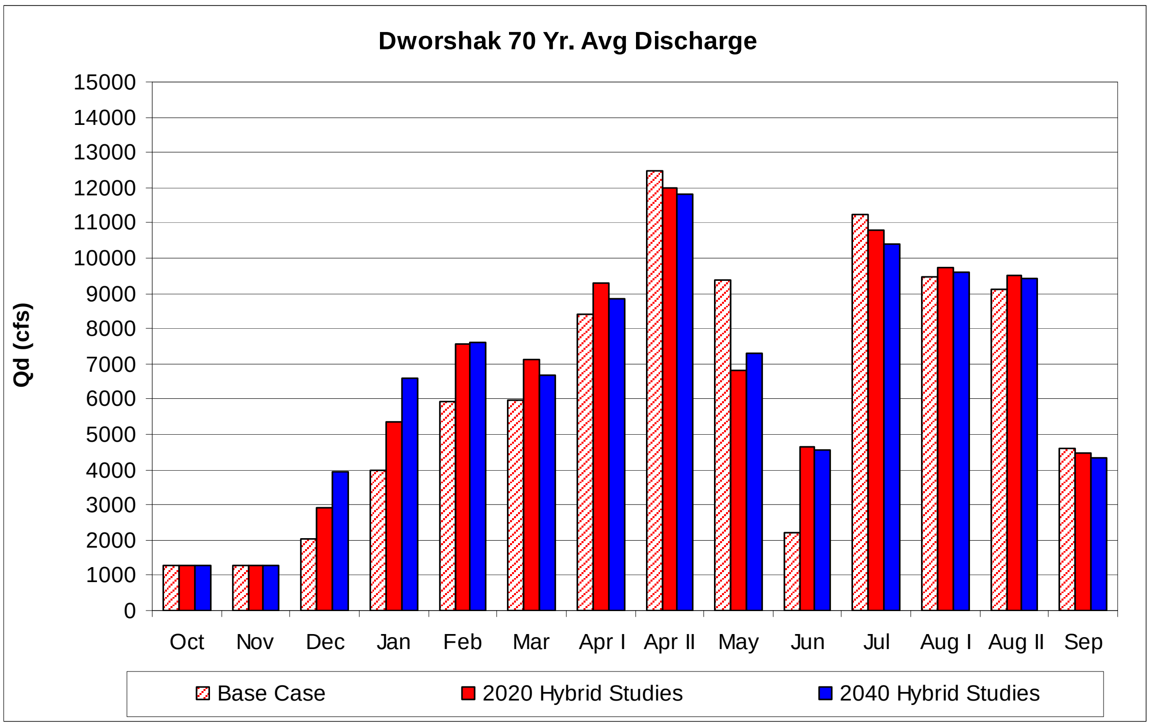

Figure 105. Dworshak Average Monthly Discharge for Base Case and Climate Change Scenarios.

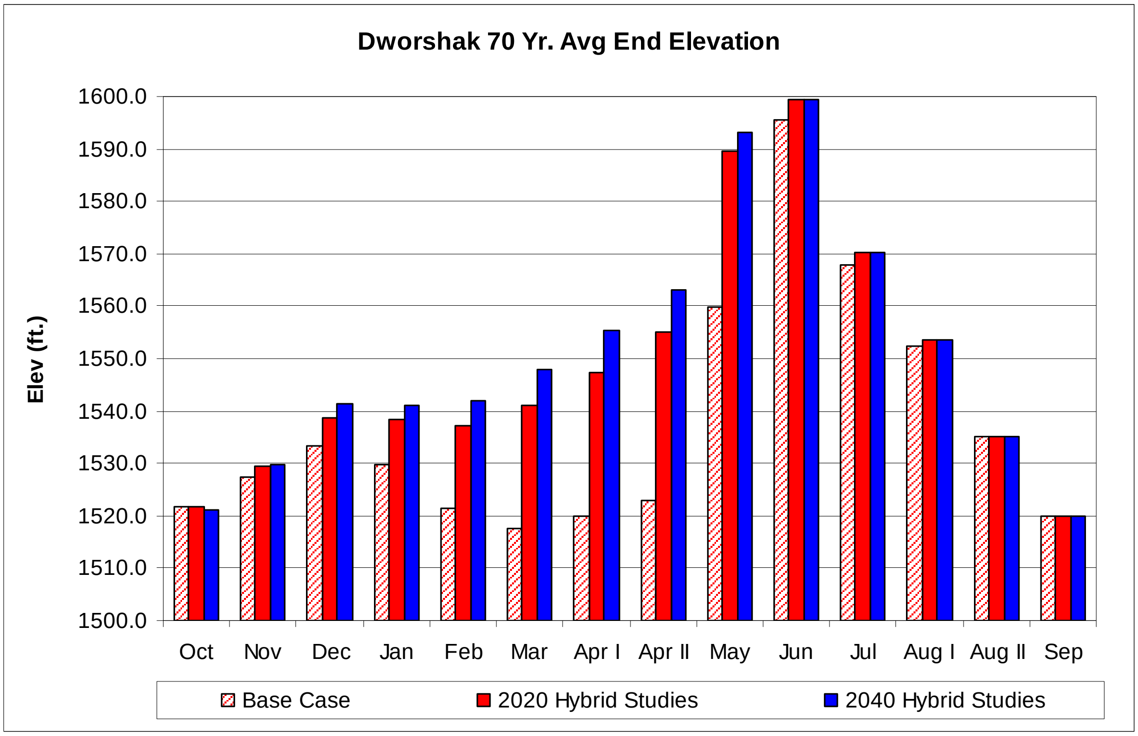

Figure 106. Dworshak Average End Elevation for Base Case and Climate Change Scenarios.

From July to September, starting at maximum elevation at the end of June, DWR operates to a set of target elevations to meet NPR for salmon, and thus elevations and discharges for climate change scenarios are quite close to those for the Base Case.

From October to June, DWR operates to either minimum flow or URC until reaching full pool elevation in June, at which time the discharges in June reach a relative minimum and then begin to increase for salmon operation in July. Because the URC partly determines DWR operations during the April through June periods, the Dworshak 70-year averaged URC is shown on Figure 105 next.

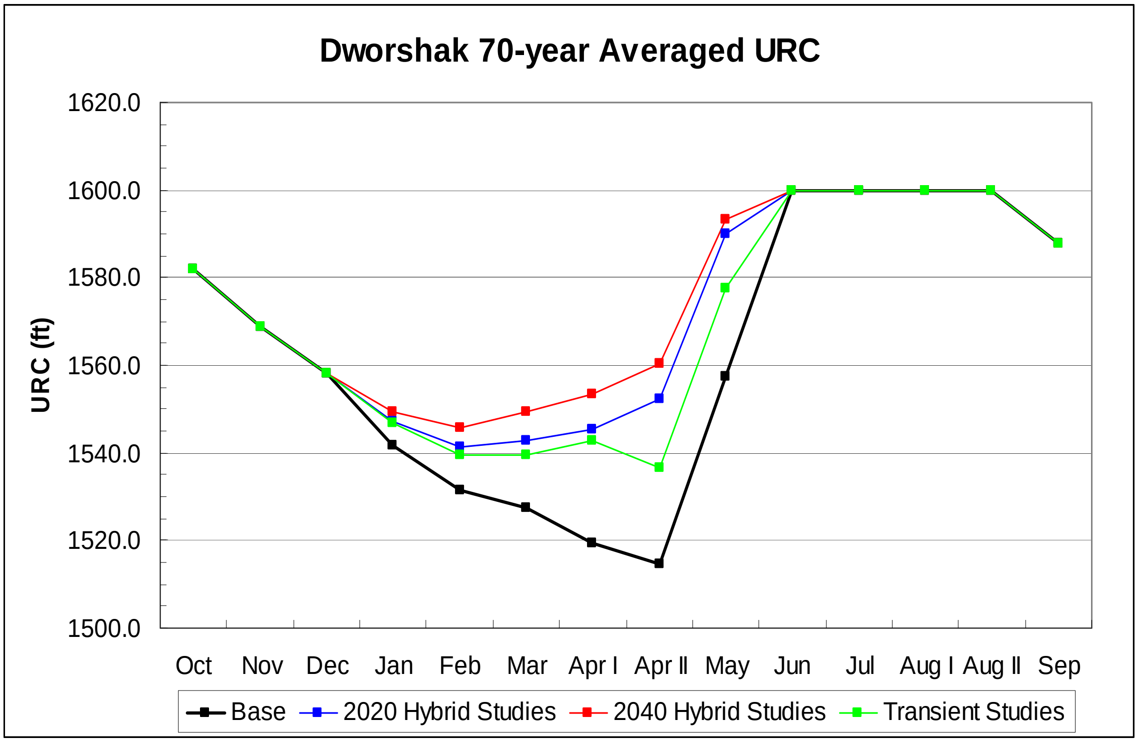

Figure 107. Dworshak seventy-year averaged URC for Base Case and Climate Change Scenarios.

In Figure 107, from January to May it is clear that URCs for climate-change scenarios are higher than that for the Base Case because their forecasted April-to-July streamflow volumes (mainly from snowpack runoff) are lower. Similarly lower runoff volumes for the Hybrid-Delta 2040 scenarios compared to the Hybrid-Delta 2020 scenarios lead to Hybrid-Delta 2040 scenarios having higher URCs than the Hybrid-Delta 2020 scenarios. The relative values of the URCs along with streamflow significantly determine DWR operations from January to May.

Because both streamflows and URCs are higher in the Hybrid-Delta 2020 climate change scenarios than those for the Base Case from December to the first half of April, both their discharges (in Figure 105) and elevations (in Figure 106) are correspondingly higher.

From the second half of April to May, lower forecasted runoffs result in higher URCs for climate change scenarios compared to the Base Case. This results in lower discharge at DWR for the climate change scenarios relative to the Base Case as the project refills.

Finally in June, the climate change scenarios discharges are higher than the Base Case as the project targets refill. Higher elevations allowed by URCs in May for climate change scenarios result in less space to refill in June.

In general, there is not much difference between discharges for the Hybrid-Delta 2020 scenarios and the Hybrid-Delta 2040 scenarios. However, higher URCs for the 2040 scenarios allow their elevations to be slightly higher than those for the 2020 scenarios.

The next four figures show the DWR monthly discharges and elevations for each of the Hybrid-Delta 2020 and Hybrid-Delta 2040 scenarios. Figure 106 is a plot of the 70-year average monthly DWR discharges for the Base Case and the six Hybrid-Delta 2020 scenarios. It could be seen that the overall shape of the discharge retains the same seasonal characteristics as that in Figure 105. Relative to the Base Case all but one of the Hybrid-Delta 2020 scenarios have more stream flow and thus more discharge from December to the first half of April, and less flow and hence less discharge from June to September. The seasonal discharge shapes are due to streamflow, URC and DWR target operations discussed earlier (full pool elevation in June; target elevations from July to September; minimum flow or URC from December to June).

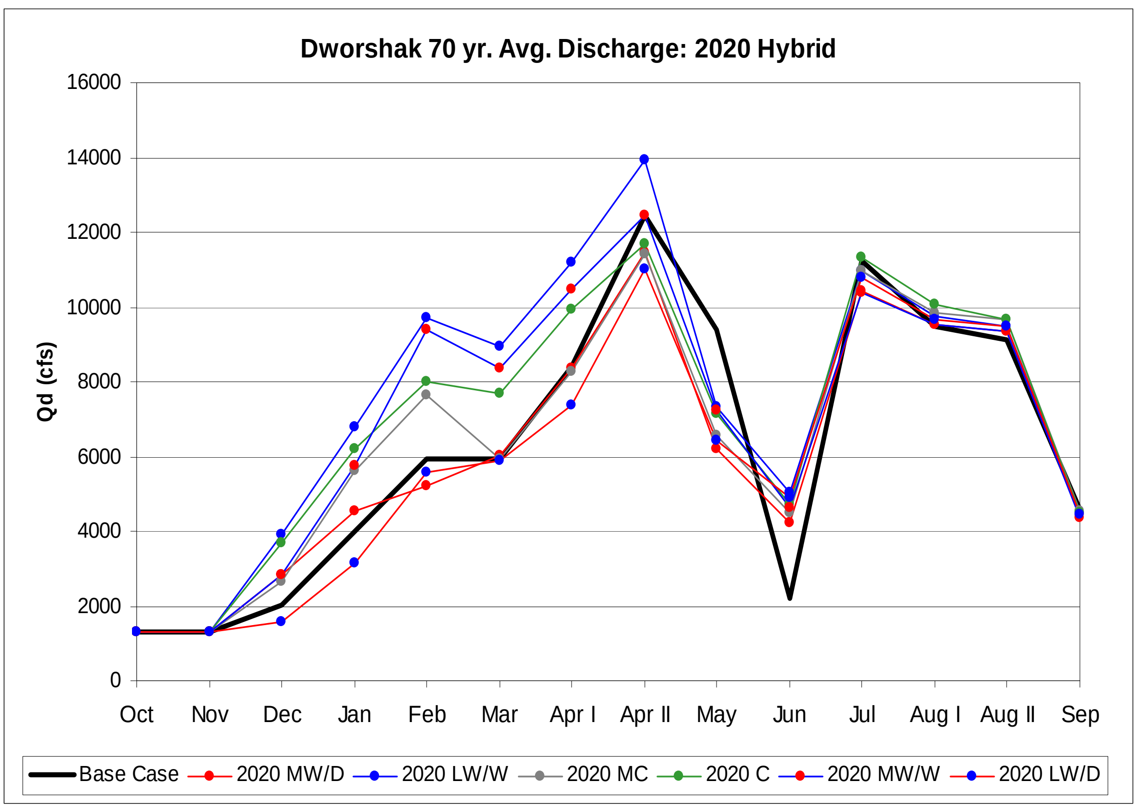

Figure 108. Dworshak seventy-year averaged Discharge: 2020s Hybrid-Delta.

Figure 107 shows the 70-year average monthly DWR discharges for the Base Case and the six Hybrid-Delta 2040 scenarios. The seasonal shape shown has the same characteristics as those in Figure 108. The two driest cases, Hybrid-Delta 2040 LW/D and Hybrid-Delta 2040

MW/D, have less precipitation than the Base Case (Table 2) which lead to less stream flow and hence less discharge than the Base Case for most months. Lastly, the Hybrid-Delta 2040 scenarios have a larger range in discharges than the Hybrid-Delta 2020 scenarios due mainly to a larger range in precipitation changes (Table 1 and Table 2).

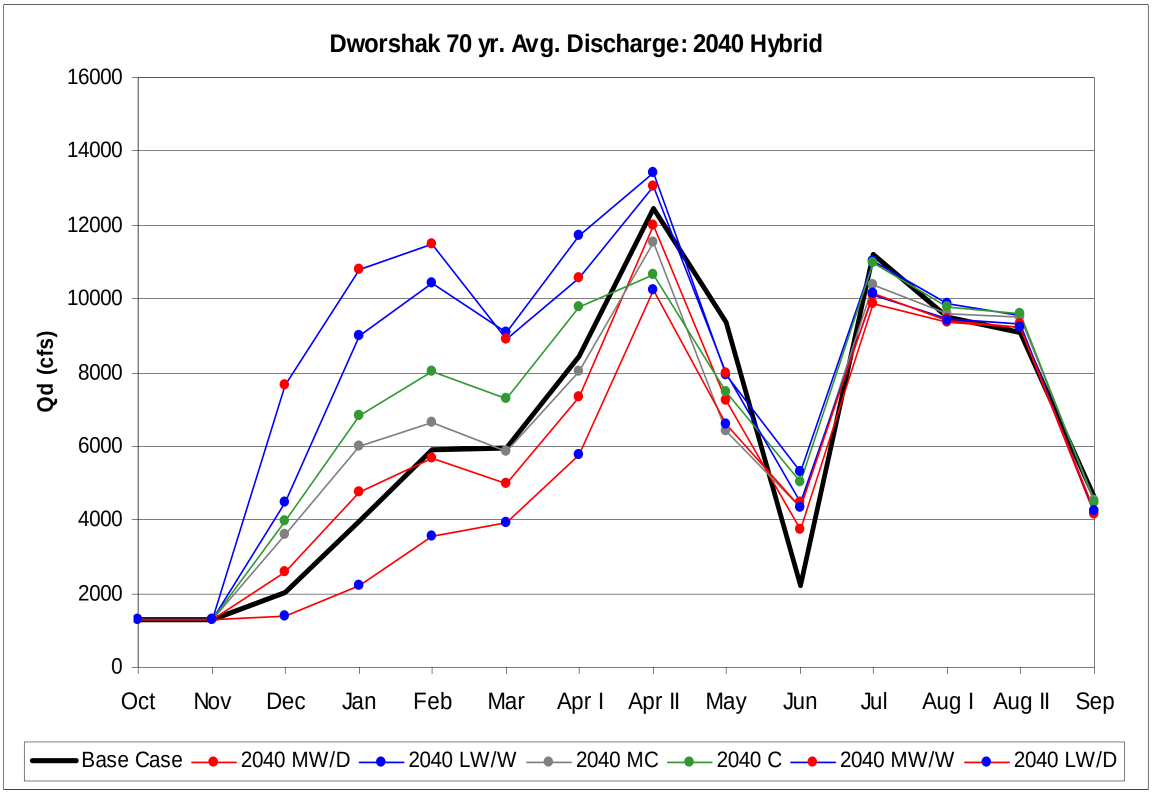

Figure 109. Dworshak seventy-year averaged Discharge: 2040s Hybrid-Delta.

Figures 108 and Figure 109 show two plots of the 70-year average DWR monthly end elevations for the Base Case, the six Hybrid-Delta 2020 scenarios and the six Hybrid-Delta 2040 scenarios respectively. As mentioned earlier, from July to September, DWR operates to target elevations for salmon, and in June, DWR operates to maximum elevation for refill. Hence all elevations are quite close together for these periods. From October to May, DWR operates to either minimum flow or to URC en route to achieving maximum elevation in June. All the climate change scenarios (with the exception of the dry LW/D scenario), show both higher elevations and higher discharge relative to the Base Case. This is due to the high natural inflows into DWR for the climate change scenarios relative to the Base Case.

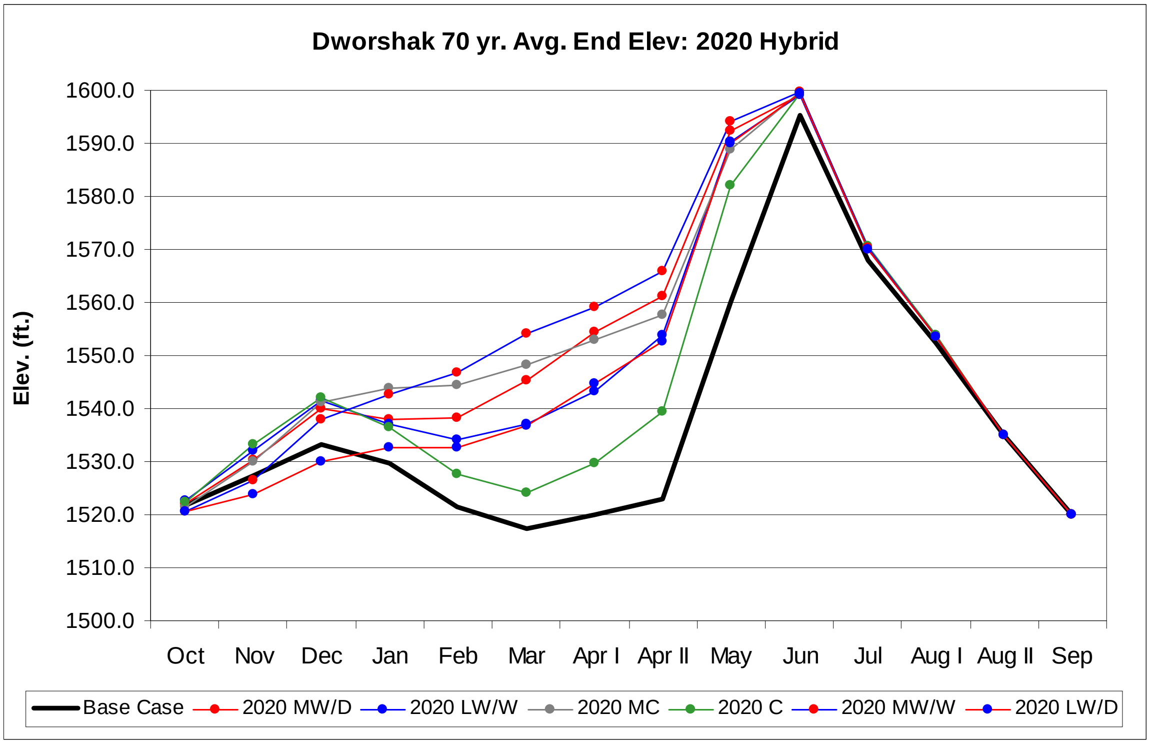

Figure 110. Dworshak End Elevations: 2020s HD.

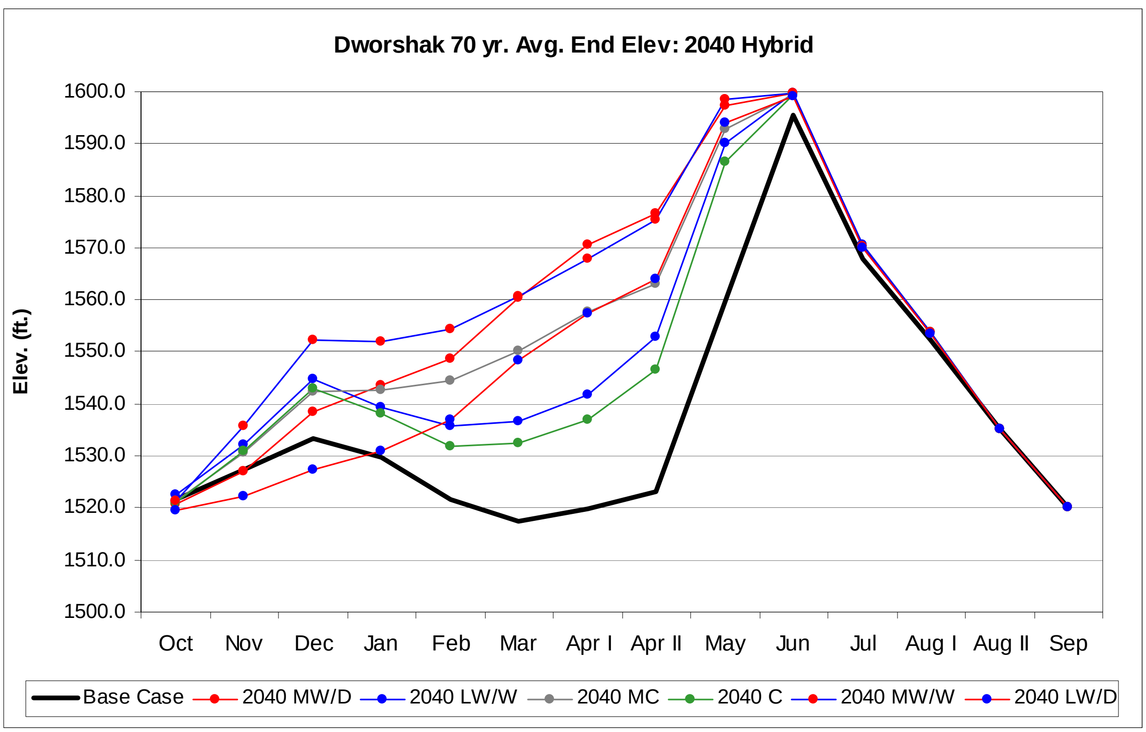

Figure 111. Dworshak End Elevations: 2040s HD.

11.2.6 Brownlee

A comparison of the average inflow into Brownlee Reservoir for the six Hybrid-Delta 2020 studies, six Hybrid-Delta 2040 studies and Base Case scenario is provided in Figure 112. The inflow into Brownlee reservoir is regulated by Reclamation projects located in the upper Snake River subbasin. A more complete description of these projects and the climate change impact on their operation are provided in Part II of this report. Figure 112 illustrates that relative to the Base Case study the climate change scenarios tend to have moderately lower inflow into Brownlee Reservoir during October and November. Between January and March average inflow is higher in the climate change scenarios with peak inflow occurring in March. The Base Case has an average peak inflow during May. Inflow is slightly higher in the climate change scenarios during April but begins to decrease relative to the Base Case in May and June. Inflows during the summer are slightly lower in the climate change scenarios.

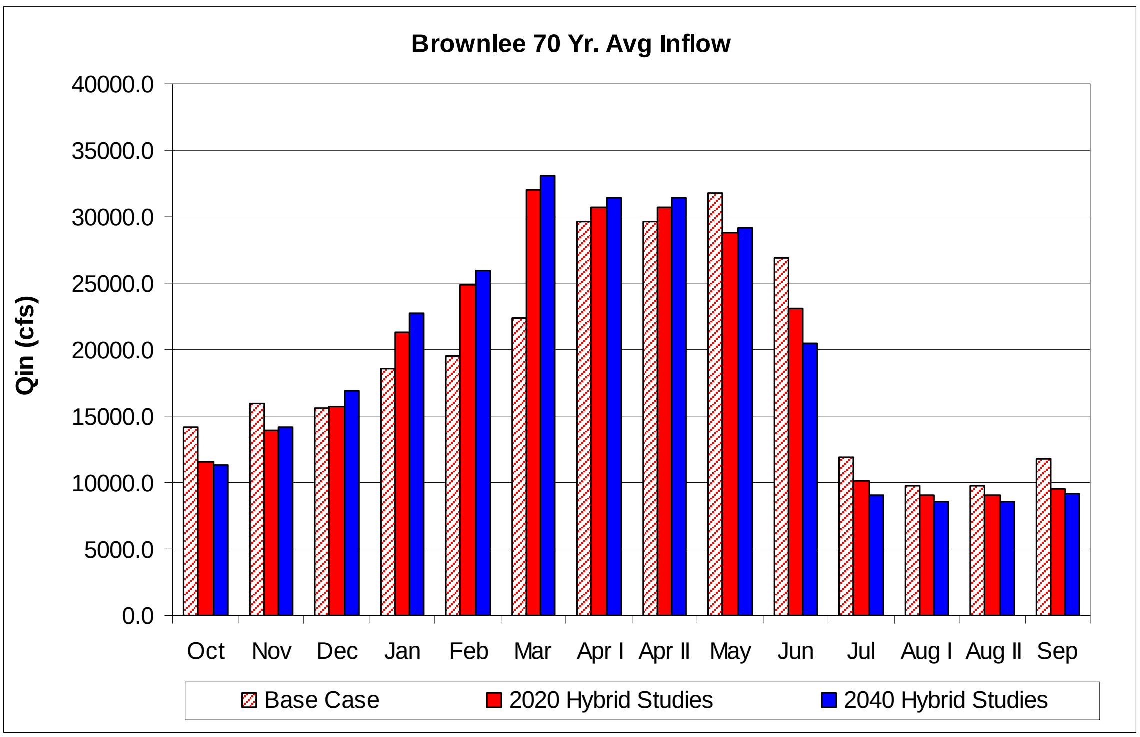

Figure 112. Comparison of month average Brownlee inflow for the Base Case, 2020 Hybrid-Delta and 2040 Hybrid-Delta climate change scenarios.

A comparison of the average period ending elevation for the Hybrid-Delta 2020 studies and Hybrid-Delta 2040 studies and the Base Case scenario is provided in Figure 113. A comparison of the average discharge from Brownlee Reservoir for each study is provided in Figure 114. Between October and December Brownlee Reservoir is operated for fall Chinook spawning. During November and December the project is operated at a flow of 8,500 cfs unless the reservoir fills to elevation 2077 feet in which case the project passes inflow. As a modeling assumption the end of October elevation varies by year and is set with the intent to keep discharge below 13,000 cfs for the fish spawning period. Because the October and November inflow tends to be lower than the Base Case in the climate change scenarios (see Figure 112) there is less need to discharge as much water during October to prevent high flows in November and December. This explains the lower discharge observed during October in the climate change scenarios when compared to the Base Case. The climate change scenarios tend to have lower inflow during November resulting in a lower average end-of-month elevation as many years are discharging near 8,500 cfs. This elevation difference decreases between November and December as higher inflows in the climate change scenarios begin to fill the reservoir faster than the Base Case.

Brownlee begins to draft for flood control in February. During this period inflows tend to be higher in the climate change scenarios resulting in higher outflow. Average elevations are also higher in the climate change studies suggesting a reduced flood control draft. However, this observation may be a bit misleading as the average may be skewed by the dry years. This is discussed in more detail later. Inflow and discharge both remain slightly higher during April in the climate change studies. However, with an earlier peak runoff the inflows in the climate change scenarios begin to decrease relative to the Base Case during May and June resulting in lower discharge when compared to the Base Case.

During the summer months the Brownlee operation is modeled with fixed monthly elevation targets for all water years. This results in a direct correlation between lower project inflow and lower project discharge for the climate change scenarios.

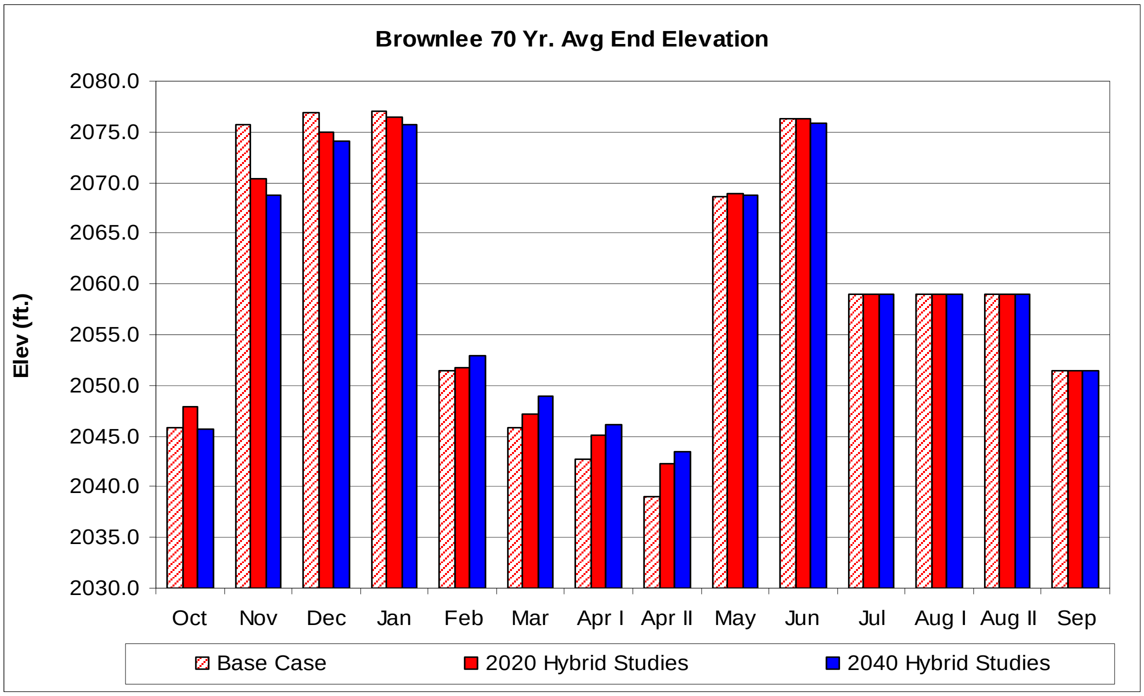

Figure 113. Comparison of period ending Brownlee reservoir elevation for the Base Case, 2020 Hybrid-Delta, and 2040 Hybrid-Delta climate change scenarios.

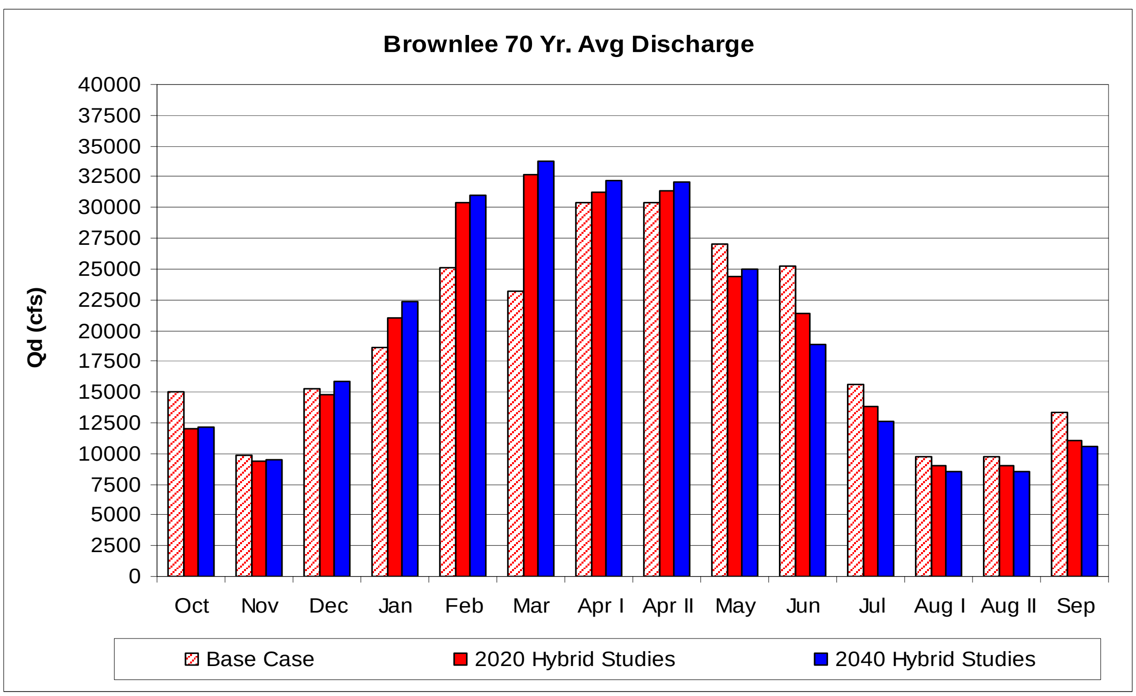

Figure 114. Comparison of month average Brownlee discharge for the Base Case, 2020 Hybrid-Delta and 2040 Hybrid-Delta climate change scenarios.

A comparison of period ending reservoir elevation for each of the six Hybrid-Delta 2020 studies and the Base Case is available in Figure 115 while Figure 116 provides a comparison of discharge for the same selections. These figures show the average November and December elevation in all climate scenarios is below the Base Case, but it begins to converge back to the Base Case by January. During the flood control drawdown period the drier scenarios have the highest reservoir elevations (MW/D and LW/D) while the wetter scenarios are drafted slightly deeper than the Base Case. The deviation from the Base Case associated with these dry years is greater than the deviation associated with the other years and may skew the average data shown in Figure 113. All but the dry climate change scenarios have a higher discharge than the Base Case during the winter drawdown period. Elevations converge in May and June and all scenarios are operated to the same reservoir elevation targets through the summer. During the late spring periods between April and May the wetter climate scenarios tend to have a higher discharge than the Base Case while the drier scenarios tend to have lower discharge. By the summer months between July and September all the climate change scenarios have an average discharge near, to below the Base Case. These trends appear to be amplified in the 2040 Hybrid-Delta studies with one exception; only the dry and less warm scenario (LW/D) has an average discharge below the Base Case during the winter drawdown period while the warmer and dry scenario (MW/D) is now above the Base Case. Figure 117 and Figure 118 provide a detailed comparison between the 2040 Hybrid-Delta scenarios and the Base Case study.

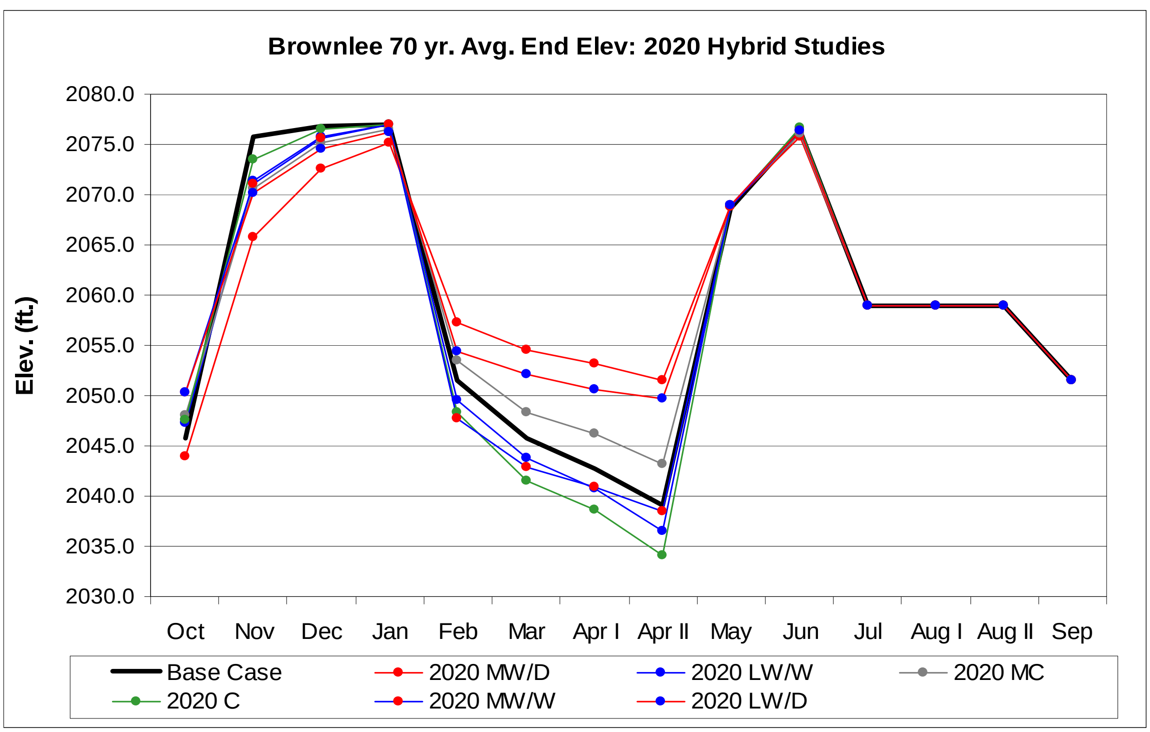

Figure 115. Brownlee period ending elevation for each 2020 Hybrid-Delta climate change scenario.

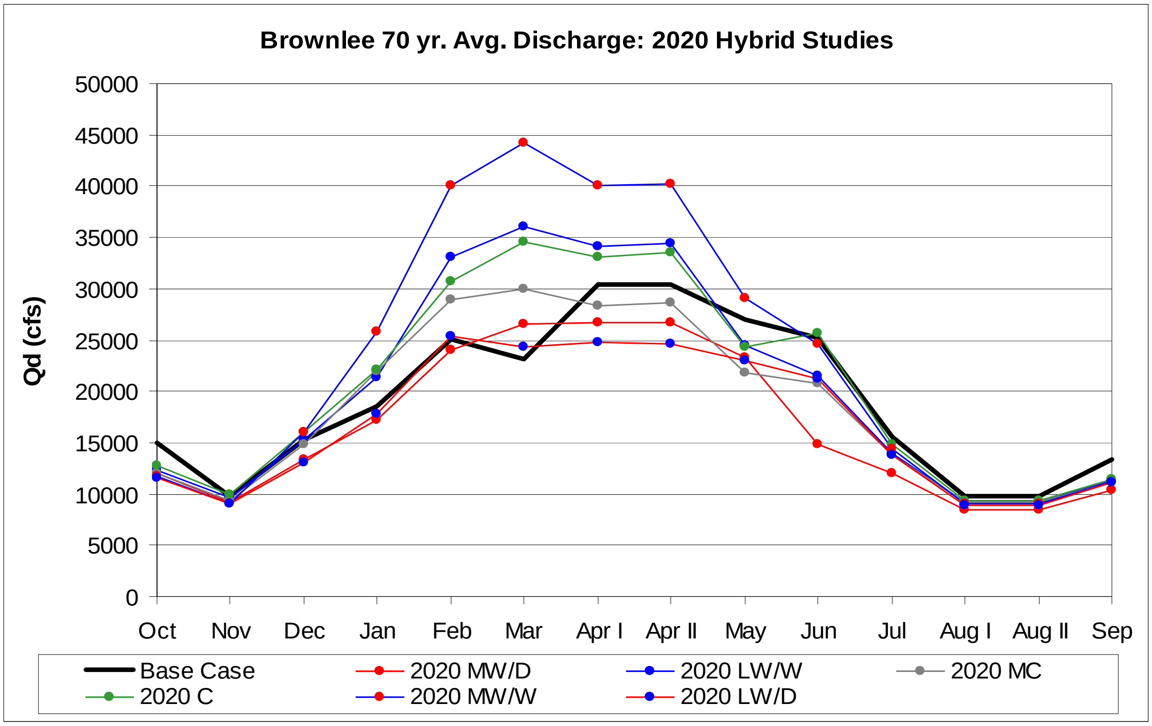

Figure 116. Brownlee month average discharge for each 2020 Hybrid-Delta climate change scenario.

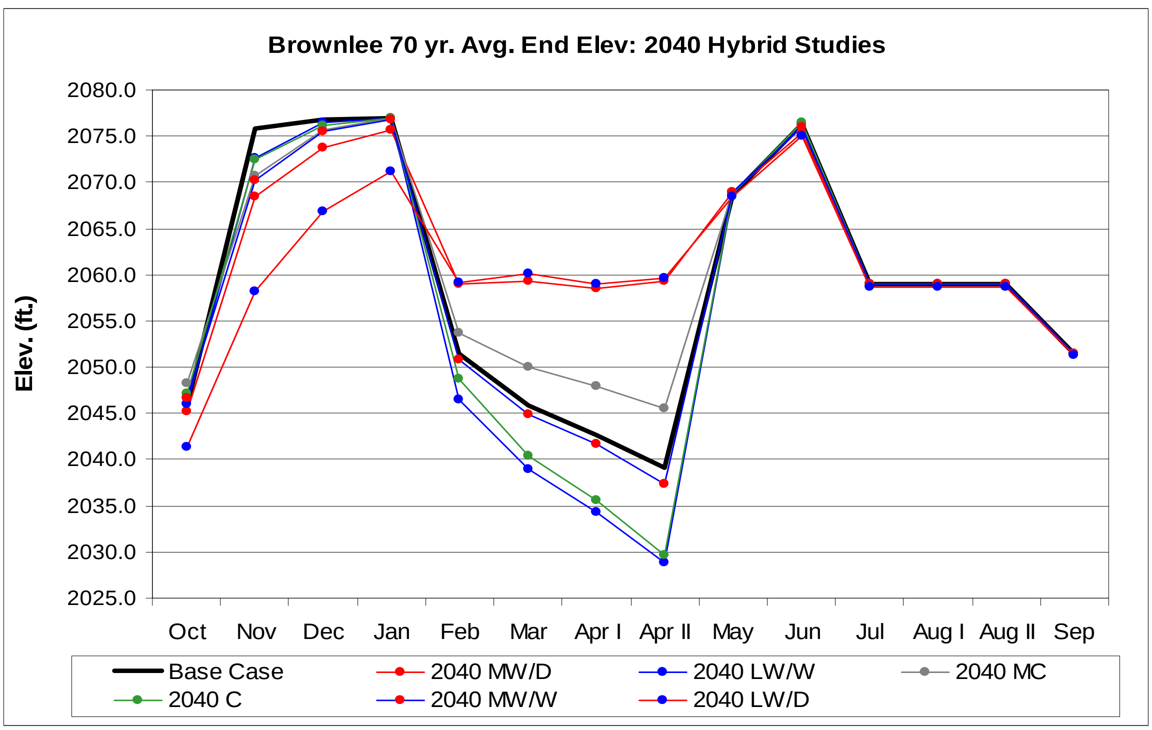

Figure 117. Brownlee period ending elevation for each 2040 Hybrid-Delta climate change scenario.

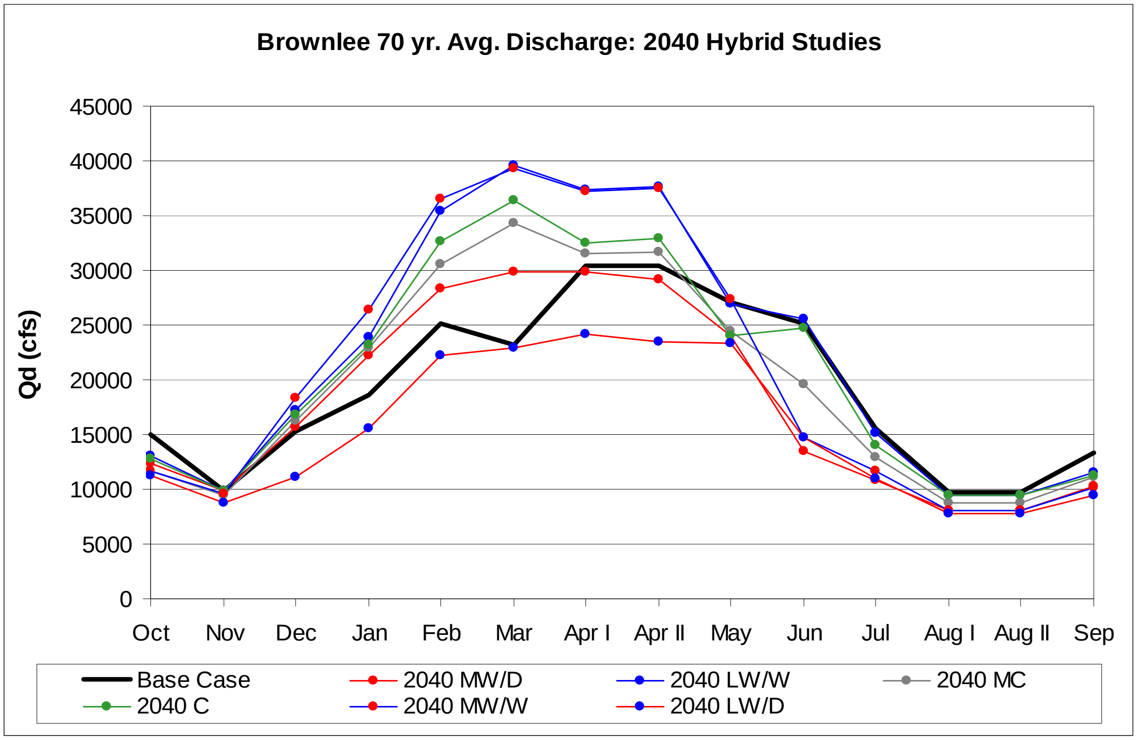

Figure 118. Brownlee monthly average discharge for each 2040 Hybrid-Delta climate change scenario.

11.2.7 Lower Granite

Discharge at Lower Granite (LWG) tends to be higher in the climate change scenarios from December through April and then lower through the late spring and summer months. Figure 119 shows the overall average discharge of each set of climate change studies as they compare with the Base Case scenario. Figure 120 shows that the overall trend of increased discharge in the cool season and less during the warm season seems to increase between the Hybrid-Delta 2020 and 2040 studies. Figure 122 does show that the less warming and drier 2040 Hybrid-Delta study is an exception in that LWG discharge is below the Base Case throughout the winter and early spring.

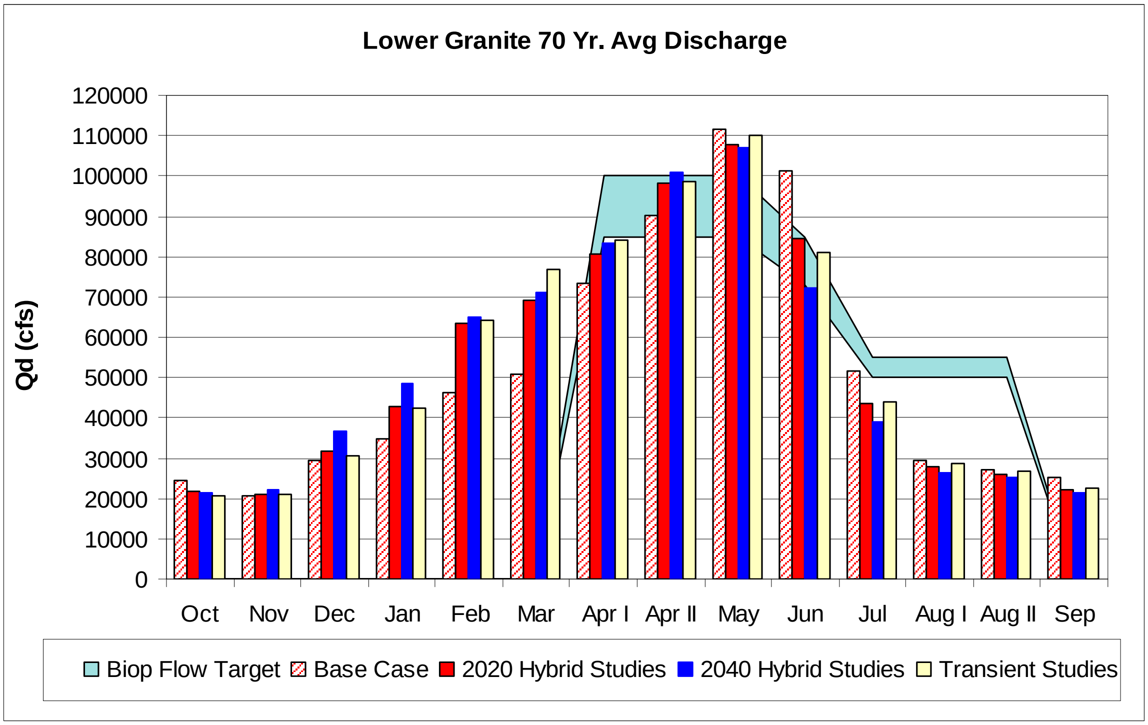

Figure 119. Lower Granite Avg. Mo. Discharge for Base Case and Climate Change Scenarios.

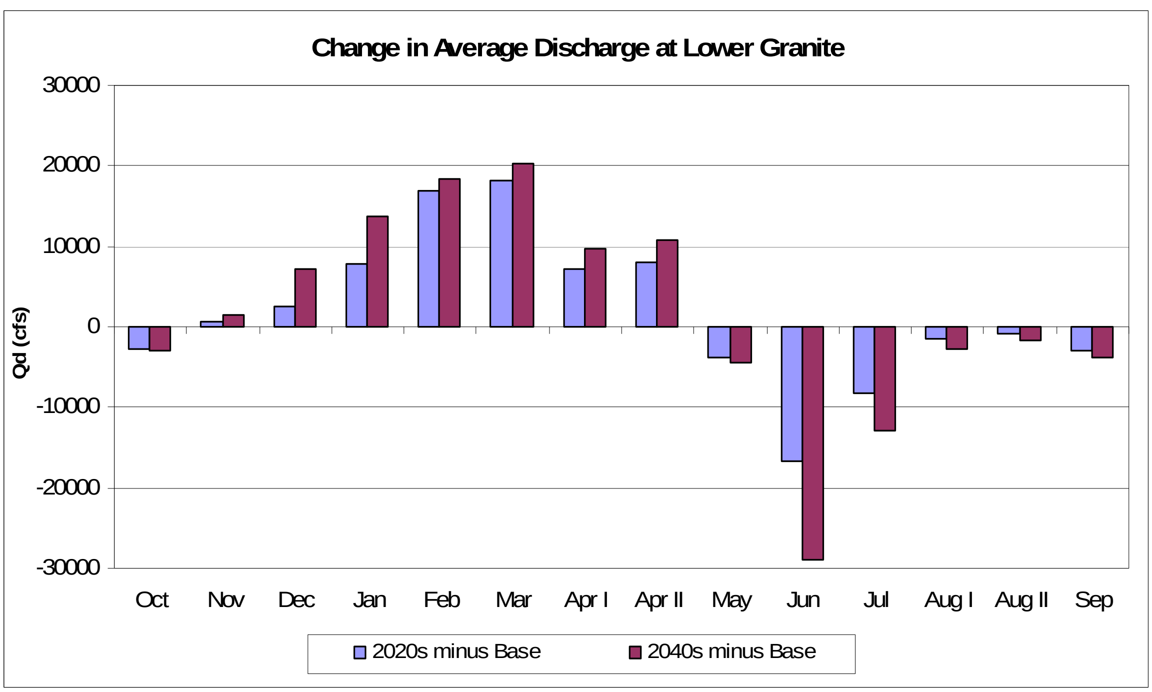

Figure 120. Lower Granite Avg. Mo. Discharge Delta for Base Case and Hybrid-Delta Scenarios.

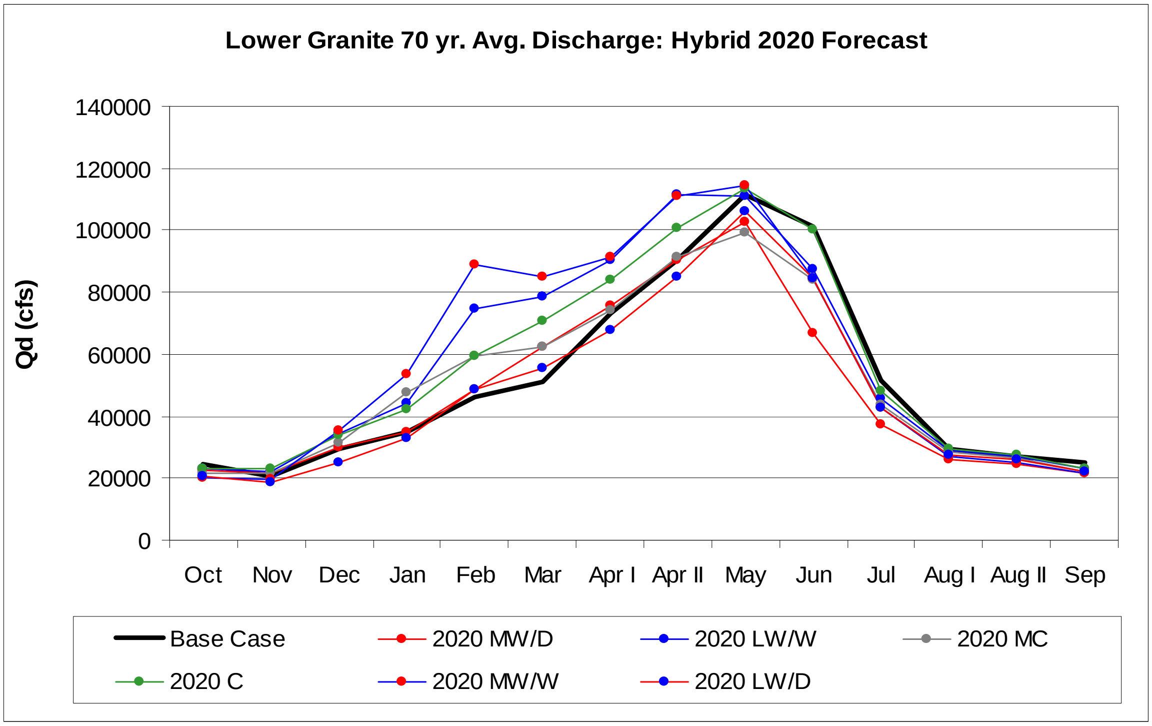

Figure 121. Lower Granite Discharge: 2020s Hybrid-Delta.

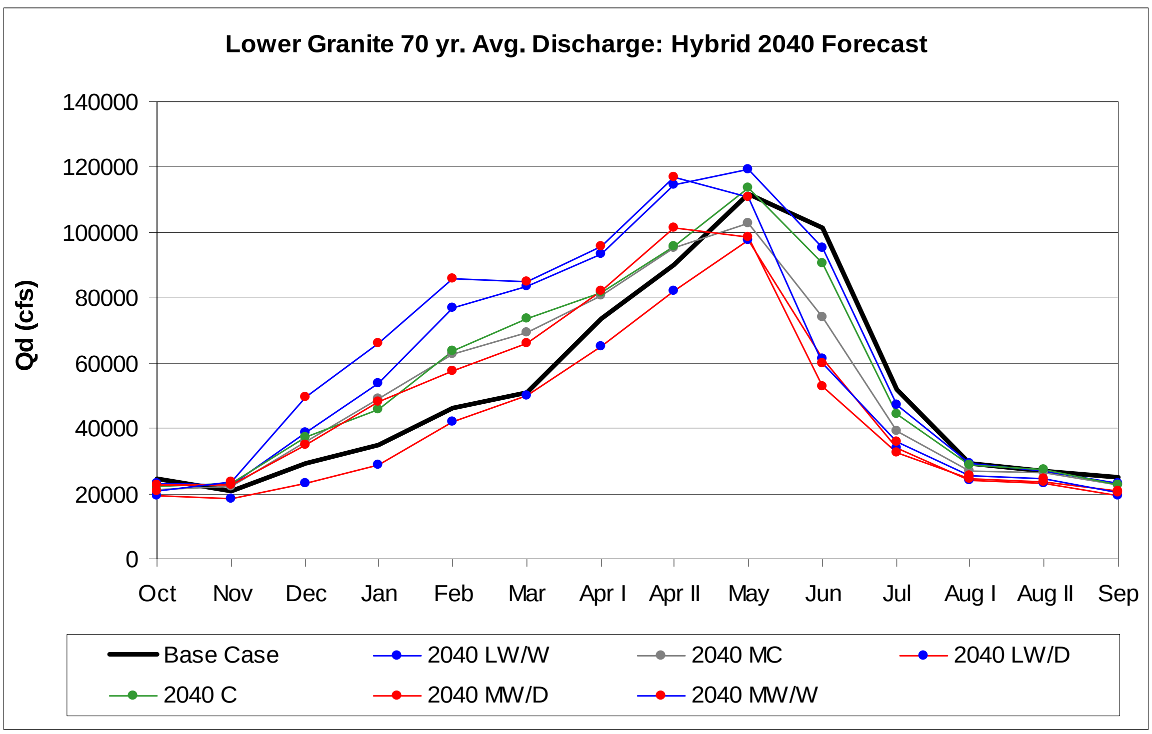

Figure 122. Lower Granite Discharge: 2040s Hybrid-Delta.

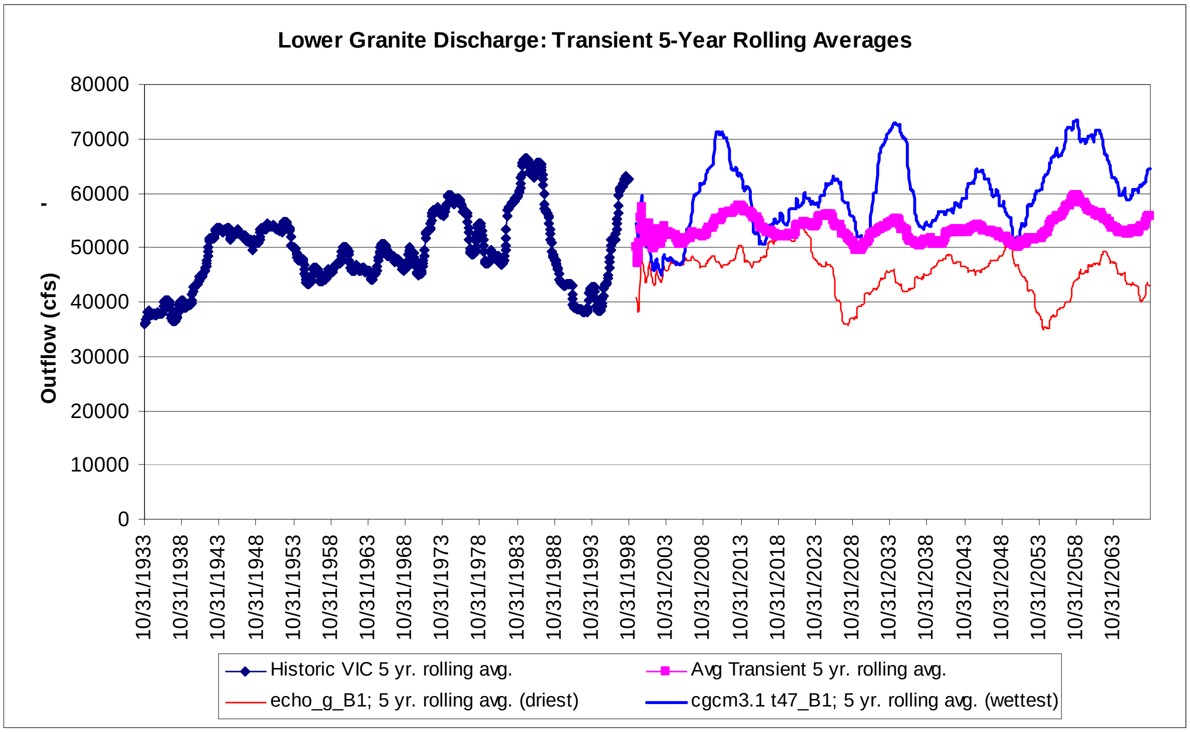

Figure 123. Lower Granite 5-Yr. Rolling Average Discharge for Historic and Transient Scenario.

The Transient scenario 5-year rolling average in Figure 124 shows the LWG discharge over the historical period, moving into the projected discharge for the future planning horizon. The average of all the transient flow scenarios indicates a relatively steady outflow with some periods of high volatility.

11.2.8 McNary

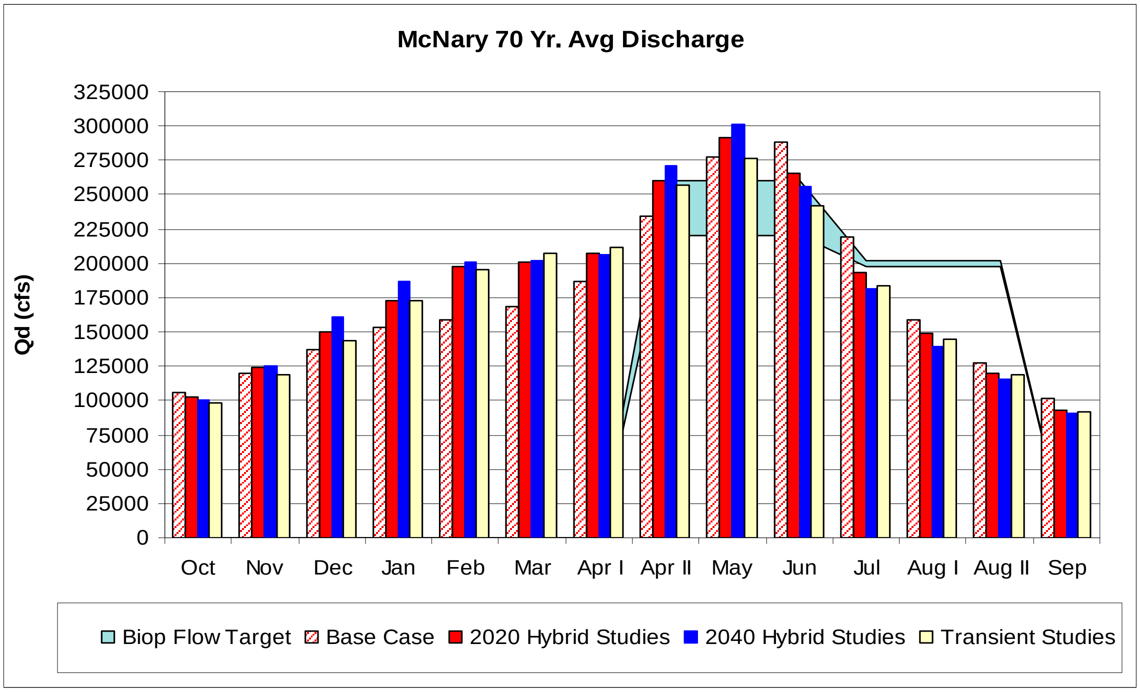

Figure 124. McNary Average Monthly Discharge for Base Case and Climate Change Scenarios.

The flow differences at between the Base Case and the climate change scenarios at McNary Dam are similar to the differences observed at Lower Granite. Figure 124 shows that the discharge associated with the various climate change scenarios tends to be higher than the Base Case November through May and then lower than the Base Case during the late spring and summer. Figure 125 shows that this trend increases between the 2020 and 2040 Hybrid-Delta studies. Figure 126 and Figure 127 show that this trend is relatively consistent among the various climate change models. One exception might be the MW/D scenarios that do not seem to be higher than the Base Case in the winter and spring but still below Base Case during the summer.

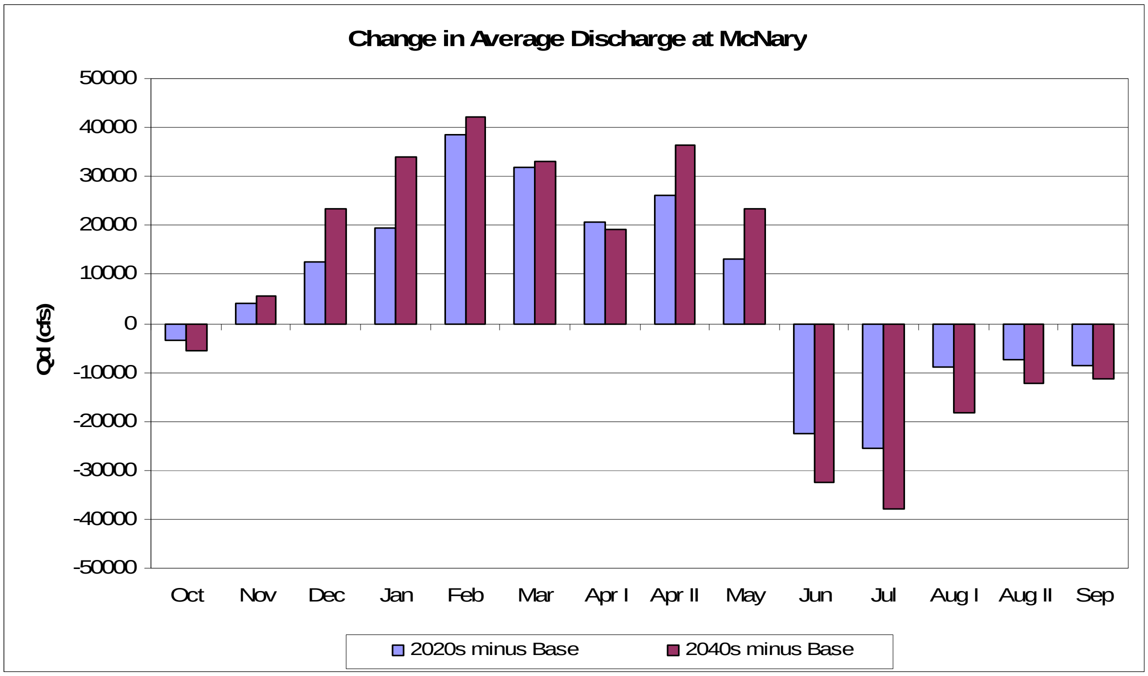

Figure 125. McNary Avg. Mo. Discharge Delta for Base Case and Hybrid-Delta Climate Change Scenarios.

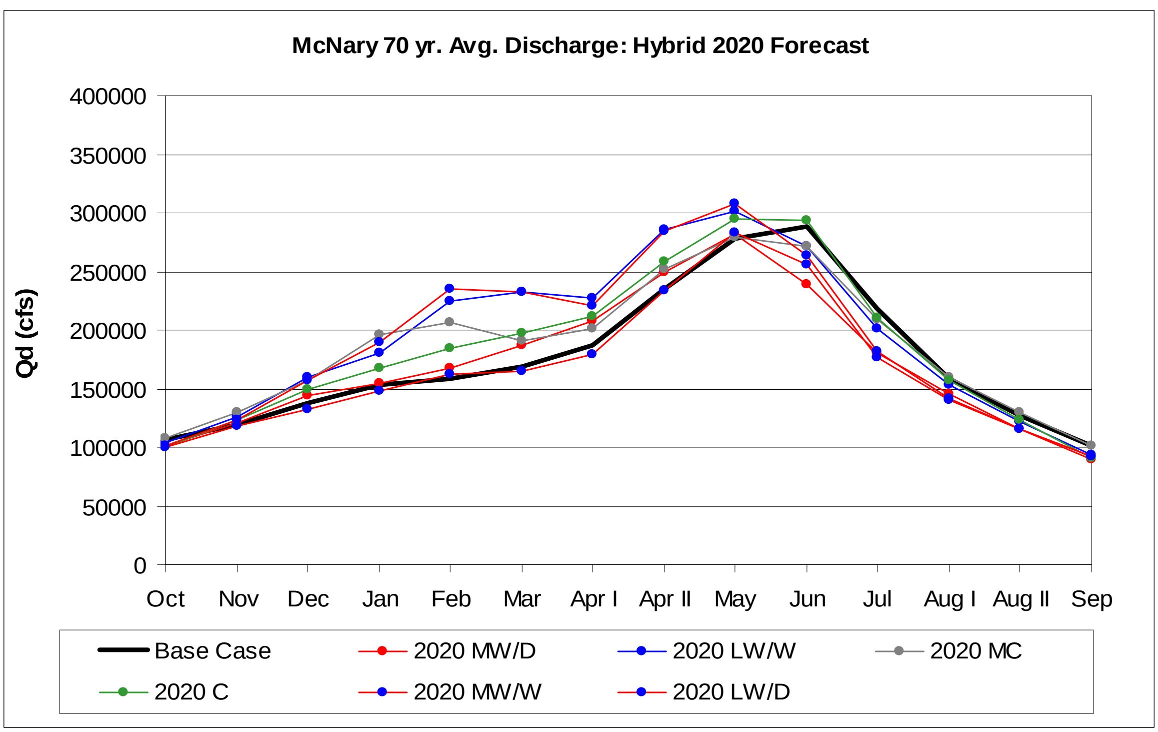

Figure 126. McNary Discharge: Hybrid-Delta 2020s

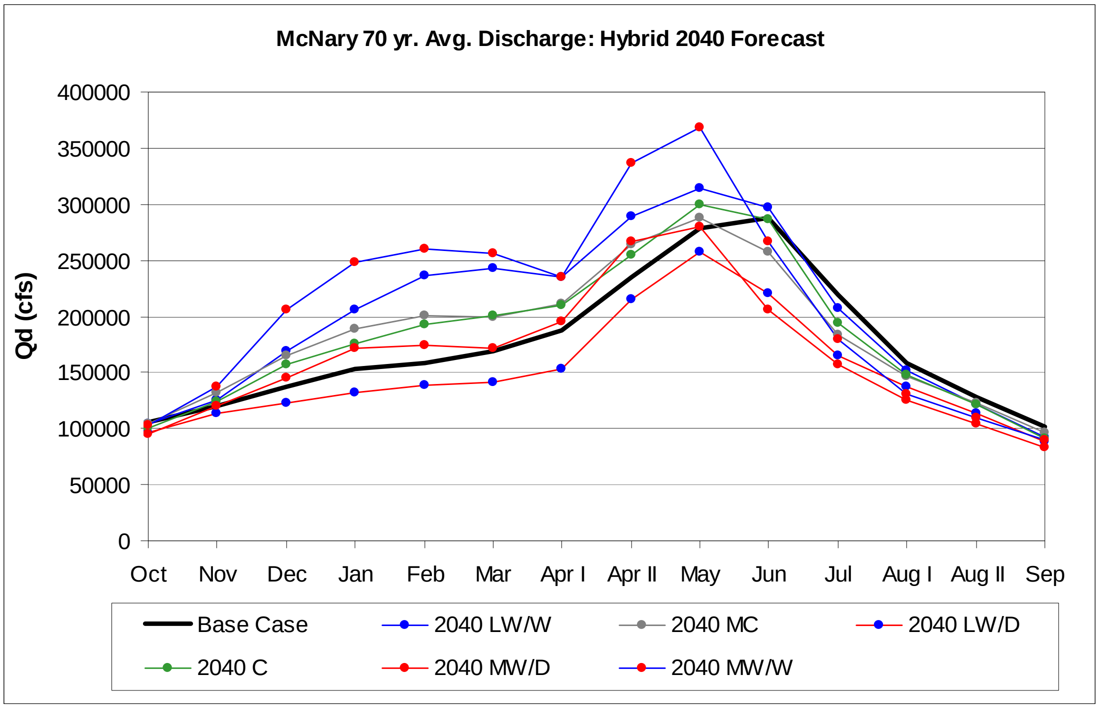

Figure 127. McNary Discharge: Hybrid-Delta 2040s

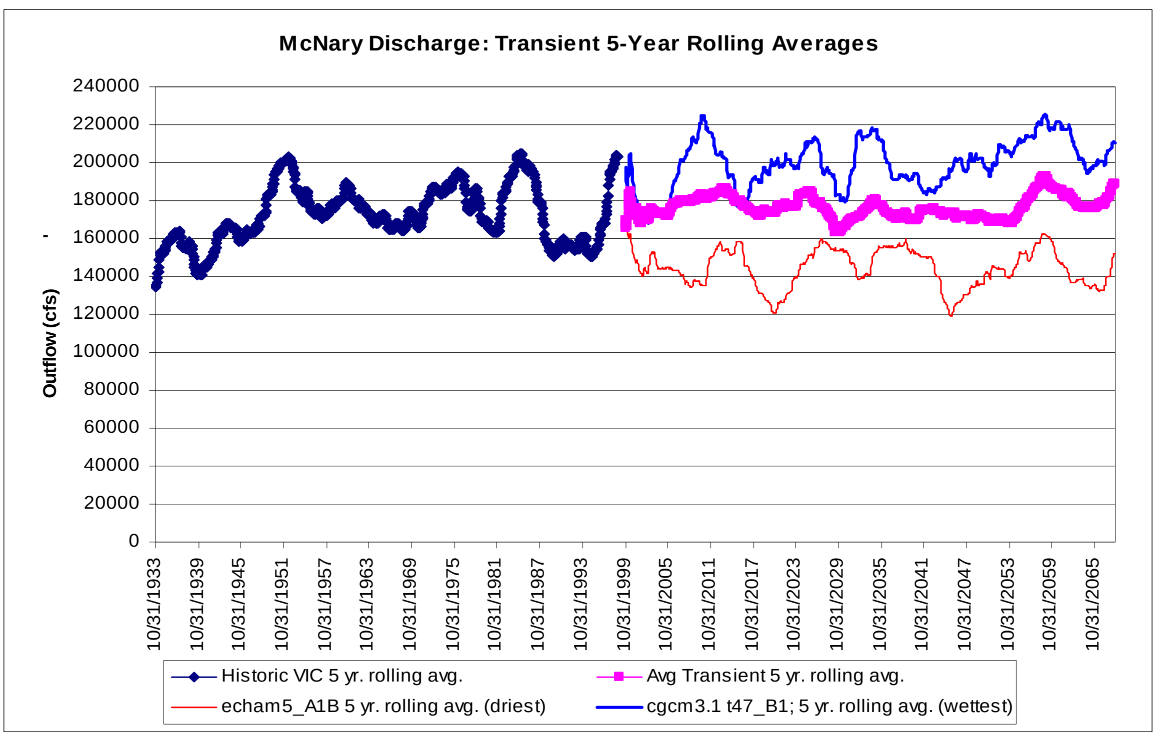

Figure 128. McNary 5-Yr. Rolling Average Discharge for Historic and Transient Scenarios.

11.2.9 The Dalles

Lower Columbia River flow comparisons are reflected in the McNary discussion above. The high flow 2040 MW/W scenario is defined in more detail in this section with respect to project discharge impacts at The Dalles. The difference in streamflows between the Base Case and this wetter scenario are significant. The following two graphs illustrate this.

Figure 129 shows the Base Case outflows at The Dalles. The box indicates the % of years that fall in the 25%-75% range. Note that 75% of the years have a maximum June outflow of less than 355 kcfs with a single year maximum outflow of 564 kcfs.

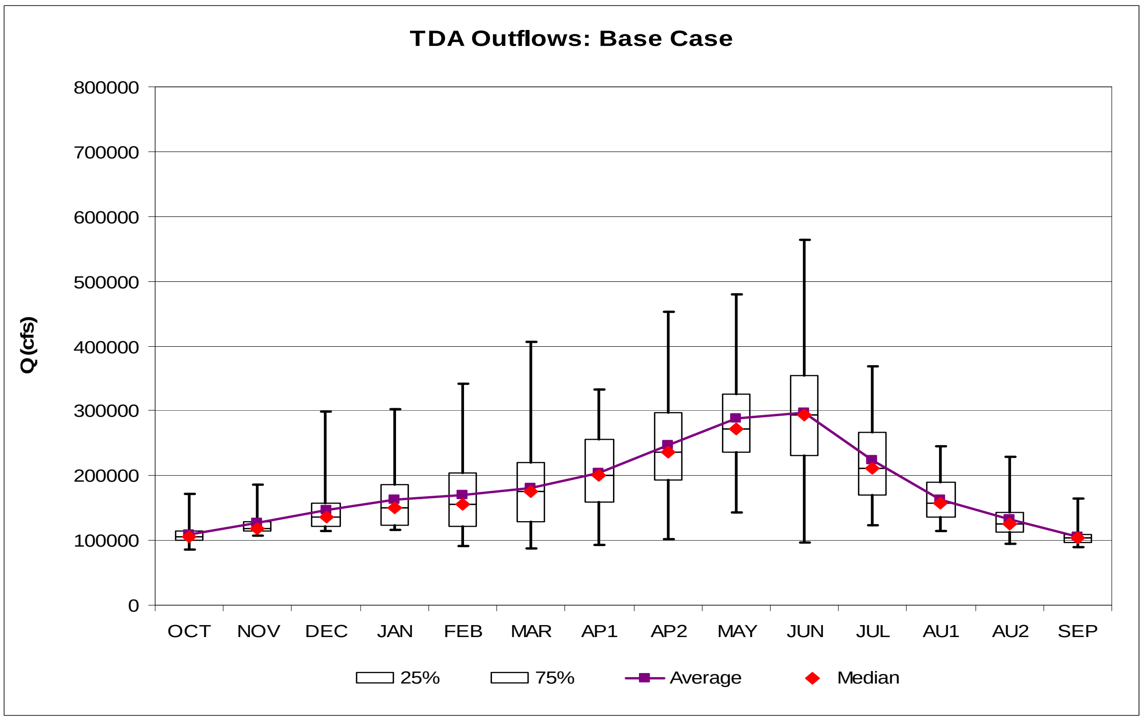

Figure 129. The Dalles Outflows for Base Case.

The graph below shows the outflows at The Dalles for the 2040 MW/W scenario. This scenario reflects the wettest scenario of all the runs. Relative to the Base Case, note that the highest flows occur in the April-May period rather than the June period and the max single year flows are approximately 700 kcfs.

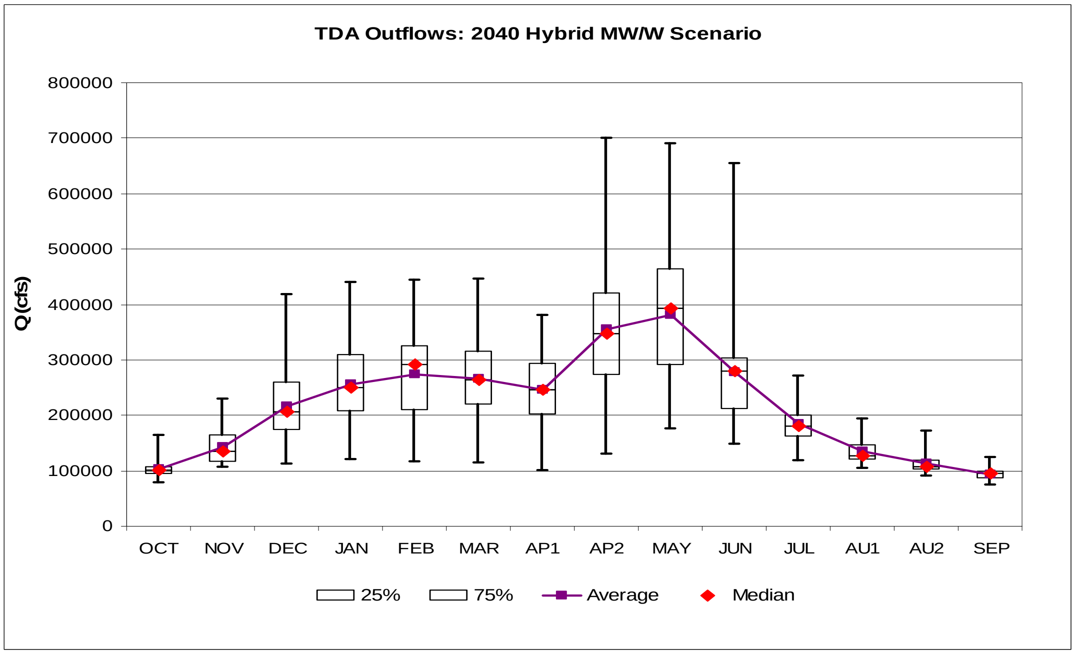

Figure 130. The Dalles Outflows for Hybrid-Delta 2040 MW/W Scenario.

11.3 Fishery Impacts: Summer Flow Objectives

11.3.1 McNary Outflows

The BiOp calls for a summer flow at McNary of 200 kcfs from July through August (bold line in graph). This BiOp flow target can be seen in Figure 124. This same figure shows that on average, this flow target is not achievable given other constraints on the hydro system. Figure 131 shows that even in the Base Case scenario, this flow is only achieved in about 45-50% of the modeled water years for July, about 10% for the period August 1-15, and less than 5% of the years during the period August 16-31. The three figures below show the distribution of summer flow for the Base Case scenario and how it compares with each of the 2020 Hybrid-Delta climate change scenarios for the periods; July, August 1-15 and August 16-31. The Base Case, C, and MC scenarios tend to have the highest flows throughout the distribution while the LW/W often falls in the middle and the MW/W, LW/D, and MW/D scenarios are clustered together with the lowest flows. The difference is smaller in low water years and increases towards the higher flow end of the distribution and occasionally converges again near the highest flow water years. This trend also seems to be most pronounced in the July distribution shown in Figure 131. For the lower flow MW/W, MW/D, and LW/D scenarios the BiOp flow targets are only met in 20-30% of the years in July, about 5% or less of the years in the period August 1-15 (August I), and no water years met the BiOp flow in August 16-31 (August II) period.

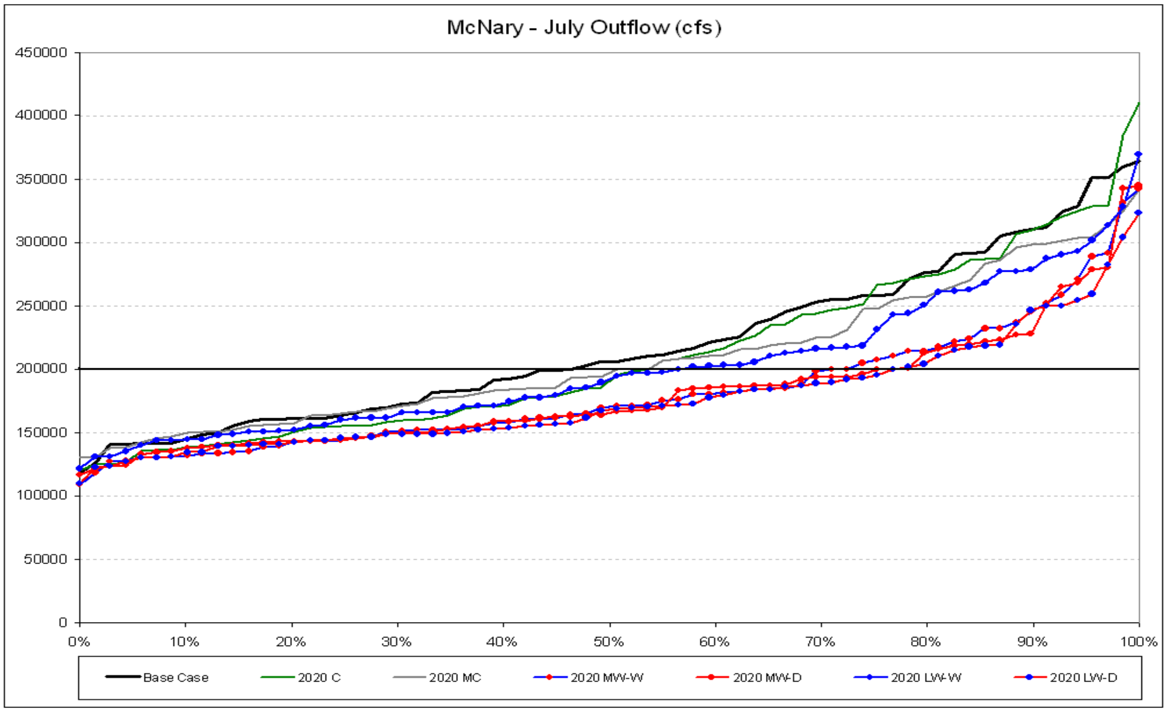

Figure 131. Comparison of Hybrid-Delta 2020 scenarios - July McNary outflow distributions.

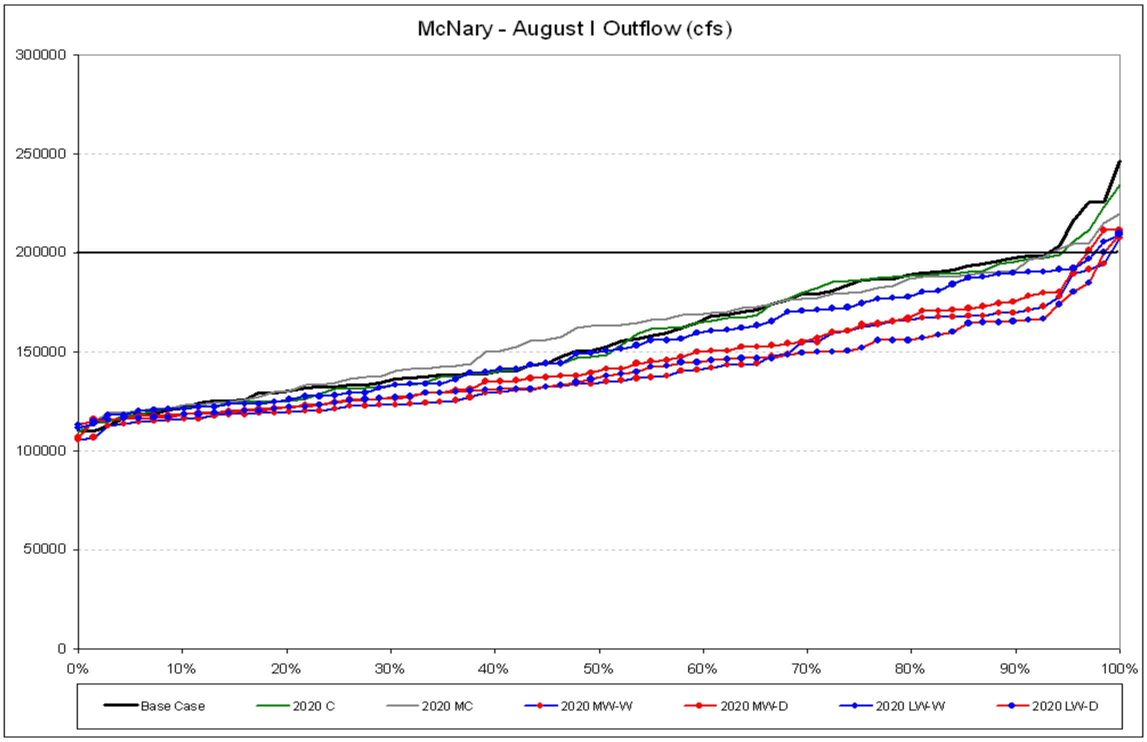

Figure 132. Comparison of Hybrid-Delta 2020 scenarios - August I McNary outflow distributions.

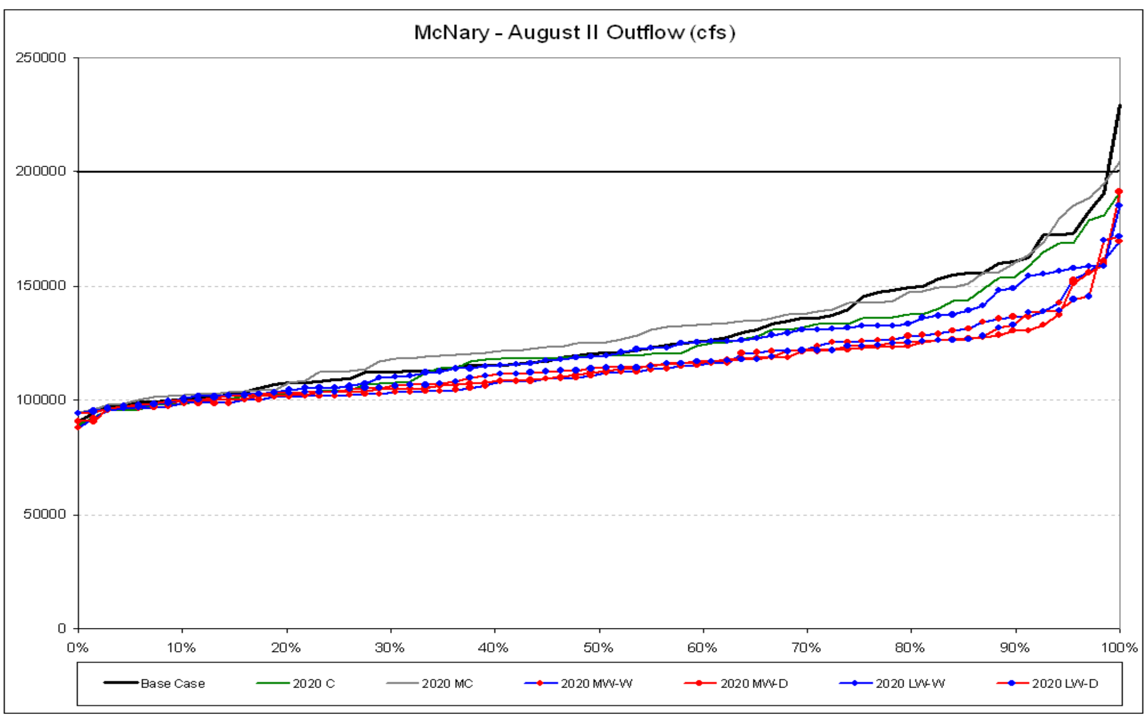

Figure 133. Comparison of Hybrid-Delta 2020 scenarios - August II McNary outflow distributions.

The following three figures show the distribution of July, August I and August II McNary flows for the 2040 Hybrid-Delta climate scenarios. The trend among the climate scenarios is similar to the Hybrid-Delta 2020 scenarios except that the LW/W scenario is much closer to the Base Case while the C and MC scenarios sometimes seem to track closer to the lower flow MW/W, LW/D, and MW/D scenarios. In addition there appears to be a lowering of flow in all of the climate change scenarios with fewer years able to meet the BiOp flows.

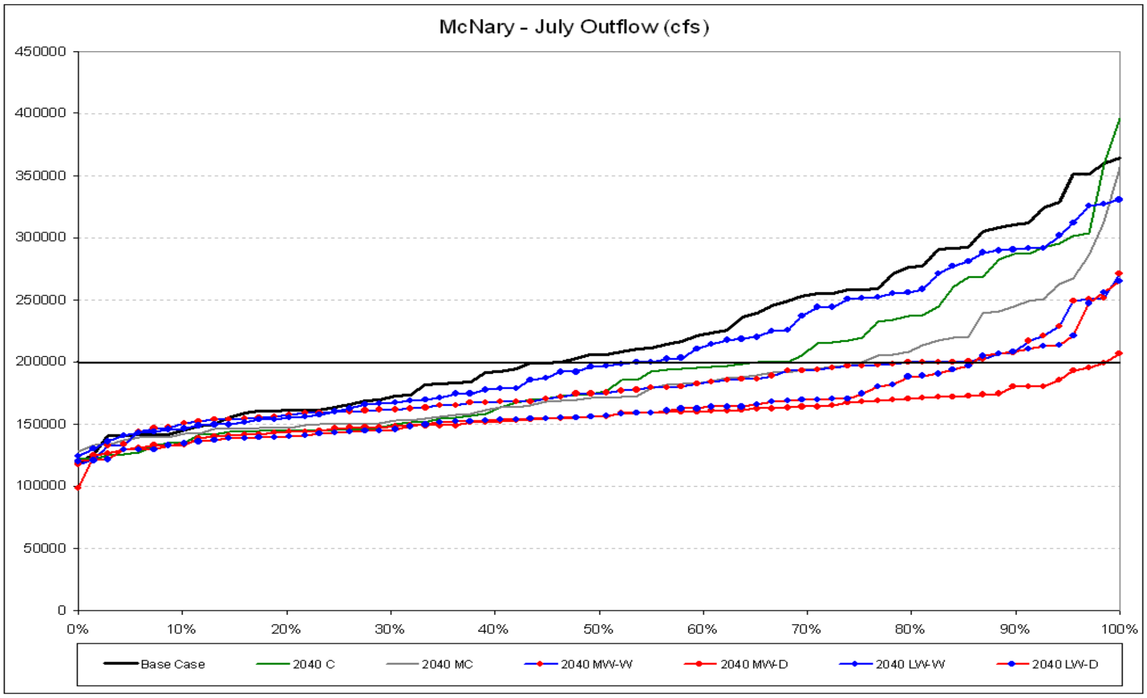

Figure 134. Comparison of 2040 Hybrid-Delta scenarios - July McNary Outflow distributions.

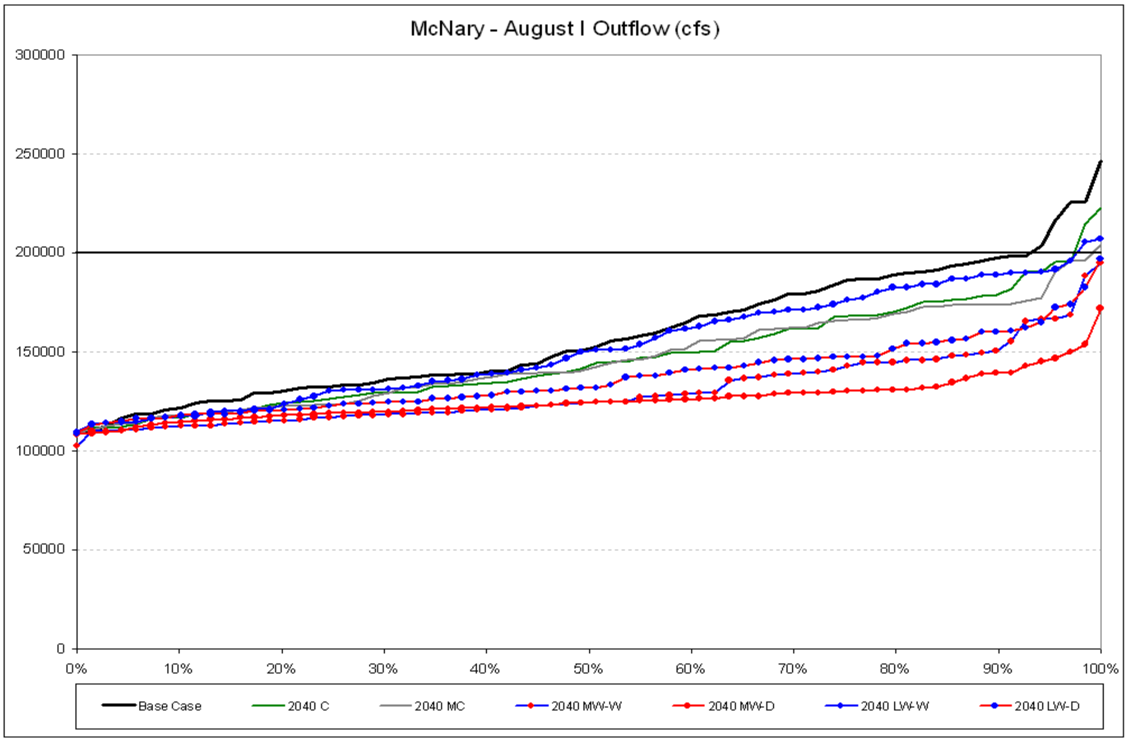

Figure 135. Comparison of 2040 Hybrid-Delta scenarios - August I McNary Outflow distributions.

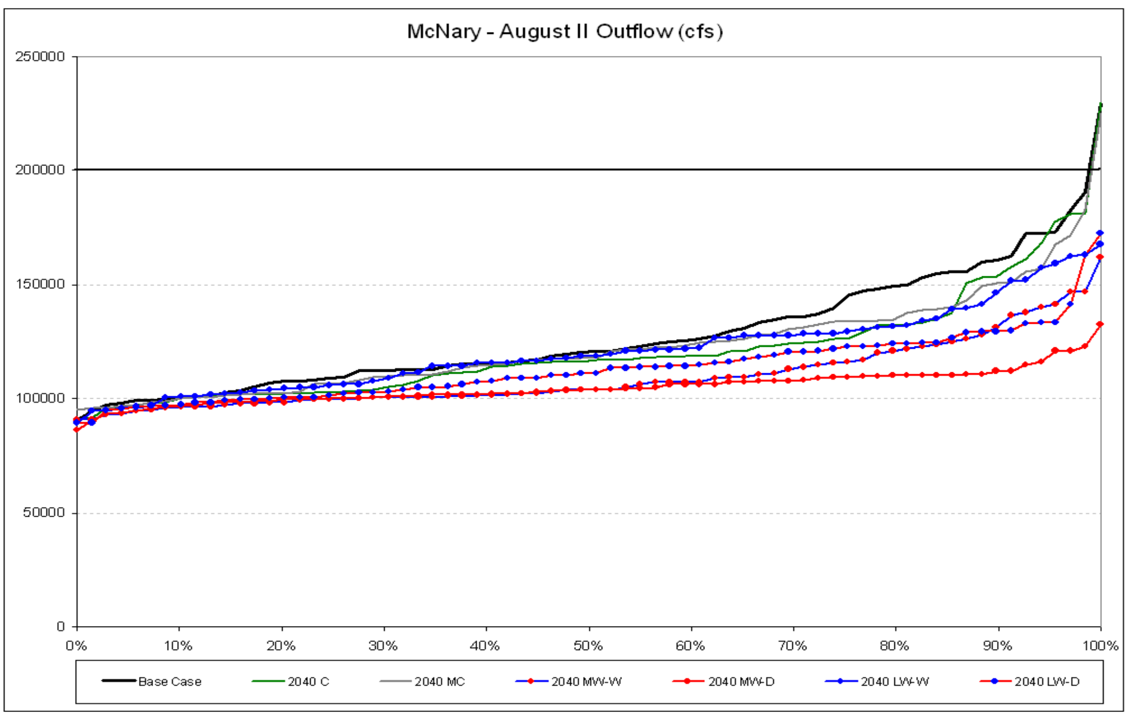

Figure 136. Comparison of 2040 Hybrid-Delta scenarios - August II McNary Outflow distributions.

11.3.2 Lower Granite Outflows

Figure 119 shows how the average Lower Granite Flows compare to the BiOp flow during July and August. The desired BiOp minimum flows for July through August is a variable 50-55 kcfs depending on the June final runoff volume forecast for Lower Granite. When the forecast is less than 16 Maf, the flow objective is 50 kcfs. If the forecast is between 16 and 28 Maf, the flow objective will be linearly interpolated between 50 and 55 kcfs. If the forecast is greater than 28 MAF, the flow objective will be 55 kcfs. Similar to McNary, based on the average flows, it is not always possible to meet the BiOp flow requirements due to other system constraints. The three figures below show the distribution of Lower Granite flows in each 2020 Hybrid-Delta model scenario along with the Base Case. The results are similar to those observed at McNary. The Base Case tends to have the highest flows through the summer months and the MW/W, MW/D, and LW/D scenarios tend to have the lowest flows. This trend is the most apparent in the July period.

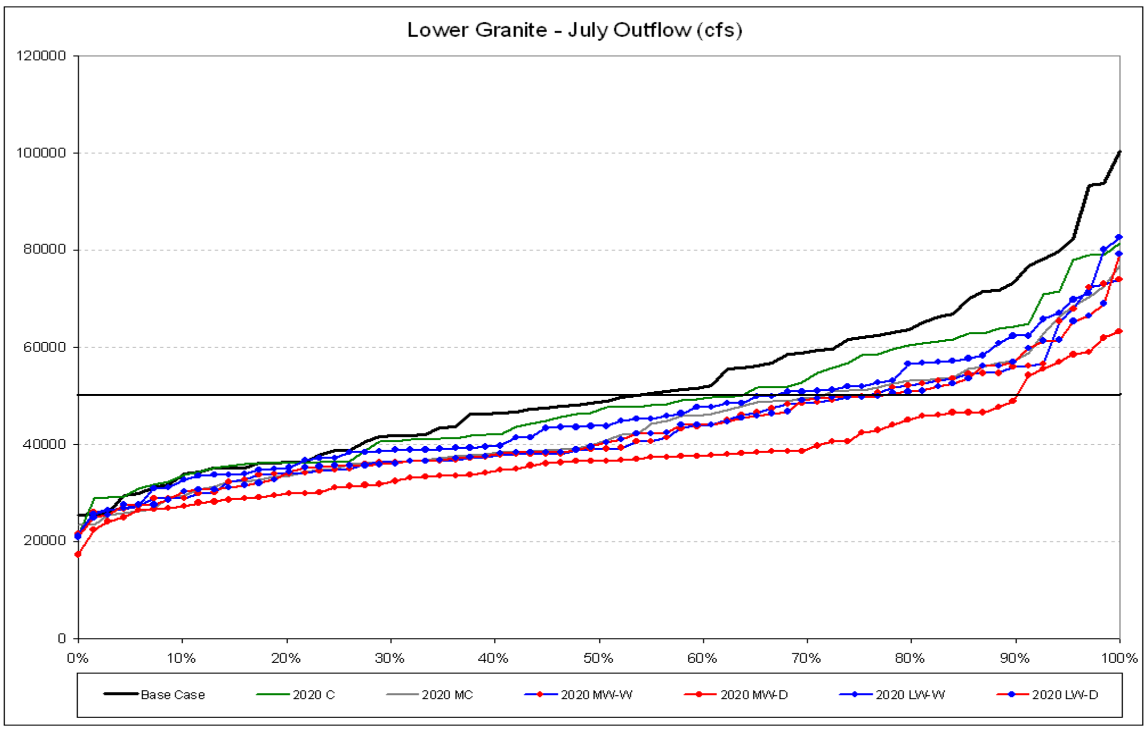

Figure 137. Comparison of 2020 Hybrid-Delta scenarios - July Lower Granite outflow distributions.

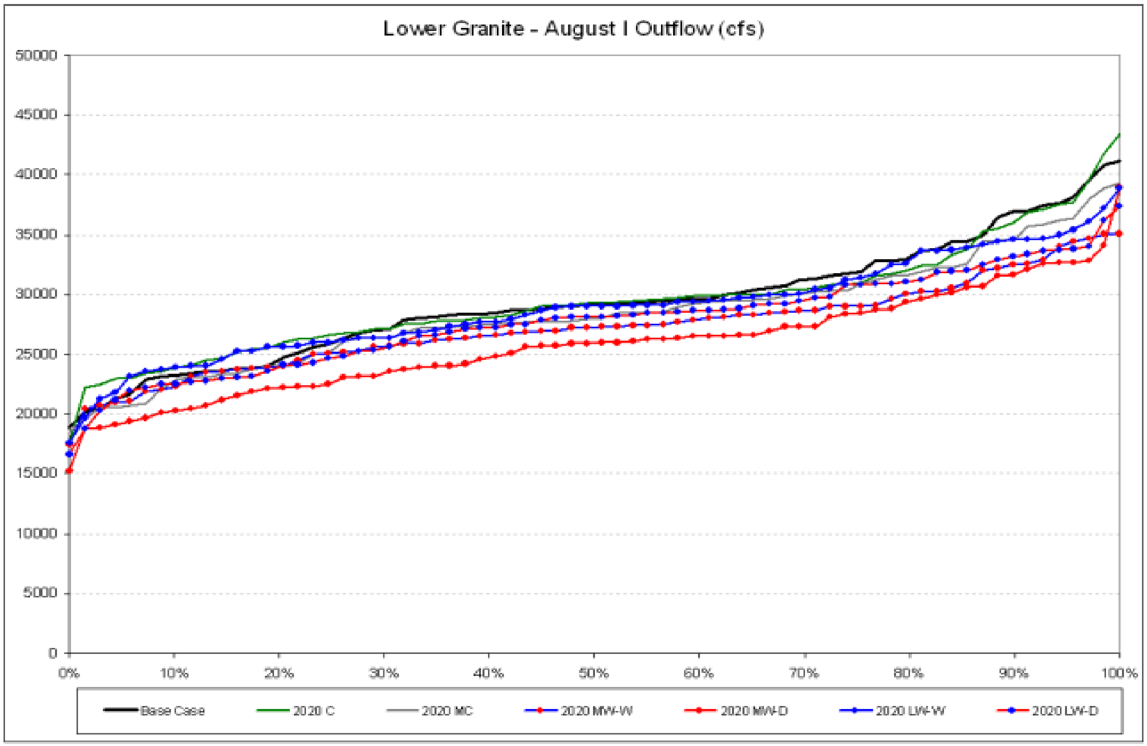

Figure 138. Comparison of 2020 Hybrid-Delta scenarios - August I Lower Granite outflow distributions.

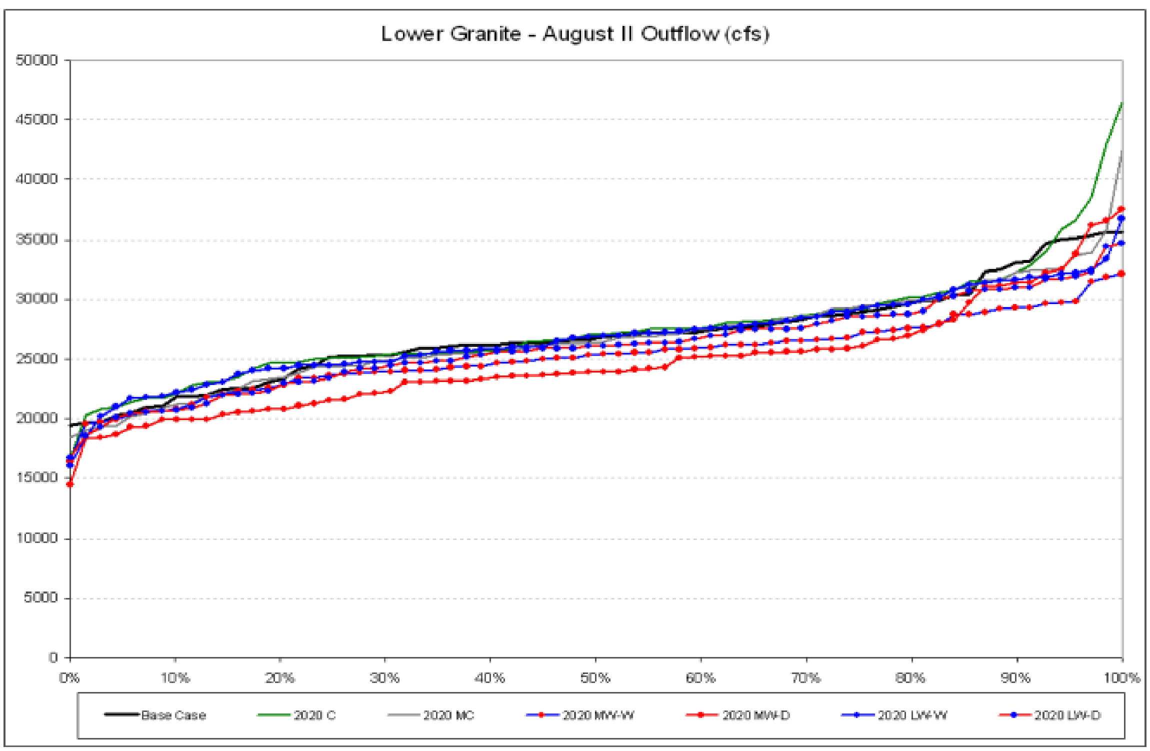

Figure 139. Comparison of 2020 Hybrid-Delta scenarios - August II Lower Granite outflow distributions.

The following three figures show the distribution of Lower Granite flows in the 2040 Hybrid-Delta model scenarios. These distributions more clearly identify the MW/W, LW/D, and MW/D scenarios as having the lowest flows. The C, MC, and LW/W scenarios are often somewhere between these lower flow scenarios and the Base Case. The LW/W and the C cases are actually slightly higher than the Base Case across portions of the distribution in the August I and August II periods.

At both Lower Granite and McNary it is clear that the MW/W, MW/D, and LW/D scenarios will have a diminished capacity to meet the BiOp summer flow objectives.

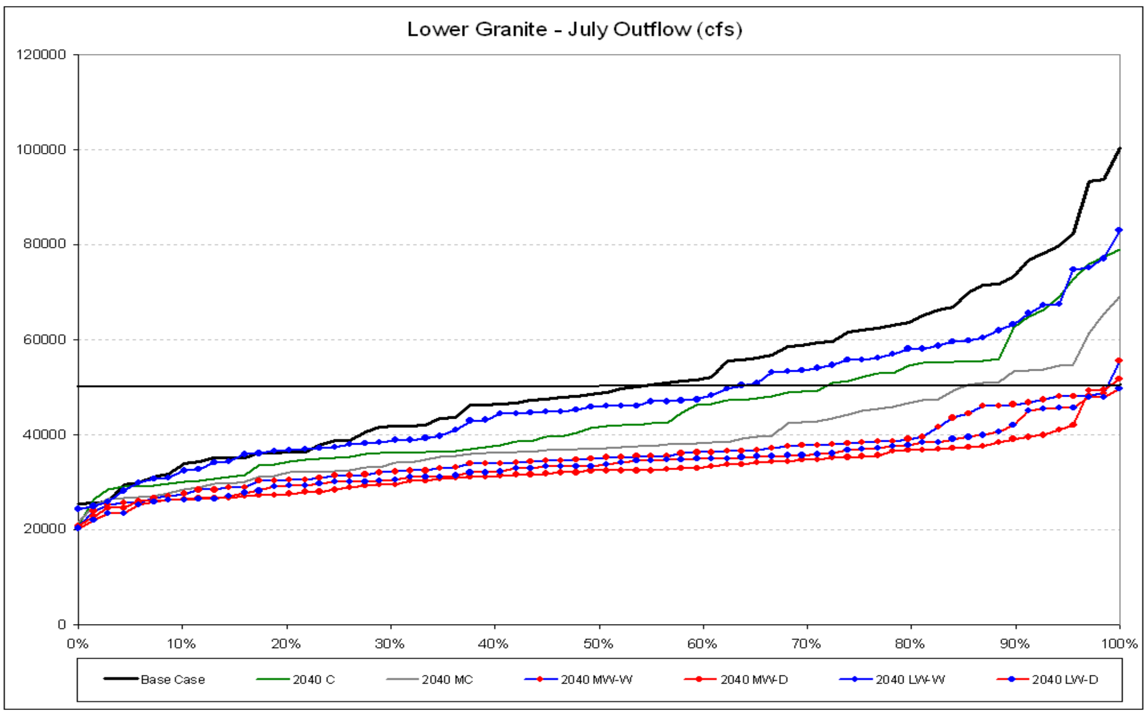

Figure 140. Comparison of 2040 Hybrid-Delta scenarios - July Lower Granite outflow distributions

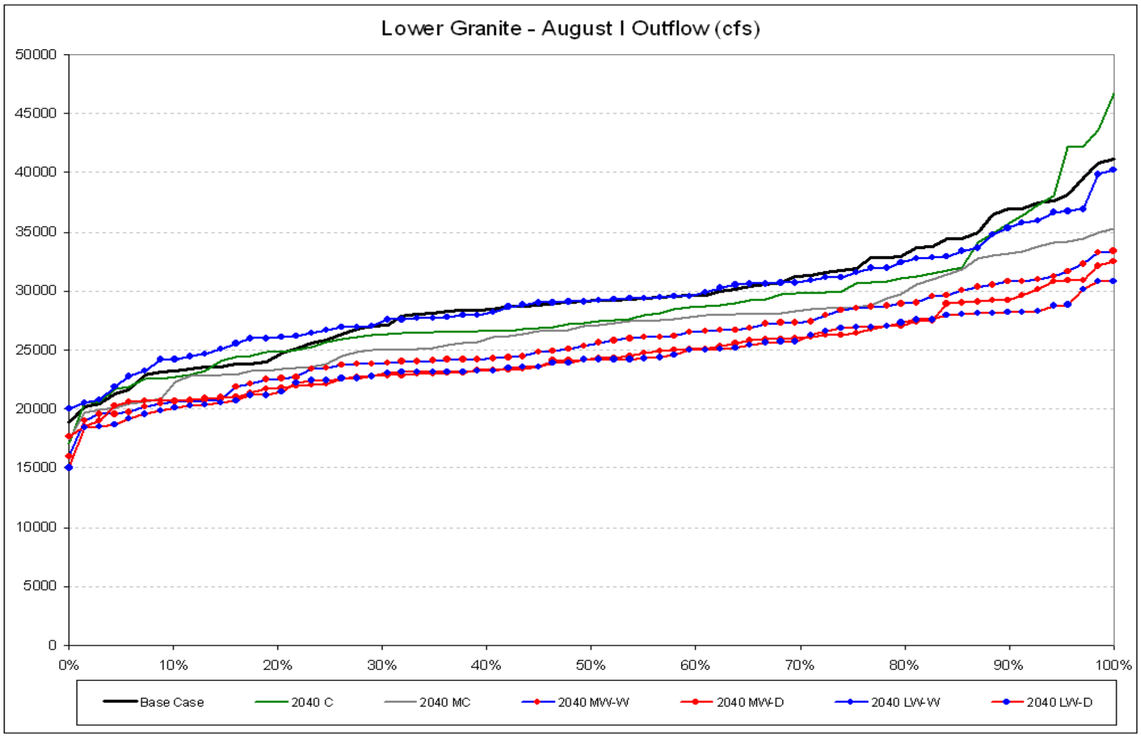

Figure 141. Comparison of 2040 Hybrid-Delta scenarios - August I Lower Granite outflow distributions.

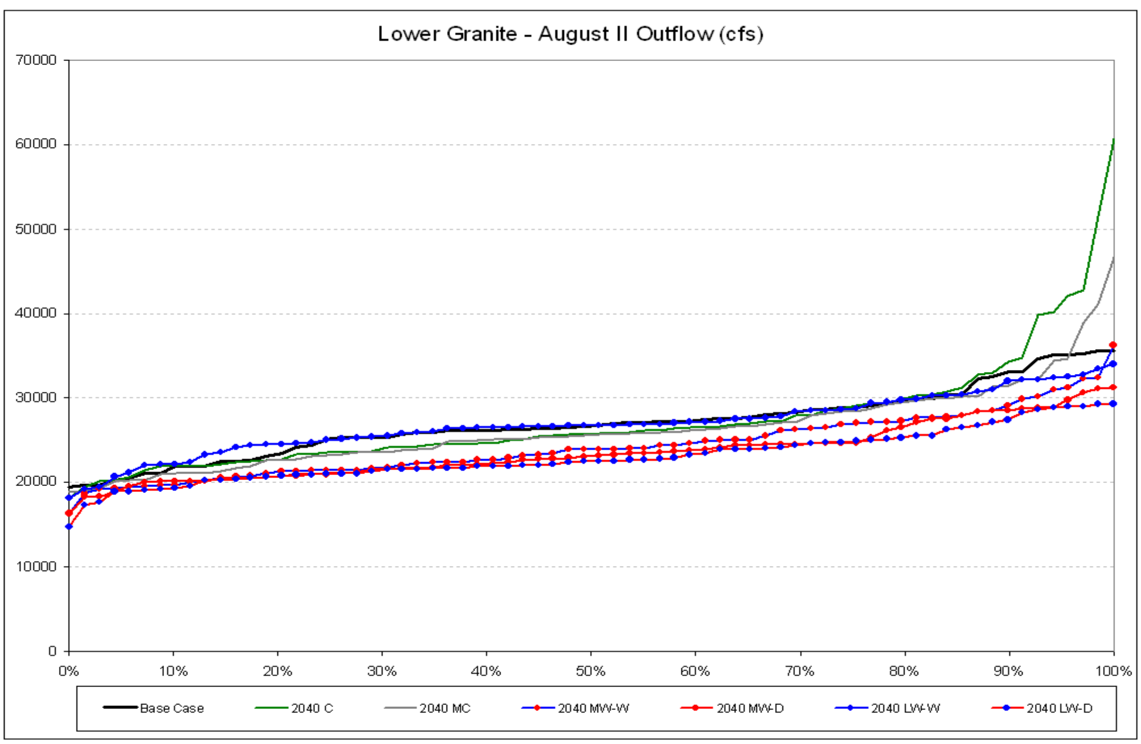

Figure 142. Comparison of 2040 Hybrid-Delta scenarios - August II Lower Granite outflow distributions.

11.4 Spill Impacts

The HydSim model classifies five types of spill. The classification and description are as follows:

- Forced Spill: This spill level is defined as the flow level greater than the maximum turbine discharge;
- OverGen or "Lack-of-Market" Spill: This is the spill amount that could not be run through the turbines because the Region was assumed to be in an excessive generation condition with all available markets saturated (no more opportunity to sell);
- Bypass or "Fish" Spill: This is the amount of spill as a result of the BiOp Fishery spill requirements. This is generally during the April-August period;
- Other Spill: This is the amount of spill due to project leakage, navigation lock activity and misc.; and
- Total Spill: This is the summation of the four types of spill described above.

Spill amounts are derived from the total discharge through a project (consisting of generation flow and spill flow), the amount of spill required by constraints such as BiOp Fish Spill requirements and the assumed amount of energy that can be reasonably sold on the market.

Occasionally the region will encounter a "saturated" market condition. This typically happens with very high flows on the system and/or with high levels of non-hydro generation such as wind farms that are generating at high levels. If the excess generation cannot be sold and project discharge levels cannot be reduced then hydro projects are forced into a spill for lack-of-market type of condition. Note that the likelihood of these occurrences increase as added wind generation comes on line. Market spill occurrences increases as loads are reduced and conversely decrease as system loads increase.

All the scenarios for the HD 2020s were run using a load forecasted for this period (2020). This load forecast was higher than the load forecast used in the Base Case. Similarly, the loads assumed in the 2040s and the Transient flow scenarios was based on the load forecast for the 2040 period, which was significantly higher than the Base Case (see section 12.1). New resources will be added to the Federal system and the Region prior to the 2020 and 2040 periods. These resources will likely be a mix of renewable and thermal resources. In addition, energy efficiencies will likely be increasing in the future which would result in a decrease in loads. The forecasted future spectrum of new resources amounts and timing for coming on-line and for the forecast for future energy efficiency levels was beyond the scope of these hydro regulation studies. Because of the added loads in all of the climate change scenarios, the resulting surplus / deficits inventory would be less, in general than the amounts found in the Base Case. Energy amounts that exceed firm loads are referred to as “surplus” and can be marketed; energy amounts insufficient to meet firm loads are referred to as “deficits” and would require energy purchases. Additional load results in more flow through the turbines to generate power resulting in less need for forced spill. The load growth assumed in the climate change scenarios prohibits an apples-to-apples comparison of the generation and spill amounts between the climate change scenarios and the Base Case. To overcome this hurdle, a select number of climate change scenarios were rerun using the identical loads of the Base Case to make a rough comparison of how climate change might impact generation and spill values without consideration of market limit conditions.

Because of the significant effort required to rerun studies, two climate change scenarios were chosen for the 2020s and two for the 2040s. As spill and generation both increase with higher inflows, the high flow cases for both of these period studies along with the central change scenarios as a more modest change comparison, were selected. The scenarios selected were: 2020 LW/W (high flow), 2020 C (Central change), 2040 MW/W (high flow) and 2040 C (Central change).

11.4.1 Spill Comparisons

This section contains figures comparing total spill amounts between the four climate change scenarios and the Base Case. These comparisons are made for the four storage reservoir projects; Libby, Hungry Horse, Grand Coulee and Dworshak and for the two run-of-river projects Lower Granite (Snake River) and McNary (Columbia River).

Climate-change spill impacts at Libby are limited to a nominal amount on average, with the notable exception of the 2040 MW/W scenario as seen in Figure 143 below. The significant increase in spill can be attributed primarily to the high natural inflows into Libby as well as the operation of the project as agreed to by the U.S. and Canadian Entities. Note that the average spill increase in May of 10,000 cfs correlates to an average increase in natural inflows of approximately 17,000 cfs, (see Figure 144).

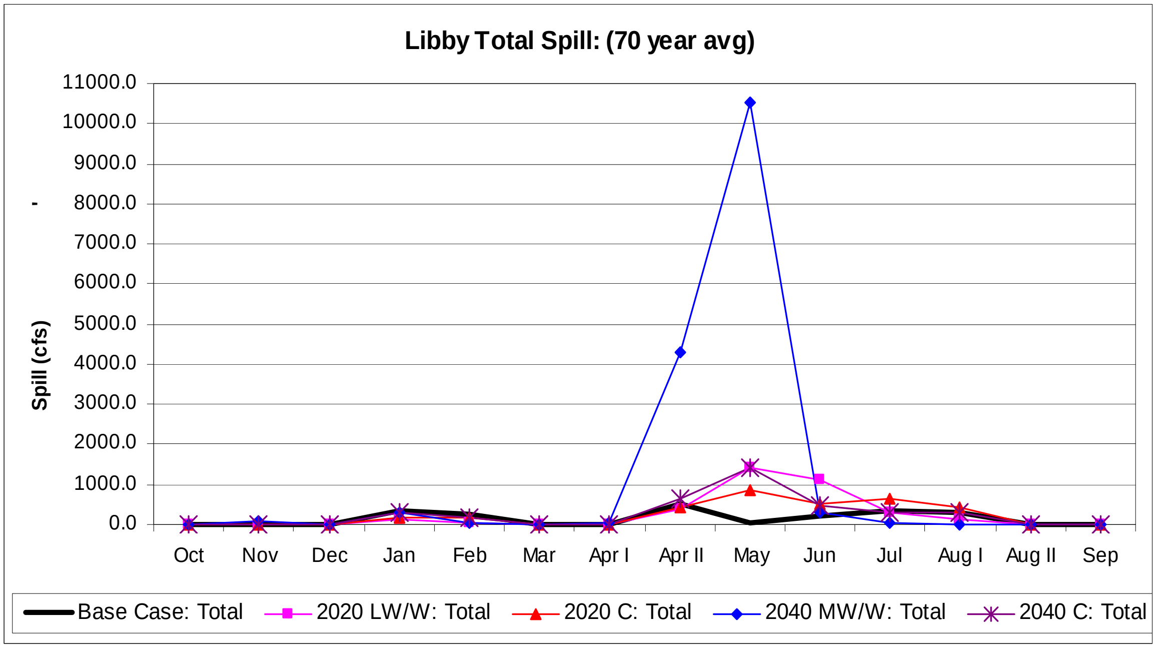

Figure 143. Libby Spill Comparison.

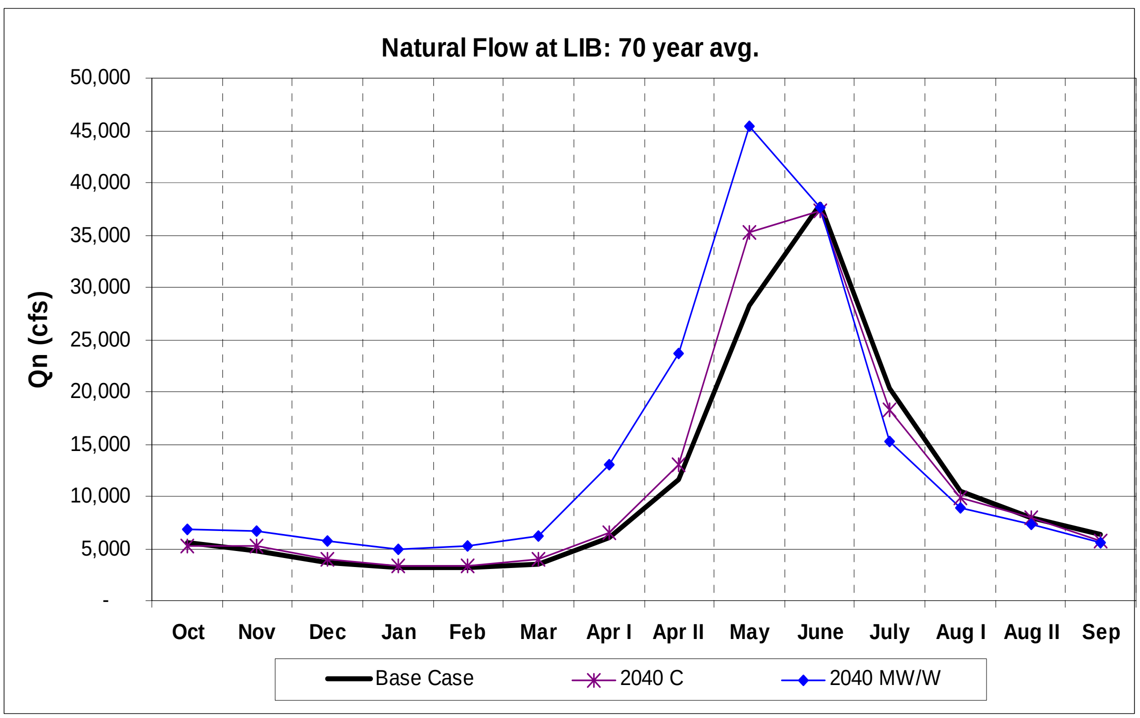

Figure 144. Libby Natural Inflows for 2040s.

Hungry Horse displays a spill increase in the second half of April in a similar manner that Libby displays in May (Figure 145). Hungry Horse currently operates to meet a minimum flow of 3,500 cfs at the Columbia Falls control point located downstream on the Flathead River, during the winter months, as the project fills to its URC elevation on April 10. The natural inflows during the second half of April increase from an average monthly value of 7,000 cfs in the Base Case to 14,000 cfs in the MW/W scenario (Figure 146). The additional 7,000 cfs of natural flow contributes to an average increase of approximately 4,000 cfs spill during this period.

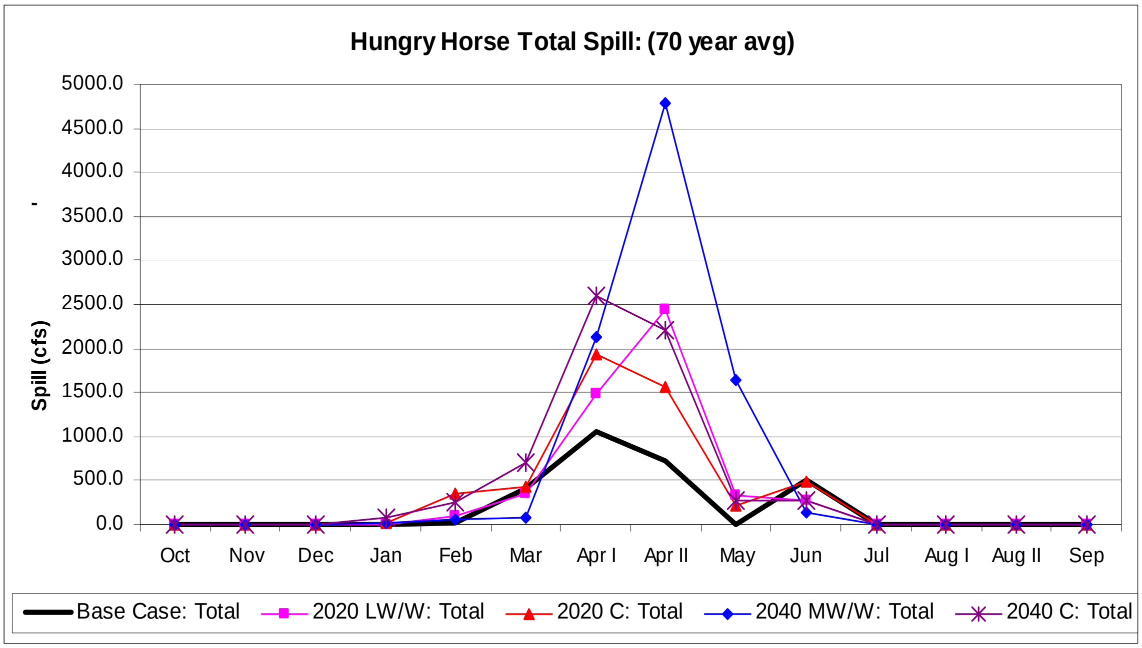

Figure 145. Hungry Horse Spill Comparison.

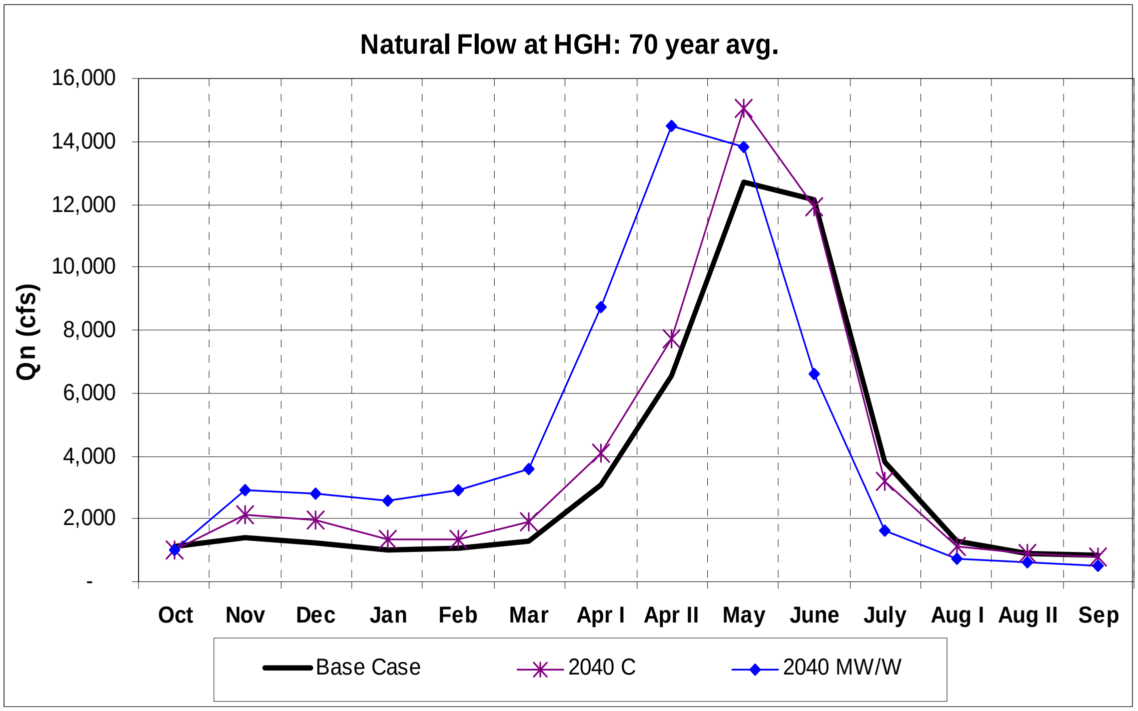

Figure 146. Hungry Horse Natural Inflows for 2040s.

The 2040 MW/W scenario has an accumulative impact on spill at the lower Columbia River projects such as McNary (Figure 150) as the high flows are observed throughout the Columbia River basin (see the graphs below for Grand Coulee, Dworshak, Lower Granite and McNary).

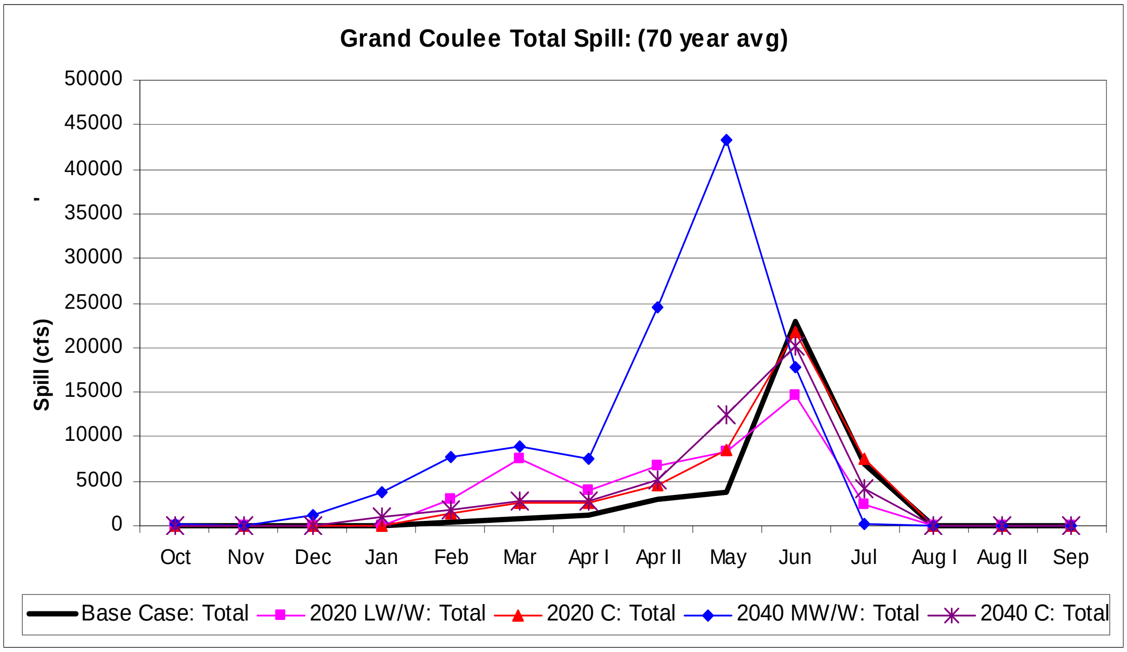

Figure 147. Grand Coulee Spill Comparison.

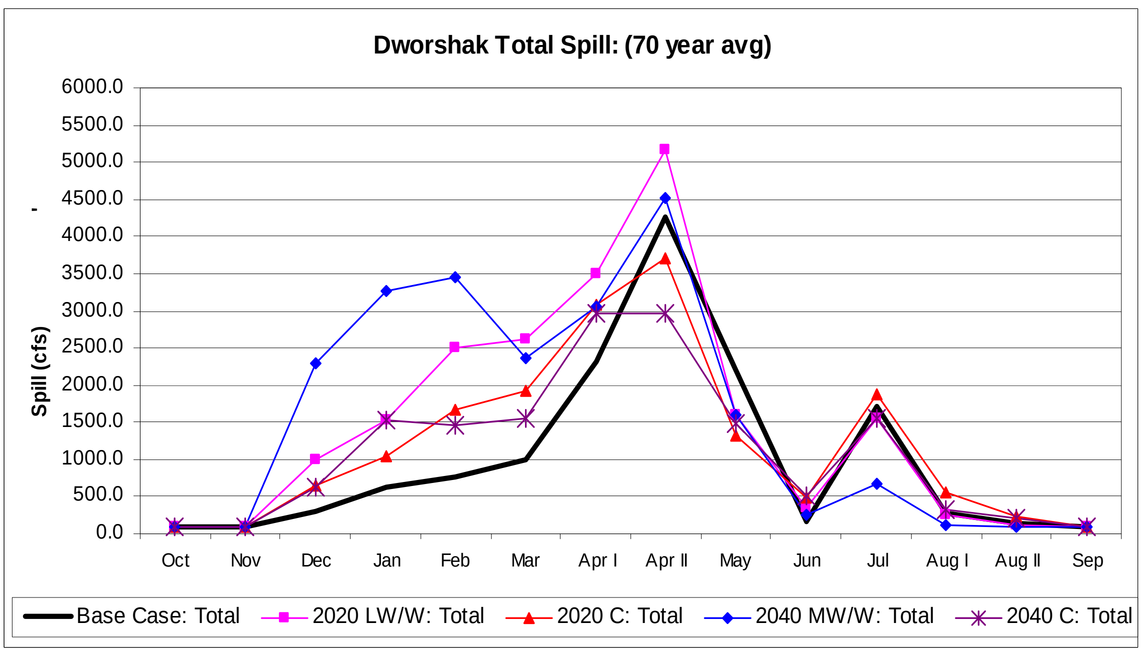

Figure 148. Dworshak Spill Comparison.

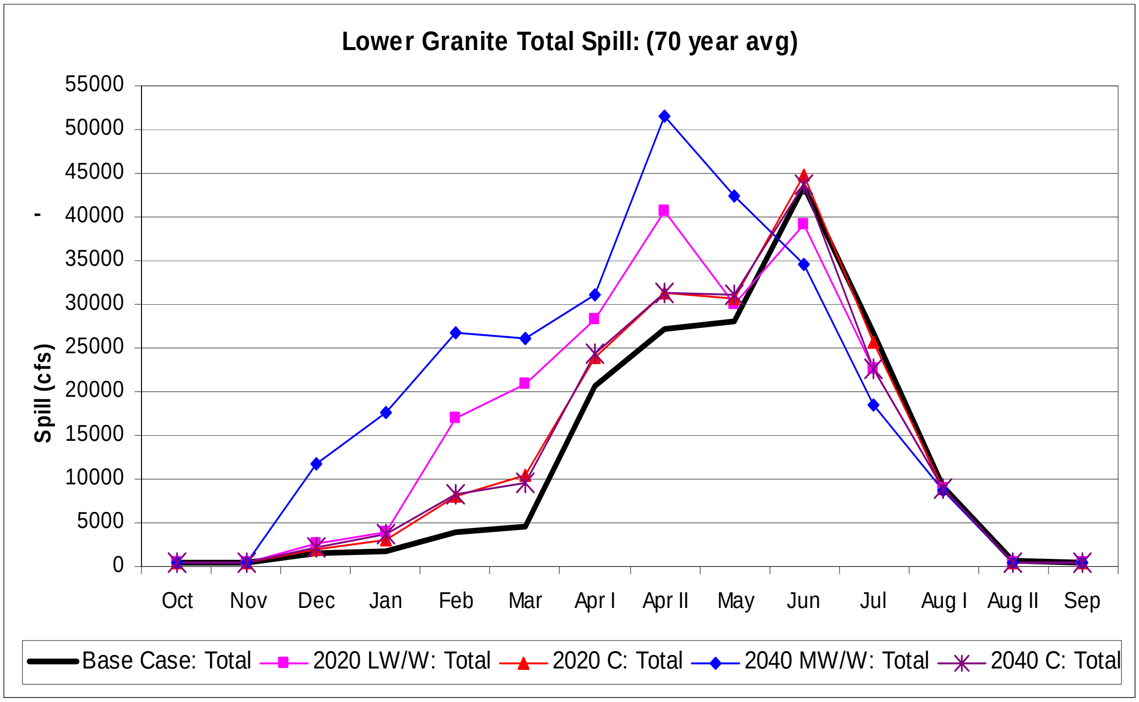

Figure 149. Lower Granite Spill Comparison.

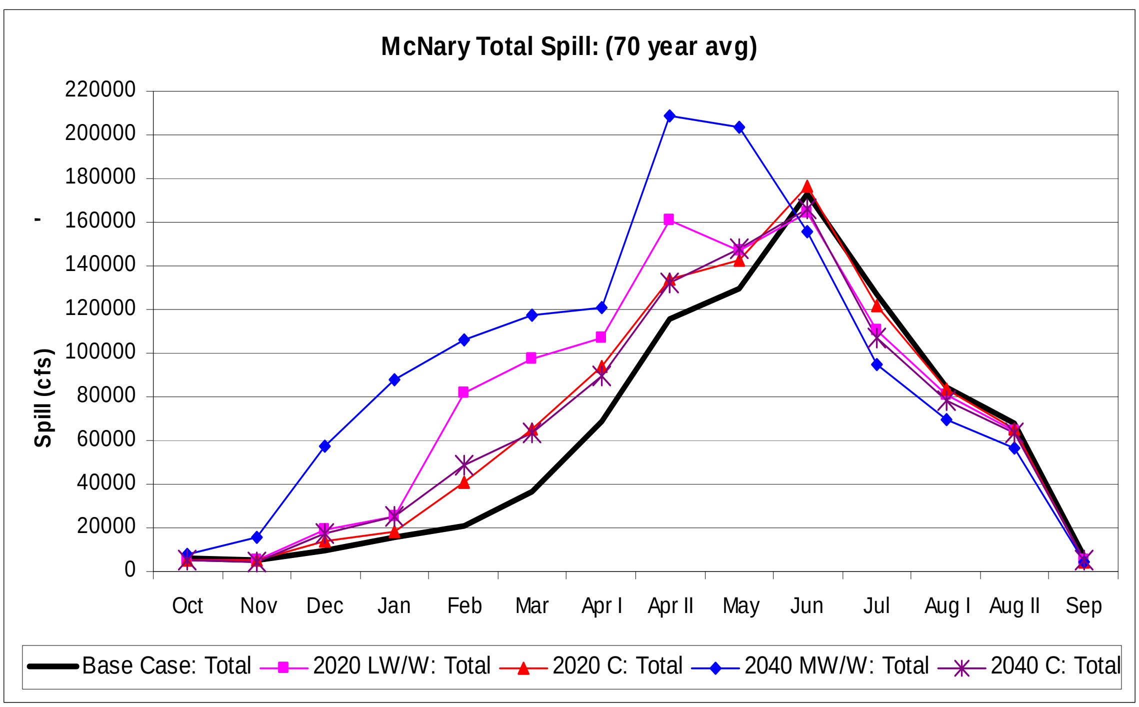

Figure 150. McNary Spill Comparison.

The Base Case breakdown into the Lower Granite spill components are displayed in Figure 151. The Central change scenarios are relatively similar in magnitude and shaping to the Base Case, Figure 152. The two wet scenarios (2020 and 2040) result in significant spill increases as would be expected under higher flow conditions, particularly in the months of February and March which are not traditionally spill periods (see Figure 153 for LWG and Figure 156 for MCN).

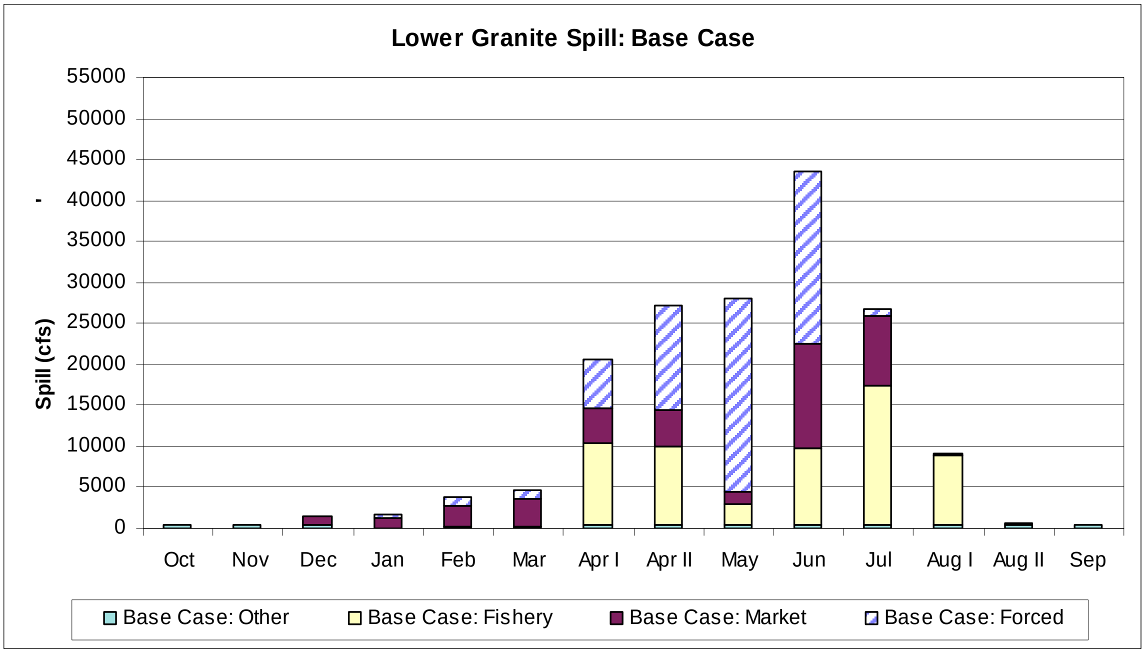

Figure 151. Base Case Lower Granite Spill Breakdown.

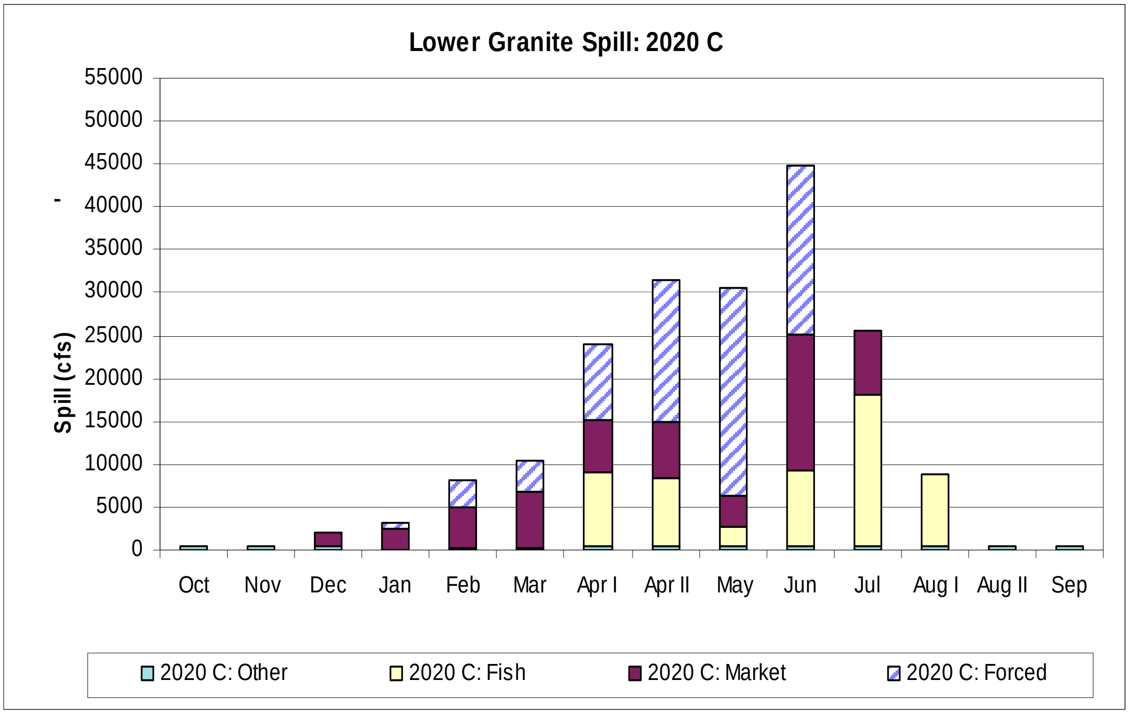

Figure 152. 2020 C Scenario: Lower Granite Spill Breakdown.

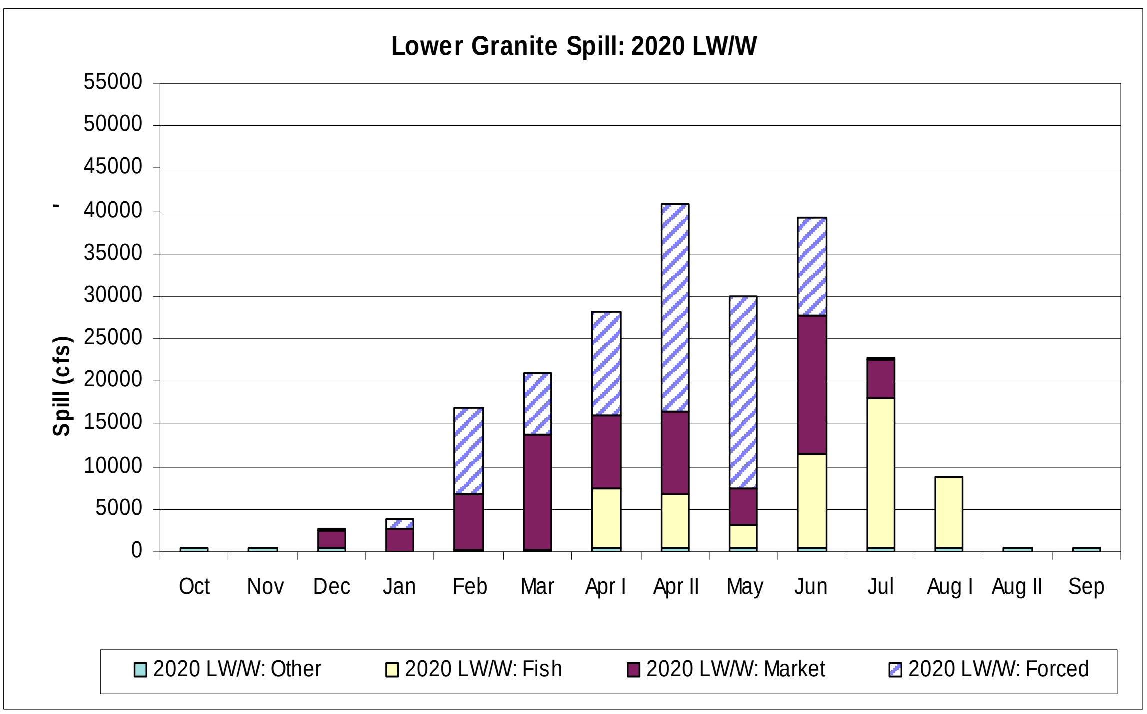

Figure 153. 2020 LW/W Scenario: Lower Granite Spill Breakdown.

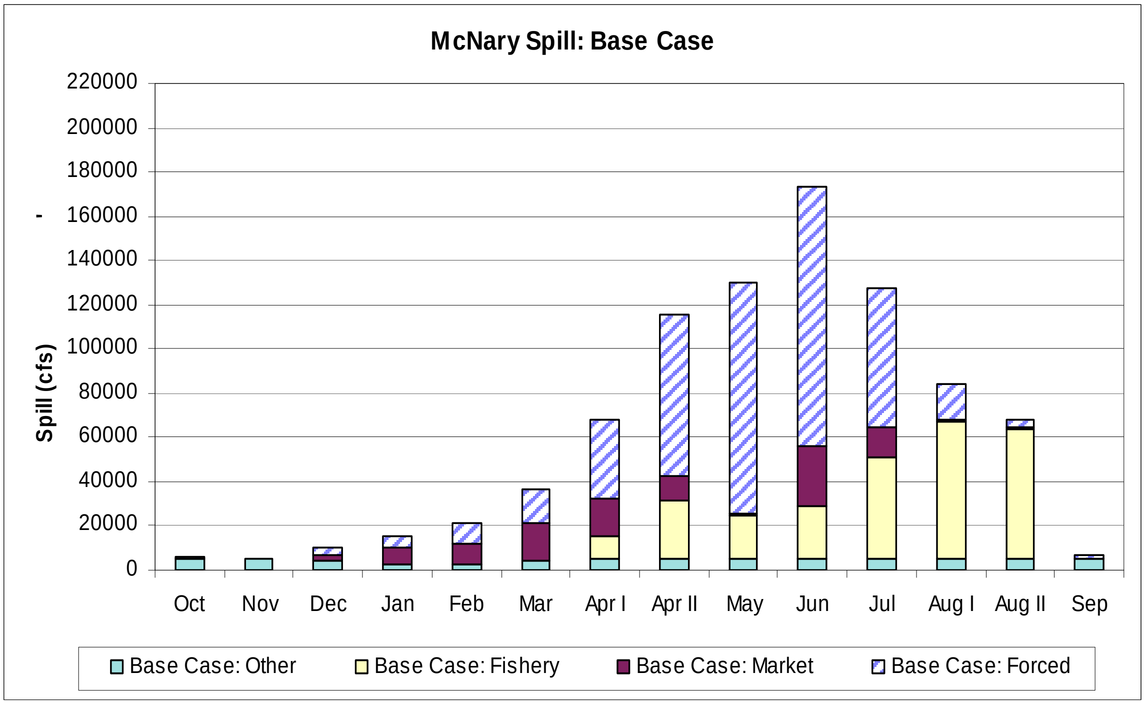

Figure 154. Base Case McNary Spill Breakdown.

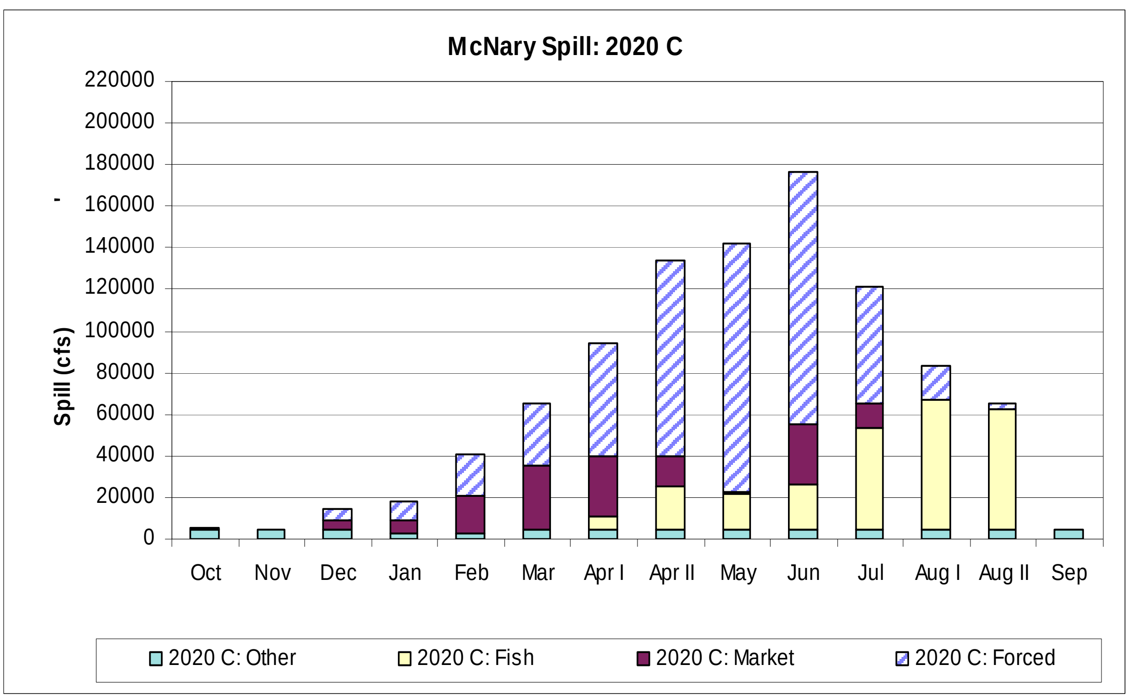

Figure 155. 2020 C Scenario: McNary Spill Breakdown.

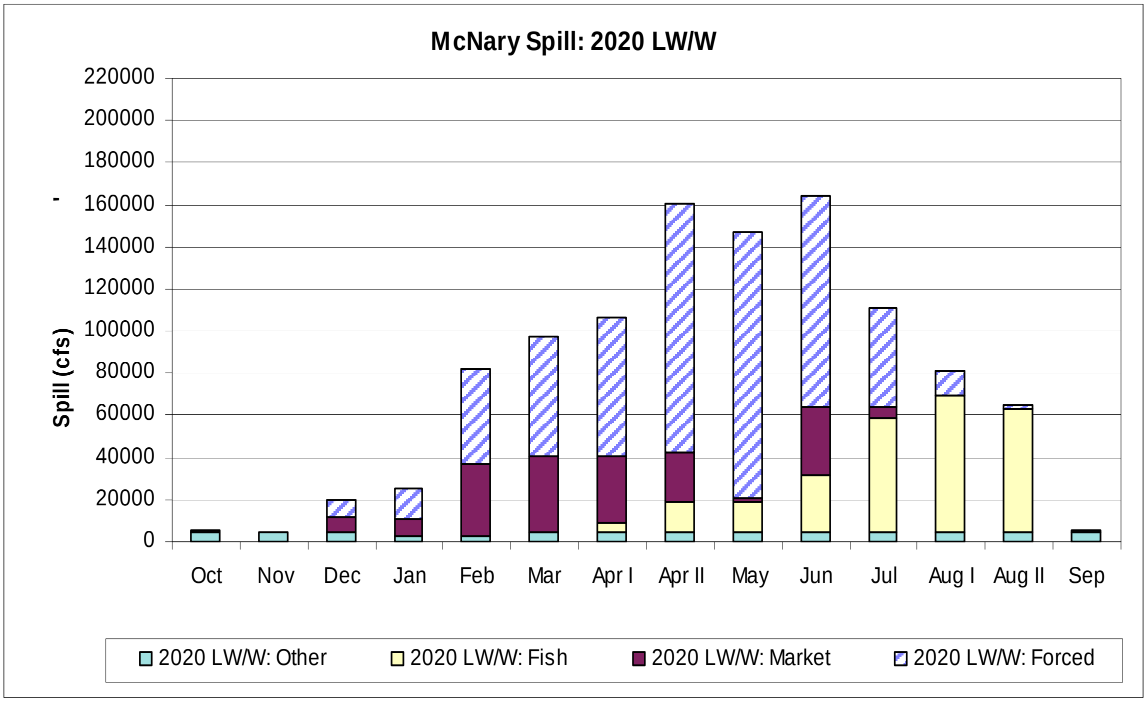

Figure 156. 2020 LW/W Scenario: McNary Spill Breakdown.

11.5 Generation Impacts

Climate change generation comparisons relative to the Base Case are shown in the following four figures. Generation comparisons to the Base Case are subject to the same market saturation limits described in Section 13.4 Spill Impacts. Because the load forecasts are higher in the climate change 2020 and 2040 scenarios, market limits are not reached as frequently as the Base Case and hence, generation comparisons are less reliable. To overcome this limitation, a selection of climate change scenarios were rerun using the Base Case (2012) loads. The same four study scenarios selected for the Spill comparisons were used to compare generation projections based on the Base Case loads and the climate change water supply. The four figures below reflect the same general trend of higher generation values in the winter-early spring period and reduced generation in the late summer periods.

The first two figures (Figure 157 and Figure 158) display the average 70-year generation projections for the Federal System (2020s and 2040s). The next two figures (Figure 159 and Figure 160) display the same projections for the Regional System.

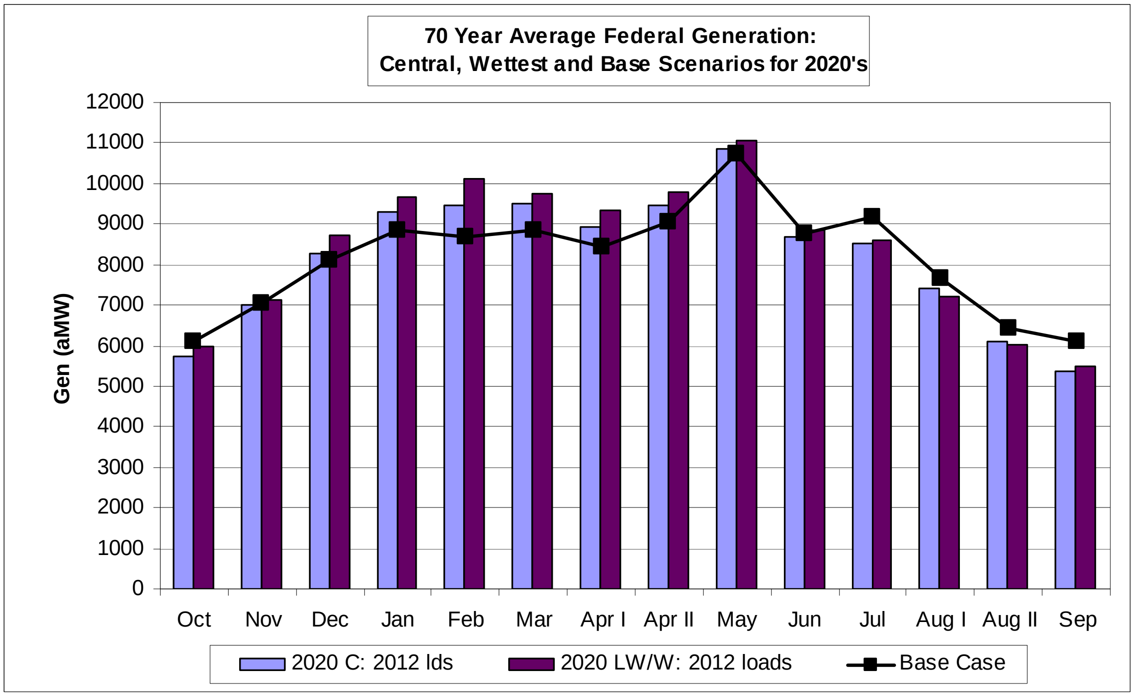

Figure 157. Federal Generation Comparison for Hybrid-Delat 2020s.

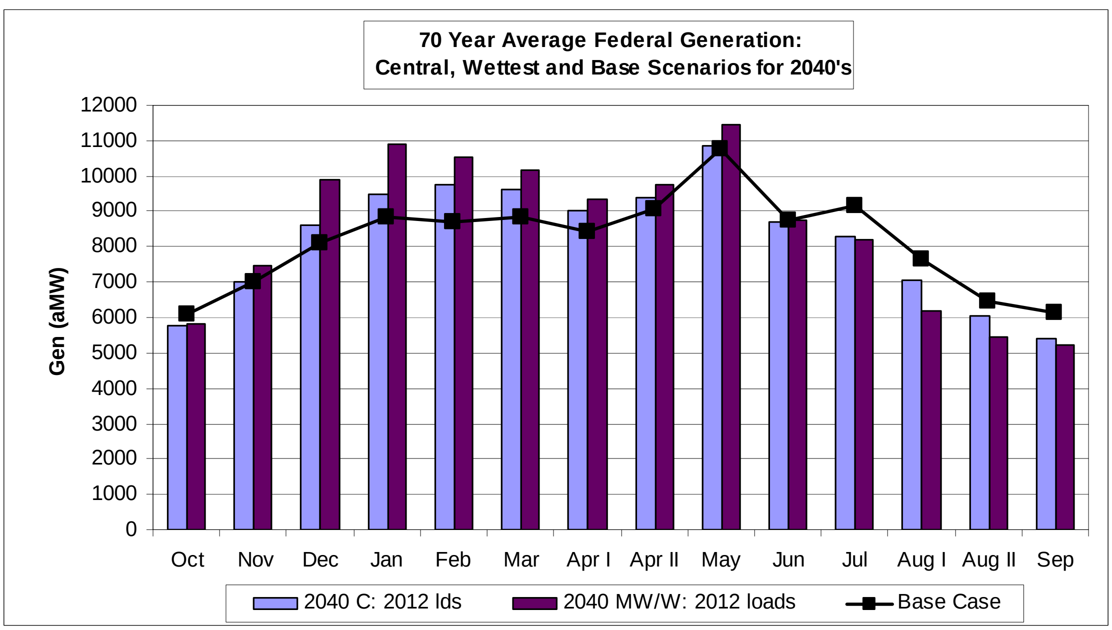

Figure 158. Federal Generation Comparison for Hybrid-Delta 2040s.

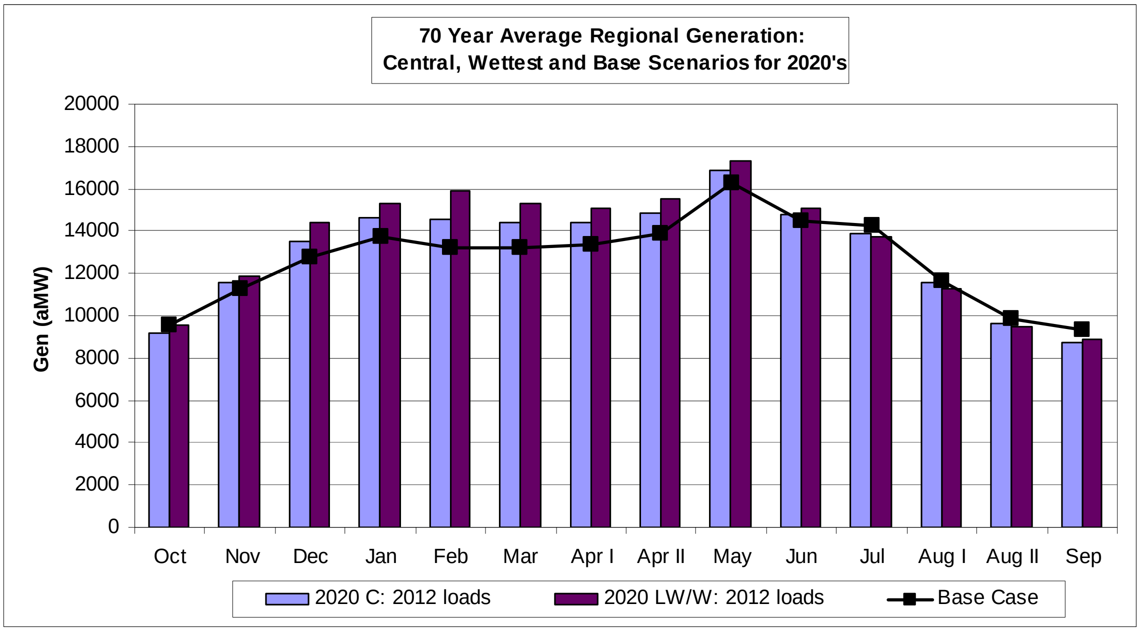

Figure 159. Regional Generation Comparison for Hybrid-Delta 2020s.

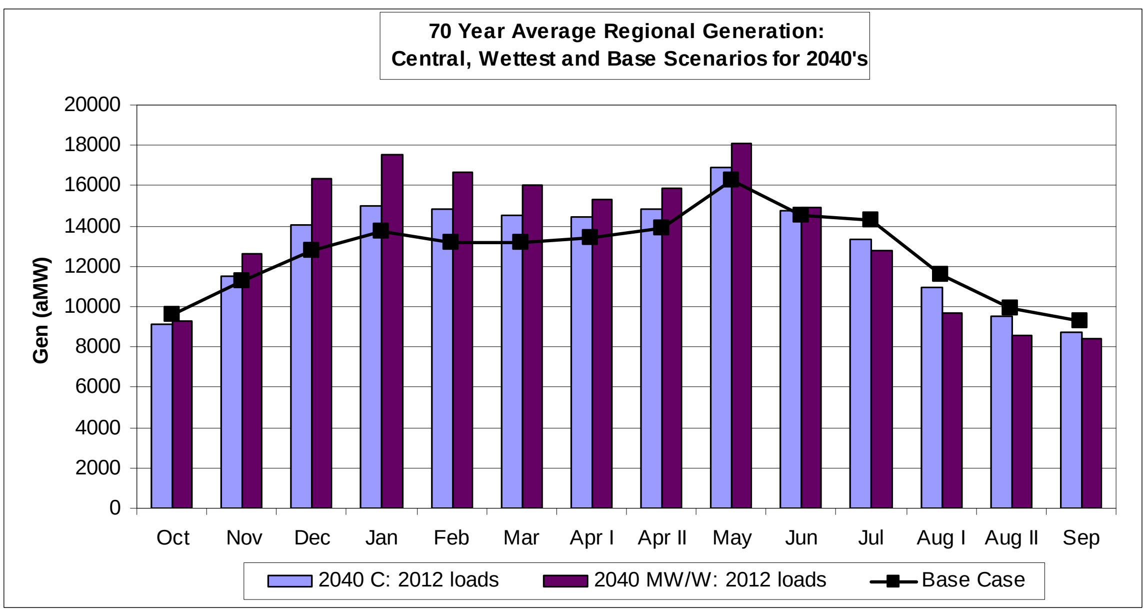

Figure 160. Regional Generation Comparison for Hybrid-Delta 2040s.

A comparison of climate change generation values compared to the Base Case is shown in Figure 161 and Figure 162 below for the Federal and Regional Systems respectively. The trend is similar in nature to the project outflows – namely higher generation during the winter and early spring months but reduced generation during the late summer period assuming 2012 loads. This trend increases in the 2040s relative to the 2020s. Note that the climate change generation impacts during the month of June, and to some extent May as well, are not as significant as one might expect at first glance. The reason for this is that the peak of the natural runoff occurs during this two month period and in most scenarios (Base Case and climate change) the natural flows are high enough to operate the projects at or near maximum turbine capacity. The additional flows are therefore manifested in higher spill amounts in general, during this two month period.

For the Regional 2020 Central scenario, winter generation increases approximately 1100 aMW, increasing to 2000 aMW in the 2020 LW/W (wet) scenario. The Regional 2040 Central scenario shows a winter generation increase of 1300 aMW, increasing to 3000 aMW in the MW/W (wet) scenario.

For the Regional 2020 Central scenario, late summer (July-Aug.) generation decreases approximately 200 aMW and a decrease of 400 aMW occurs in the 2020 LW/W (wet) scenario. The Regional 2040 Central scenario shows a late summer generation decrease of 650 aMW and a decrease of 1560 aMW in the MW/W (wet) scenario (Figure 162).

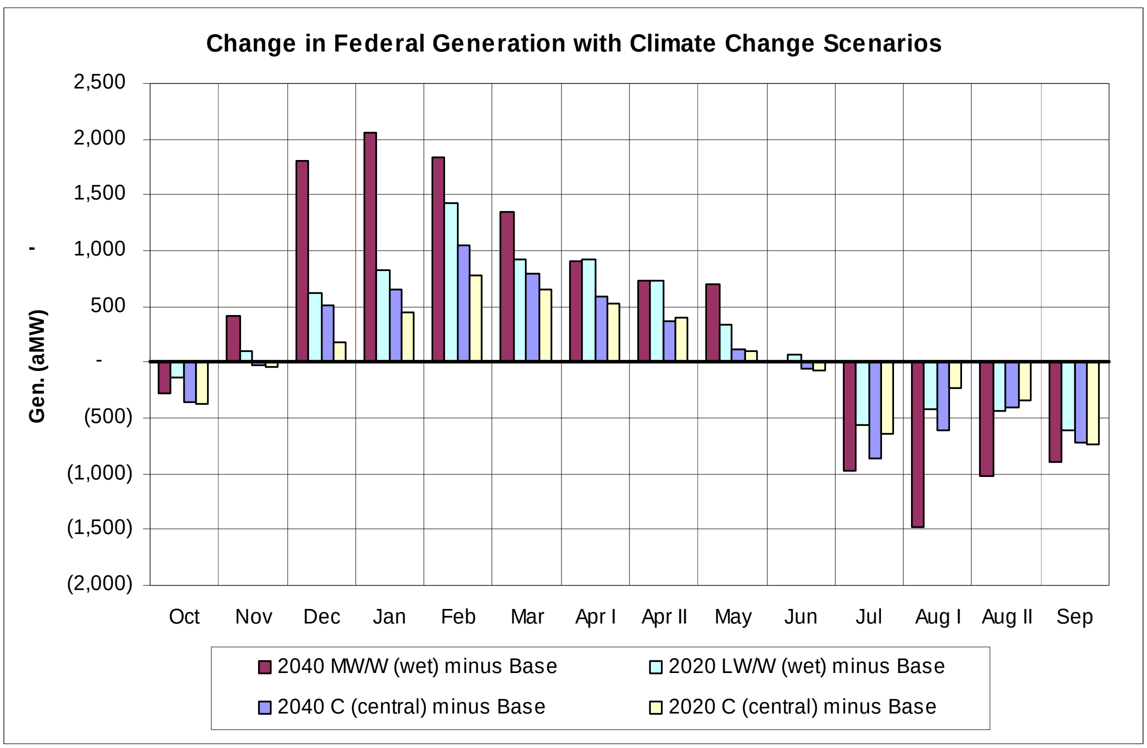

Figure 161. Climate Change Average Changes in Federal Generation.

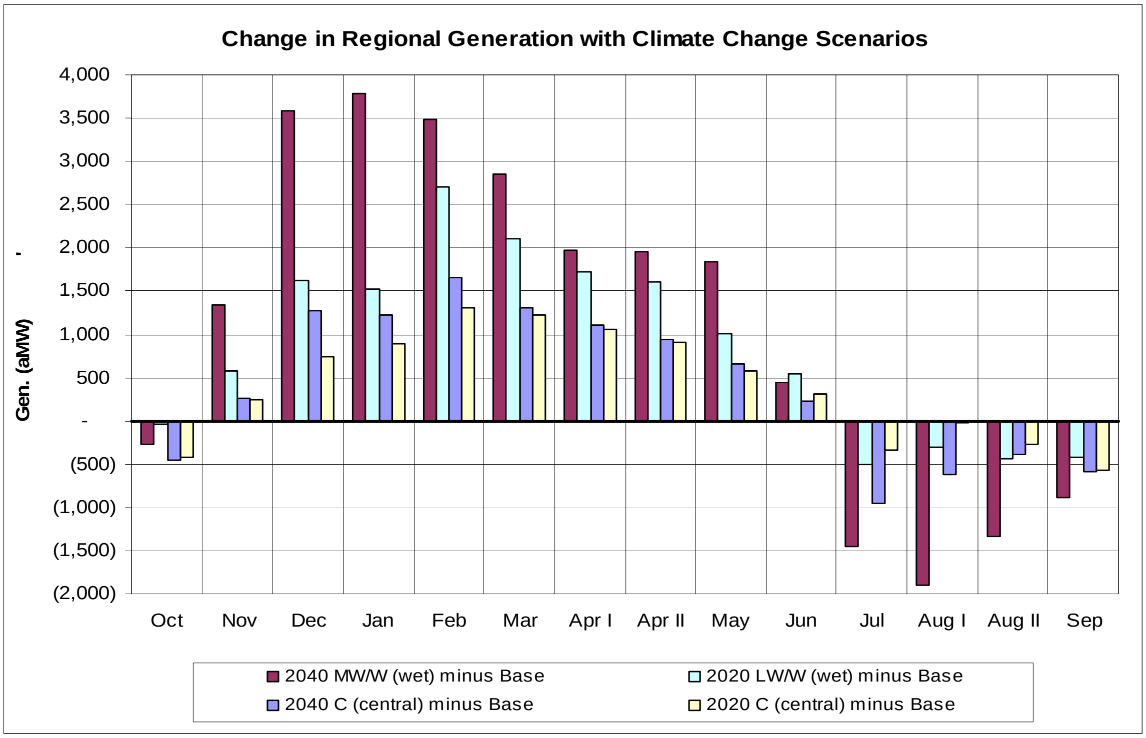

Figure 162. Climate Change Average Changes in Regional System Generation.

A comparison of Federal and Regional hydrogenation in the 2020 climate change scenarios is shown in Figure 161 and Figure 162 below. The Base Case scenario is not shown in these graphs for the same reasons described in Section 11.4. Note the high variability in the January through March periods, particularly in the Hybrid-Delta 2040s (Figure 165 and Figure 166).

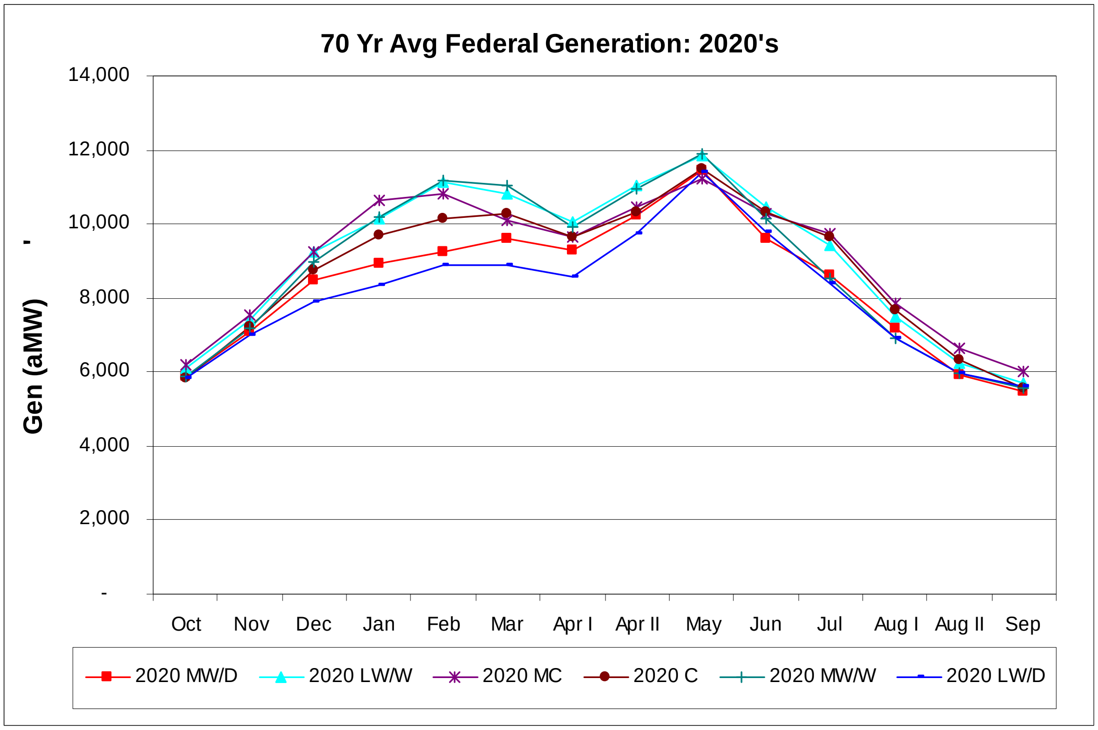

Figure 163. Federal Generation for Hybrid-Delta 2020s Scenarios.

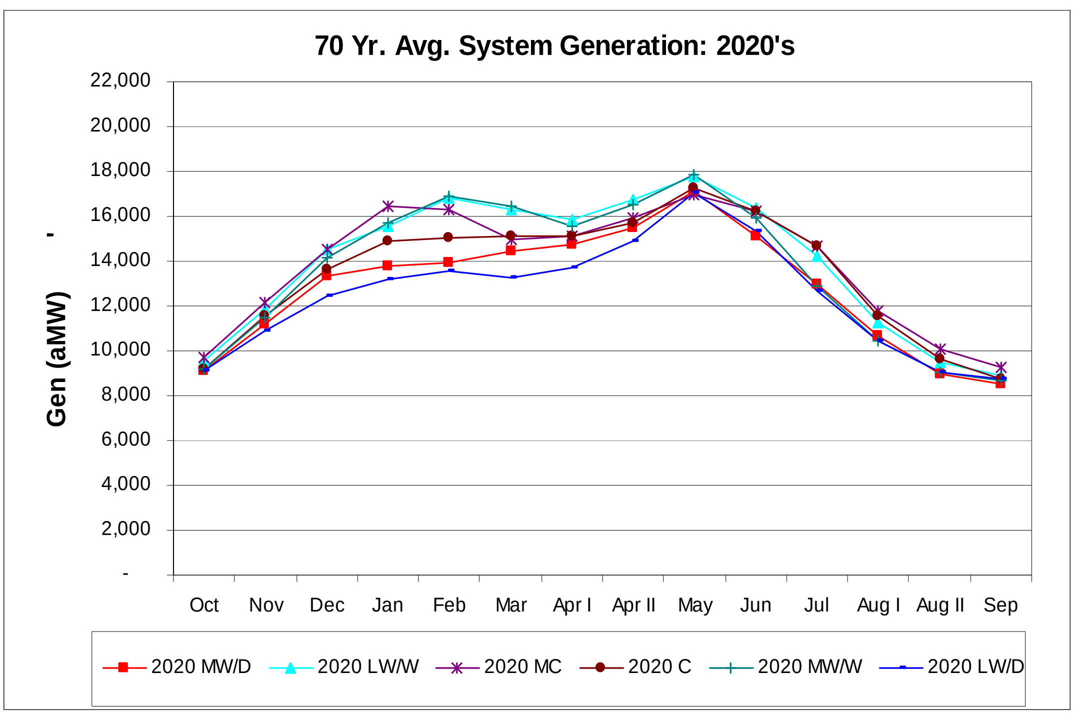

Figure 164. Regional System Generation for Hybrid-Delta 2020s Scenarios.

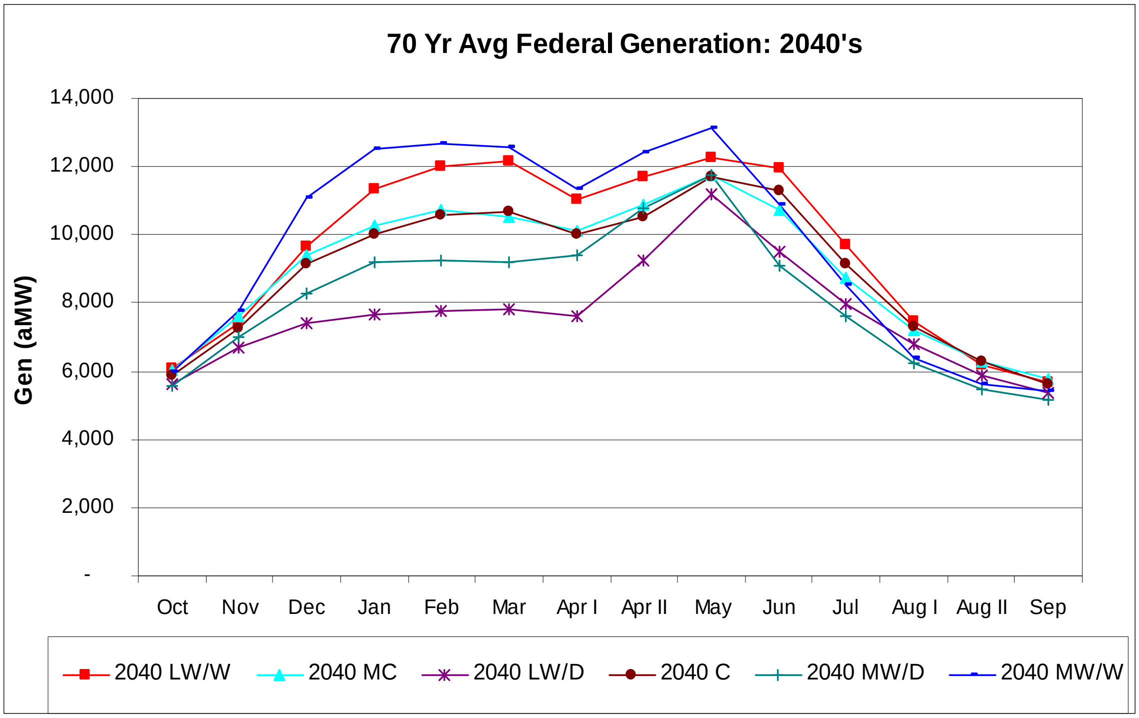

Figure 165. Federal Generation for Hybrid-Delta 2040s Scenarios.

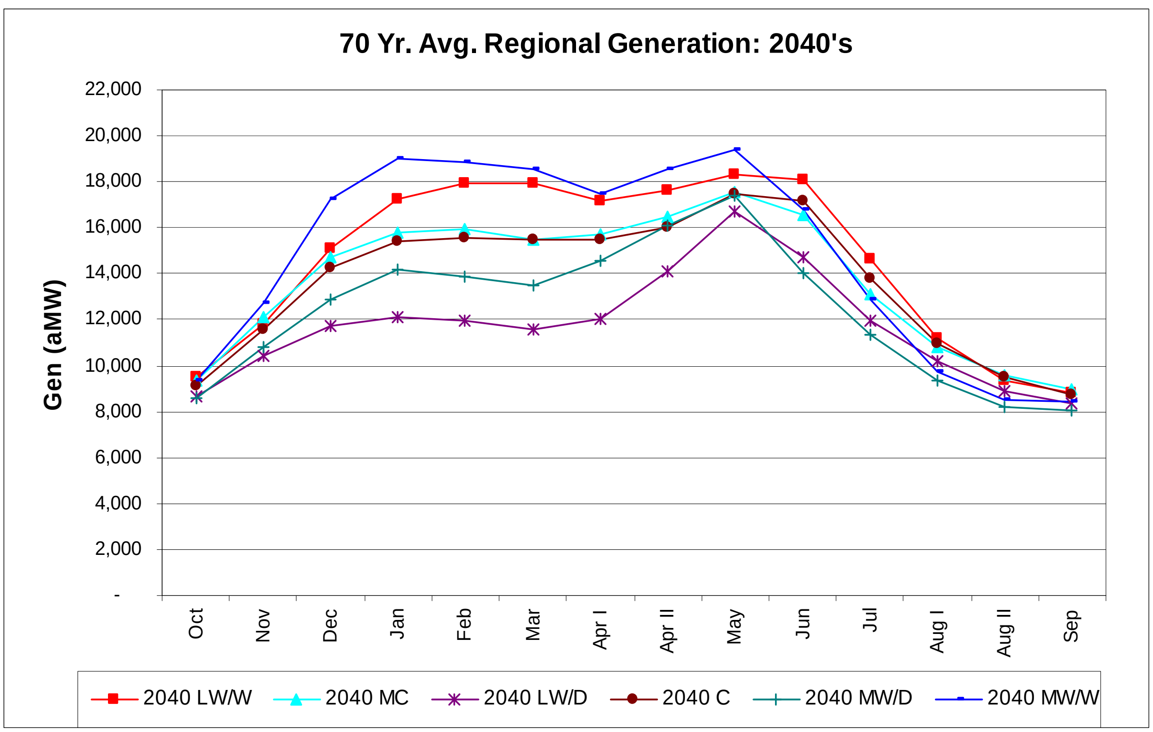

Figure 166. Regional System Generation for Hybrid-Delta 2040s Scenarios.

12.0 RESERVOIR OPERATIONS UNCERTAINTIES AND LIMITATIONS

12.1 Flood Control Impacts on Operations

The uncertainties associated with the flood control preparation have been described in more detail in Section 7.0. The lack of daily time-step modeling during the refill period prevented the ability to balance the multi-objectives; such as refill, fishery operations and flood control, and add to the uncertainty of the resultant summer discharges from the storage reservoirs. While the monthly average flows during the May through June period may be reasonable indicators of the level of flood control concern, the reader is cautioned to put too much weight in any one month as a more detailed daily modeling may reflect a smoother flow regime across the May through June period. Notwithstanding this lack of tuning to the modeling results, it is worth noting that actual peak flows in any given month may far exceed the month average depending on the nature of the natural flow runoff and the ability of the storage projects to capture high peak flows.

In addition to the lack of daily time-step modeling and more precise tuning, the fixed URCs for flood control in December (for some projects) and the variable URCs for the all the storage projects during the Jan-April period were developed using historical periods that may not capture the natural flow characteristics seen in the future climate change scenarios. A more detailed analysis of climate change precipitation and temperature patterns might suggest modifications to the current January through April SRDs used in guiding the storage projects. Any modifications to these SRDs would result in changes to the operations (including winter operations) that are presented in this Part. As noted in Section 13.0, future studies will be needed to investigate whether changes to flood control operations would be warranted.

12.2 Operational Uncertainties and Limitations

There are several modeling limitations that should be noted. This Part contains results from 26 scenarios. Each scenario consists of 70 different hydrologic years. In terms of focusing very closely on the final regulation of each of the 6 primary Federal storage projects for each study period, one would need to assess; 6 projects * 26 scenarios * 70 years * 14 periods = 152,880 operations. Because of the sheer number of operations modeled, it was not feasible to perform a “hand-tuning” of water-year specific reservoir operations as one might do if one were running only one scenario. The focus was therefore on maintaining consistency between the scenarios while maintaining a high level of modeling reasonable operations. As an example, the flood control refill percentage at Grand Coulee assumed the reservoir would refill 43% of the flood control space drafted on April 30, during the month of May (percent of the space on April 30th to be filled in May, see Table 2), for each year. If one had the time to hand-tune the hydro regulation, it might be more realistic to have some years at say 30% and other years at say 60%. Similarly, the assumption associated with storing and releasing 1.0 MAF of storage in Arrow Lakes would likely vary from year to year. However, the assumptions were all applied consistently in each scenario so that the change or deltas between the studies would still be applicable as a good and reasonable attribute of climate change.

Operational objectives – particularly the fishery objectives are subject to change over time. Any future set of assumptions on fishery requirements must therefore be considered under an envelope of change.

The rule curves that were developed for the studies in this Part all assumed no changes to current process or inputs. Many of these rule curves are directly correlated to volume forecasts. Climate change may result in some revisions to these processes or volume forecast periods. Such revisions would also result in different results.

Finally, any planning horizons that stretch out over the next 50 years or so could not possibly anticipate notable changes in technology, resources, efficiencies and energy policies. These variables could have an equal or greater bearing on the operational characteristics of the Columbia River Basin as climate change.

13.0 NEXT STEPS

The next steps in the investigation of climate change are first, to understand the meaning of climate change data, and second, their limitations. Understanding the proportion of runoff between rainfall or snowmelt is needed to ascertain the level of predictability. Climate change scenarios other than those selected for this study should be evaluated and assessed and be considered for further analyses. In addition, glacial snowmelt information, not available at the onset of this study should be considered in future climate change data sets.

Developing suitable methods for temporal downscaling from monthly General Circulation Models to daily data - for example the daily flows used to compute flood control curves - is challenging. Furthermore present methods for bias correction of monthly data to account for hydrologic models with inherent biases even after model calibration, and the subsequent disaggregation to a daily sequence need more exploration. The Corps will look to climate scientists and experts in the field to develop methods appropriate for use.

In parallel, preliminary daily modeling could be performed, to set up tools and procedures for future modeling, and to identify areas of concern to guide future paths. The preliminary modeling would consist of developing a test run of climate change daily streamflow input data. Processes and tools to convert daily flows and forecast data into an input format usable by the flood model should also be developed. To assess the effectiveness of using current procedures on climate change flows, flood control modeling should be performed to determine peak regulated flows and compared to the 2000 Level regulated flow frequency curves. In addition daily modeling can help to determine if earlier spring peaks are problematic with current methods. Resulting peak flows during the winter events may also be analyzed.

If preliminary modeling shows that climate change has an undesirable effect on the regulated frequency of peak flows (i.e., an increase in the frequency of flows at levels that cause flood damages), then the next step would be to determine how flood control operations should change to reduce flood impacts. However, this is dependent on developing regionally accepted methods and processes to create climate change daily flow and forecast data for input into reservoir models.

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) is now underway. The final reports of this assessment may be available early 2015. The data associated with this report has its roots in the AR4 Report (2007). It is anticipated that each new IPCC Assessment will contain new and refined information with improvements made in many areas. This RMJOC effort will likely be updated and revised as new information and data feeds through the global and regional scientific community.

14.0 LITERATURE CITED

Parenthetical Reference	Bibliographic Citation
	U.S. Corps of Engineers. 2003. *Columbia River Treaty Flood Control Operating Plan.* Corps of Engineers, Northwestern Division, North Pacific Region, For the United States Entity. May 2003
	U.S. Corps of Engineers. 1991. *Review of Flood Control Columbia River Basin, Columbia River and Tributaries Study, CRT-63*. U.S. Army Corps of Engineers, North Pacific Division. June 1991.
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	Climate and Hydrology Datasets for use in the RMJOC Agencies' Longer-Term Planning Studies: Part I – Future Climate and Hydrology Datasets. U.S. Department of the Interior, Bureau of Reclamation, Pacific Northwest Regional Office, U.S. Corps of Engineers, Northwestern Division, and Bonneville Power Administration. December 2010.

15.0 RESULTS ON CD

A compilation of the entire set of Climate Change HydSim modeling results has been downloaded onto a CD. The CD contains the following:

1. Instructions; “A_Read_me_first.doc”
2. Instructions for viewing results; “Using Sumreptdb.doc” and “Data types available in database.doc”
3. The database querying worksheet; “SUMREPTDB.XLS”
4. Five Directories containing the Study Result Databases
    a) Base Case Studies
    b) Hybrid-Delta -2020
    c) Hybrid-Delta-2040
    d) Transient flows
    e) Rerun_2012_loads

The purpose of producing the modeling results CD is to provide addition results that are not contained in the body of this report as well as providing the data in a format (Excel), that can be easily viewed or copied for addition use or processing.

16.0 APPENDIX A

Hydro Project Information

Project Information

		Federal Projects Name	Abrev.	In Service Date	Operator	# Units	Plant Capacity (1) (MW)	Max. Elev. (ft)	Min. Elev. (ft)	Max. Stor. (ksfd)	Max H/K (MW/kcfs)	Res. Lgth. (miles)	Dam Type	River, State
Lower Columbia	1	BONNEVILLE	BON	1938	Corps	20	1077	77.0	70.0	267	4.4	44	ROR	Columbia, OR/WA
	2	THE DALLES	TDA	1957	Corps	24	1808	160.0	155.0	NA	6.3	22	ROR	Columbia, OR/WA
	3	JOHN DAY	JDA	1971	Corps	16	2160	268.0	257.0	270	7.7	72	STO	Columbia, OR/WA
	4	MCNARY	MCN	1952	Corps	14	980	340.0	335.0	NA	5.2	50	ROR	Columbia, OR/WA
	5	CHANDLER	CDR	1956	USBR	2	12	618.5	NA	NA	8.0	NA	DIV	Yakima, WA
	6	ROZA	RZA	1958	USBR	1	11	1,220.5	1,220.5	NA	13.0	NA	DIV	Yakima, WA
Upper Columbia	7	CHIEF JOSEPH	CHJ	1958	Corps	27	2458	956.0	930.0	NA	13.0	51	ROR	Columbia, WA
	8	GRAND COULEE (2)	GCL	1942	USBR	33	6765	1,290.0	1,208.0	2,614	25.2	151	STO	Columbia, WA
	9	ALBENI FALLS	ALF	1955	Corps	3	43	2,062.5	2,051.0	582	2.4	65	STO	Pend Oreille, ID
	10	LIBBY	LIB	1975	Corps	5	525	2,459.0	2,287.0	2,511	26.7	90	STO	Kootenai, MT
	11	HUNGRY HORSE	HGH	1953	USBR	4	428	3,560.0	3,336.0	1,549	33.5	27	STO	Flathead, MT
Lower Snake	12	ICE HARBOR	IHR	1962	Corps	6	603	440.0	437.0	NA	7.4	33	ROR	Snake, WA
	13	LOWER MONUMENTAL	LMN	1969	Corps	6	810	540.0	537.0	NA	7.2	28	ROR	Snake, WA
	14	LITTLE GOOSE	LGS	1970	Corps	6	810	638.0	633.0	NA	7.2	39	ROR	Snake, WA
	15	LOWER GRANITE	LWG	1975	Corps	6	810	738.0	733.0	NA	7.3	28	ROR	Snake, WA
	16	DWORSHAK	DWR	1973	Corps	3	400	1,600.0	1,445.0	1,016	47.6	54	STO	Clearwater, ID
Upper Snake	17	BLACK CANYON	BCD	1925	USBR	2	10	2,498.0	2,478.9	6	6.4	7	STO	Payette, ID
	18	BOISE DIVERSION	BOI	1912	USBR	3	3	2,817.0	2,814.0	0	1.8	3	DIV	Boise, ID
	19	ANDERSON RANCH	AND	1950	USBR	2	40	4,196.0	4,111.3	177	23.5	13	STO	Boise, ID
	20	MINIDOKA	MIN	1909	USBR	4	28	4,245.0	4,236.0	48	15.6	26	STO	Snake, ID
	21	PALISADES	PAL	1958	USBR	4	176	5,620.0	5,497.9	605	16.0	18	STO	Snake, ID
Willamettes & Rogue	22	BIG CLIFF	BCL	1953	Corps	1	18	1,206.0	1,182.0	na	7.0	3	ROR	Santiam, OR
	23	DETROIT	DET	1953	Corps	2	100	1,569.0	1,425.0	162	26.2	9	STO	Santiam, OR
	24	FOSTER	FOS	1967	Corps	2	20	641.0	609.0	14	8.7	4	STO	Santiam, OR
	25	GREEN PETER	GPR	1967	Corps	2	80	1,015.0	922.0	158	23.2	10	STO	Santiam, OR
	26	COUGAR	CGR	1963	Corps	2	25	1,699.0	1,516.0	77	32.3	6	STO	McKenzie, OR
	27	DEXTER	DEX	1954	Corps	1	15	695.0	690.0	na	4.2	3	ROR	Willamette, OR
	28	LOOKOUT POINT	LOP	1953	Corps	3	120	929.0	819.0	170	17.0	14	STO	Willamette, OR
	29	HILLS CREEK	HCR	1962	Corps	2	30	1,543.0	1,414.0	123	23.3	7	STO	Willamette, OR
	30	LOST CREEK	LOS	1977	Corps	2	49	1,872.0	1,751.0	159	23.5	10	STO	Rogue, OR
	31	GREEN SPRINGS	GSP	1960	USBR	1	16	4,413.0		0	135.3	0	DIV	Keene/Emigrant Creek, OR
					Total		**20430**	**MW**		**10,507**	**ksfd**			

Other Projects of Interest

		Name	Abrev.	In Service Date	Operator	# Units	Plant Capacity (1) (MW)	Max. Elev. (ft)	Min. Elev. (ft)	Max. Stor. (ksfd)	Max H/K (MW/kcfs)	Res. Lgth. (miles)	Dam Type	River, State
		MICA	MCDB		BCH	4	1792	2,475.0	2,320.0	3,529	42.5		STO	Columbia, British Columbia
		ARROW	ARDB		BCH	2	185	1,444.0	1,377.9	3,580	65.5		STO	Columbia, British Columbia
		DUNCAN	DCDB		BCH	na	na	1,892.0	1,794.2	706	na		STO	Duncan, British Columbia
		BROWNLEE	BRN		IPC	5	728	2,077.0	1,976.0	710	20.0		STO	Snake, ID
					Total					**8,524**	**ksfd**			

Notes
(1) Nameplate rating from *"2010 BPA Facts"*
(2) Includes pump generation